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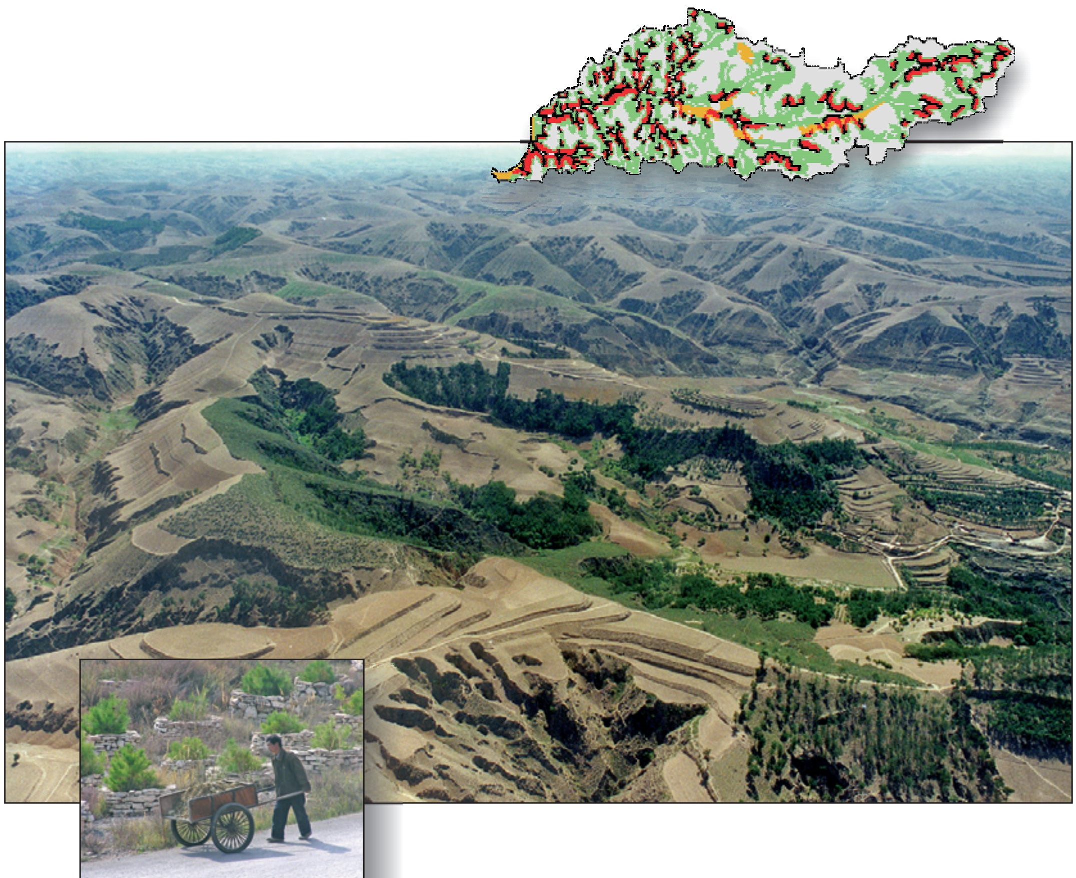
CSIRO Land and Water Technical Report 18/05



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Cover:
The main photograph is a typical landscape of the Coarse Sandy Hilly Catchments of the Loess Plateau, China. Severe gullying is present, some of which almost reach the ridges, to reduce erosion rates large areas of re-vegetation can be seen; this re-vegetation also reduces the water yield from this landscape. Summer cropping is conducted on the terraces and extensive grazing of sheep is undertaken throughout the landscape. This photo was taken by XianMo Zhu near Yan'an City, Shaanxi Province, May 1985. The bottom left insert shows a worker tending 5-year old pines; photo by Tim McVicar, Pianguan County, Shanxi Province, 7th October 2004. The top right insert is the re-vegetation map for the 127 km^2 ZhongZhuang catchment. The red cells are steep slopes and gullies ($\geq$ 15° from horizontal defined from the 100 m resolution DEM), green cells are the level 3 re-vegetation target areas, black cells define the priority re-vegetation areas where perennial vegetation will slow the water running off the steep slopes (also reducing the amount of sediment reaching the stream network), orange cells represent land-uses that exclude them for being used in the re-vegetation program, including water, urban, forestry, and highly productive agricultural land, and grey represents other unsuitable areas.

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Contents

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Further project information, including free access to the bilingual decision support tool ReVegIH (Re-Vegetation Impacts on Hydrology), are found at http://www.clw.csiro.au/ReVegIH/.

Executive Summary

The Chinese Central government's policy to re-vegetate large areas of the Loess Plateau is currently being rapidly implemented at the provincial, prefecture, county, township, and village levels of government. Managers at these five levels of government need access to information to assist them to plan the land use change prior to making on-the-ground decisions. To this end, the suitability of 38 predominately native species in the 113,000 km^2 Coarse Sandy Hilly Catchments (CSHC) study site has been mapped at a 100 m resolution. This was achieved by using a quint-variate spatial overlay approach as we were able to readily access the required environmental variables and rules defining the species' requirements (or tolerances). As the rules did not consider optimal growth they were possibly 'too inclusive', so the spatial extent of areas suggested for re-planting were refined by defining 'target areas' for trees, shrubs and grasses. In the land use planning criteria developed here we suggest that hill-slopes and gullies with slopes greater than or equal to 15 degrees (defined from a 100 m resolution DEM) be left for natural succession. Due to lateral flow of water (and sediment) from these steep slope and gullies, prioritising re-vegetation to areas adjacent to and downslope from the steep portions of the landscape will reduce sediment entering the river network. As these so-called priority areas are a subset of the target areas, this results in a minimal decrease of regional stream flow by performing the re-vegetation activities on a much smaller area. All of these functions are captured within the decision support tool called ReVegIH (Re-Vegetation Impacts on Hydrology) which allows users to determine: (1) what species are suitable for a specific location at a 100 m resolution; (2) where priority and target re-vegetation activities should be undertaken (again at a 100 m resolution); and (3) simulate the related hydrological impact at the catchment (or county) level.

The project team recommend that some detailed site assessment be undertaken prior to performing any re-planting as ReVegIH is a regional scale decision support tool, and local factors (near and below the resolution of the data used in the application) may be critical in determining success (or failure) of re-vegetation schemes.

1 Introduction

There has been increasing use of predictive vegetation mapping both globally and specifically in China over the last 30 years for a range of issues including: (1) ecological restoration planning; (2) biodiversity conservation planning; (3) site selection for afforestation programs; and (4) assessing disturbance impacts on the distribution and function of vegetation. Predictive vegetation mapping is based on ecological niche theory and vegetation gradient analysis, and it relies on the concept that vegetation distribution can be estimated from the spatial distributions of environmental variables that correlate with, or control, plant distributions (Franklin 1995). While the number and complexity of approaches to predict vegetation suitability (in both space and time) has increased dramatically over the last 30 years (for comprehensive reviews see Elith and Burgman 2003; Guisan and Zimmermann 2000) all methodological refinements aim to better model the fundamental associations between species and spatial distributions of environmental variables.

Elith and Burgman (2003) list seven main classes of predictive vegetation mapping approaches, they are:

1. conceptual models based on expert opinion;
2. geographic envelopes and spaces;
3. climate envelopes;
4. multivariate association methods;
5. regression analysis;
6. tree-based methods; and
7. machine learning methods.

All of these approaches are empirical, in that they are data driven, and are listed in ascending order with regard to complexity of statistical implementation (*i.e.*, 1 is the least complex, and 7 is the most complex); they do not incorporate issues governing population dynamics such as survival, dispersion and succession, so they are not mechanistic in nature. A conceptual model is the most general of the approaches as it allows expert opinion to be captured into a rule based analysis. These rules can be comprised of: (1) an algebraic formulation of key variables (that may be continuous or categorical); or (2) Boolean logical operators (*e.g.*, AND, OR, *etc*.) that define an environmental envelope based on limits of physiological tolerance. The conceptual model approach explicitly predicts vegetation suitability (or ‘potential natural vegetation’) rather then actual vegetation (Franklin 1995). Approaches 2 and 3 above require presence data describing a species environment, and

Elith and Burgman (2003) note that they can result in an overestimation of area mapped as suitable for individual species. Approaches 4 to 7 above require access to databases of presence-absence data at the level of the mapping performed and some complex statistical processing software. In a comparison of all seven methods, Elith and Burgman (2003) found a general correspondence between all 7 approaches when mapping *Leptospermum grandifolium* a small tree located in subalpine areas of southeast Australia. The resulting maps were perceived to be 'roughly equivalent', yet it was noted that in places they differed in important details.

The findings of Elith and Burgman (2003) indicates that for predictive vegetation mapping, the choice of model may not be the most critical element. Two other key criteria for model approach selection are: (1) the goals of the project (Guisan and Zimmermann 2000); and (2) data availability (Franklin 1995; Van Niel 2003). Here the term 'data availability' is used broadly, in that it means both access to environmental variables over the extent (spatial and/or temporal) of the study AND access to a database of species presence data, species presence-absence data or rules defining the species' requirements (or tolerances).

Following Austin (1980; 2002), three types of environmental variables may be used to determine vegetation distribution, abundance and quantities. They are: (1) resource gradients that are consumed by the plant, *e.g.*, CO_2, water, light and nutrients; (2) direct gradients that are not consumed by the plant yet have a direct physiological influence on growth, *e.g.*, temperature (both air and soil) and pH; and (3) indirect gradients that have no direct physiological influence on growth, but are correlated with species distribution due to their correlation with variables such as temperature, soil moisture and precipitation. Examples of indirect variables include aspect, altitude, longitude and latitude, and distance from the coast, among others. For predictive vegetation mapping to be practical, Franklin (1995) notes that maps of the environmental variables (or their surrogates) must be available, or easier to map then the vegetation itself. Having access to readily available datasets, then, is a key criterion determining the selection of a modelling approach to underpin a predictive vegetation mapping exercise. This access to relevant data can be particularly constraining in developing countries where expensive ground-based data collection might not often be performed. In this case, reliance on spatial datasets and expert opinion is increased and the approach more frequently may be restricted to some form of conceptual model (1, above).

In China, ecological restoration is a key concern of the Central Government, and as mentioned above, this is one of the four main uses of predictive vegetative mapping. In 1998 the Chinese Central Government established the “National Forest Protection Project (NFPP)” which aims to halt the destruction of natural forests (Ye *et al.* 2003). Under the umbrella of the NFPP the “Grain for Green” (Tui Geng Huan Lin) project was established in 1999 to return cultivated land with slopes of 25° or more to perennial vegetation (*e.g.*, Ke and Zhou 2005; Wenhua 2004; Winkler 2002; Xu *et al.* 2004; Yang 2004; Ye *et al.* 2003). Since 1999 as part of the “Grain for Green” project (or Sloping Land Conversion Program, Xu *et al.* 2004), over 7 million ha have been re-vegetated, with 5.9 million ha being converted in 2002 and 2003 (Xu *et al.* 2004). Implementation of these national re-vegetation programs occurs at the provincial, prefecture, county, township, and village levels, in which there exists a great variation in ecological understanding, financial capacity, and management goals (Rozelle *et al.* 1997; Skinner *et al.* 2001). To help maximise the financial commitment of the Chinese Central Government, these disparate management groups need assistance in designing management plans, while considering specific local issues. A major issue to successfully implement the re-vegetation program in the Loess Plateau is that county level managers need assistance to determine where in the landscape to re-vegetate and what species to re-vegetate with. Research in this report addresses both of those questions. To assist distributing these research findings to the relevant leaders of the Bureau of Hydrology, Bureau of Forestry, and Bureau of Agriculture that are found in each county in the Loess Plateau, a bilingual decision support tool called ReVegIH (Re-Vegetation Impacts on Hydrology) has been developed (Li *et al.* 2005b; McVicar *et al.* 2006). In addition to providing county level managers with assistance determining where in the landscape to re-vegetate and what species to re-vegetate with, ReVegIH also allows managers to understand the impact that implementing the re-revegetation policies in their jurisdiction will have on water resources downstream from them.

In the next section the study site is briefly introduced. In Section 3, the selection of the model underpinning the predictive vegetative mapping is described and the methods used to identify target and priority areas, as well as land limits, are documented. Also in this section we describe how we compress the many species suitability maps into one dataset for inclusion within the ReVegIH decision support tool. Section 4 shows the results for each species, with frequency maps for several groups also shown. The area and percent of target and priority areas excluding the land limits of each catchment and county (with more than 90% of its area in the study site) are also tabulated in this section; their exact spatial location can be explored at 100 m resolution using ReVegIH. In Section 5 further discussion of key issues and conclusions from this research are presented. In Appendix A an example of the output available using ReVegIH is illustrated for SuiDe county. In Appendix B and C, the target and priority areas for the three re-vegetation growth forms (*i.e.*, trees, shrubs and grass) excluding two land limits are shown for each catchment and county (with more than 90% of its area in the study site), respectively.

2 Study Site

The Yellow River basin in China (752,444 km^2) is one of its most important basins, directly supporting a population of 107 million people with another 400 million living on the North China Plain (Figure 1) who partly rely on water from this basin. The average annual erosion rate (2,480 t km^{-2}) for the entire Yellow River basin is the highest of any major river system worldwide (Shi and Shao 2000). This is caused by the middle reaches of the Yellow River draining the Loess Plateau (623,586 km^2 - Figure 1), where severe soil erosion rates ranging from 20,000 to 30,000 $t.km^{-2}.year^{-1}$ are commonly reported (*e.g.* Xiang-zhou *et al.* 2004), though extremely high rates (59,700 $t.km^{-2}.year^{-1}$) have also been documented (Shi and Shao 2000). Approximately 90% of the sediment delivered to the Yellow River comes from the major south-flowing branch draining the region of the Loess Plateau, locally known as the 'sandy coarse-sandy area' (Li 2003). Our study site is defined by the catchments encompassing this sandy area where the landform is hilly and is thus termed the Coarse Sandy Hilly Catchments (CSHC see Figure 1).

Due to these high rates of erosion (Li 2003), the Central Government have implemented several programs (as mentioned above) aimed at reducing associated environmental problems. Two complementary soil conservation management actions are currently used to achieve this: (1) 're-vegetation schemes', where large areas of pasture and cropping lands are re-planted with deeper rooted perennial species (Douglas 1989; Liang *et al.* 2003; Ritsema 2003); and (2) 'engineering methods', which involve the construction of terraces and check dams (Douglas 1989; Ritsema 2003; Xiang-zhou *et al.* 2004). While the effectiveness of both of these two soil conservation measures are critical to the overall management of the Yellow River (Douglas 1989; Huang 1988), in the remainder of this report we primarily generate information to support the re-vegetation program. We specifically focus on mapping vegetation suitability and defining re-vegetation target and priority areas for use in the re-vegetation management planning (through ReVegIH). Further information about the study site, including a more complete summary of the complex environmental management, are found in McVicar *et al*. (2005) and Li *et al*. (2005a).

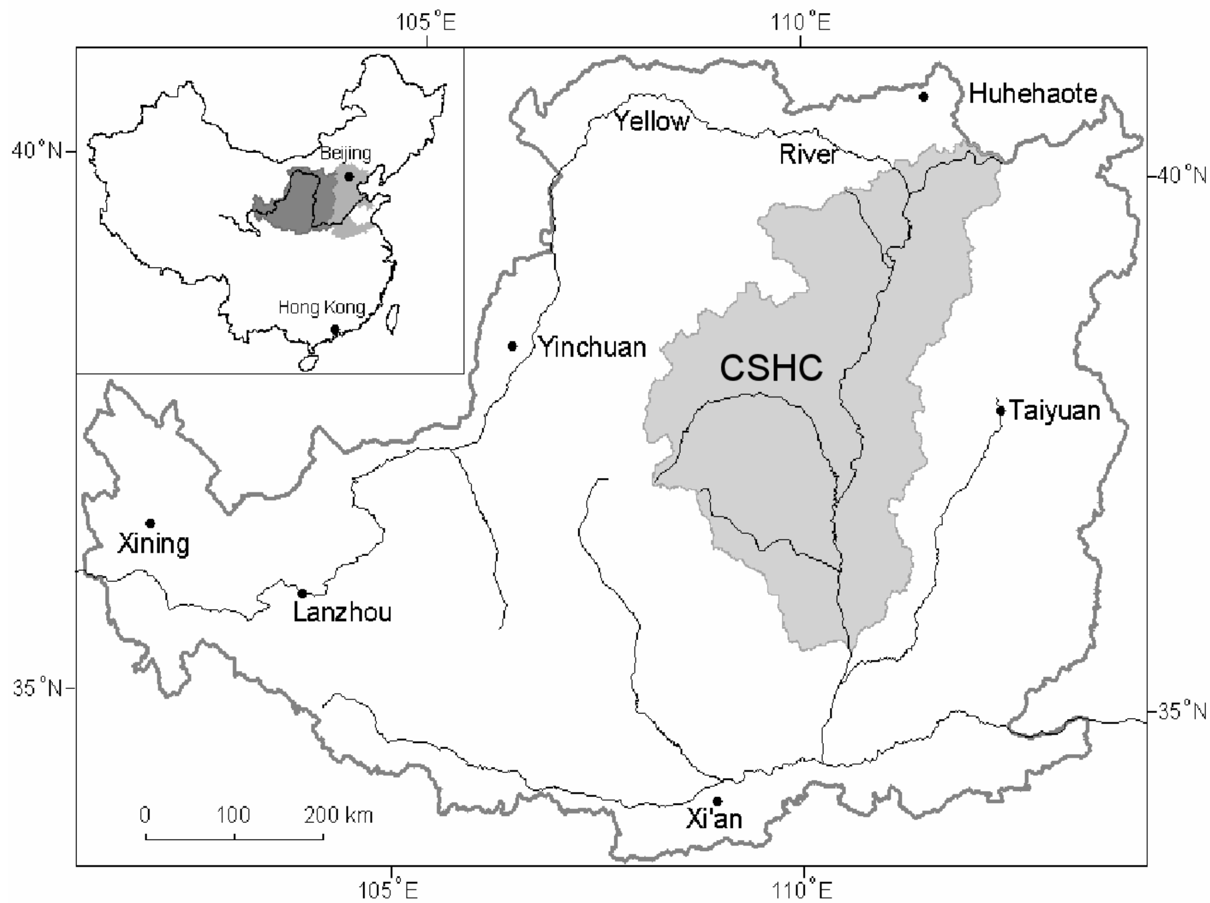


Figure 1. The inset map shows the location of the 623,586 km^2 Loess Plateau (darker shading) on the middle reaches of the Yellow River that supports a population of 82 million people (Xiubin *et al*. 2003) and the North China Plain (lighter shading). The main map shows the location of the 112,728 km^2 Coarse Sandy Hilly Catchments (CSHC).

3 Methods

3.1 Modelling Vegetation Suitability

Our aim is to map vegetation suitability for re-vegetation planning in the CSHC. Following Guisan and Zimmerman (2000), this broad aim has the characteristics of: (1) being general; (2) not incorporating disturbance and dynamics; (3) being conducted over a large spatial scale (meaning a large geographic area); and (4) will not incorporate climate change effects. This means the range of models could be either empirical or mechanistic, and that the variables used can be any combination of resource, direct, and/or indirect variables (Guisan and Zimmermann 2000). In our case, using the conceptualisation of criteria for model / variable selection for predictive vegetation mapping proposed by Guisan and Zimmerman (2000) has not assisted refining our options.

Subsequently, data availability (Franklin 1995; Van Niel 2003) became the criterion which we used to select our regional predictive vegetation modelling approach. In some regions (defined here as > 50, 000 km^2) where floristic research has not been performed in detail, the most pressing requirement is gaining access to presence or presence-absence field data to perform vegetation suitability modelling (when using methods 2 through 7 outlined in the introduction). In our case we did not have access to a large database documenting species distribution and abundance and we believe that one does not exist for the CSHC. Consequently, we could not use the stochastic approaches described by methods 2 through 7. Additionally, while isolated cases of mechanistic modelling of plant growth have been reported for three tree species (Zhang *et al.* 2001; Zhang *et al.* 2003), and two tree and two shrub species in small catchments (the 8.27 km^2 Zhifanggou catchment Gao *et al.* 2004) in the Loess Plateau, these methods are not 'scaleable' to our 113,000 km^2 study site. Consequently we can not consider models that: (1) require presence or presence-absence data; or (2) are mechanistic.

Suitability of several commercially important introduced forestry species has been mapped in data-sparse environments over large areas in: China (Booth 1996); Africa (Booth and Jovanic 2002); Latin America (Booth and Jones 1998); and globally (Booth *et al.* 2002). The interactions are captured using a Boolean logical AND operator for six climatic variables (that have had thresholds applied) that are considered to most influence site suitability for vegetation growth (Booth and Jones 1998; Booth *et al.* 2002). The six climatic variables are: (1) mean annual precipitation; (2) rainfall seasonality; (3) dry season length; (4) mean maximum air temperature of the hottest month; (5) mean minimum air temperature of the coldest month; and (6) mean annual air temperature. To account for frosts this has been extended to include lowest minimum temperature on record (Booth and Jovanic 2002). While only using climatic data, it should be noted that Booth *et al*. (2002) acknowledge that soils information would have been used if a consistent database were available globally.

The Boolean approach used in broad-scale, data-sparse areas is an example of a conceptual model based on expert opinion (the first class outlined in the introduction). Due to our research being conducted regionally in a data sparse environment, this Boolean approach of mapping the suitability of introduced species for forestry plantations is aligned to our requirements. Given this, we found that sets of rules defining species' requirements (or tolerances) for implementing the re-vegetation program for the Loess Plateau have been previously formulated (Cheng and Wan 2002; Liang *et al.* 2003; Wu and Yang 1998; Yuan and Zhang 1991; Zhao *et al.* 1994). These rules were used to form the basis to implement the first approach (conceptual models based on expert opinion – see Section 1) identified by Elith and Burgman (2003). This has also been termed 'using overlays of environmental variables' and is one of several simple models identified by Guisan and Zimmerman (2000) that can be implemented directly in a GIS. In their review 15 examples of Boolean approaches are cited in the international literature (see footnote 17 of Guisan and Zimmermann 2000, pp 165). This simple method is still used operationally and a recently identified research issue is that the shortcomings of these approaches (including complete assessment of error and uncertainty propagation) needs to be studied so potential users can better understand their limitations (Elith and Burgman 2003). Most likely the continued operational use of conceptual models based on expert opinion (or overlays of environmental variables) is purely pragmatic, as is the case here.

In previous vegetation studies in the Loess Plateau (Cheng and Wan 2002; Liang *et al.* 2003; Wu and Yang 1998; Yuan and Zhang 1991; Zhao *et al.* 1994), the choice of species mainly focused on trees and shrubs, and this limits the data available for the suitability assessment conducted here to these two growth forms. Yuan and Zhang (1991) listed 66 species, and provided the basis for the Boolean GIS overlay rules used to map suitability assessments; a few final rules implemented here were modified based on information presented in Liang *et al*. (2003) and Zhao *et al*. (1994) and with reference to the personal experience of the authors (see Table 3 for full details). Given that only broad requirements (or tolerances) for each species are provided a quint-variant discrete gradient model using Boolean logic was implemented. Several inherent assumptions are ignored when using this approach including: (1) ecological interactions that vary in space and time; (2) underlying environmental change such as climate change since the rules were developed; (3) seed dispersion; and (4) succession. The term ‘ecological interactions’ incorporates many issues such as competition for resources (both interspecies and intraspecies), and grazing when considering vegetation in ecosystems (Guisan *et al.* 2006). Models for seed dispersal could be improved by incorporating metrics of spatial autocorrelation from seed trees (Guisan *et al.* 2006), and including anthropogenic boundaries such as roads and canals (Urban *et al.* 1987) into spatial modelling.

In this study, we selected a subset of primarily native species (Liang *et al.* 2003; Zhao *et al.* 1994, see Table 1) from a list of 66 relevant for the Loess Plateau found in the literature. Our subset of species were chosen as the ones having optimal growth in the CSHC (Yuan and Zhang 1991). Exactly 38 species were selected; 24 were trees and 14 were shrubs (Table 1). There are 22 common species identified in Table 1, these species are widely accepted and are already used by the local county-level Forestry Bureaus in their re-vegetation programs, hence their seedlings are usually easy to acquire. Seven different vegetation groupings defined in Table 2 were derived from the 38 species and have been implemented in the previously introduced decision support tool called ReVegIH (Li *et al.* 2005b; McVicar *et al.* 2006).

Table 1. The 38 species used in the vegetation suitability analysis for the CSHC are listed. In the column labeled ‘Number’, the common species are identified with an asterisk. In the ‘Growth form’ column, S and T represent shrub and tree, respectively. In the column labeled ‘Fruit’ a ‘Yes’ indicates a horticultural species whereas ‘Yes ~’ indicates a non-horticultural species that produces edible fruit.

Number	Native	Growth form	Chinese name	*Latin name* (Common name)	Fruit
1 *	Yes	T	油松	*Pinus tabulaeformis Carr.* (Chinese pine)	No
2 *	Yes	T	白桦	*Betula Platyphylla Suk.* (Asian white birch)	No
3 *	Yes	S	山毛桃	*Amygdalus davidiana (Carr.) C.de Vos. ex Henry.* (Wild hairy peach)	No
4	Yes	S	黄刺梅	*Rosa xanthina Lindl.* (Yellow rose)	No
5 *	Yes	T	辽东栎	*Quercus liaotungensis Koidz.* (Manchurian oak)	No
6 *	Yes	T	白榆	*Ulmus pumila* (Siberian elm)	No
7 *	Yes	T	小叶杨	*Populus simonii Carr.* (Chinese small leaf poplar)	No
8 *	Yes	T	侧柏	*Platycladus orientalis (L.)* (Chinese arborvitae)	No
9	Yes	S	荆条	*Vitex negundo Linn.var.heterophylla (Franch.) Rehd* (Cut-leaf chastetree)	No
10	Yes	S	狼牙刺	*Sophora davidii* (David’s mountain laurel)	No
11 *	No	T	刺槐	*Robinia pseudoacia* (Black locust)	No
12 *	Yes	T	旱柳	*Salix matsudana* (Corkscrew willow)	No
13	Yes	S	酸枣	*Ziziphus jujuba var. spinosa* (Chinese sour date)	Yes~
14	Yes	T	山杨	*Populus davidiana* (Mountain poplar)	No
15 *	Yes	S	虎榛子	*Ostryopsis davidiana Decne* (Hazel-hornbeam)	No
16 *	No	S	紫穗槐	*Amorpha fruticosa* (False indigo)	No
17	Yes	S	沙枣	*Elaeagnus angustifolia* (Russian olive)	Yes~
18 *	Yes	S	柠条	*Caragana microphylla* (Littleleaf peashrub)	No
19 *	Yes	S	沙柳	*Salix psammophila* (Dune willow)	No
20	Yes	S	柽柳	*Tamarix spp* (Salt cedar)	No
21	Yes	S	乌柳	*Salix cheilophila Schneider* (Black willow)	No
22 *	Yes	T	臭椿	*Ailanthus altissima* (Tree of heaven)	No
23 *	Yes	S	沙棘	*Hippophae rhamnoides* (Seabuckthorn)	Yes~
24	Yes	T	青杨	*Populus cathayana Rehd* (Korean poplar)	No
25	No	T	新疆杨	*Populus alba cv.* ([Western] White poplar)	No
26 *	Yes	T	桃	*Prunus davidiana* (Peach)	Yes
27 *	Yes	T	杏	*Prunus armeniana var.ansu* (Apricot)	Yes
28	Yes	T	毛白杨	*Populus tomentosa carr.* (Chinese white poplar)	No
29 *	Yes	T	河北杨	*Populus hopeiensis* (Hopei poplar)	No
30 *	Yes	T	苹果	*Malus domestica Borkh* (Apple)	Yes
31 *	Yes	T	梨	*Pyrus bretschneideri* (Pear)	Yes
32	Yes	T	桑	*Morus alba L.* (Mulberry)	Yes
33	Yes	T	核桃	*Juglans regia* (Walnut)	Yes
34	Yes	S	文冠果	*Xanthoceras sorbifolia Bunge.* (Yellow horn)	No
35 *	Yes	T	杜梨	*Pyrus betulaefolia* (Birch-leaved pear)	No
36	Yes	T	楸树	*Catalpa bungei C.A.Mey* (Beijing Catalpa)	Yes~
37 *	Yes	T	枣	*Ziziphus jujuba Mill* (Chinese date)	Yes
38	No	T	箭杆杨	*Populus nigra var. thevestina (Dode) Bean.* (Lombardy poplar)	No

Table 2. The seven vegetation groups are listed; the number of species and the species codes (see Table 1) in each group are identified.

Vegetation Grouping	Number of Species	Species Codes
All Species	38	1 through to 38
All Trees	24	1,2,5,6,7,8,11,12,14,22,24,25,26,27,28,29,30,31,32,33,35,36,37,38
All Shrubs	14	3,4,9,10,13,15,16,17,18,19,20,21,23,34
Common Trees	16	1,2,5,6,7,8,11,12,22,26,27,29,30,31,35,37
Common Shrubs	6	3,15,16,18,19,23
Common Species	22	1,2,3,5,6,7,8,11,12,15,16,18,19,22,23,26,27,29,30,31,35,37
Fruit Trees	11	13,17,23,26,27,30,31,32,33,36,37

Of the 38 species only four are introduced (or non-native); they are *Robinia pseudoacia* (# 11), *Amorpha fruticosa* (# 16), *Populus alba cv.* (# 25) and *Populus nigra var. thevestina* (# 38). Each has a long history of cultivation in the Loess Plateau (Zhou and Luo 1997) and hence they are considered for the re-vegetation program in the CSHC. *Robinia pseudoacia* originated in North America and was introduced to China in the late 19th century; it is widely planted in the Yellow River Basin. *Amorpha fruticosa* also originated in North America and was first introduced into Northeast China from Japan in the early 20th century. It is now widely planted in North China and the Yangtze River Basin, and has become a very important species for soil and water conservation. *Populus alba c.v.* is native in Xinjiang Autonomous Region (north western China) and is now planted in many other places in China including the CSHC. *Populus nigra var. thevestina* was introduced into China a long time ago, and from where it originated and when it was introduced is not known; it is mainly planted in moist ground and along road sides. The above information for the four species introduced to the Loess Plateau was sourced from Zhou and Luo (1997).

Species distribution is mainly controlled by climatic, landscape, soil conditions and other resources (Franklin 1995). In the rules provided by Yuan and Zhang (1991) there are five variables used to map vegetation suitability for re-vegetation planning. They are: (1) annual precipitation; (2) average July air temperate; (3) soil pH; (4) soil total nitrogen; and (5) landform (incorporating slope, aspect, curvature and distance from rivers). Variables (1) and (4) are examples of resource gradients, with (2) and (3) being direct gradients and (5) is an indirect gradient (Austin 1980; 2002). The first four variables are continuous, with landscape position being categorical or thematic; (see Table 3).

Table 3. Rules defining suitability for the five environmental variables for the 38 species used to implement the re-vegetation program in the CSHC are presented. The term 'No limit' means that in the study area the variable is not a limiting factor. In the column labeled 'Code number' an * indicates a common species. A few annual precipitation and pH rules were changed from those provided by Yuan and Zhang (1991); their original values are provided in brackets and those we have implemented are not in brackets. Landform rules different from the original rules presented by Yuan and Zhang (1991) are in brackets, those we have added have a plus sign (+) in the brackets and those we have removed have a minus sign (-) in the brackets. Landform codes are: LM = Liang, Mao and other high flat area; NFS = north facing slopes; SFS = south facing slopes; FB = flat bottom; and RM = rocky mountains.

Code number	Mean Annual Precipitation (mm)	Mean July Air Temperature (°C)	pH	TN (%)	Landform
1*	200 ≤ R (≤400)	T ≥ 14	5.6 < pH (<6.5)	No limit	LM, NFS, RM
2*	R > 400	No limit	5.6 < pH <6.5	No limit	SFS, RM
3*	R > 200	No limit	No limit	No limit	SFS, RM
4	R > 400	No limit	No limit	No limit	(SFS +), RM
5*	R > 200	No limit	No limit	No limit	RM
6*	R > 200	No limit	No limit	No limit	SFS, NFS, FB, RM
7*	R > 200	No limit	No limit	≥ 0.05	SFS, NFS, FB
8*	R > 200	T ≥ 14	No limit	No limit	(LM +), SFS, FB, RM
9	R > 200	T ≥ 14	No limit	No limit	SFS
10	R > 200	T ≥ 14	No limit	No limit	SFS
11*	R > 200	T ≥ 14	No limit	No limit	(LM -), SFS, NFS, FB, RM
12*	R > 200	T ≥ 14	No limit	No limit	(SFS +), FB
13	R > 300 (400)	T ≥ 14	No limit	No limit	SFS, RM
14	R > 400	T ≥ 14	No limit	No limit	(NFS +), RM
15*	R > 400	T ≥ 14	No limit	No limit	(NFS +), RM
16*	R > 200	No limit	No limit	No limit	(LM +), SFS, FB, RM
17	R > 200	No limit	No limit	No limit	SFS, FB, RM,
18*	R > 200	No limit	No limit	No limit	LM, SFS, FB
19*	R > 200	No limit	No limit	No limit	FB,
20	R > 400 (200)	No limit	No limit	No limit	(LM -), SFS, NFS, FB
21	R > 200	No limit	No limit	No limit	FB,
22*	R > 200	No limit	No limit	No limit	LM, SFS, FB
23*	R > 200 (400)	T ≥ 14	No limit	No limit	LM, SFS, NFS, FB, RM
24	R > 200 (400)	No limit (T ≥ 14)	No limit	≥ 0.05	(LM -), NFS, FB
25	R > 200 (400)	No limit (T ≥ 14)	No limit	≥ 0.05	(LM -), FB
26*	R > 400	T ≥ 14	No limit	≥ 0.05	LM, FB, RM
27*	R > 200 (400)	T ≥ 14	No limit	≥ 0.05	LM, SFS, FB, RM
28	R > 500 (400)	T ≥ 14	No limit	≥ 0.05	LM, FB
29*	R > 200 (400)	T ≥ 14	No limit	≥ 0.05	NFS, (FB +), RM, (SFS -)
30*	R > 400	T ≥ 14	No limit	≥ 0.05	LM, FB, RM
31*	R > 400	T ≥ 14	No limit	≥ 0.05	LM, FB, RM
32	R > 400	T ≥ 14	No limit	≥ 0.05	LM, FB, (RM -)
33	R > 400	T ≥ 14	No limit	≥ 0.05	LM, SFS, FB, RM
34	R > 400	T ≥ 14	No limit	≥ 0.05	LM, SFS
35*	R > 300 (400)	T ≥ 14	No limit	≥ 0.05	LM, SFS, FB,
36	R > 400	T ≥ 18	No limit	≥ 0.05	NFS, FB, (LM -)
37*	R > 400	T ≥ 18	No limit	≥ 0.05	NFS, FB, (LM -)
38	R > 400	T ≥ 14	No limit	> 0.08	LM, FB,

The sources of the five variables required to implement the GIS overlay rules defined in Table 3 are described in turn below.

1. <u>Mean annual precipitation (mm):</u>

Monthly precipitation data at 58 meteorological stations in and around the CSHC for the 21-year period from 1980 through 2000 were obtained. These data were then interpolated with ANUSPLIN Version 4.3 (Hutchinson 2004b) using a bi-variate thin plate spline to produce monthly precipitation surfaces; see McVicar *et al.* (2005) for full details. To derive mean annual precipitation, 12 monthly surfaces were cumulated for each of the 21 years, and then these 21 annual surfaces were averaged, see Figure 3a. For the resulting surface, the maximum, mean, minimum and standard deviation values are 557 mm, 413 mm, 276 mm and 57 mm, respectively.

2. <u>Mean July air temperature (°C):</u>

For the same 21 years as above, McVicar *et al*. (2005) produced monthly maximum and minimum air temperature surfaces using a tri-variate partial thin plate spline that incorporated a bi-variate thin plate spline with a linear dependence on elevation using ANUSPLIN Version 4.3 (Hutchinson 2004b). The maximum and minimum air temperature surfaces for each July were averaged to obtain the mean July temperature for that year. These 21 July surfaces were then averaged to get the overall mean July temperature surface, see Figure 3b. For the study site, the maximum, mean, minimum and standard deviation values are 27.6 °C, 22.1 °C, 10.3 °C and 1.7 °C, respectively.

3. <u>Soil pH:</u>

Soil pH data for each soil class and sub-class were extracted from Wang *et al*. (1992), as the latest 1:500,000 Loess Plateau soil map (Wang *et al.* 1991) does not contain soil properties – only the soil name is mapped in each polygon. We clipped the soil map with the CSHC boundary, and appended pH data to its attribute table, then extracted a pH map from the soil map, see Figure 3c. There are 24 soil classes and 61 sub-classes in the CSHC; their name, pH and TN values are listed in Table 4.

4. <u>Soil TN (%):</u>

The soil TN variable was processed using the same method as reported for soil pH; see Table 4 and Figure 3d.

Table 4. The soil classes and sub-classes found in the CSHC are shown.

No.	Soil class name	Sub-class name	Soil pH	Soil TN (%)
1	Lou soil	Oily lou soil	8.6	0.083
2		Lu lou soil	8.4	0.072
3		Licha lou soil	8.4	0.085
4		Aquic lou soil	8.5	0.111
5		Salinized lou soil	8.6	0.055

No.	Soil class name	Sub-class name	Soil pH	Soil TN (%)
6	Heilu soil	Heilu soil	8.4	0.055
7		Purple heilu soil	8.4	0.078
8		jiao heilu soil	8.0	0.045
9		Ma heilu soil	8.2	0.102
10	Huang mian soil	Shan huang mian soil	8.3	0.066
11		Huang mian soil	8.4	0.072
12		Sandy huang mian soil	8.7	0.023
13		Grey huang mian soil	8.2	0.172
14	Cinnamon soil	Cinnamon soil	8.1	0.092
15		Luvie cinnamon soil	7.5	0.123
16	Castanozem	Dark castanozem	8.6	0.130
17		Castanozem	8.7	0.100
18		Light castanozem	8.6	0.03
19	Chernozem	Chernozem	8.4	0.200
20		Luvic chernozem	8.1	0.170
21	Sierozem	Sierozem	8.9	0.132
22		Light sierozem	8.2	0.069
23		Irrigated—warping sierozem	8.3	0.055
24	Calcic brown soil	Calcic brown soil	9.0	0.050
25		Light calcic brown soil	8.9	0.020
26		Aquic calcic brown soil	9.2	0.050
27	Grey desert soil	Grey desert soil	8.6	0.060
28		Salinized grey desert soil	9.1	0.030
29	Aeolian sand soil	Mobile aeolian sand soil	8.2	0.003
30		Semi—stable aeolian sand soil	8.4	0.070
31		Stable aeolian sand soil	8.3	0.028
32	Irrigated warping soil	Irrigated warping soil	8.5	0.073
33		Surpaie rusted—irrigated warping soil	8.1	0.110
34		Aquic irrigated warping soil	8.3	0.070
35	Paddy soil	Submergic paddy soil	8.2	0.043
36		Temporary submergic paddy soil	6.4	0.121
37	Red soil	Red soil	8.5	0.038
38		Clayey red soil	8.4	0.027
39	Purple soil	Calcic—purple soil	9.1	0.022
40	Light brown earth	Light brown earth	6.3	0.550
41		Albic light brown earth	5.3	0.580
42	Grey cinnamon soil	Grey cinnamon soil	8.3	0.207
43		Luvic grey cinnamon soil	7.0	0.129
44		Calcic grey cinnamon soil	8.0	0.540
45		Albic Grey cinnamon soil	7.4	0.204
46	Meadow soil	Light meadow soil	8.8	0.093
47		Meadow soil	8.2	0.222
48		Salinized meadow soil	8.3	0.070
49	Bog soil	Meadow bog soil	7.8	0.678
50		Salinized bog soil	8.2	0.258
51	Aquic soil	Aquic soil	8.4	0.082
52		Gleyic—aquic soil	8.3	0.710
53		Satinized—aquic soil	7.7	0.072
54	Fluvent soil	Fluvent soil	8.4	0.075
55	Solonchak	Solonchak	9.0	0.034
56		Gleyic solonchak	8.3	0.025
57		Solonetzic solonchak	9.3	0.056
58		Dry solonchak	7.3	0.028
59	Solonetze	Takgric solonetz	9.9	0.013
60	Lithosol	Lithosol	8.3	0.045
61	Alpine meadow soil	Alpine meadow soil	7.4	0.535

5. <u>Landform:</u>

Landform, due to it governing the lateral flow of water in the soils of the Loess Plateau (especially in the shallow soil layer between 0 cm and 150 cm Liu *et al.* 2005) and its control over incoming solar radiation (*e.g.*, Iqbal 1983; Moore *et al.* 1993; Wilson and Gallant 2000), has a great impact on site conditions, and thus affects the distribution of species. Seven landforms were proposed by Yuan and Zhang (1991) as relevant for the Loess Plateau; Figure 2 illustrates landforms not widely known by non-Chinese scientists. The seven landforms are:

1. Yuan (plateau form);
2. top of Liang and Mao;
3. south facing slopes;
4. north facing slopes;
5. bottom of gully;
6. alluvial flat land; and
7. rocky mountainous area.

Yuan and Zhang's (1991) seven proposed landforms are relevant for the whole Loess Plateau (Figure 1), and some landforms do not exist or just occupy a small proportion of the study site, thus we needed to modify the classes to suit the CSHC. Yuan was deleted from the list as it covers an area less than 0.5% of the CSHC (Zhao *et al.* 1992) and it is primarily productive agricultural land which is not considered for re-vegetation activities. The bottom of gullies and alluvial flats were merged into one class, called 'flat bottom', as they cannot be distinguished from each other at the scale at which we are working. Although Yuan and Zhang (1991) assumed that all landforms were suitable for trees or shrubs, this has resulted in the widespread stunted growth, and in some cases death, of re-vegetation activities (McVicar *et al.* 2006) and has caused some serious soil hydrological problems (Li 2001). To avoid these problems, we defined an additional landform class called steep slopes and gullies (SSG), which will not be actively re-vegetated; we propose leaving this area for natural succession (Miao and Marrs 2000). The adjusted classes and their identities are listed in Table 5 and the grass and shrub species expected to naturally re-generate the SSG areas are listed in Table 6.

Name	Explanation	Oblique Aerial Photo
(a) Yuan	Yuan are plain highlands covered by deep loess, they are generally large and flat. In this photo the agricultural area bounded by the red polygon overlaid on this oblique aerial photograph is the Yuan.	
(b) Liang	Liang are the elongated highlands with rounded tops between gullies. They are tens to hundreds of metres wide, and hundreds to thousands of metres long. The areas typifying Liang geomorphic units are bounded by the red polygon overlaid on this oblique aerial photograph.	
(c) Mao	Mao are small quaquaversal hills that look like an inverted bowl, in that they are primarily circular. The ancient base is covered by loess, or they may be the result of heavily eroded Liang landforms. The Mao shown here are bounded by the red polygon overlaid on this oblique aerial photograph and have been terraced.	

Figure 2. Detailed explanations and oblique aerial photographs illustrating the three typical Loess landforms of: (a) yuan; (b) liang; and (c) mao. The portion of the landscape described is inside the red polygon(s) in the three examples.

Table 5. Identification codes, names and detailed definitions for the six landforms in the CSHC are shown; N/A stands for not applicable.

Code	Name	Detailed Definition			
		Slope (°)	Aspect (°)	Curvature	River buffer area
LM	Top of Liang and Mao	< 0.8	N/A	≥ 0	N/A
SFS	South facing slopes	0.8 ≤ and < 15	≥ 90 and < 270	N/A	N/A
NFS	North facing slopes	0.8 ≤ and < 15	≥ 270 or < 90	N/A	N/A
FB	Flat bottom	< 0.8	N/A	≤ 0	In
SSG	Steep slope and gullies	≥ 15	N/A	N/A	N/A
RM	Rock mountains	Derived from class # 60 of the soil map (see Table 4)			

Table 6. Names of the grass and shrub species that are expected to perform the natural succession in the CSHC are listed.

Growth Form	Chinese Name	*Latin Name* (Common name)
Grass	铁杆蒿	*Artemisia gmelinii Webb.ex stechmann** (Russian wormwood)
Grass	茭蒿	*Artemisia giraldii Pamp.* (Wormwood)
Grass	白羊草	*Bothriochloa ischaemum (L.)Keng* (Yellow bluestem)
Grass	长芒草	*Stipa bungeana Trin.* (Bunge needlegrass)
Grass	大针茅	*Stipa grandis* (Needlegrass)
Grass	达乌里胡枝子	*Lespedeza davurica* (Japanese clover)
Grass	糙隐子草	*Cleistogenes squarrose* (Bunchgrass)
Grass	地椒（百里香）	*Thymus mongolicus* (Mongolian thyme)
Shrub	黄蔷薇	*Rosa hugonis* (Golden rose of China)
Shrub	狼牙刺	*Sophora davidii* (David's mountain laurel)
Shrub	荆条	*Vitex negundo Linn.var.heterophylla (Franch.) Rehd* (Cut-leaf chastetree)
Shrub	杠柳	*Periploca sepium* (Chinese silk vine)

* This species is a sub-shrub (or called a semi-shrub in China) as it is not entirely a grass, nor is it a shrub. It should be noted that Lucerne is regarded as a crop, and hence has not been used in re-vegetation strategies in the Loess Plateau.

Slope, aspect and curvature were derived from the 100 m resolution DEM created using ANUDEM Version 5.1 (Hutchinson 2004a) from contours, rivers and spot height data (Yang *et al.* 2005). The resulting DEM is hydrologically correct, in that the river network defined from it is connected without spurious small parallel streams being introduced (Yang *et al.* 2005). The elevations for the CSHC range from 312 m to 2,760 m, and slopes can exceed 30° from horizontal in the 100 m resolution model (Yang *et al.* 2006). The river buffer was defined as a 100 m zone around the stream network, which was in turn calculated from the 100 m resolution DEM using a stream threshold of 10,000 contributing cells (Wilkinson *et al.* 2004). The landform classes abbreviated LM and FB were distinguished using slope profile curvature from the DEM. A positive curvature indicates that the surface is upwardly convex at that cell, and a negative curvature indicates that the surface is upwardly concave at that cell. Areas with either positive or negative profile curvature were defined as LM. A curvature value of zero indicates that the surface is flat, so these areas were classified as FB. RM was extracted from the soil map (class 60 in Table 4). The resultant landform map is shown in Figure 3e.

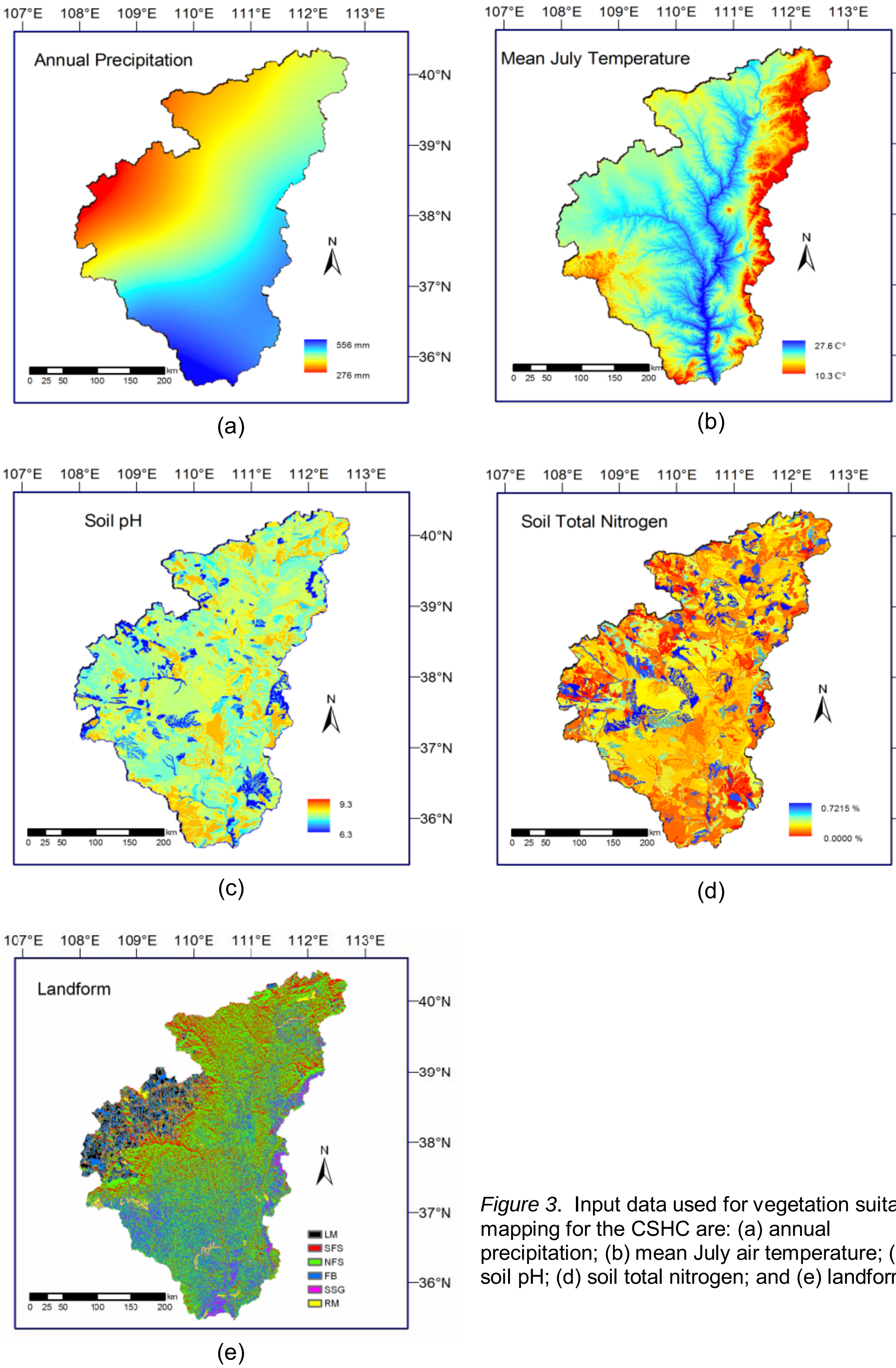


Figure 3. Input data used for vegetation suitability mapping for the CSHC are: (a) annual precipitation; (b) mean July air temperature; (c) soil pH; (d) soil total nitrogen; and (e) landform.

3.2 Identifying Target and Priority Areas

The vegetation suitability rules derived from Yuan and Zhang (1991) define broad areas where individual species may grow. The rules provide no discrimination about how well each will grow; our consensus from careful analysis of the rules and the subsequent results presented in Section 4.1 was that the suitability maps were too inclusive (or 'generous'). For example, while trees may survive in some of the more arid areas in the northwest of the study site (due to localized conditions – *e.g.*, access to groundwater) generally some of the area deemed suitable will at best be marginal when considering vegetation growth. For this reason the vegetation suitability map is passed through a refining lens called a target area map. The target area focuses the activities of the re-vegetation program to areas more suited to provide optimal growth of trees species, as in our semi-arid study site plant-available water is the primary factor limiting growth (Liu *et al.* 2005; Palmer and Van Staden 1992).

There were four factors considered in the definition of re-vegetation target areas: precipitation, slope, topographic position and aspect. Topographic position and aspect cause large differences in solar loading, which in turn impacts evapotranspiration and hence soil moisture; these lead to differences in a species' growth performance. Precipitation and slope have been discussed in section 3.1, where the steep slope and gully (SSG) class was derived for the vegetation suitability mapping. The use of slope in defining the upper limit of the target areas is mainly via the SSG class, described by the following logic. In the Loess Plateau steep slopes are usually dry (due to lateral flow and low precipitation) and performing re-vegetation activities there may accelerate erosion due to disturbing the fragile soils (Zhang 2006; Zhu *et al*. 2004). Although it has been found that re-vegetating areas in the Loess Plateau initially results in active growth due to exploiting the antecedent water stored in the soil matrix (Chen *et al.* 2005; Huang *et al.* 2005; Liu *et al.* 2005; Wang *et al.* 2004; Yang *et al.* 2004; Yang 2001), this active growth usually precludes recharging of the soil stores and results in the development of a dry soil layer (ranging from 3 m to 8 m deep Yang *et al*. 2004). When the stores are exhausted there is not enough available water (due to low precipitation rates in the Loess Plateau and especially in the CSHC) to maintain normal growth rates in the re-vegetated area (Yang *et al*. 2004). In some cases this has resulted in mortality of the vegetation (*e.g.*, Wang *et al.* 2004; Xiubin *et al.* 2003; Yang *et al.* 2004), and in other cases while the trees survive, their growth is stunted so that some patches of 30 year old plantation forests are only about 20% of their normal height – colloquially referred to as 'little old man trees' (Yang *et al*. 2004; Yang 2001). Therefore in the rules defined here, SSG was excluded from re-vegetation, and left for natural succession only.

There are three target levels determined by the combination of the above four factors corresponding to three vegetation growth forms: level 1 target areas are the places where trees can grow well (*i.e.*, to within expected size and lifespan ranges); level 2 target areas are the places where shrubs can grow well; and level 3 target areas are where grasses can grow well. As the CSHC is predominately a semi-arid environment (Gao *et al.* 2004; Köppen 1931; Liu *et al.* 2005), plant-available water is an important determinant of growth (Liu *et al.* 2005; Palmer and Van Staden 1992). Therefore, since shrubs and grasses generally have a lower water requirement than trees to survive, in our general definition of target areas, anywhere trees can grow, are also suitable for shrubs and grasses. Likewise, anywhere shrubs can grow, are also suitable for grasses.

It should be emphasised that target areas and suitability are two different concepts, although they have very close links. Target areas define the places where re-vegetation should concentrate first and are particularly useful to define if money or time limits the amount of land that managers can re-vegetate. Suitability solely describes if a specific species can grow in a certain place or not. This means that although an area may be suitable for re-vegetation, it may not be where initial planting occurs as it may not be within a target area. Also, it is important to point out that target and suitability maps provide different information for management of re-vegetation. For example, if an area belongs to target level 1, it would most likely be re-vegetated in the initial stages of the re-vegetation scheme, but to get guidance on what species to plant there (peach, for example) would be defined by the suitability map. However, it should be noted that ReVegIH users are strongly encouraged to perform some detailed ground-level site assessment prior to performing any re-planting as the decision support tool is designed for regional analysis, and local factors (near and below the resolution of the data used in the application) may be critical in determining success (or failure) of re-vegetation schemes.

Table 7. Definitions of target levels to implement the re-vegetation program in the CSHC are presented. Target level 1 is for trees, level 2 is for shrubs, and level 3 is for grasses. Target level 0 in the table indicates that the area is not suitable for re-vegetation.

Precipitation (mm a^{-1})	Aspect ° (from north)	Landform	Slope ° (from horizontal)	Target level
< 500	North facing (≤ 90 or ≥ 270)	Hills	≤ 8.5	0
			8.5 to 15	2
		Gullies	2.2 to 15	2
			≤ 2.2	0
		Hills/Gullies	≥ 15	0
		Bottom	≤ 2.2	0
	South facing (90 to 270)	Hills	≤ 8.5	0
			8.5 to 15	3
		Gullies	≤ 2.2	0
			2.2 to 15	3
		Hills/Gullies	≥ 15	0
		Bottom	≤ 1.1	0
500 to 800	North facing (≤ 45 or ≥ 315)	Hills	≤ 8.5	0
			8.5 to 15	1
		Gullies	≤ 2.2	0
			2.2 to 15	1
		Hills/Gullies	≥ 15	0
		Bottom	≤ 1.1	0
	East facing (45 to 135)	Hills	≤ 8.5	0
			8.5 to 15	1
		Gullies	≤ 2.2	0
			2.2 to 15	1
		Hills/Gullies	≥ 15	0
		Bottom	≤ 1.1	0
	West and south facing (135 to 315)	Hills	≤ 8.5	0
			8.5 to 15	1
		Gullies	≤ 1.1	0
			1.1 to 15	1
		Hills/Gullies	≥ 15	0
		Bottom	≤ 1.1	0

If it is unfeasible to re-vegetate the entire target area due to substantial constraints such as funds, time, or labour, the subset of the target area having the highest potential impact should be planted first; we call this the priority area. Priority areas are those cells located in a target area that are both lower than and adjacent to a SSG boundary cell; see Figure 4. Due to the grid size of the datasets, this means that priority areas are 100 metre wide zones downhill from the highly erodible SSG areas. The priority areas are usually located at a 'break-of-slope' where the landform is dominated by hills and gullies and tend to be placed between highly erodible slopes and river channels. In general, re-vegetation of these areas first would have the most significant impact on intercepting and utilising soil and water coming from upslope (Liu *et al.* 2005). The combined effect of re-planting the priority zones only (compared to re-vegetating the entire, larger target area) will be that the reduction in streamflow will be minimised while maximising the reduction of soil entering the river network.

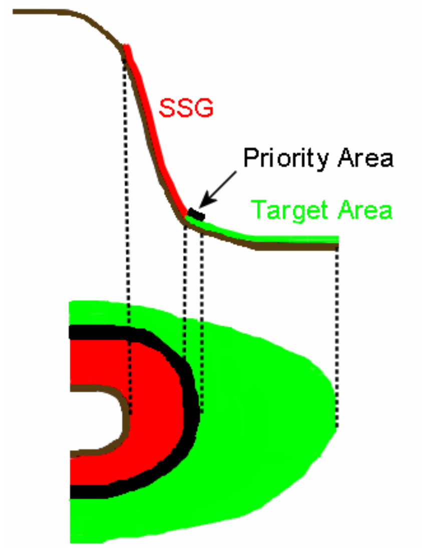


Figure 4. The conceptual spatial relationships of steep slope and gullies (SSG), re-vegetation target and re-vegetation priority areas are shown. The top portion is a cross-sectional view of a typical gullied landscape of the CSHC, whereas the lower portion provides a planar view like what is shown when using the decision support tool called ReVegIH.

3.3 Identifying Land Limits

As in any re-vegetation scheme, it does not make sense to re-vegetate already existing forests, lakes, urban areas, or highly productive agricultural areas. Because of this, it is not advisable to re-vegetate the entire target area as it has been defined up to this point. Therefore, we have defined areas where re-vegetation should not occur and use these as "masks" within our target areas. These masks are called land limits. In this report, there are two types of land limits:

- WUF, which defined from the 1986 land use data, includes areas of water, urban and forest;
- WUFA, which defined from the 1986 land use data, includes areas of water, urban, forest and agricultural land.

The areas within WUF and WUFA obviously changes for different re-vegetation target levels. The land use classes from which the two land limits are defined is based on the vector database mapped in 1986 at a scale of 1:500,000 (Shen 1991), which was converted to raster data with a cell size of 100 m for all the regional modelling performed here.

Figure 5 is an example of locating SSG areas, the target and priority areas, and land limits for the ZhongZhuang catchment; the smallest catchment in the study site covering an area of 127 km^2. The concept is built step by step. In Figure 5a the SSG ($\geq$ 15°) is shown in red and is overlaid on the slope map. The target area for level 2 is shown in bright green in

Figure 5b; the orange colour is the WUF land limit. The re-vegetation target level is 2, that is, where shrubs and grasses can grow well, but trees do not grow well. Figure 5c shows where the priority areas are located below the SSG class with a buffer of 100 m shown in black – this is the only difference between Figure 5c and Figure 5b. As introduced previously, orange areas represent the land limit that can not be used in the re-vegetation program as it is currently an important land-use. In Figure 5c and Figure 5d, land limits are WUF and WUFA respectively. The addition of agricultural land in the land limit from WUF (Figure 5c) to WUFA (Figure 5d) is the only difference between them.

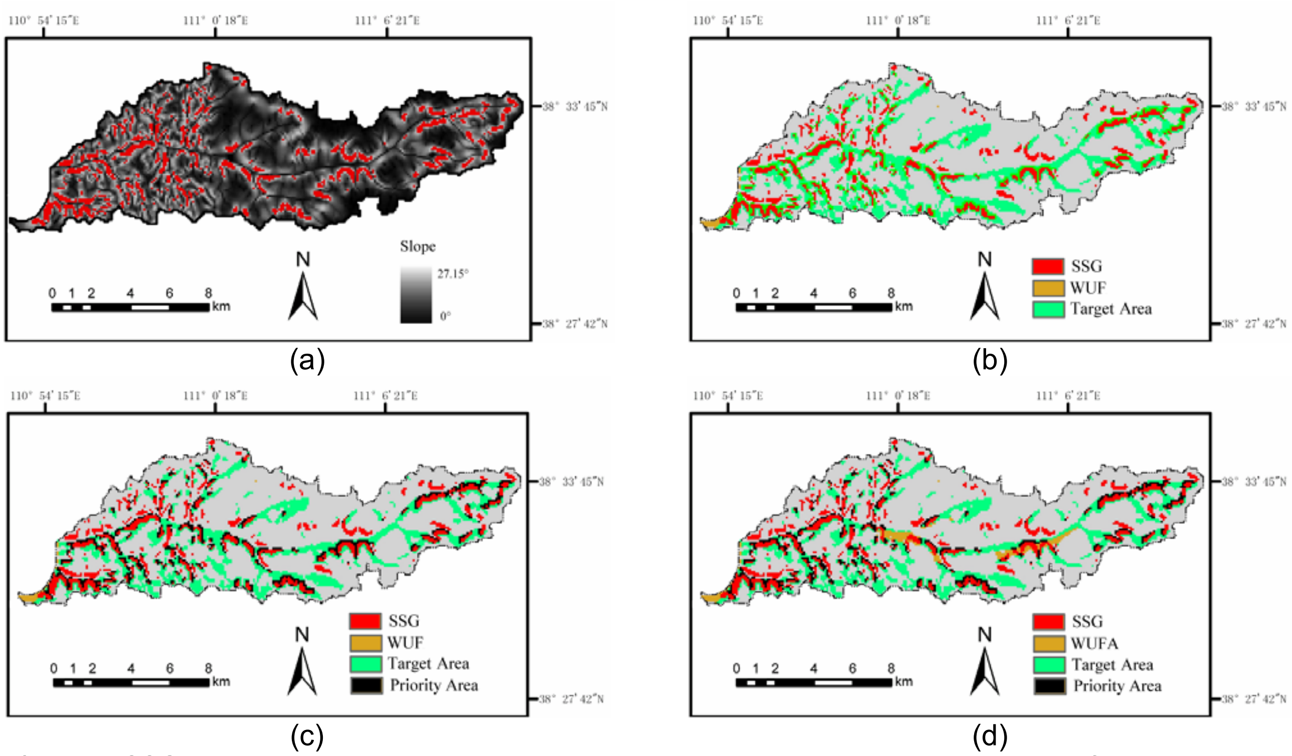


Figure 5. SSG, land limits, and target level 2 re-vegetation and priority re-vegetation areas of ZhongZhuang catchment are illustrated. (a) SSG (red) is displayed on top of the slope map; (b) SSG (red), target area (green) and the WUF land limit (orange) are shown; (c) is the same as (b) with priority re-vegetation area included (black); and (d) is the same as (c) except with the land limit set to WUFA. When using the WUF land limit class agricultural land can potentially be re-vegetated whereas in the WUFA land limit class, agricultural land is excluded from the re-vegetation target area, and grey represents other unsuitable areas in (b), (c) and (d).

Target area accounting for the WUF and WUFA land limits for each of the 42 catchments and the 36 counties with over 90% of their area located within the CSHC are summarised in Table 8 and Table 9 respectively. The priority areas, taking into consideration the land limits, for implementing the re-vegetation program for the 42 catchments of the study site and the 36 counties with over 90% of their area located within the CSHC are shown in Table 10 and Table 11 respectively. The locations of these different classes (the SSG areas, the locations of target, priority areas and land limits for the three different re-vegetation target levels) are identified for the entire 113,000 km^2 study site (comprising 42 catchments or the 70 counties) and can be explored at 100 m resolution using the ReVegIH decision support tool (Li *et al.* 2005b; McVicar *et al.* 2006).

3.4 Compressing All Suitability Maps into One Dataset (VegeBin)

In order to represent the suitability of species for the entire CSHC in the interactive and user-friendly decision support tool called ReVegIH (Li *et al.* 2005b; McVicar *et al.* 2006), all 38 species maps needed to be combined into a single dataset, otherwise the speed and disk space required to present all of the data would limit the tools' usefulness. This combination of species-level vegetation suitability data required a compression of each species presence into uniquely coded values that could be stored in a single dataset. We used a binary encoding system in which each species was given a unique binary position between 0 and 37 (*i.e.*, between 2^0 and 2^{37}). After encoding them with their unique codes, all 38 individual species maps were summed together and the resulting values for each cell represented the unique binary code for any possible combination of the 38 species. For example, in the combined dataset, if only the first species on the list was suitable at a certain cell, then the unique identifier for that cell would be $2^0 = 1$. If only the first two species were suitable at a given cell, then the unique identifier for that cell would be $2^0 + 2^1 = 3$. If, for example, only the first and the last species in the list of 38 species were suitable for a given cell, then that cell's unique identifier would be $2^0 + 2^{37} = 137,438,953,473$. Since there were 38 species, this information would require a number of the size of the mathematical progression of 2^0 to 2^{37}, or $\sum_{i=0}^{37} 2^i$ to capture all possible combinations. The maximum number from this encoding process (*i.e.*, if all species were present in one cell), was 274,877,906,943 – which can be stored as a 64-bit long integer. For brevity, the action of **Vege**tation species **Bin**ary encoding is termed VegeBin in the following discussion.

Once the values were stored in a single VegeBin dataset, a series of text files were generated and used as look up tables (LUTs). These LUTs allowed for programmatic decoding of the VegeBin dataset in the tool on-demand as the user requests species information by moving their mouse over a 100 m resolution model of the landscape (Li *et al.* 2005b). Separate LUTs were generated for the various vegetation groupings listed in Table 2, and also included the frequency information displayed in Figure 8. In this way, all the species suitability and frequency information can be programmatically decoded from a single 64-bit long integer dataset by ReVegIH very quickly. Furthermore, this dataset, along with the other required datasets and programs, easily fits on a single CD, partly accounting for the low user computer hardware requirements of ReVegIH (Li *et al.* 2005b; McVicar *et al.* 2006). As an example, Figure 6a shows the suitability of common species for SuiDe County. By clicking a cell (Figure 6b), the information tool lists the suitability status of the 22 common tree species for that specific cell (Figure 6c, 1 is suitable, 0 is not suitable).

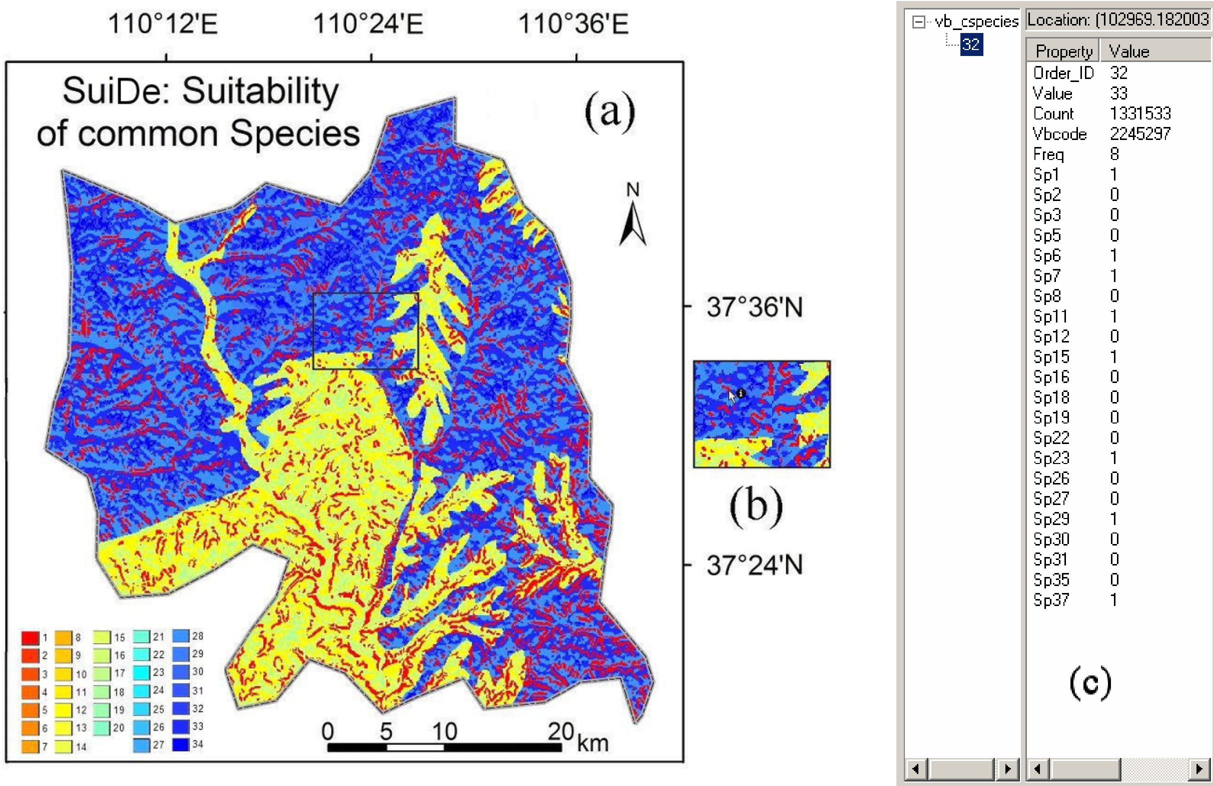
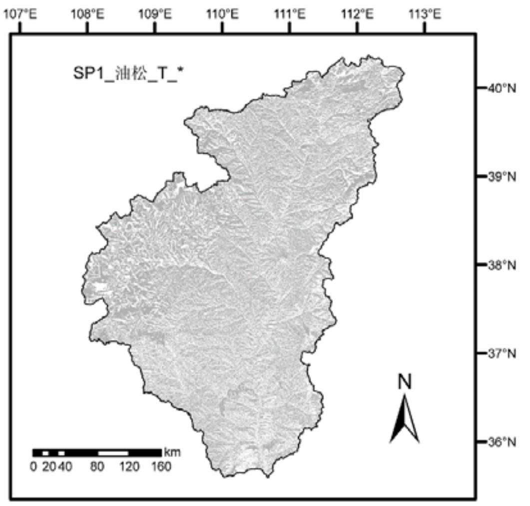


Figure 6. VegeBin suitability map of SuiDe County shows: (a) the binary vegetation map for common species for the entire county; (b) an enlargement showing the location of the cursor; and (c) the suitability information (1 = suitable and 0 = not suitable) for the 22 common trees species for the selected 100 m resolution grid cell. This information updates instantaneously as the user explores species suitability using the ReVegIH decision support tool with the species name being shown in both Chinese and English, rather than the code used here. The zoomed area shown in (b) is located in the black rectangle in the centre of (a).

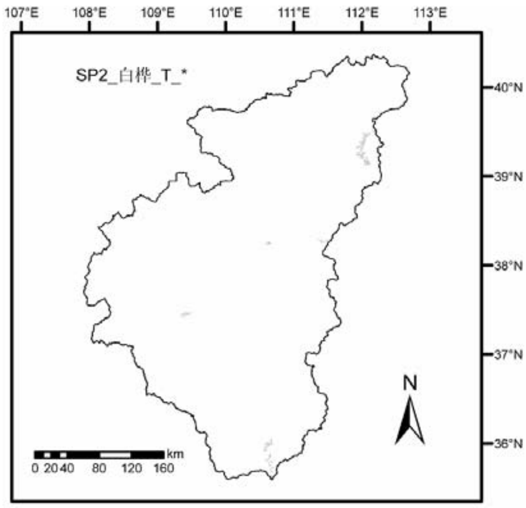
4 Results

4.1 Suitability Mapping of Trees and Shrubs

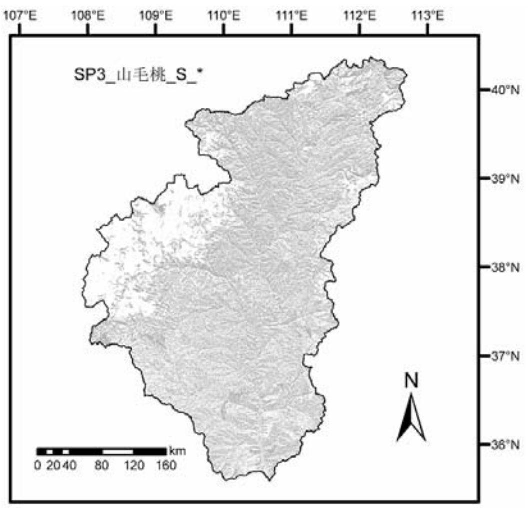
Based on the rules in Table 3, using the data shown in Figure 3, suitability maps for each of the 38 species listed in Table 1 were produced and are displayed below in Figure 7.



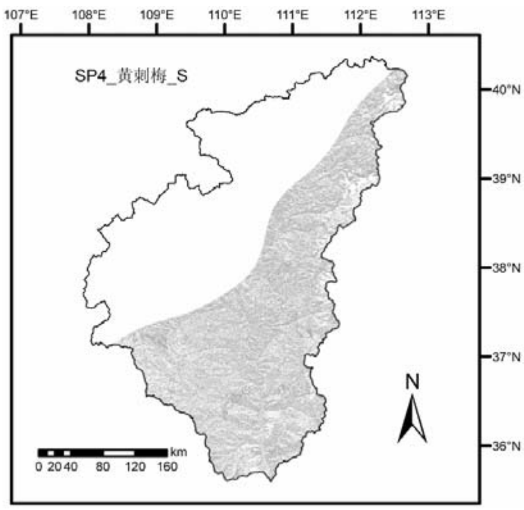
1. Suitability map of *Pinus tabulaeformis Carr.*



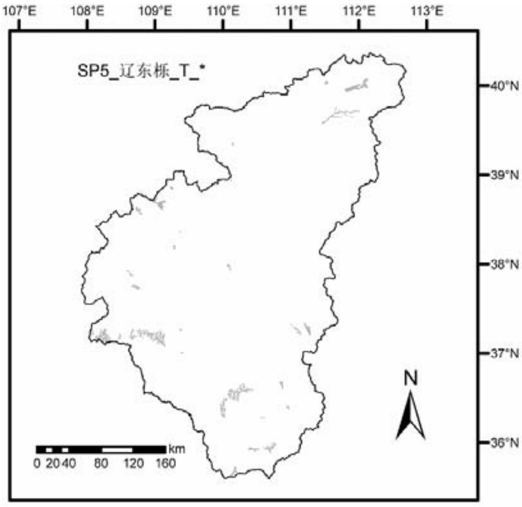
2. Suitability map of *Betula Platyphylla Suk.*



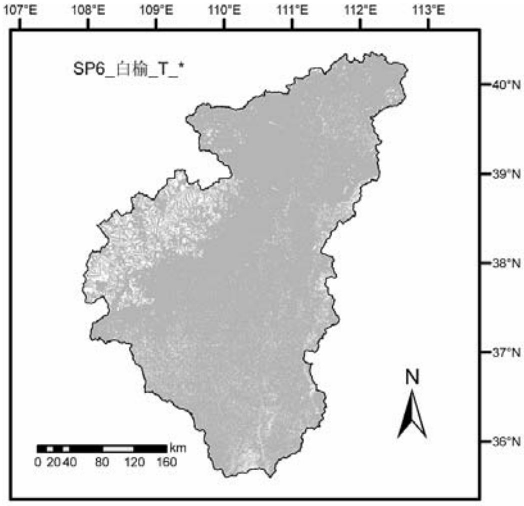
3. Suitability map of *Amygdalus davidiana Carr.*



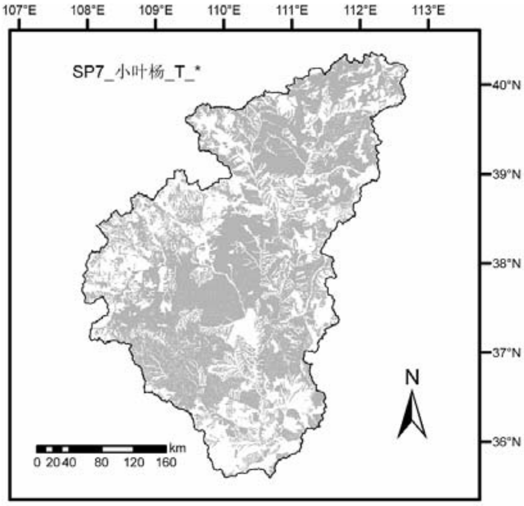
4. Suitability map of *Rosa xanthina Lindl.*



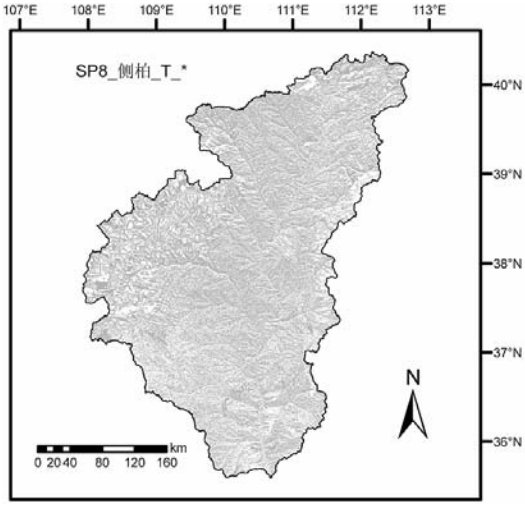
5. Suitability map of *Quercus liaotungensis Koidz.*



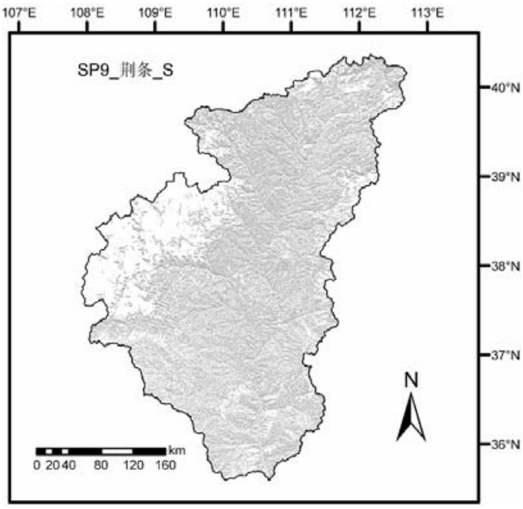
6. Suitability map of *Ulmus pumila*



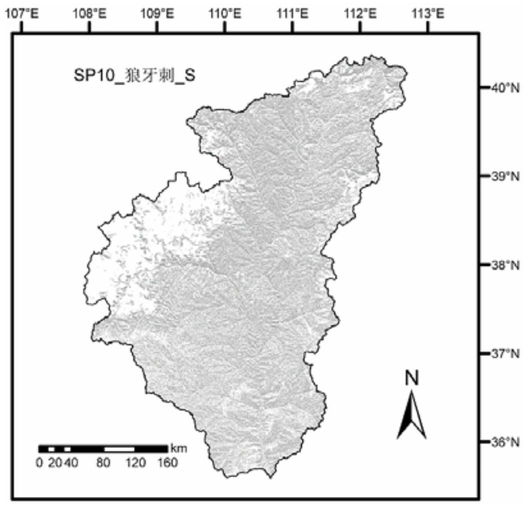
7. Suitability map of *Populus simonii Carr.*



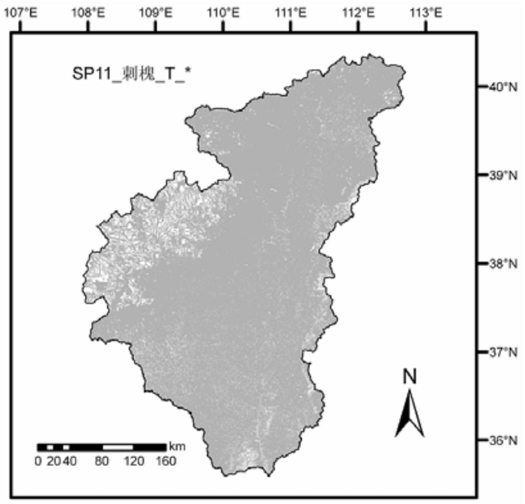
8. Suitability map of *Platycladus orientalis (L.)*



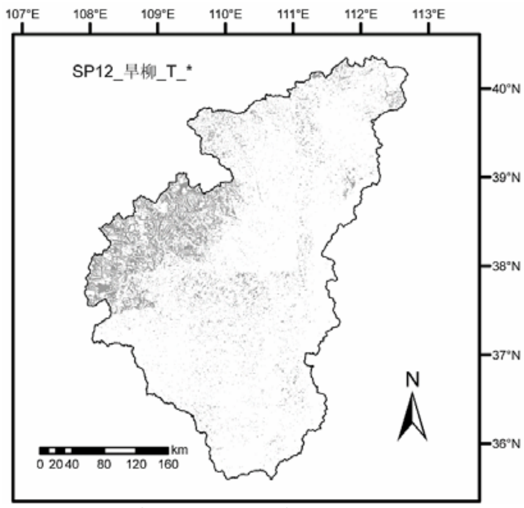
9. Suitability map of *Vitex negundo Linn.var.*



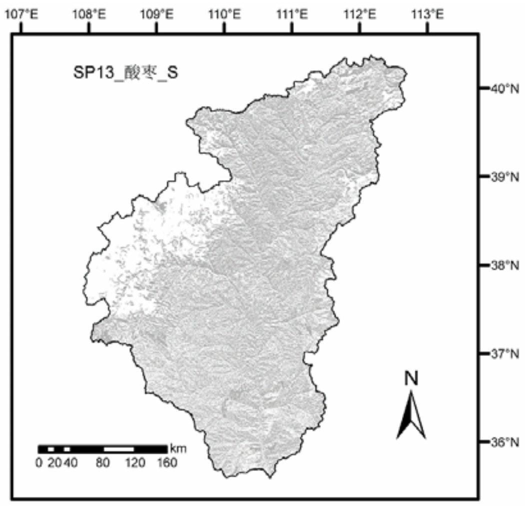
10. Suitability map of *Sophora davidii*



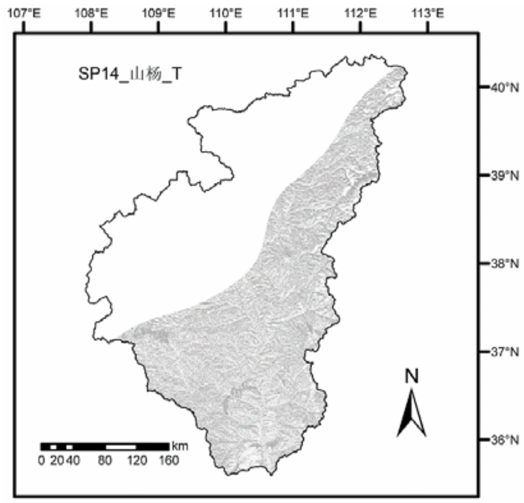
11. Suitability map of *Robinia pseudoacia*



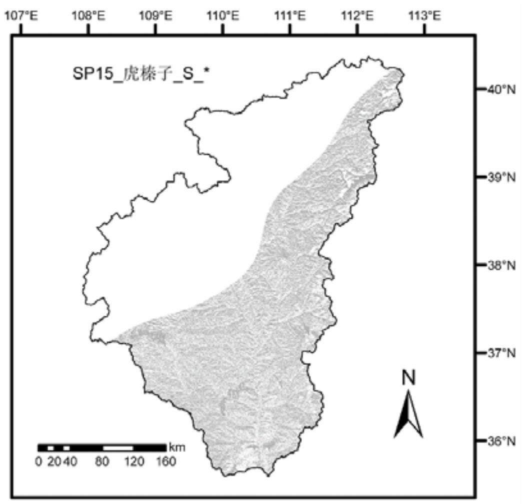
12. Suitability map of *Salix matsudana*



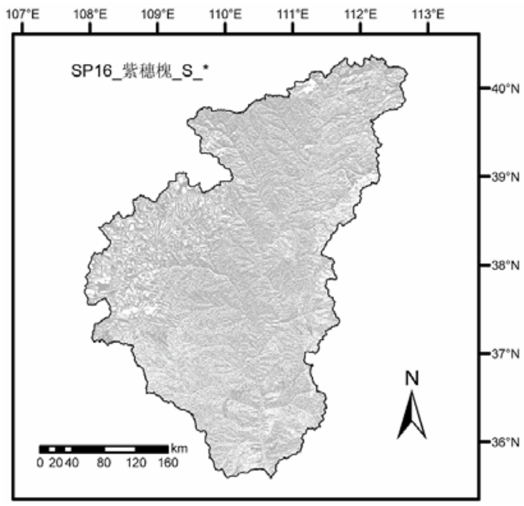
13. Suitability map of *Ziziphus jujuba var. spinosa*



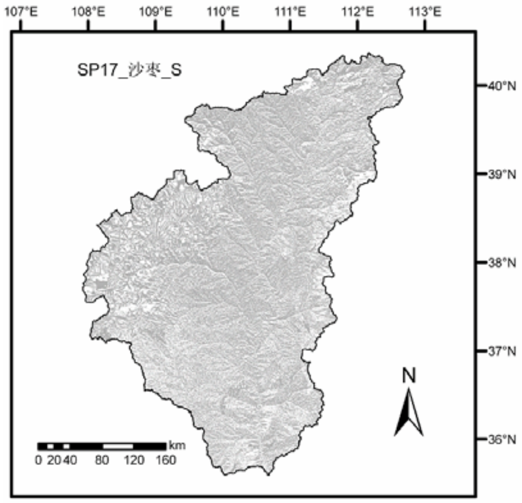
14. Suitability map of *Populus davidiana*



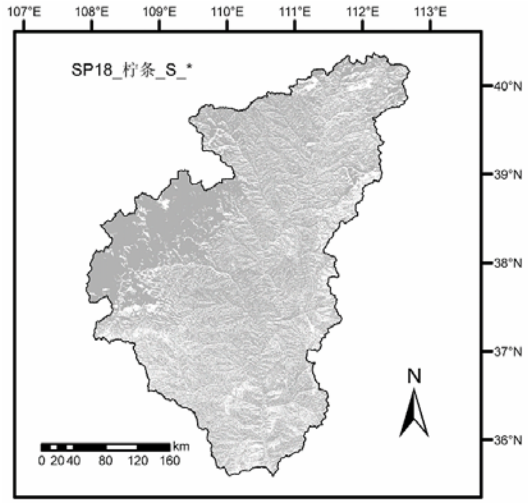
15. Suitability map of *Ostryopsis davidiana Decne*



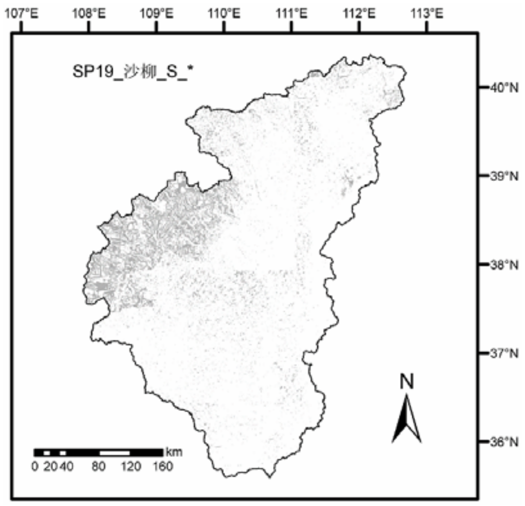
16. Suitability map of *Amorpha fruticosa*



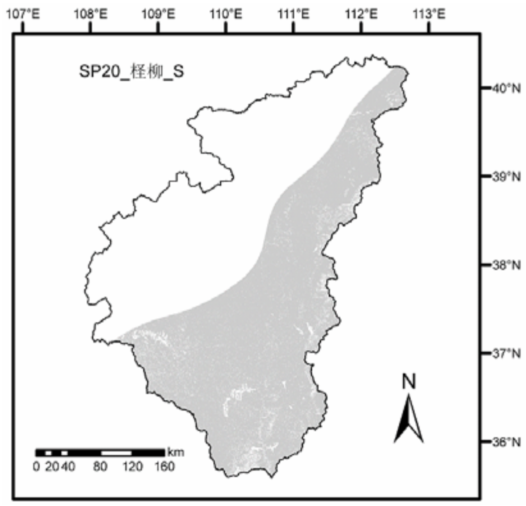
17. Suitability map of *Elaeagnus angustifolia*



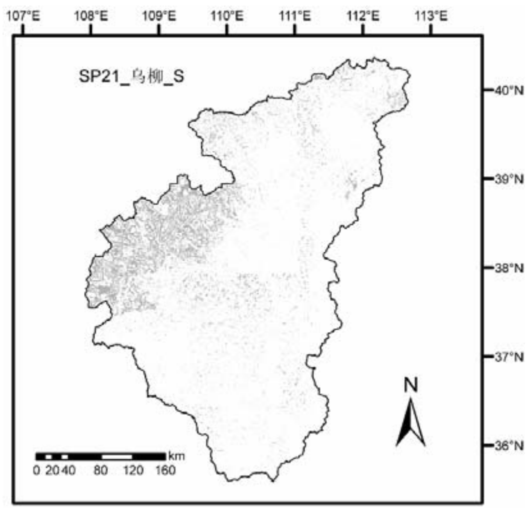
18. Suitability map of *Caragana microphylla*



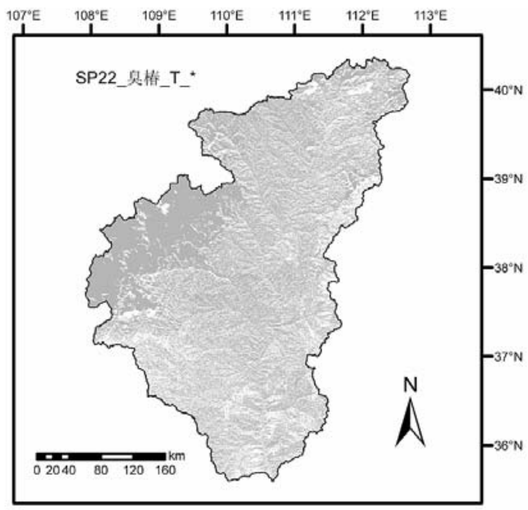
19. Suitability map of *Salix psammophila*



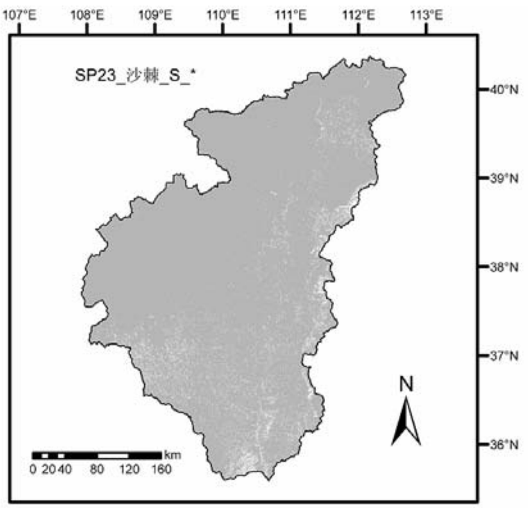
20. Suitability map of *Tamarix spp*



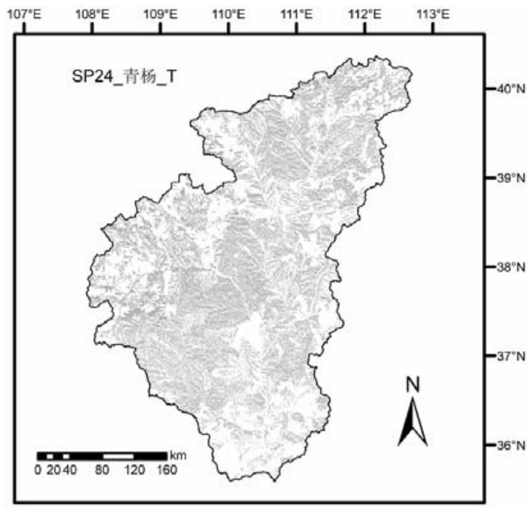
21. Suitability map of *Salix cheilophila Schneider*



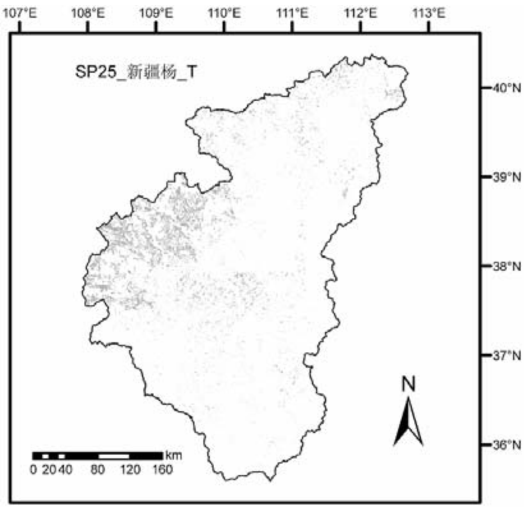
22. Suitability map of *Ailanthus altissima*



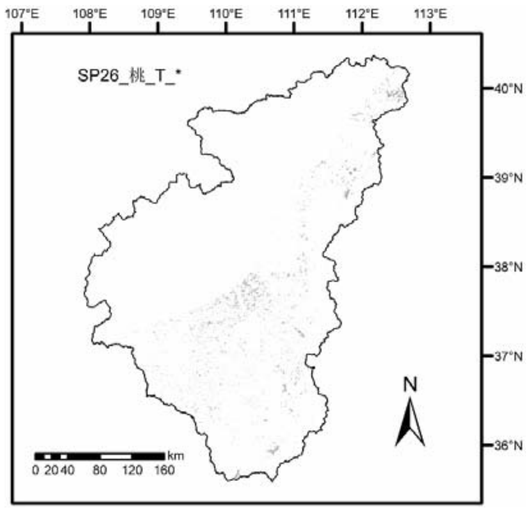
23. Suitability map of *Hippophae rhamnoides*



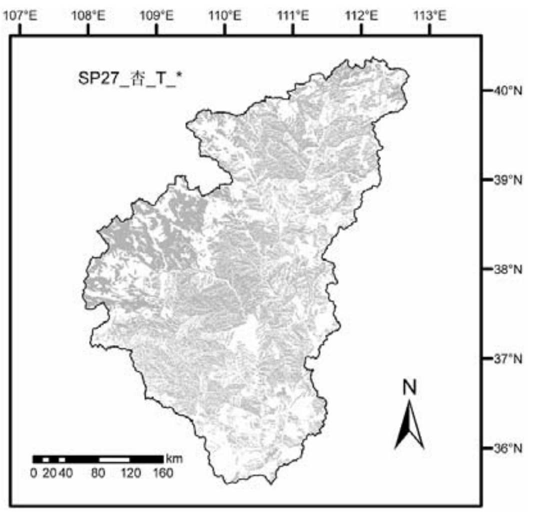
24. Suitability map of *Populus.cathayana Rehd*



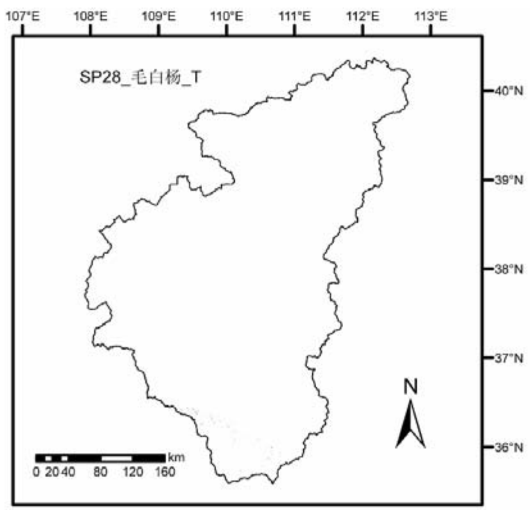
25. Suitability map of *Populus alba cv*



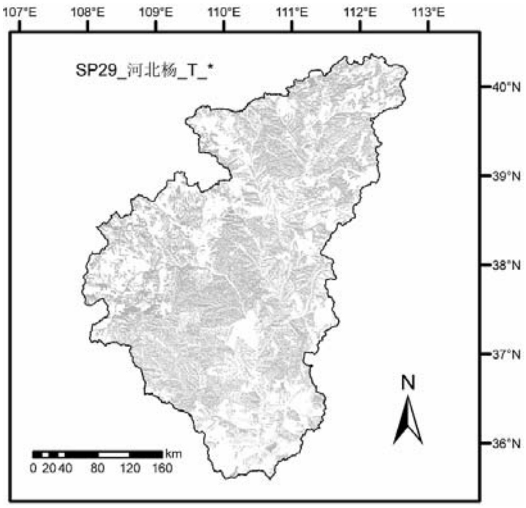
26. Suitability map of *Prunus davidiana*



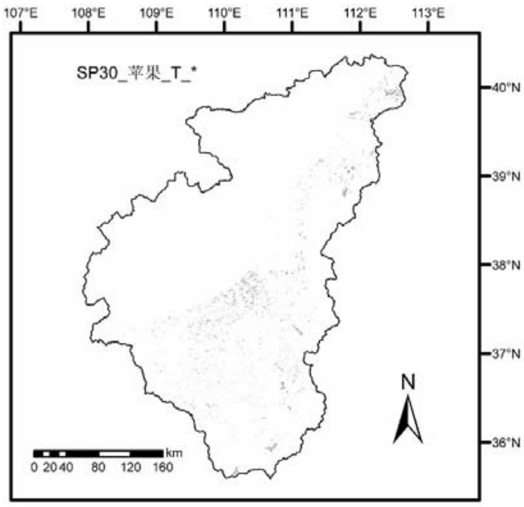
27. Suitability map of *Prunus armeniana var.ansu*



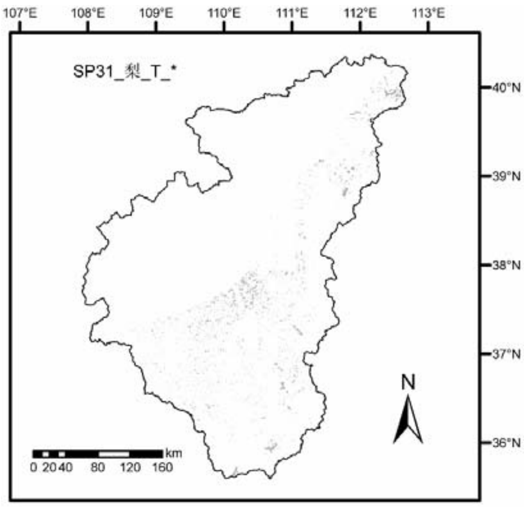
28. Suitability map of *Populus tomenttosa carr.*



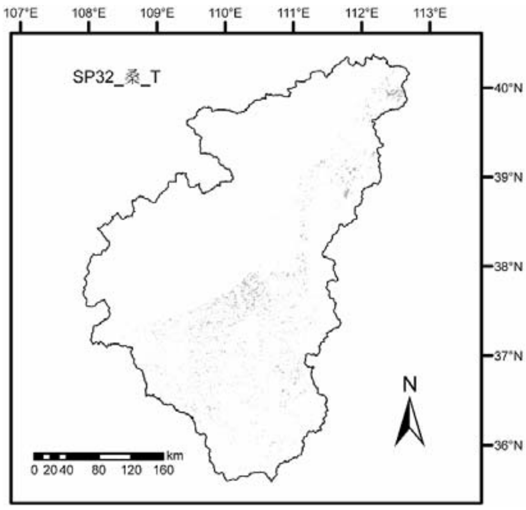
29. Suitability map of *Populars hopeiensis*



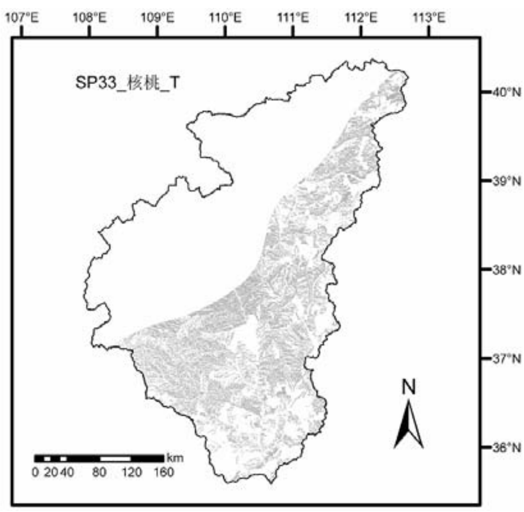
30. Suitability map of *Malus domestica Borkh*



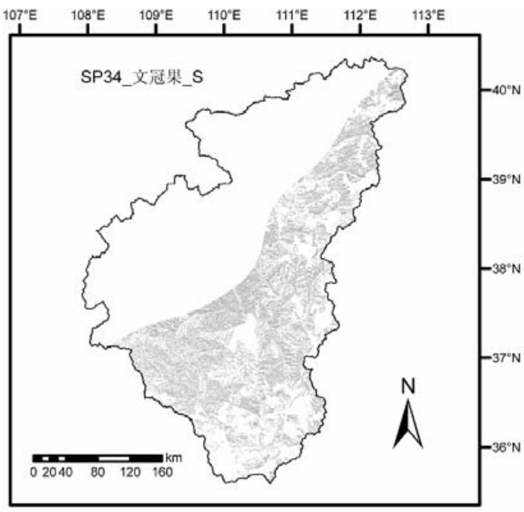
31. Suitability map of *Pyrus bretschneideri*



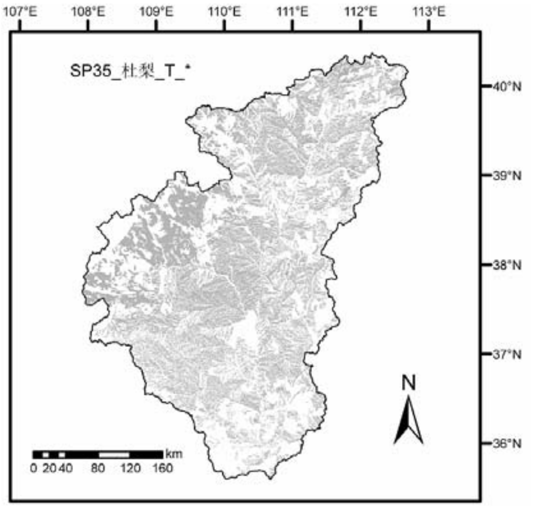
32. Suitability map of *Morus alba L.*



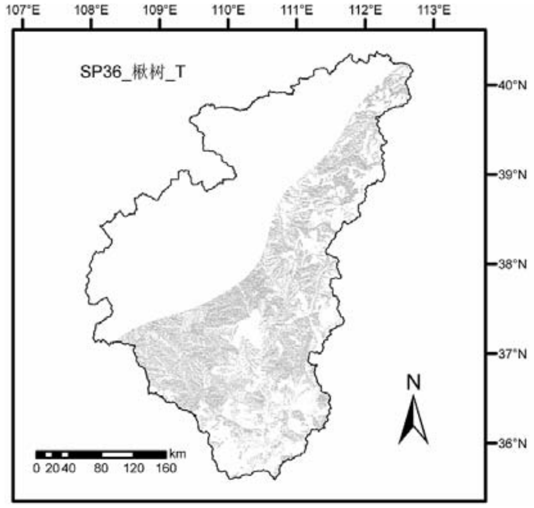
33. Suitability map of *Juglans regia*



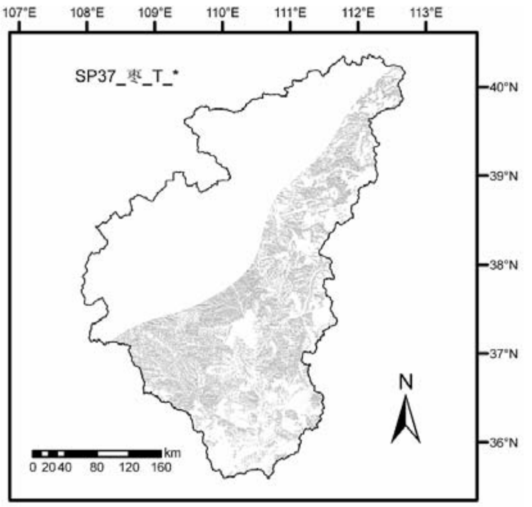
34. Suitability map of *Xanthoceras sorbifolia Bunge*.



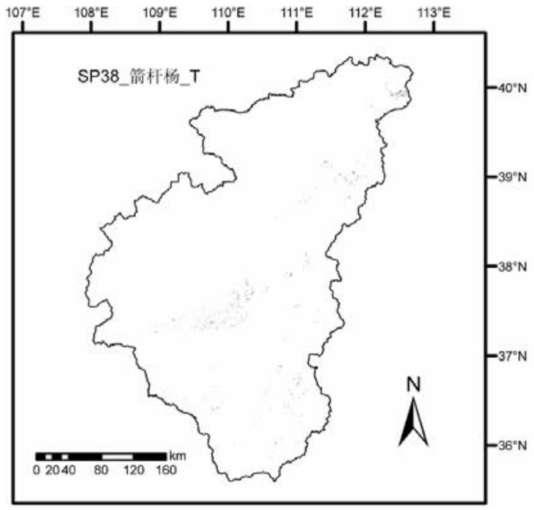
35. Suitability map of *Pyrus betulaefoli*



36. Suitability map of *Catalpa bungei C.A.Mey*



37. Suitability map of *Ziziphus jujuba Mill*

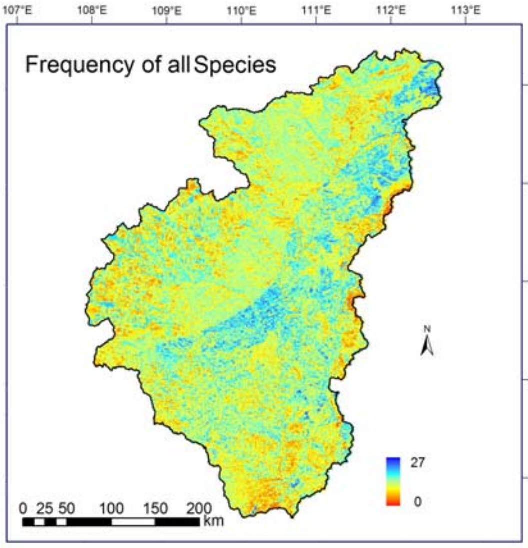


38. Suitability map of *Populus nigra var.*

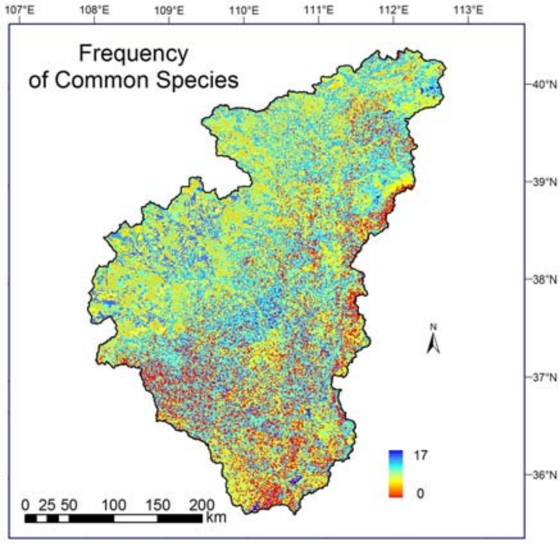
Figure 7. Suitability maps for each of 38 species listed in Table 1 are shown. The small numbers under each map are their species code number followed by their Latin name. On each map the code number follows the letters SP (for species), which is in turn followed by the Chinese characters for the species name, whether it is a tree (T) or shrub (S), with the * indicating a common species; they are separated by underscores. In the CSHC boundary, grey areas indicate where a species is suitable and white represents areas that are not suitable.

4.2 Frequency of Suitable Species

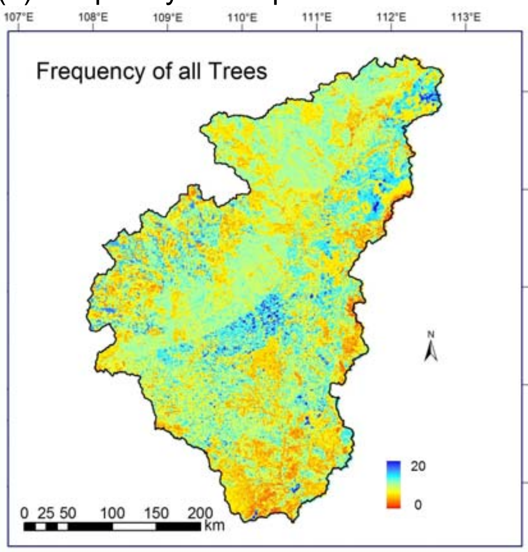
Based on the individual species suitability maps (Figure 7) frequency maps were produced for the 7 groups introduced in Table 2 by adding on a cell-by-cell basis the number of suitability species for: (1) all species; (2) all common species; (3) all tree species; (4) all common trees; (5) all shrub species; (6) all common shrubs; and (7) all fruit trees. The resulting surfaces are shown in Figure 8 (a) to (g), respectively.



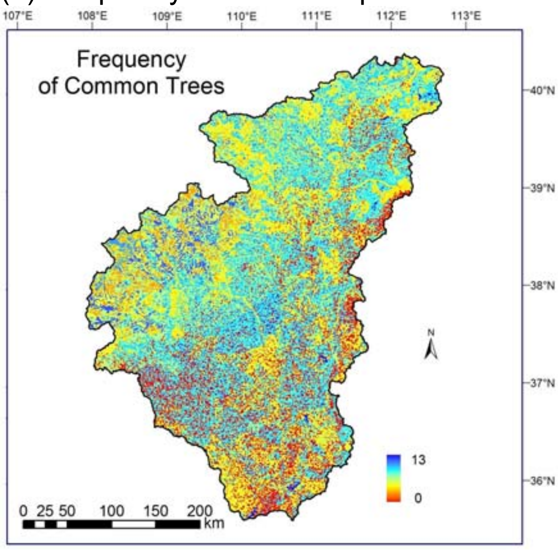
(a) Frequency of all species



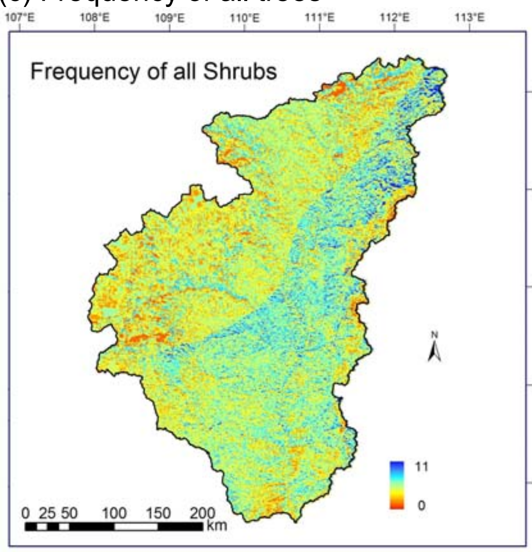
(b) Frequency of common species



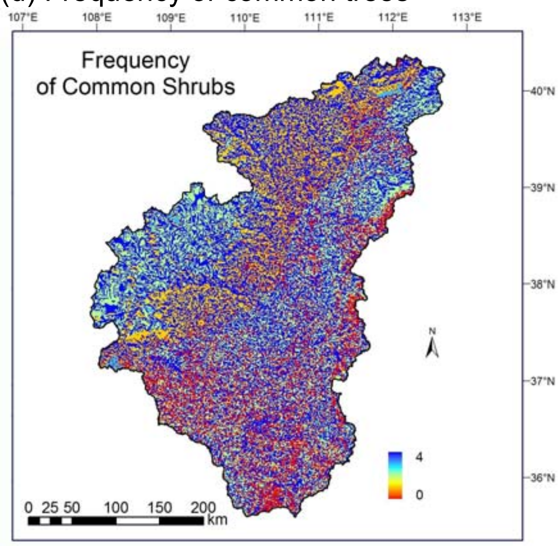
(c) Frequency of all trees



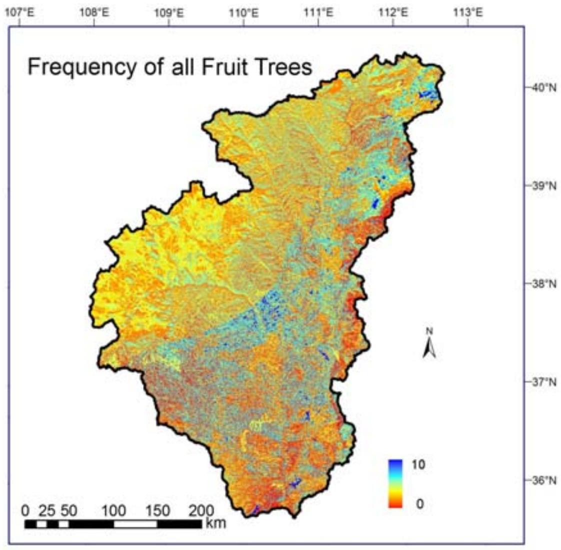
(d) Frequency of common trees



(c) Frequency of all shrubs



(f) Frequency of common shrubs



(g) Frequency of all fruit trees

Figure 8. Maps showing the frequency of species suitable for each 100 m resolution grid cell for the 7 vegetation grouping introduced in Table 2. They are: (a) all species; (b) common species; (c) all trees; (d) common trees; (e) all shrubs; (f) common shrubs; and (g) all fruit trees.

4.3 Re-vegetation Target and Priority Areas Excluding Land Limits

Target areas excluding the WUF and WUFA land limits for each of the 42 catchments and the 36 counties with over 90% of their area located within the CSHC are summarised in Table 8 and Table 9 respectively.

Table 8. The target area (km^2 and %) of the 42 catchments for the three different re-vegetation levels after the land limits have been subtracted. The three different re-vegetation levels are denoted 1 for trees, 2 for shrubs and 3 for grasses. There are two land limits (LL) considered, they are: LL_WUF, which denotes the area where the current land use is water, urban or forestry and LL_WUFA is the area where current land use is water, urban, forestry or agricultural land.

Catchment name	Catchment name (in Chinese)	Target 1 area				Target 2 area				Target 3 area			
		LL_WUF		LL_WUFA		LL_WUF		LL_WUFA		LL_WUF		LL_WUFA	
		km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Honghe River	红河	0	0.0	0	0.0	806	14.2	738	13.0	1560	27.4	1440	25.3
Lamawan	喇嘛湾	0	0.0	0	0.0	42	8.9	41	8.7	97	20.7	92	19.6
Longwanggou River	龙王沟	0	0.0	0	0.0	223	12.5	218	12.2	443	25.0	435	24.5
Huangfuchuan River	皇甫川	0	0.0	0	0.0	628	17.9	576	16.4	1307	37.2	1233	35.1
Yangjiachuan River	杨家川	0	0.0	0	0.0	266	23.9	265	23.8	545	48.9	542	48.7
Kuyehe River	窟野河	0	0.0	0	0.0	1357	15.0	1255	13.9	2818	31.1	2663	29.4
Pianguanhe River	偏关河	0	0.0	0	0.0	517	24.9	496	23.9	1057	50.8	1025	49.3
Qingshuichuan River	清水川	0	0.0	0	0.0	236	24.4	214	22.2	484	50.0	457	47.2
Hequ	河曲	0	0.0	0	0.0	120	20.6	117	20.1	222	38.0	218	37.3
Xianchuanhe River	县川河	0	0.0	0	0.0	371	23.2	361	22.6	755	47.4	740	46.4
Gushanchuan River	孤山川	0	0.0	0	0.0	312	23.7	284	21.6	658	49.9	618	46.9
Zhujiachuan River	朱家川	0	0.0	0	0.0	564	19.3	534	18.3	1071	36.7	1020	34.9
Baode	保德	0	0.0	0	0.0	58	24.0	58	24.0	105	43.5	105	43.5
Wudinghe River	无定河	0	0.0	0	0.0	3051	9.7	2853	9.1	6189	19.7	5840	18.6
Tuweihe River	秃尾河	0	0.0	0	0.0	396	11.9	360	10.8	824	24.7	763	22.9
Wujiazhuang	武家庄	0	0.0	0	0.0	222	22.0	220	21.8	492	48.9	488	48.5
Huashuta-Luzihe	化树塔-芦子河	0	0.0	0	0.0	139	23.8	136	23.4	281	48.1	277	47.5
Lanyihe River	岚漪河	0	0.0	0	0.0	523	23.6	476	21.5	1023	46.1	962	43.4
Weifenhe River	蔚汾河	0	0.0	0	0.0	395	24.0	371	22.6	770	46.8	739	44.9
ZhongZhuang	中庄	0	0.0	0	0.0	31	24.4	29	23.0	64	50.2	61	48.4
Jialuhe River	佳芦河	0	0.0	0	0.0	264	21.9	256	21.3	544	45.1	533	44.2
Yangjiapu-Zhaojiaping	杨家铺-赵家坪	0	0.0	0	0.0	539	22.8	537	22.7	1140	48.2	1136	48.1
Qiushuihe River	湫水河	0	0.0	0	0.0	445	22.4	415	20.9	907	45.7	860	43.3
Nuanqushan	暖渠山	0	0.0	0	0.0	45	20.8	45	20.6	98	45.0	97	44.5
Sanchuanhe River	三川河	0	0.0	0	0.0	766	18.5	697	16.8	1587	38.3	1479	35.7
Hedi-Mutouyu	河底-木头峪	0	0.0	0	0.0	337	18.6	337	18.6	731	40.3	731	40.3
Chengjiazhuang	程家庄	0	0.0	0	0.0	62	20.9	62	20.9	134	45.3	134	45.3
Jinjiazhuang	靳家庄	0	0.0	0	0.0	90	19.5	88	19.1	190	41.3	188	40.8
Yanhe River	延河	100	1.3	94	1.2	1593	20.7	1511	19.6	3091	40.1	2976	38.6
Qingjianhe River	清涧河	0	0.0	0	0.0	869	21.3	809	19.9	1760	43.2	1680	41.2
Lijiashan-Yanchasi	李家山-眼岔寺	0	0.0	0	0.0	143	18.3	143	18.3	321	41.2	321	41.1
Quchanhe River	屈产河	0	0.0	0	0.0	241	19.6	219	17.8	485	39.6	453	36.9
Yonghe River	雍河	0	0.0	0	0.0	397	19.2	385	18.6	851	41.1	831	40.1
Xinshuihe River	昕水河	0	0.0	0	0.0	733	16.8	675	15.5	1545	35.5	1443	33.2
Anhe-Guandao	安河-关道	0	0.0	0	0.0	78	20.3	78	20.3	157	41.0	157	41.0
Fenchuanhe River	汾川河	424	22.5	372	19.8	460	24.5	408	21.7	520	27.7	468	24.9
Xigelou	西葛沟	0	0.0	0	0.0	50	15.2	50	15.2	121	36.5	121	36.5
Wencheng-Wangjiayao	文城-王家窑	38	7.6	38	7.6	84	17.0	84	17.0	143	28.9	143	28.9
Zhouchuan River	州川河	66	9.2	63	8.9	143	20.1	136	19.1	247	34.6	239	33.5
Shiwanghe River	仕望川	445	18.7	407	17.1	445	18.7	407	17.1	445	18.7	407	17.1
Ehe River	鄂河	244	23.9	239	23.4	325	31.8	315	30.8	418	40.9	401	39.2
Sili-Jiyizhen	寺里-集义镇	213	18.8	204	18.0	213	18.8	204	18.0	213	18.8	204	18.0

Table 9. The target area (km^2 and %) of counties with over 90% area located within the CSHC for the three different re-vegetation levels after the land limits have been subtracted. The three different re-vegetation levels are denoted 1 for trees, 2 for shrubs and 3 for grasses. There are two land limits (LL) considered, they are: LL_WUF, which denotes the area where the current land use is water, urban or forestry and LL_WUFA is the area where current land use is water, urban, forestry or agricultural land.

County name	Name	Target 1 area				Target 2 area				Target 3 area			
		LL_WUF		LL_WUFA		LL_WUF		LL_WUFA		LL_WUF		LL_WUFA	
		km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
KeLanXian	岢岚县	0	0.0	0	0.0	479	24.4	442	22.6	909	46.4	861	43.9
HeQuXian	河曲县	0	0.0	0	0.0	265	21.7	261	21.3	525	42.9	518	42.3
BaoDeXian	保德县	0	0.0	0	0.0	232	22.8	223	21.9	478	47.0	465	45.8
PianGuanXian	偏关县	0	0.0	0	0.0	438	24.5	430	24.0	884	49.4	869	48.5
XianXian	兴县	0	0.0	0	0.0	767	24.8	728	23.5	1505	48.6	1450	46.8
LinXian	临县	0	0.0	0	0.0	665	21.3	637	20.4	1451	46.4	1406	45.0
LiuLinXian	柳林县	0	0.0	0	0.0	254	19.9	249	19.5	565	44.3	557	43.6
JiXian	吉县	157	8.7	151	8.4	354	19.7	336	18.7	582	32.4	560	31.1
DaNingXian	大宁县	0	0.0	0	0.0	175	17.7	165	16.8	365	37.0	352	35.7
YongHeXian	永和县	0	0.0	0	0.0	235	18.5	228	18.0	528	41.6	517	40.7
YanChangXian	延长县	0	0.0	0	0.0	432	19.4	421	18.9	882	39.6	866	38.9
YanChuanXian	延川县	0	0.0	0	0.0	411	21.0	383	19.6	832	42.6	796	40.7
ZiChangXian	子长县	0	0.0	0	0.0	522	21.9	493	20.6	1039	43.5	1002	42.0
YuLinXian	榆林县	0	0.0	0	0.0	435	6.2	385	5.5	926	13.1	825	11.7
FuGu	府谷县	0	0.0	0	0.0	754	23.0	702	21.4	1561	47.6	1492	45.5
HengShanXian	横山县	0	0.0	0	0.0	769	17.1	712	15.8	1509	33.5	1412	31.3
SuiDeXian	绥德县	0	0.0	0	0.0	344	19.1	324	18.0	768	42.7	725	40.3
MiZhiXian	米脂县	0	0.0	0	0.0	191	17.1	183	16.4	406	36.3	392	35.0
JiaXian	佳县	0	0.0	0	0.0	427	21.5	419	21.0	881	44.2	869	43.6
WuBuXian	吴堡县	0	0.0	0	0.0	80	19.4	80	19.4	177	42.9	177	42.9
QingJianXian	清涧县	0	0.0	0	0.0	348	19.3	337	18.7	770	42.8	753	41.8
ZiZhouXian	子州县	0	0.0	0	0.0	401	20.1	377	18.9	849	42.6	813	40.7
ShiLouXian	石楼县	0	0.0	0	0.0	367	20.3	343	18.9	736	40.6	699	38.6
WuZhaiXian	五寨县	0	0.0	0	0.0	233	17.5	221	16.5	410	30.8	388	29.1
YiChuanXian	宜川县	617	22.3	571	20.6	643	23.2	597	21.6	681	24.6	635	22.9
QingShuiHeXian	清水河县	0	0.0	0	0.0	570	21.8	565	21.6	1115	42.7	1105	42.3
LiShiXian	离石县	0	0.0	0	0.0	237	18.6	218	17.1	504	39.6	472	37.1
YanAnShi	延安市	382	11.0	330	9.4	814	23.3	727	20.8	1240	35.5	1136	32.5
AnSaiXian	安塞县	1	0.0	1	0.0	571	20.0	544	19.1	1138	39.9	1102	38.6
FangShanXian	方山县	0	0.0	0	0.0	293	19.9	258	17.5	595	40.3	540	36.6
ZhongYangXian	中阳县	0	0.0	0	0.0	243	17.5	230	16.5	473	33.9	453	32.5
PuXian	蒲县	0	0.0	0	0.0	273	18.3	259	17.3	564	37.7	543	36.2
ShenChiXian	神池县	0	0.0	0	0.0	284	19.7	271	18.8	576	40.0	549	38.1
XiXian	隰县	0	0.0	0	0.0	225	15.4	197	13.5	506	34.6	450	30.8
JingBianXian	靖边县	0	0.0	0	0.0	734	15.3	700	14.6	1404	29.2	1356	28.2
ShenMuXian	神木县	0	0.0	0	0.0	1102	15.6	1016	14.4	2331	33.1	2188	31.1

The priority areas, taking into consideration the land limits, for implementing the re-vegetation program for each of the 42 catchments and the 36 counties with over 90% of their area located within the CSHC are shown in Table 10 and Table 11, respectively.

Table 10. The priority area (km^2 and %) of the 42 catchments for the three different re-vegetation levels after the land limits have been subtracted. The three different re-vegetation levels are denoted 1 for trees, 2 for shrubs and 3 for grasses. There are two land limits (LL) considered, they are: LL_WUF, which denotes the area where the current land use is water, urban or forestry and LL_WUFA is the area where current land use is water, urban, forestry or agricultural land.

Catchment name	Catchment name (in Chinese)	Priority 1 area				Priority 2 area				Priority 3 area			
		LL_WUF		LL_WUFA		LL_WUF		LL_WUFA		LL_WUF		LL_WUFA	
		km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Honghe River	红河	0	0.00	0	0.00	73	1.28	67	1.17	138	2.41	126	2.22
Lamawan	喇嘛湾	0	0.00	0	0.00	1	0.17	1	0.16	3	0.53	2	0.51
Longwanggou River	龙王沟	0	0.00	0	0.00	19	1.05	19	1.05	38	2.13	38	2.12
Huangfuchuan River	皇甫川	0	0.00	0	0.00	58	1.66	56	1.59	101	2.89	99	2.81
Yangjiachuan River	杨家川	0	0.00	0	0.00	60	5.37	60	5.37	126	11.34	126	11.34
Kuyehe River	窟野河	0	0.00	0	0.00	234	2.58	219	2.42	451	4.99	430	4.75
Pianguanhe River	偏关河	0	0.00	0	0.00	128	6.17	125	6.02	262	12.63	259	12.45
Qingshuichuan River	清水川	0	0.00	0	0.00	52	5.36	46	4.77	90	9.27	83	8.56
Hequ	河曲	0	0.00	0	0.00	23	3.86	22	3.83	38	6.52	38	6.49
Xianchuanhe River	县川河	0	0.00	0	0.00	65	4.06	65	4.05	132	8.28	132	8.27
Gushanchuan River	孤山川	0	0.00	0	0.00	67	5.08	61	4.65	122	9.29	115	8.76
Zhujiachuan River	朱家川	0	0.00	0	0.00	115	3.92	112	3.82	203	6.95	199	6.82
Baode	保德	0	0.00	0	0.00	12	5.07	12	5.07	21	8.60	21	8.60
Wudinghe River	无定河	0	0.00	0	0.00	763	2.43	732	2.33	1424	4.53	1377	4.38
Tuweihe River	秃尾河	0	0.00	0	0.00	86	2.59	80	2.39	158	4.75	148	4.44
Wujiazhuang	武家庄	0	0.00	0	0.00	75	7.45	74	7.32	150	14.85	147	14.62
Huashuta-Luzihe	化树塔-芦子河	0	0.00	0	0.00	38	6.60	38	6.48	67	11.51	66	11.36
Lanyihe River	岚漪河	0	0.00	0	0.00	144	6.51	137	6.20	279	12.55	270	12.17
Weifenhe River	蔚汾河	0	0.00	0	0.00	108	6.58	103	6.27	200	12.18	194	11.79
ZhongZhuang	中庄	0	0.00	0	0.00	8	6.50	8	6.08	16	12.36	15	11.90
Jialuhe River	佳芦河	0	0.00	0	0.00	76	6.33	74	6.16	140	11.62	137	11.37
Yangjiapu-Zhaojiaping	杨家铺-赵家坪	0	0.00	0	0.00	216	9.13	215	9.09	416	17.60	415	17.53
Qiushuihe River	湫水河	0	0.00	0	0.00	117	5.87	112	5.67	228	11.49	222	11.18
Nuanqushan	暖渠山	0	0.00	0	0.00	16	7.56	16	7.42	31	14.12	30	13.96
Sanchuanhe River	三川河	0	0.00	0	0.00	222	5.37	213	5.16	464	11.21	451	10.90
Hedi-Mutouyu	河底-木头峪	0	0.00	0	0.00	116	6.41	116	6.41	220	12.12	220	12.12
Chengjiazhuang	程家庄	0	0.00	0	0.00	25	8.36	25	8.36	45	15.31	45	15.31
Jinjiazhuang	靳家庄	0	0.00	0	0.00	35	7.53	34	7.36	67	14.58	66	14.41
Yanhe River	延河	38	0.49	35	0.46	722	9.37	685	8.88	1391	18.04	1341	17.39
Qingjianhe River	清涧河	0	0.00	0	0.00	381	9.35	355	8.72	751	18.44	717	17.60
Lijiashan-Yanchasi	李家山-眼岔寺	0	0.00	0	0.00	60	7.69	60	7.69	123	15.69	122	15.68
Quchanhe River	屈产河	0	0.00	0	0.00	98	8.00	89	7.27	183	14.94	171	13.95
Yonghe River	雍河	0	0.00	0	0.00	180	8.70	174	8.40	361	17.46	352	17.01
Xinshuihe River	昕水河	0	0.00	0	0.00	267	6.14	245	5.63	532	12.22	499	11.46
Anhe-Guandao	安河-关道	0	0.00	0	0.00	33	8.53	33	8.53	62	16.19	62	16.19
Fenchuanhe River	汾川河	162	8.62	144	7.67	177	9.40	159	8.45	200	10.66	183	9.71
Xigelou	西葛沟	0	0.00	0	0.00	23	7.05	23	7.05	55	16.74	55	16.74
Wencheng-Wangjiayao	文城-王家窑	18	3.54	18	3.54	41	8.33	41	8.33	66	13.42	66	13.42
Zhouchuan River	州川河	24	3.42	23	3.28	56	7.84	53	7.46	93	13.06	90	12.63
Shiwanghe River	仕望川	184	7.75	167	7.04	184	7.75	167	7.04	184	7.75	167	7.04
Ehe River	鄂河	94	9.14	93	9.06	120	11.69	118	11.49	149	14.55	146	14.25
Sili-Jiyizhen	寺里-集义镇	106	9.35	100	8.83	106	9.35	100	8.83	106	9.35	100	8.83

Table 11. The priority area (km^2 and %) of counties with over 90% area located within the CSHC for the three different re-vegetation levels after the land limits have been subtracted. The three different re-vegetation levels are denoted 1 for trees, 2 for shrubs and 3 for grasses. There are two land limits (LL) considered, they are: LL_WUF, which denotes the area where the current land use is water, urban or forestry and LL_WUFA is the area where current land use is water, urban, forestry or agricultural land.

County name	Name (in Chinese)	Priority 1 area				Priority 2 area				Priority 3 area			
		LL_WUF		LL_WUFA		LL_WUF		LL_WUFA		LL_WUF		LL_WUFA	
		km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
KeLanXian	岢岚县	0	0.00	0	0.00	127	6.47	121	6.19	242	12.36	236	12.01
HeQuXian	河曲县	0	0.00	0	0.00	61	4.97	60	4.93	112	9.16	112	9.10
BaoDeXian	保德县	0	0.00	0	0.00	60	5.87	57	5.63	108	10.61	105	10.32
PianGuanXian	偏关县	0	0.00	0	0.00	105	5.88	105	5.84	215	12.00	213	11.93
XianXian	兴县	0	0.00	0	0.00	249	8.03	241	7.77	457	14.75	446	14.39
LinXian	临县	0	0.00	0	0.00	207	6.62	203	6.49	423	13.55	417	13.33
LiuLinXian	柳林县	0	0.00	0	0.00	97	7.58	95	7.44	193	15.15	191	14.99
JiXian	吉县	58	3.25	57	3.16	146	8.13	139	7.74	238	13.25	230	12.76
DaNingXian	大宁县	0	0.00	0	0.00	81	8.19	75	7.65	157	15.90	150	15.23
YongHeXian	永和县	0	0.00	0	0.00	103	8.10	100	7.83	217	17.09	212	16.67
YanChangXian	延长县	0	0.00	0	0.00	188	8.44	182	8.17	373	16.78	366	16.43
YanChuanXian	延川县	0	0.00	0	0.00	185	9.47	173	8.83	362	18.51	345	17.65
ZiChangXian	子长县	0	0.00	0	0.00	217	9.07	205	8.60	424	17.74	410	17.15
YuLinXian	榆林县	0	0.00	0	0.00	81	1.15	75	1.07	152	2.16	143	2.03
FuGu	府谷县	0	0.00	0	0.00	170	5.20	159	4.86	310	9.46	297	9.05
HengShanXian	横山县	0	0.00	0	0.00	145	3.21	138	3.07	259	5.76	251	5.56
SuiDeXian	绥德县	0	0.00	0	0.00	116	6.43	111	6.18	228	12.66	219	12.17
MiZhiXian	米脂县	0	0.00	0	0.00	50	4.49	50	4.43	93	8.27	92	8.16
JiaXian	佳县	0	0.00	0	0.00	134	6.74	132	6.62	239	12.02	236	11.85
WuBuXian	吴堡县	0	0.00	0	0.00	28	6.90	28	6.90	54	13.06	54	13.06
QingJianXian	清涧县	0	0.00	0	0.00	144	8.01	140	7.80	296	16.42	290	16.08
ZiZhouXian	子州县	0	0.00	0	0.00	138	6.90	131	6.54	258	12.93	248	12.45
ShiLouXian	石楼县	0	0.00	0	0.00	159	8.78	149	8.21	300	16.58	286	15.78
WuZhaiXian	五寨县	0	0.00	0	0.00	39	2.91	39	2.89	67	5.00	66	4.98
YiChuanXian	宜川县	271	9.77	249	9.00	282	10.18	261	9.42	297	10.72	276	9.95
QingShuiHeXian	清水河县	0	0.00	0	0.00	89	3.39	88	3.38	179	6.84	179	6.84
LiShiXian	离石县	0	0.00	0	0.00	79	6.23	77	6.03	166	13.01	162	12.72
YanAnShi	延安市	142	4.05	123	3.53	327	9.36	295	8.44	514	14.72	477	13.66
AnSaiXian	安塞县	0	0.01	0	0.01	268	9.39	255	8.93	522	18.30	505	17.69
FangShanXian	方山县	0	0.00	0	0.00	73	4.95	70	4.77	154	10.44	150	10.16
ZhongYangXian	中阳县	0	0.00	0	0.00	72	5.14	67	4.83	137	9.83	131	9.41
PuXian	蒲县	0	0.00	0	0.00	86	5.73	80	5.37	166	11.06	158	10.55
ShenChiXian	神池县	0	0.00	0	0.00	45	3.09	44	3.07	85	5.90	84	5.85
XiXian	隰县	0	0.00	0	0.00	76	5.19	68	4.68	163	11.14	149	10.21
JingBianXian	靖边县	0	0.00	0	0.00	180	3.74	173	3.61	336	6.99	328	6.82
ShenMuXian	神木县	0	0.00	0	0.00	257	3.65	241	3.43	501	7.11	477	6.77

In Appendix A, SuiDe County is used as an example to illustrate the locations of the different classes including the SSG areas, the target and priority areas and land limits for the different re-vegetation target levels. For all other counties, and for all catchments, the ReVegIH decision support tool allows users to locate these areas in each spatial unit at 100 m resolution. Appendix B shows the area (and % area) of each catchment that is SSG, and the target and priority areas, taking into account the land limits, for each of the 42 catchments. Appendix C shows similar analysis for the 36 counties with over 90% of their area located within the study site.

5 Discussion and Conclusion

While our results provide the suitability of 38 species we also acknowledge that a successful re-vegetation program in the Loess Plateau will likely involve planting a mix of trees, shrubs and grasses, and that these plantings may occur at various times following initial on-ground activity. For example, the first re-vegetation activity may primarily focus on grasses and some shrubs with trees species being introduced several years later. Such a strategy may improve soil characteristics by gradually increasing soil organic matter that overall may result in a more successful re-vegetation program. All species initially planted may not be required to be present once the re-vegetation activities have reached an ‘end product’ (Lockwood 1997). In other words, localised extinctions of species used in the re-vegetation program should not mean that the localised re-vegetation program be considered a failure. Success, or failure, of the re-vegetation program should be gauged by how well the ecosystem functioning of the resultant (also termed ‘novel’ or ‘emerging’ Hobbs *et al.* 2006) ecosystem matches the management specifications of the re-vegetation program (Hobbs *et al.* 2006).

Due to the high mortality and sub-optimal growth rates of re-vegetation activities conducted in the Loess Plateau (the ‘old man small trees’) research developing site specific knowledge about vegetation water use and soil water storage relationships (*e.g.*, Fu *et al.* 2003; Huang *et al.* 2005; Liu *et al.* 2005) that can be upscaled to the larger region needs to be performed. In addition to taking into account climatology drivers, this research needs to take planting density, and soil properties (e.g., particle size distribution that partly governs soil moisture that change as a function of slope and land form Liu *et al.* 2005) and other factors that govern soil moisture into account. Considering the size and the extreme landscapes of the CSHC (Yang *et al*. 2005, their Figure 3) that govern the lateral flow of water (especially in the shallow soil layer between 0 cm and 150 cm Liu *et al.* 2005), determining the specific water requirement of the 22 common species is a not a trivial task for our 113,000 km^2 study site.

If managers wish to better understand the limits of the spatial modelling conducted here it would be advantageous if some form of error and uncertainty analysis was performed (e.g., Barry and Elith 2006; Guisan and Zimmermann 2000; Van Niel 2003). Performing error (known errors) and uncertainty (unknown errors) analysis of environmental variables (Van Niel *et al.* 2004) and propagating these into predictive vegetation suitability modelling (Van Niel and Austin 2006) provides users with knowledge about where more effort could be placed to reduce error and uncertainty in the output (within the logical bounds of the modelling framework, or approach, used to perform the assessment). Error and uncertainty can be considered in the three main areas of vegetation suitability mapping: models, data and methods (Van Niel 2003). For example when considering the quint-variate overlay approach used here there are at least three main issues that could be assessed in terms of the data model, they are: (1) positional accuracy of vector data (*e.g.*, Van Niel and McVicar 2001; Van Niel and McVicar 2002); (2) errors introduced when converting the soil vector data to raster data (*e.g.*, Congalton 2001; Shortridge 2004); and (3) how errors in the map overlay process interact (*e.g.*, Macdougal 1975).

If, for the study site, a floristic database of presence (or presence-absence) becomes available then it would be advisable to perform the suitability modelling using the more sophisticated approaches outlined in the introduction (Elith and Burgman 2003; Guisan and Zimmermann 2000). Such research could also include some of the new statistical approaches for vegetation suitability mapping that have been recently developed (*e.g.*, Elith *et al.* 2006; Guisan *et al.* 2006).

While advocating native species for the re-vegetation scheme, we also acknowledge that managers need to consider a wider range of issues including biodiversity. For example, Jiang *et al*. (2003) report that areas re-vegetated with the CSHC native shrub *Hippophae rhamnoides* (or Seabuckthorn) have a lower biodiversity compared with other re-vegetated patches and other land uses (including grassland, farmland and an abandoned field). They also note that areas with a greater density of patches have greater biodiversity. Again, the function of the resultant re-vegetation ecosystem needs to be assessed against the overall goals of the re-vegetation program (Hobbs *et al.* 2006).

In conclusion, the research findings presented here support the managers implementing the re-vegetation program in the study site by mapping the suitability of 38 predominately native species. This was achieved using readily available data, including access to environmental variables and rules defining the species' requirements (or tolerances). Given our consensus that the rules were possibly 'too inclusive', as they did not consider optimal growth, the spatial extent of areas suggested for re-planting were refined by defining 'target areas' for trees, shrubs and grasses. In the land use planning criteria developed here we suggest that hill-slopes and gullies with slopes greater than or equal to 15 degrees (defined from a 100 m resolution DEM) be left for natural succession. Due to lateral flow of water (and sediment) from these steep slope and gullies prioritising the re-vegetation of target areas adjacent to and downslope from the steep portions of the landscape will reduce sediment entering the river network. As these so-called priority areas are a subset of the target areas, this means that the simulated decrease of stream flow is smaller when re-vegetation activities are simulated to only occur on the priority areas. This is as the simulated impacts of land use on stream flow calculations are performed on a proportional aerial-weighted basis. All these functions are captured in the previously introduced decision support tool called ReVegIH, which allows users to determine: (1) which of 38 tree and shrub species are suitable for a specific location at a 100 m resolution; (2) where priority and target re-vegetation activities should be undertaken for trees, shrubs and grasses (again at a 100 m resolution); and (3) simulate the related hydrological impact at the catchment (or county) level.

6 References

Austin MP (1980) Searching for a Model for Use in Vegetation Analysis. *Vegetatio* **42**, 11-21.

Austin MP (2002) Spatial Prediction of Species Distribution: An Interface between Ecological Theory and Statistical Modelling. *Ecological Modelling* **157**, 101-118.

Barry S, Elith J (2006) Error and uncertainty in habitat models. *Journal of Applied Ecology* **43**, 413-423.

Booth TH (Ed.) (1996) 'Matching Trees and Sites. Proceedings of an international workshop held in Bangkok 27-30 March 1995.' (ACIAR Proceedings No. 63)

Booth TH, Jones PG (1998) Identifying climatically suitable areas for growing particular trees in Latin America. *Forest Ecology and Management* **108**, 167-173.

Booth TH, Jovanic T (2002) Identifying climatically suitable areas for growing particular trees in Africa: An example using Grevillea robusta. *Agroforestry Systems* **54**, 41-49.

Booth TH, Jovanovic T, New M (2002) A new world climatic mapping program to assist species selection. *Forest Ecology and Management* **163**, 111-117.

Chen HS, Shao MA, Wang KL (2005) Desiccation of Deep Soil Layer and Soil Water Cycle Characteristics on the Loess Plateau. *ACTA Ecologica Sinica (In Chinese with an English abstract)* **25**, 2491-2498.

Cheng JM, Wan HE (2002) 'Vegetation Construction and Soil and Water Conservation on the Loess Plateau, China (In Chinese).' (China Forestry Publishing House Beijing)

Congalton RG (2001) Accuracy assessment and validation of remotely sensed and other spatial information. *International Journal of Wildland Fire* **10**, 321-328.

Douglas I (1989) Land degradation, soil conservation and the sediment load of the Yellow River, China: review and assessment. *Land Degradation and Rehabilitation* **1**, 141-151.

Elith J, Burgman MA (2003) Habitat Models for Population Viability Analysis. In 'Population Viability in Plants: Conservation, Management and Modeling of Rare Plants'. (Eds CA Brigham and MW Schwartz) pp. 203-235. (Springer-Verlag: New York)

Elith J, Graham CH, Anderson RP, Dudík M, Ferrier S, Guisan A, Hijmans RJ, Huettmann F, R. Leathwick J, Lehmann A, Li J, G. Lohmann L, A. Loiselle B, Manion G, Moritz C, Nakamura M, Nakazawa Y, McC. Overton J, Townsend Peterson A, Phillips SJ, Richardson K, Scachetti-Pereira R, Schapire RE, Soberón J, Williams S, Wisz MS, Zimmermann NE (2006) Novel methods improve prediction of species' distributions from occurrence data. *Ecography* **29**, 129-151.

Franklin J (1995) Predictive vegetation mapping: geographic modelling of biospatial patterns in relation to environmental gradients. *Progress in Physical Geography* **19**, 474-499.

Fu B, Wang J, Chen L, Qiu Y (2003) The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. *Catena* **54**, 197-213.

Gao Q, Zhang X, Huang Y, Xu H (2004) A comparative analysis of four models of photosynthesis for 11 plant species in the Loess Plateau. *Agricultural and Forest Meteorology* **126**, 203-222.

Guisan A, Lehmann A, Ferrier S, Austin MP, Overton JMC, Aspinall R, Hastie T (2006) Making better biogeographical predictions of species' distributions. *Journal of Applied Ecology* **43**, 386-392.

Guisan A, Zimmermann NE (2000) Predictive habitat distribution models in ecology. *Ecological Modelling* **135**, 147-186.

Hobbs RJ, Arico S, Aronson J, Baron JS, Bridgewater P, Cramer VA, Epstein PR, Ewel JJ, Klink CA, Lugo AE, Norton D, Ojima D, Richardson DM, Sanderson EW, Valladares F, Vilà M, Zamora R, Zobel M (2006) Novel ecosystems: theoretical and management aspects of the new ecological world order. *Global Ecology & Biogeography* **15**, 1-7.

Huang BW (1988) River conservancy and agricultural development on the North China Plains and Loess Highlands: strategies and research. *Great Plains Quarterly* **6**, 218-224.

Huang YL, Chen LD, Fu BJ, Zhang LP, Wang YL (2005) Evapotranspiration and Soil Moisture Balance for Vegetative Resortation in a Gully Catchment on the Loess Plateau, China. *Pedosphere* **15**, 509-517.

Hutchinson MF (2004a) ANUDEM Version 5.1 User Guide, http://cres.anu.edu.au/outputs/software.php. In. (The Australian National University, Centre for Resource and Environmental Studies: Canberra)

Hutchinson MF (2004b) ANUSPLIN Version 4.3 User Guide, http://cres.anu.edu.au/outputs/software.php. In. (The Australian National University, Centre for Resource and Environmental Studies: Canberra)

Iqbal M (1983) 'An Introduction to Solar Radiation.' (Academic Press: Vancouver)

Jiang Y, Kang M, Gao Q, He L, Xiong M, Jia Z, Jin Z (2003) Impact of land use on plant biodiversity and measures for biodiversity conservation in the Loess Plateau in China - a case study in a hilly-gully region of the Northern Loess Plateau. *Biodiversity and Conservation* **12**, 2121-2133.

Ke BS, Zhou SY (2005) Land acquisition in China: policy development and reform recommendations. In 'China’s agricultural and rural development in the early 21st century: challenges, opportunities and policy options'. (Eds BH Sonntag, JK Huang, S Rozelle and JH Skerritt) pp. 469-487. (ACIAR Monograph No. 116: Canberra)

Köppen W (1931) 'The Climates of the Earth.' (DeGruyter: Berlin)

Li GY (2003) 'Ponderation and Practice of the Yellow River Control.' (Yellow River Conservancy Press: Zhengzhou)

Li LT, McVicar TR, Van Niel TG, Mu XM, Zhang XP, Yang QK, Liu ZH (2005a) 'Quality Control of 21 Years of Monthly Meteorological and Hydrological Data in the Coarse Sandy Hilly Catchments of the Loess Plateau, China.' CSIRO Land and Water Technical Report 6/05, Canberra, Australia http://www.clw.csiro.au/publications/technical2005/tr6-05.pdf.

Li LT, McVicar TR, Van Niel TG, Zhang L, Li R, Yang QK, Zhang XP, Mu XM, Wen ZM, Liu WZ, Zhao YA, Liu ZH (2005b) 'A Bilingual User's Guide for the Decision Support Tool for Managing Re-Vegetation and its Impact on Hydrology (ReVegIH) in the Coarse Sandy Hilly Catchments of the Loess Plateau, China.' CSIRO Land and Water Technical Report 19/05, Canberra http://www.clw.csiro.au/publications/technical2005/tr19-05.pdf.

Li YS (2001) Effects of Forest on Water Circle on the Loess Plateau. *Journal of Natural Resources (In Chinese)* **16**, 427-432.

Liang YM, Li R, Cheng JM, Liu GB, Chen YM, Liu WZ (2003) 'Vegetation Construction on the Loess Plateau (in Chinese and English).' (Yellow River Conservancy Press: Zhengzhou)

Liu WZ, Hu MJ, Li FM, Zhang XC (2005) Ecological characteristics of soil water and its relation to land and vegetation in a small semiarid watershed in a loess hilly area of China. *International Journal of Sustainable Development and World Ecology* **12**, 326-333.

Lockwood JL (1997) An Alternative to Succession: Assembly Rules Offer Guide to Restoration Efforts. *Restoration and Management Notes* **15**, 45-51.

Macdougal EB (1975) The Accuracy of Map Overlays. *Landscape Planning* **2**, 23-30.

McVicar TR, Li LT, Van Niel TG, Hutchinson MF, Mu XM, Liu ZH (2005) 'Spatially Distributing 21 Years of Monthly Hydrometeorological Data in China: Spatio-Temporal Analysis of FAO-56 Crop Reference Evapotranspiration and Pan Evaporation in the Context of Climate Change.' CSIRO Land and Water Technical Report, 8/05, Canberra, Australia http://www.clw.csiro.au/publications/technical2005/tr8-05.pdf.

McVicar TR, Li LT, Van Niel TG, Zhang L, R. L, Yang QK, X.P. Z, Mu XM, Wen ZM, Liu WZ, Y.A. Z, Liu ZH, Gao P (2006) Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on streamflow in the Loess Plateau. *Forest Ecology and Management* **(Submitted)**.

Miao Z, Marrs R (2000) Ecological restoration and land reclamation in open-cast mines in Shanxi Province, China. *Journal of Environmental Management* **59**, 205-215.

Moore ID, Norton TW, Williams JE (1993) Modelling Environmental Heterogeneity in Forested Landscapes. *Journal of Hydrology* **150**, 717-747.

Palmer AR, Van Staden JM (1992) Predicting the distribution of plant communities using annual rainfall and elevation: an example from southern Africa. *Journal of Vegetation Science*, 261-266.

Ritsema CJ (2003) Introduction: soil erosion and participatory land use planning on the Loess Plateau in China. *Catena* **54**, 1-5.

Rozelle S, Huang J, Zhang L (1997) Poverty, population and environmental degradation in China. *Food Policy* **22**, 229-251.

Shen HQ (1991) China Loess Plateau 1:500 000 Land-Use Map (part of the Loess Plateau Resources and Environmental Remote Sensing Series). In. (Xi'an Atlas Press: Xi'an)

Shi H, Shao M (2000) Soil and water loss from the Loess Plateau in China. *Journal of Arid Environments* **45**, 9-20.

Shortridge AM (2004) Geometric variability of raster cell class assignment. *International Journal of Geographical Information Science* **18**, 539-558.

Skinner MW, Kuhn RG, Joseph AE (2001) Agricultural land protection in China: a case study of local governance in Zhejiang Province. *Land Use Policy* **18**, 329-340.

Urban DL, O'Neill RV, Shugart Jr HH (1987) Landscape Ecology: A hierarchical perspective can help scientists understand spatial patterns. *BioScience* **37**, 119-127.

Van Niel KP (2003) Geographical Issues in Predictive Vegetation Modelling: Error and Uncertainty in GIS Data, Methods, and Models. Australian National University.

Van Niel KP, Austin MP (2006) Predictive vegetation modelling for conservation: Impact of error propagation from digital elevation data. *Ecological Applications*, In Press.

Van Niel KP, Laffan SW, Lees BG (2004) Effect of error in the DEM on environmental variables for predictive vegetation modelling. *Journal of Vegetation Science* **15**, 747–756.

Van Niel TG, McVicar TR (2001) Assessing positional accuracy and its effects on rice crop area measurement: an application at Coleambally Irrigation Area. *Australian Journal of Experimental Agriculture* **41**, 557-566.

Van Niel TG, McVicar TR (2002) Experimental evaluation of positional accuracy estimates of a linear network using point- and line-based testing methods. *International Journal of Geographical Information Science* **16**, 455-473.

Wang HJ, Zhang SG, and Team Members of the Comprehensive Scientific Expedition on Loess Plateau (1991) 'Soil Resources and Its Utilization in the Loess Plateau (In Chinese).' (Science Press: Beijing)

Wang L, Shao MA, Wang QJ, Jia ZK, Li J (2004) Review of Research on Soil Desiccation in the Loess Plateau. *Transactions of the Chinese Society of Agricultural Engineering (In Chinese with an English abstract)* **20**, 27-31.

Wang NB, Shen HQ, Zhao CX, Lu JF (1992) 'China Loess Plateau 1:500 000 Resources and Environmental Remote Sensing Series Maps (In Chinese).' (Xi'an Map Press: Xi'an)

Wenhua L (2004) Degradation and restoration of forest ecosystems in China. *Forest Ecology and Management* **201**, 33-41.

Wilkinson S, Henderson A, Chen Y (2004) 'SedNet User Guide. Client Report for the Cooperative Research Centre for Catchment Hydrology.' CSIRO Land and Water, Canberra, Australia

Wilson JP, Gallant JC (2000) Secondary Topographic Attributes. In 'Terrain Analysis'. (Eds JP Wilson and JC Gallant) pp. 87-131. (John Wiley & Sons, Inc.: New York)

Winkler D (2002) Participation in Forestry in Tibetan Southwest China: A Strategy to Resolve Resource Use Conflicts. *Mountain Research and Development* **22**, 397–399.

Wu QX, Yang WZ (1998) 'Forest and Grassland Vegetation Construction and Its Sustainable Development in Loess Plateau (In Chinese).' (Science Press: Beijing)

Xiang-zhou X, Hong-wu Z, Ouyang Z (2004) Development of check-dam systems in gullies on the Loess Plateau, China. *Environmental Science and Policy* **7**, 79-86.

Xiubin H, Zhanbin L, Mingde H, Keli T, Fengli Z (2003) Down-scale analysis for water scarcity in response to soil-water conservation on Loess Plateau of China. *Agriculture, Ecosystems and Environment* **94**, 355-361.

Xu ZG, Bennett MT, Tao R, Xu JT (2004) China's Sloping Land Conversion Programme four year on: current situation and pending issues. *International Forestry Review* **6**, 317-326.

Yang H (2004) Land conservation campaign in China: integrated management, local participation and food supply option. *Geoforum* **35**, 507-518.

Yang QK, McVicar TR, Van Niel TG, Hutchinson MF, Li LT, Zhang XP (2006) Improving a digital elevation model by reducing source data errors and optimising interpolation algorithm parameters: an example in the Loess Plateau, China. *International Journal of Applied Earth Observation and Geoinformation* **(Accepted)**.

Yang QK, Van Niel TG, McVicar TR, Hutchinson MF, Li LT (2005) 'Developing a digital elevation model using ANUDEM for the Coarse Sandy Hilly Catchments of the Loess Plateau, China.' CSIRO Land and Water Technical Report 7/05, Canberra, Australia http://www.clw.csiro.au/publications/technical2005/tr7-05.

Yang RJ, Fu BJ, Liu GH, Ma KM (2004) Research on the Relationship between Water and Eco-environment Construction in Loess Hilly and Gully Region. *Environmental Science (In Chinese with an English abstract)* **25**, 37-42.

Yang WZ (2001) Soil Water Resources and Afforestation in Loess Plateau. *Journal of Natural Resources (In Chinese with an English abstract)* **16**, 433-438.

Ye YQ, Chen GJ, Fan H (2003) Impacts of the "Grain for Green" Project on Rural Communities in the Upper Min River Basin, Sichuan, China. *Mountain Research and Development* **23**, 345-352.

Yuan JZ, Zhang HX (1991) 'Optimized Models for Estimating Forest Vegetation on the Loess Plateau (In Chinese).' (Science Press: Beijing)

Zhang HC, He KM, Liu X (2001) Fitting Soil Moisture Environment of Trees Growth on Loess Plateau in Semi-arid Region. *Journal of Soil and Water Conservation* **15**, 1-5.

Zhang HC, Liu X, He KM (2003) Grading of *Robinia Pseudoacacia* and *Platycladus Orientalis* Woodland Soil's Water Availability and Productivity in Semi-arid Region of Loess Plateau. *Chinese Journal of Applied Ecology (In Chinese with an English abstract)* **14**, 858 - 862.

Zhang ZF (2006) Formation and Prevention of Soil and Water Loss in the Southern Mountains of Ningxia Province, China. In. (Hydraulic Engineering Network (In Chinese))

Zhao J, Gao QJ, Liu HP, Yang YH (1992) 'Research on Remote Sensing Application of Loess Plateau Area in Shanxi Province.' (Beijing Normal University Press: Beijing)

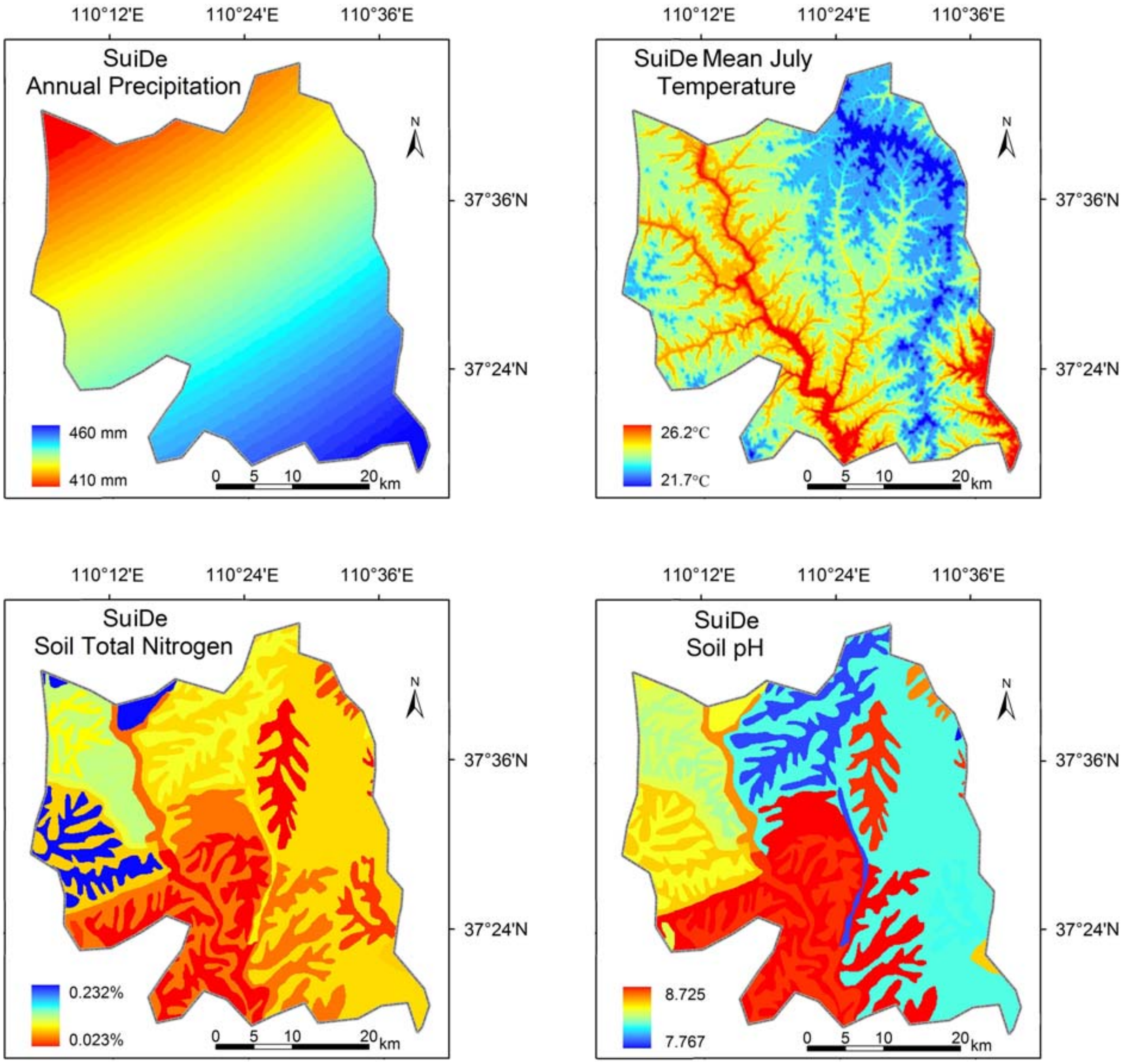
Zhao JR, Sun LD, Zhu JZ (1994) 'Shrubs for Soil and Water Conservation on Loess Plateau (In Chinese).' (China Forestry Publishing House: Beijing)

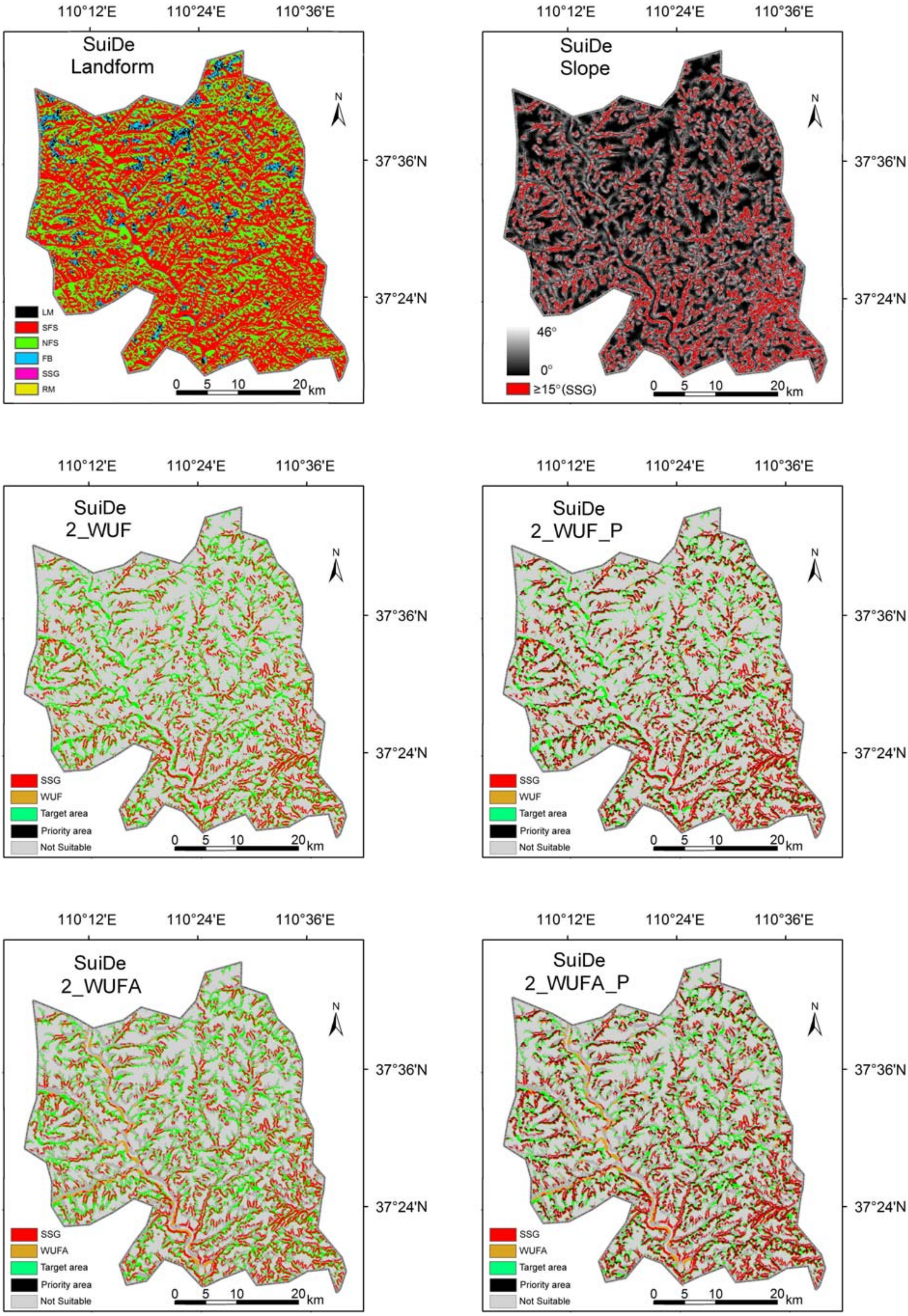
Zhou NG, Luo WX (1997) 'Silviculture of Loess Plateau.' (China Forestry Publishing House: Beijing)

Zhu JZ, Zhou XC, Hu JZ (2004) On the Objectives of Plantation Establishment on Loess Plateau. *China Water Resources (In Chinese)* **16**, 28-30.

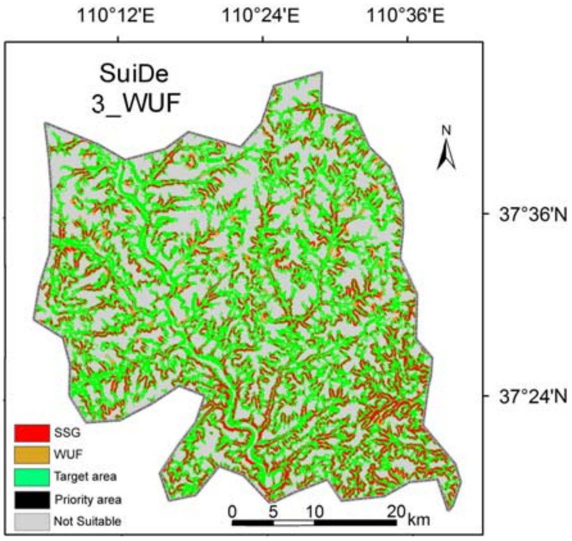
7 Appendix A: SuiDe County Vegetation Suitability Mapping

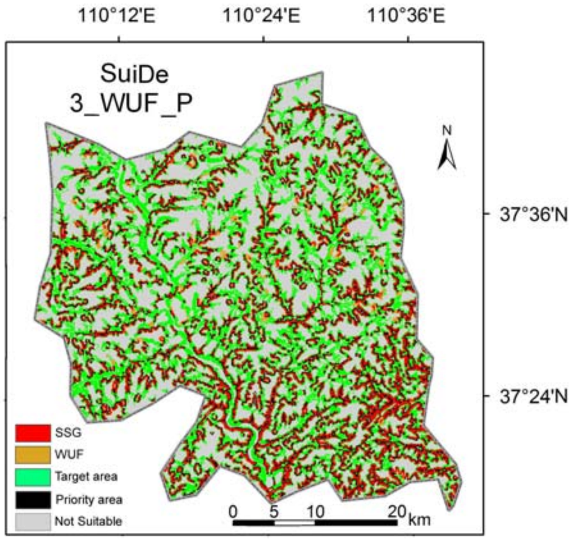
As SuiDe is dry (*i.e.*, no part of the county has precipitation greater than 500 mm per annum), it does not contain any target area level 1 (*i.e.*, trees – see Table 7) so this is not included here. In this appendix codes combining the different target levels, land limits and if it is a priority area (or not) are provided on some figures. The first number refers to the target level (2 or 3 – for trees and shrubs respectively), next is the code for the land limits (WUF and WUFA as introduced previously), followed by a P if the area mapped is a priority area; they are separated by underscores.

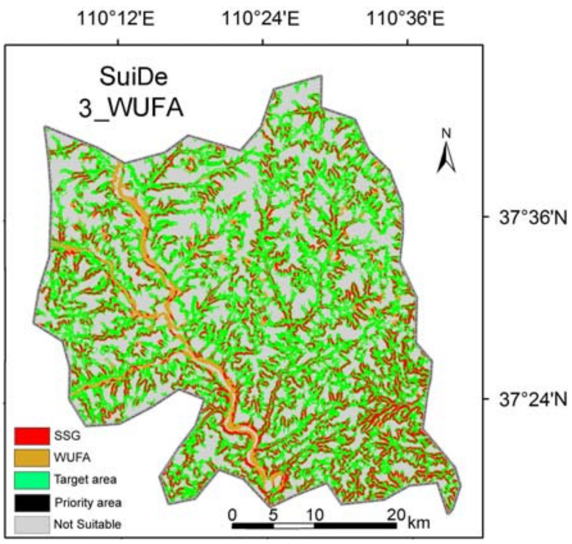


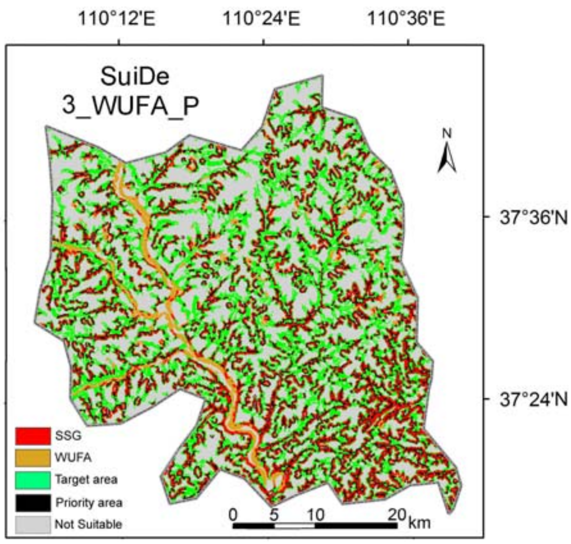


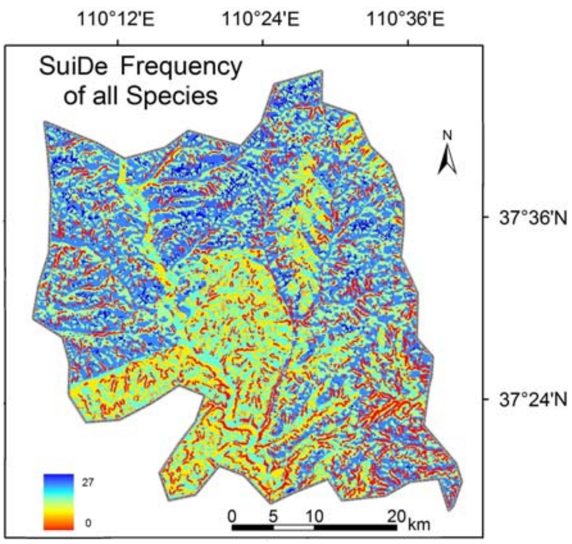
SuiDe
Landform
LM
SFS
NFS
FB
SSG
RM
SuiDe
Slope
46°
0°
≥15°(SSG)
SuiDe
2_WUF
SuiDe
2_WUF_P
SSG
WUF
Target area
Priority area
Not Suitable
SuiDe
2_WUFA
SuiDe
2_WUFA_P
SSG
WUFA
Target area
Priority area
Not Suitable
110°12'E
110°24'E
110°36'E
37°36'N
37°24'N
0 5 10 20 km
N

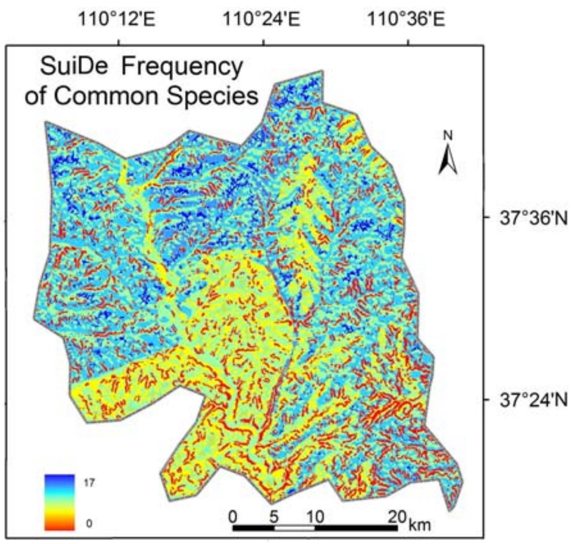

110°12'E
110°24'E
110°36'E
SuiDe
3_WUF
N
37°36'N
37°24'N
SSG
WUF
Target area
Priority area
Not Suitable
0 5 10 20 km

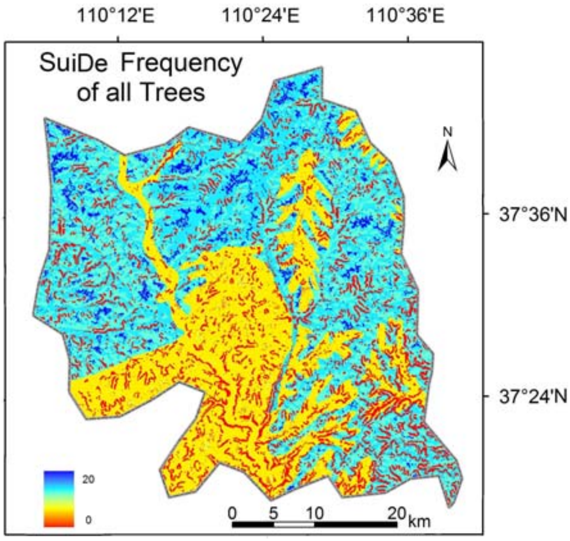

110°12'E
110°24'E
110°36'E
SuiDe
3_WUF_P
N
37°36'N
37°24'N
SSG
WUF
Target area
Priority area
Not Suitable
0 5 10 20 km

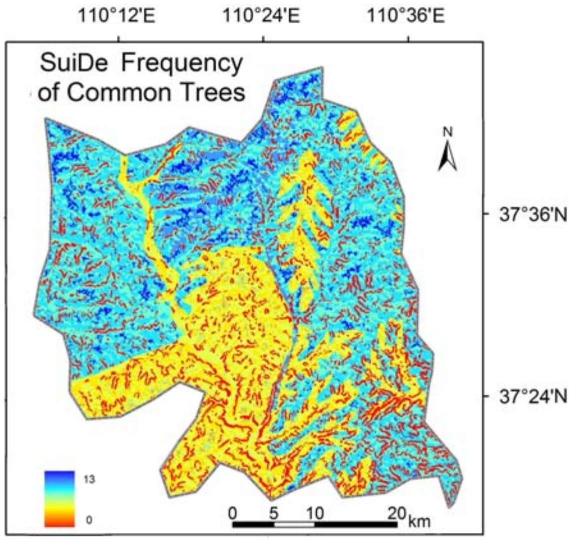

110°12'E
110°24'E
110°36'E
SuiDe
3_WUFA
N
37°36'N
37°24'N
SSG
WUFA
Target area
Priority area
Not Suitable
0 5 10 20 km

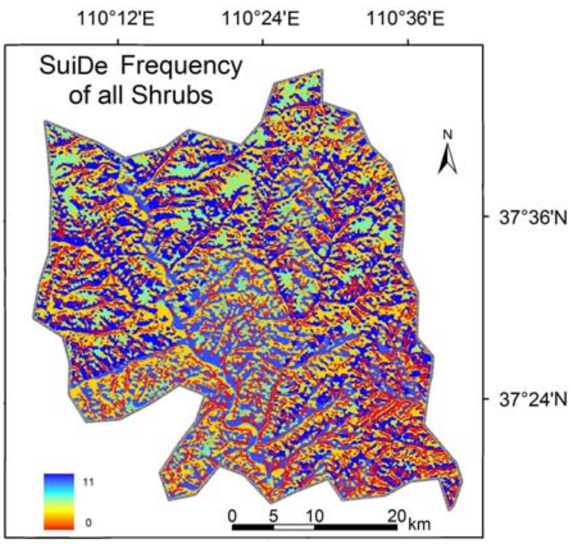

110°12'E
110°24'E
110°36'E
SuiDe
3_WUFA_P
N
37°36'N
37°24'N
SSG
WUFA
Target area
Priority area
Not Suitable
0 5 10 20 km

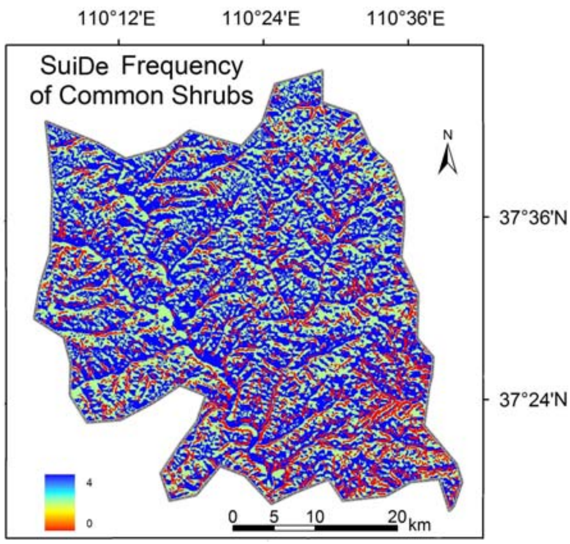

110°12'E
110°24'E
110°36'E
SuiDe Frequency
of all Species
N
37°36'N
37°24'N
27
0
0 5 10 20 km

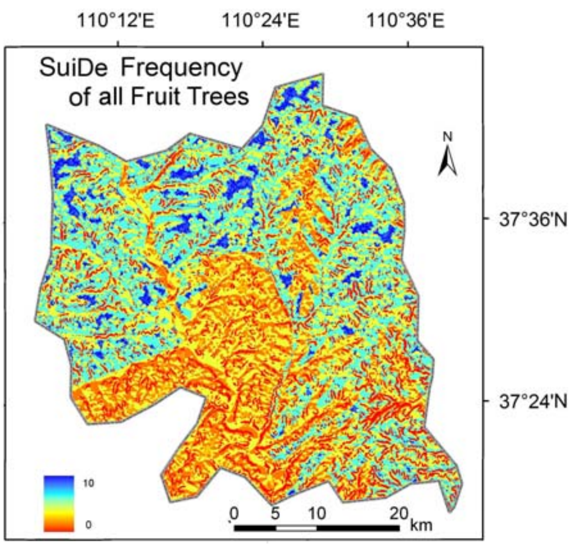

110°12'E
110°24'E
110°36'E
SuiDe Frequency
of Common Species
N
37°36'N
37°24'N
17
0
0 5 10 20 km


110°12'E
110°24'E
110°36'E
SuiDe Frequency
of all Trees
N
37°36'N
37°24'N
20
0
0 5 10 20 km


110°12'E
110°24'E
110°36'E
SuiDe Frequency
of Common Trees
N
37°36'N
37°24'N
13
0
0 5 10 20 km

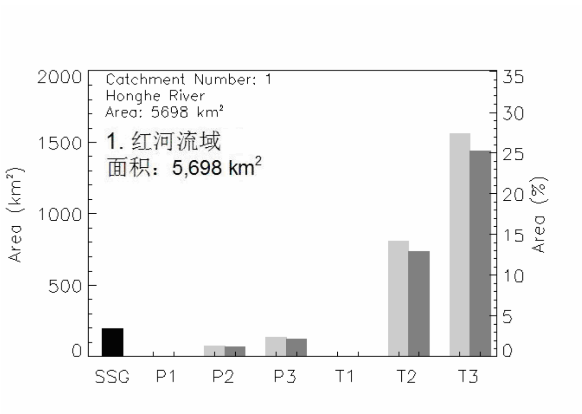

110°12'E
110°24'E
110°36'E
SuiDe Frequency
of all Shrubs
N
37°36'N
37°24'N
11
0
0 5 10 20 km

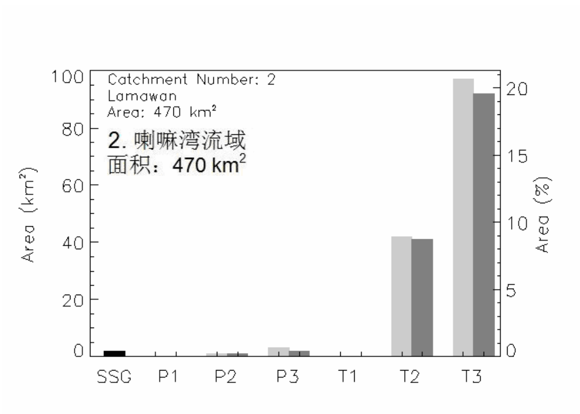

110°12'E
110°24'E
110°36'E
SuiDe Frequency
of Common Shrubs
N
37°36'N
37°24'N
4
0
0 5 10 20 km

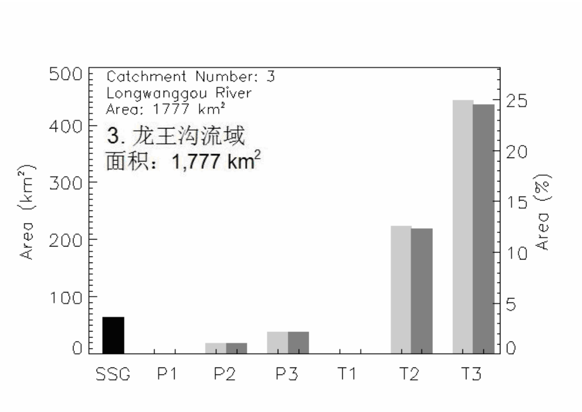

110°12'E
110°24'E
110°36'E
SuiDe Frequency
of all Fruit Trees
N
37°36'N
37°24'N
10
0
0 5 10 20 km

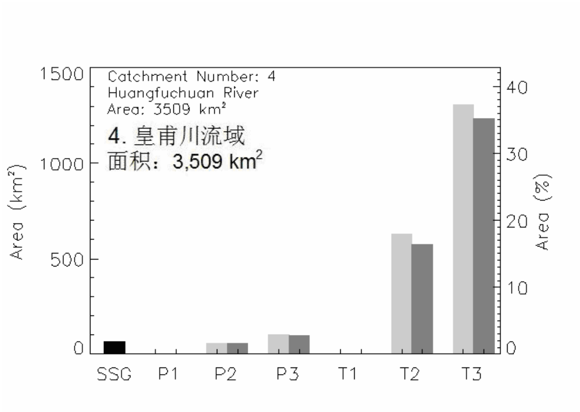
8 Appendix B: SSG, Target and Priority Areas by Catchment

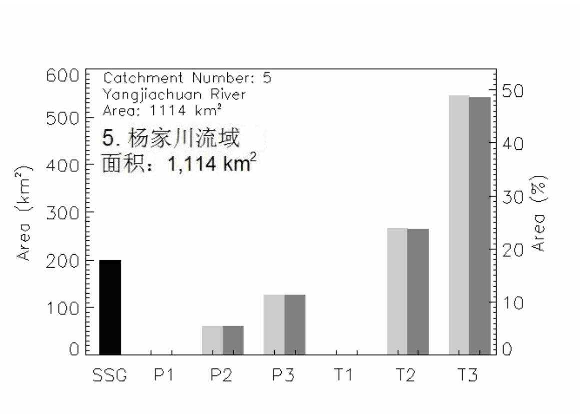
Comparison of SSG, re-vegetation priority (denoted P) and target (abbreviated as T) areas for the three re-vegetation target level (1 = trees, 2 = shrubs and 3 = grasses) for each catchment. In this and the following appendix, all codes (bar SSG) used on the X-axis are a combination of these two classes, for example P1 is the priority area for trees, whereas T3 represents the target area for grasses. For P1 to T3 the lighter bar on the left of the pair represents the WUF land limit, while the darker bar on the right of the pair represents the WUFA land limit; hence the difference between the two represents the highly productive agricultural areas. The map showing the location of the 42 catchments ranging from 31,460 km^2 to 127 km^2 are overlaid on the DEM (from where the catchment boundaries were generated using the sediment transport and hydrology program called SedNet Wilkinson *et al.* 2004) is shown in Figure 9 at the end of this appendix.

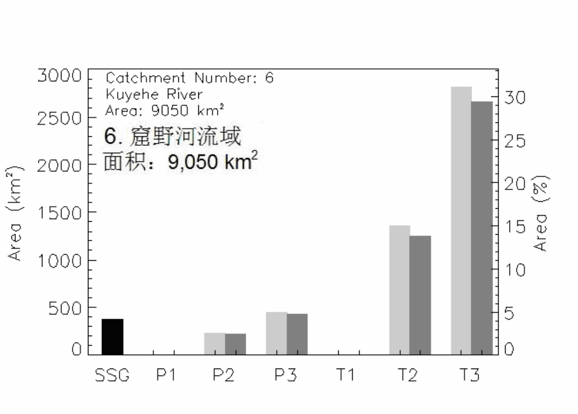


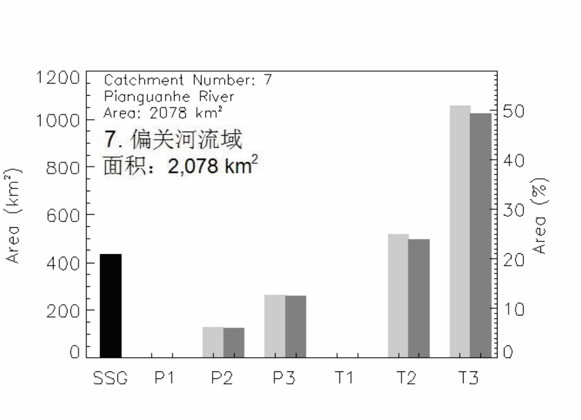


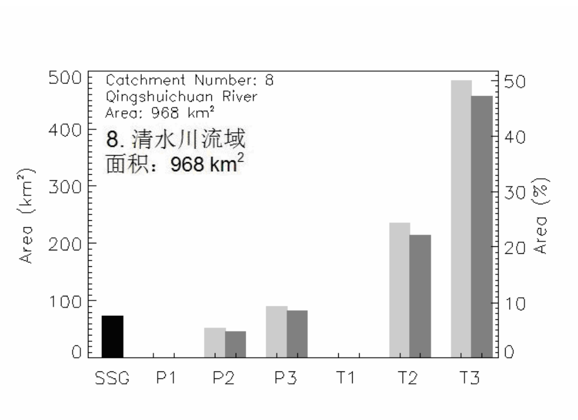


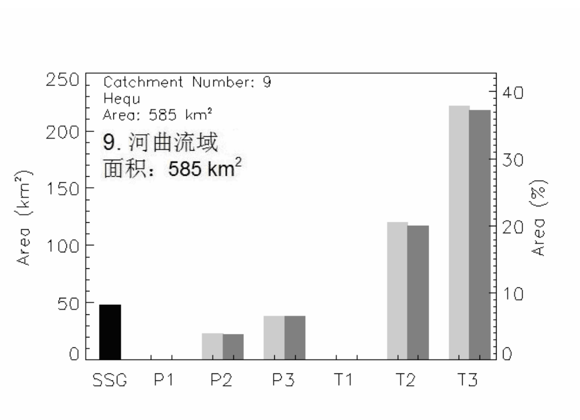


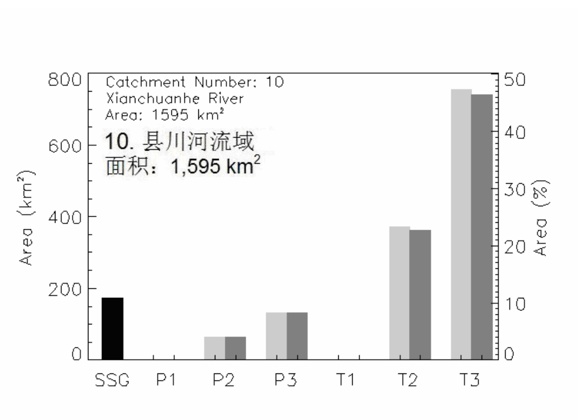

Catchment Number: 5
Yangjiachuan River
Area: 1114 km²
5. 杨家川流域
面积：1,114 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

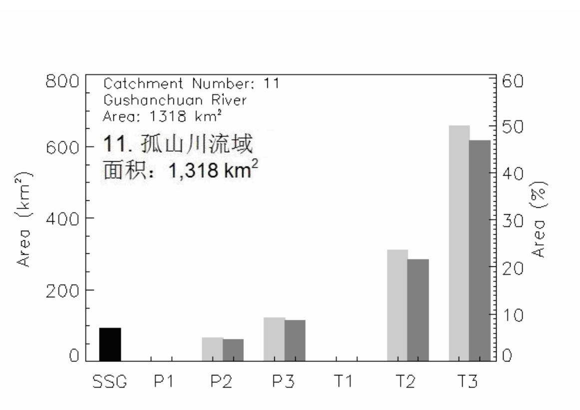

Catchment Number: 6
Kuyehe River
Area: 9050 km²
6. 窟野河流域
面积：9,050 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

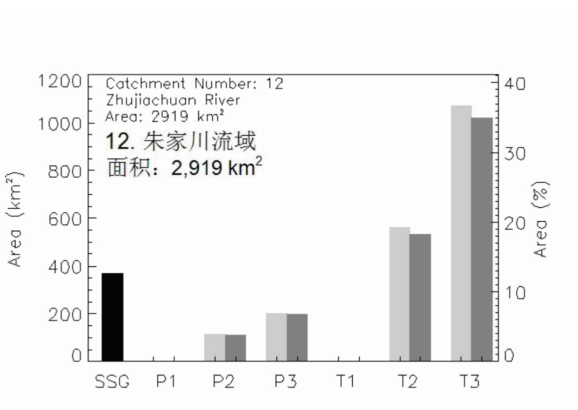

Catchment Number: 7
Pianguanhe River
Area: 2078 km²
7. 偏关河流域
面积：2,078 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

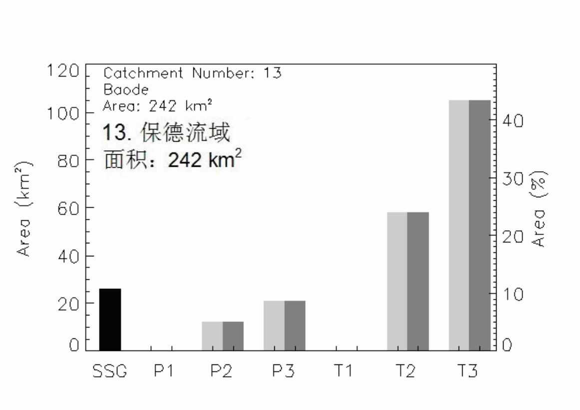

Catchment Number: 8
Qingshuichuan River
Area: 968 km²
8. 清水川流域
面积：968 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

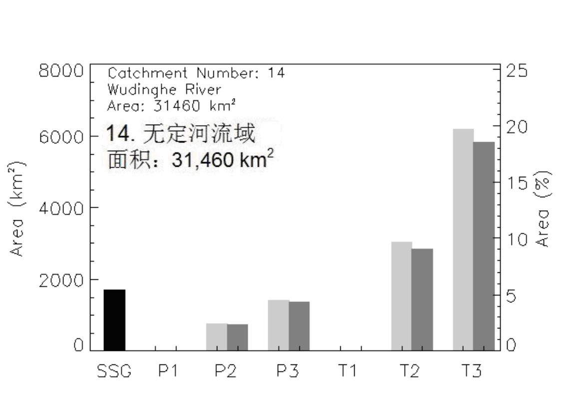

Catchment Number: 9
Hequ
Area: 585 km²
9. 河曲流域
面积：585 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

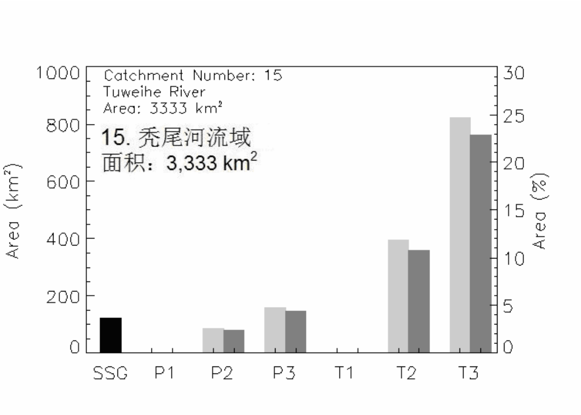

Catchment Number: 10
Xianchuanhe River
Area: 1595 km²
10. 县川河流域
面积：1,595 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

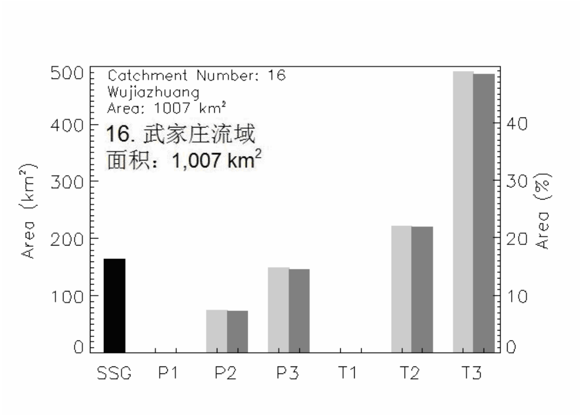

Catchment Number: 11
Gushanchuan River
Area: 1318 km²
11. 孤山川流域
面积：1,318 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

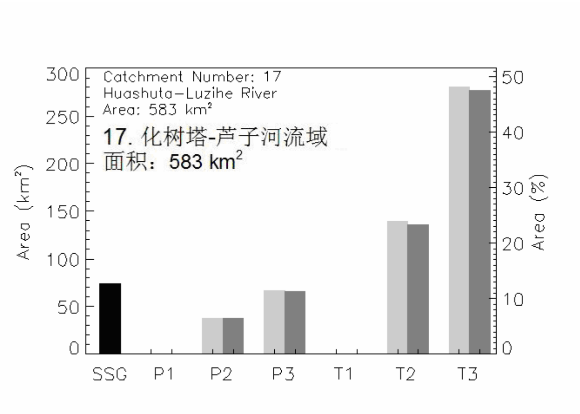

Catchment Number: 12
Zhujiachuan River
Area: 2919 km²
12. 朱家川流域
面积：2,919 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

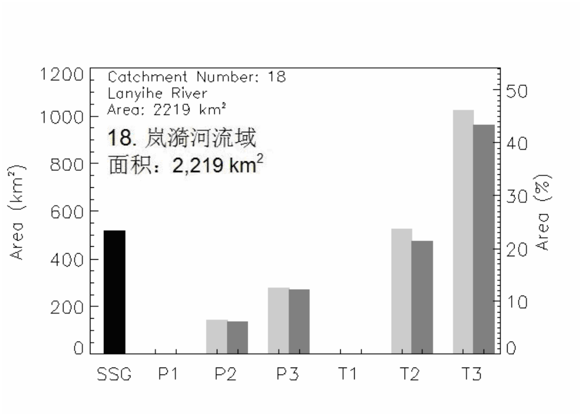

Catchment Number: 13
Baode
Area: 242 km²
13. 保德流域
面积：242 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

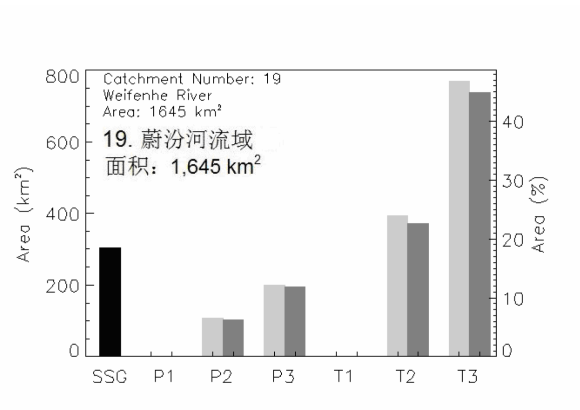

Catchment Number: 14
Wudinghe River
Area: 31460 km²
14. 无定河流域
面积：31,460 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

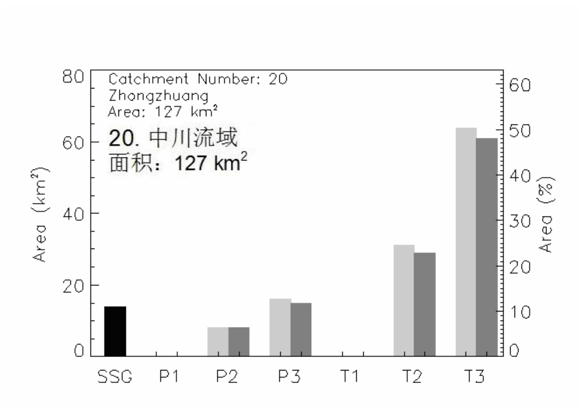

Catchment Number: 15
Tuweihe River
Area: 3333 km²
15. 秃尾河流域
面积：3,333 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

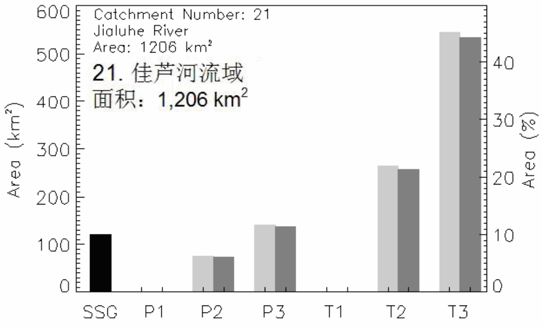

Catchment Number: 16
Wujiazhuang
Area: 1007 km²
16. 武家庄流域
面积：1,007 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

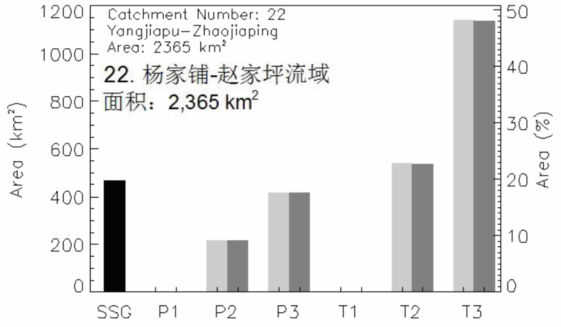

Catchment Number: 17
Huashuta-Luzihe River
Area: 583 km²
17. 化树塔-芦子河流域
面积：583 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

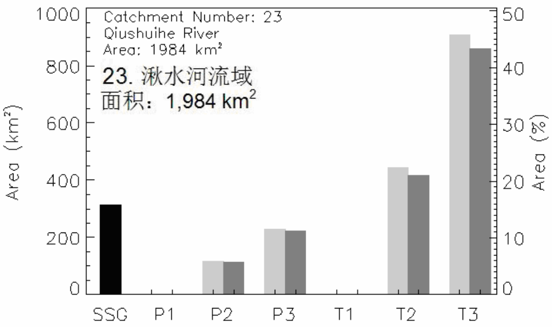

Catchment Number: 18
Lanyihe River
Area: 2219 km²
18. 岚漪河流域
面积：2,219 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

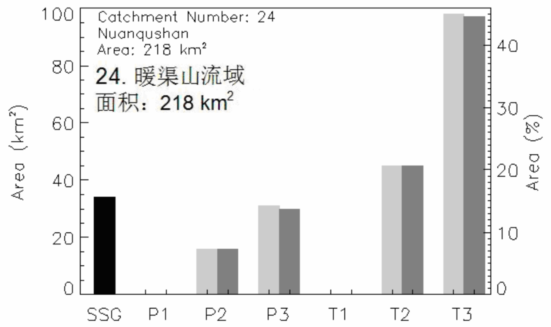

Catchment Number: 19
Weifenhe River
Area: 1645 km²
19. 蔚汾河流域
面积：1,645 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

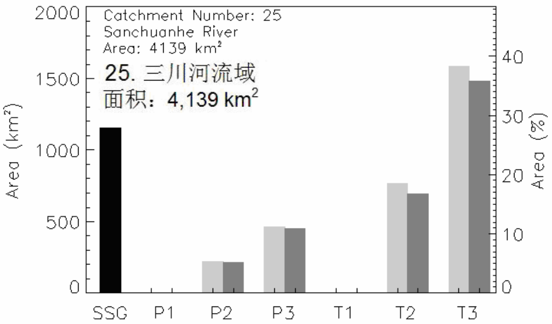

Catchment Number: 20
Zhongzhuang
Area: 127 km²
20. 中川流域
面积：127 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

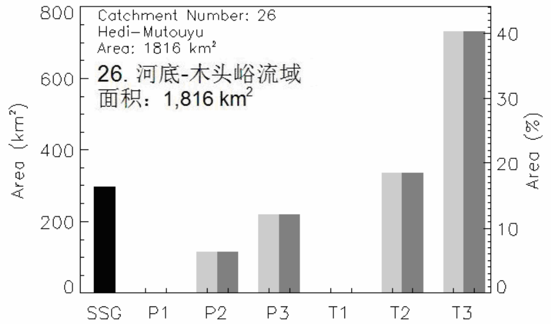

Catchment Number: 21
Jialuhe River
Area: 1206 km²
21. 佳芦河流域
面积：1,206 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

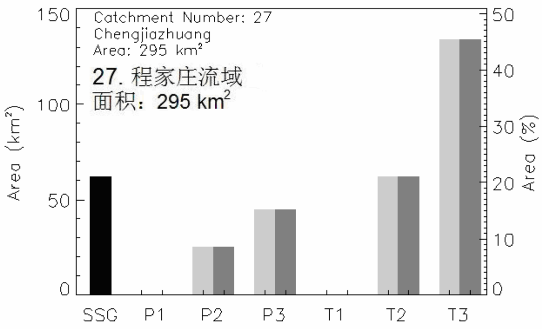

Catchment Number: 22
Yangjiapu–Zhaojiaping
Area: 2365 km²
22. 杨家铺-赵家坪流域
面积：2,365 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

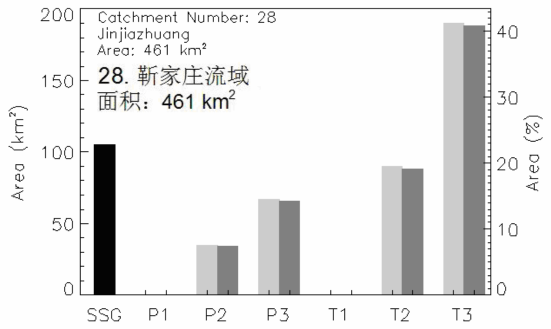

Catchment Number: 23
Qiushuihe River
Area: 1984 km²
23. 湫水河流域
面积：1,984 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

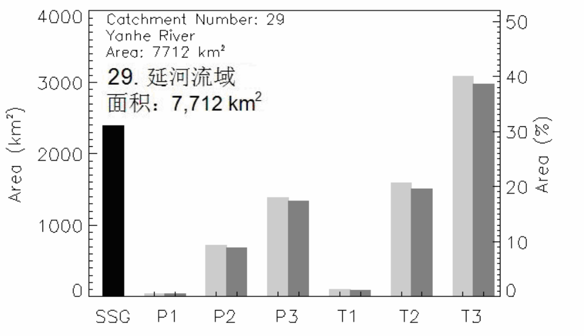

Catchment Number: 24
Nuanqushan
Area: 218 km²
24. 暖渠山流域
面积：218 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

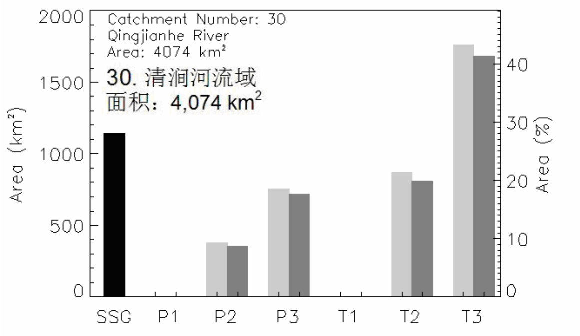

Catchment Number: 25
Sanchuanhe River
Area: 4139 km²
25. 三川河流域
面积：4,139 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

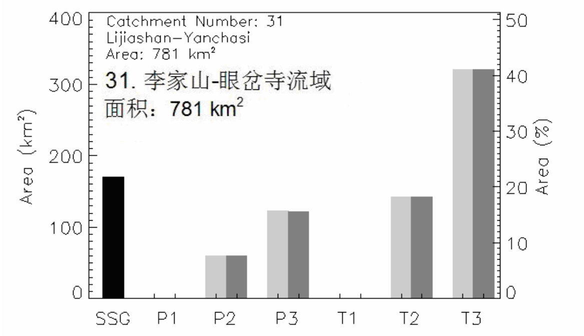

Catchment Number: 26
Hedi–Mutouyu
Area: 1816 km²
26. 河底-木头峪流域
面积：1,816 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

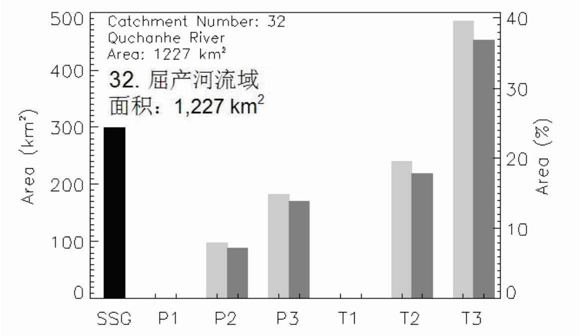

Catchment Number: 27
Chengjiazhuang
Area: 295 km²
27. 程家庄流域
面积：295 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

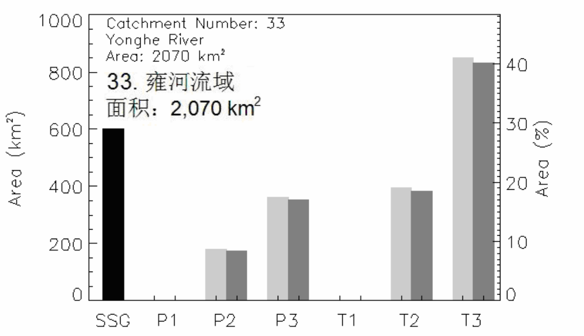

Catchment Number: 28
Jinjiazhuang
Area: 461 km²
28. 靳家庄流域
面积：461 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

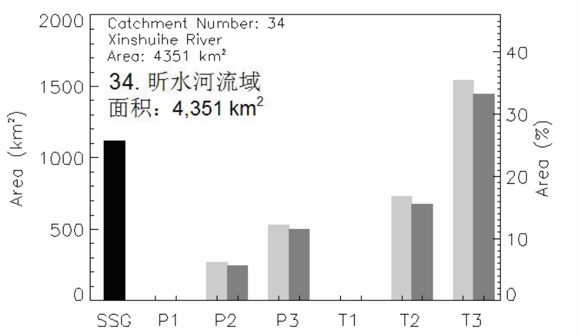

Catchment Number: 29
Yanhe River
Area: 7712 km²
29. 延河流域
面积：7,712 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

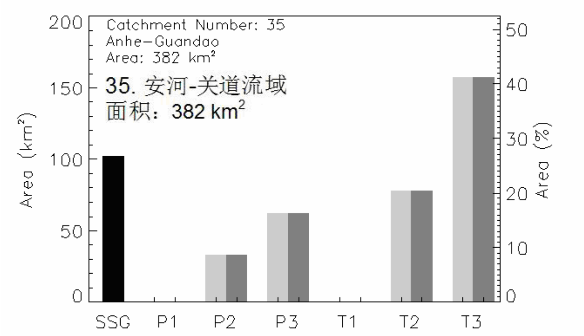

Catchment Number: 30
Qingjianhe River
Area: 4074 km²
30. 清涧河流域
面积：4,074 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

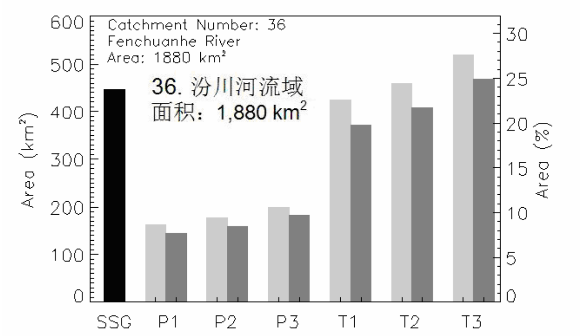

Catchment Number: 31
Lijiashan–Yanchasi
Area: 781 km²
31. 李家山-眼岔寺流域
面积：781 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

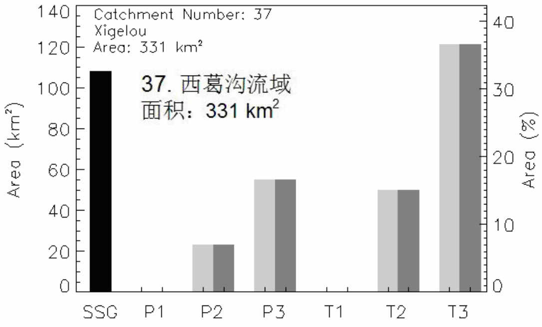

Catchment Number: 32
Quchanhe River
Area: 1227 km²
32. 屈产河流域
面积：1,227 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

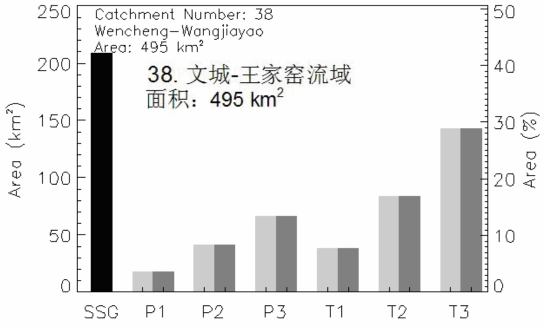

Catchment Number: 33
Yonghe River
Area: 2070 km²
33. 雍河流域
面积：2,070 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

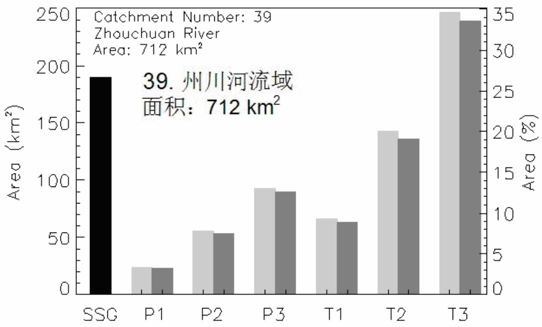

Catchment Number: 34
Xinshuihe River
Area: 4351 km²
34. 昕水河流域
面积：4,351 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

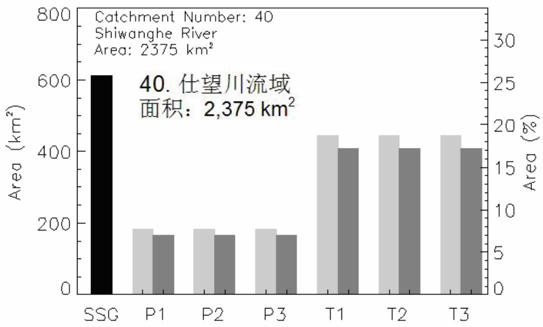

Catchment Number: 35
Anhe–Guandao
Area: 382 km²
35. 安河-关道流域
面积：382 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

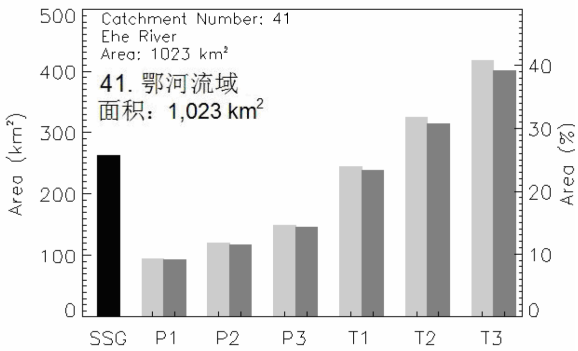

Catchment Number: 36
Fenchuanhe River
Area: 1880 km²
36. 汾川河流域
面积：1,880 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

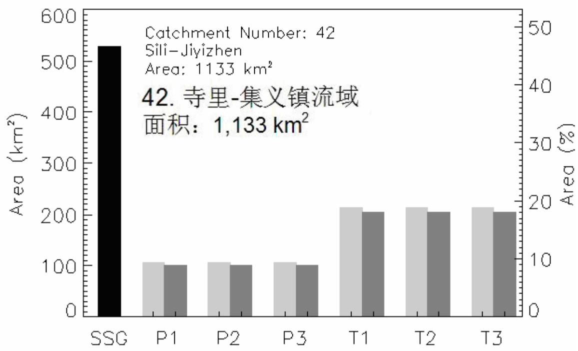

Catchment Number: 37
Xigelou
Area: 331 km²
37. 西葛沟流域
面积：331 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


Catchment Number: 38
Wencheng–Wangjiayao
Area: 495 km²
38. 文城-王家窑流域
面积：495 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


Catchment Number: 39
Zhouchuan River
Area: 712 km²
39. 州川河流域
面积：712 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


Catchment Number: 40
Shiwanghe River
Area: 2375 km²
40. 仕望川流域
面积：2,375 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


Catchment Number: 41
Ehe River
Area: 1023 km²
41. 鄂河流域
面积：1,023 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


Catchment Number: 42
Sili–Jiyizhen
Area: 1133 km²
42. 寺里-集义镇流域
面积：1,133 km2
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

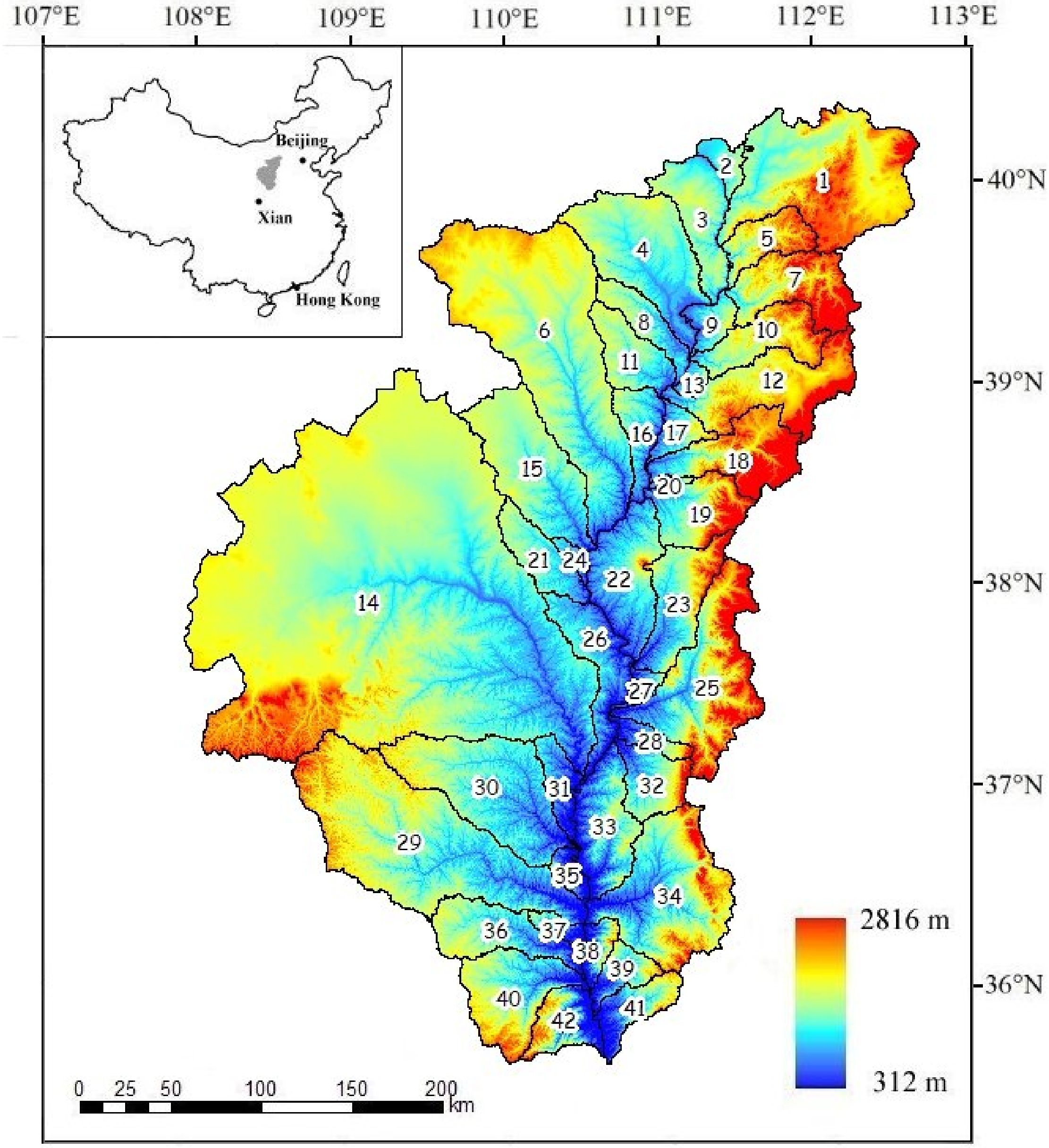


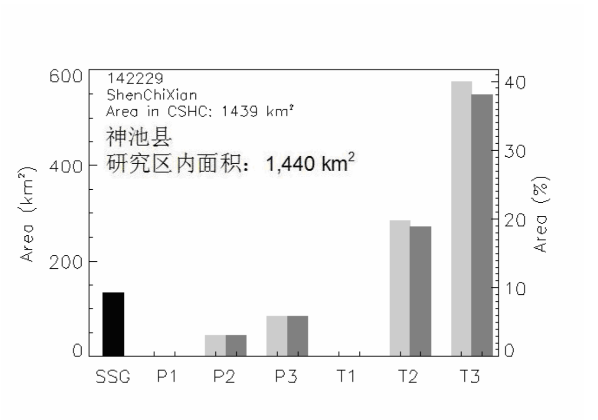
Figure 9. On the main map the CSHC catchment boundaries are overlaid on the resultant DEM. Each catchment is numbered (consecutively from north to south) with additional information being provided in Table 12. The inset map shows the location of the CSHC in all China.

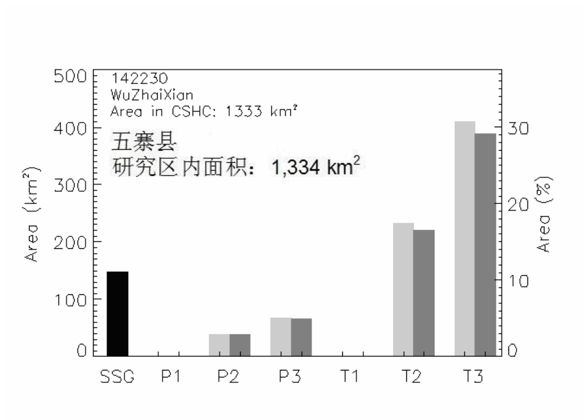
Table 12. Listing of the 42 catchments in the CSHC.

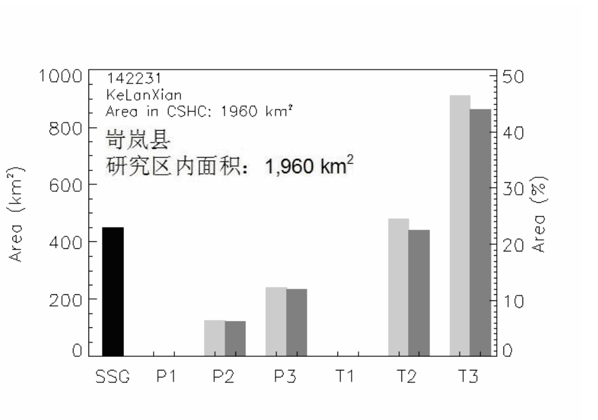
Rec #	Catchment Name	流域名称	Area (km^2)
1	Honghe River	红河	5,698
2	Lamawan	喇嘛湾	470
3	Longwanggou River	龙王沟	1,777
4	Huangfuchuan River	皇甫川	3,509
5	Yangjiachuan River	杨家川	1,114
6	Kuyehe River	窟野河	9,050
7	Pianguanhe River	偏关河	2,078
8	Qingshuichuan River	清水川	968
9	Hequ	河曲	585
10	Xianchuanhe River	县川河	1,595
11	Gushanchuan River	孤山川	1,318
12	Zhujiachuan River	朱家川	2,919
13	Baode	保德	242
14	Wudinghe River	无定河	31,460
15	Tuweihe River	秃尾河	3,333
16	Wujiazhuang	武家庄	1,007
17	Huashuta-Luzihe River	化树塔-芦子河	583
18	Lanyihe River	岚漪河	2,219
19	Weifenhe River	蔚汾河	1,645
20	ZhongZhuang	中庄	127
21	Jialuhe River	佳芦河	1,206
22	Yangjiapu-Zhaojiaping	杨家铺-赵家坪	2,365
23	Qiushuihe River	湫水河	1,984
24	Nuanqushan	暖渠山	218
25	Sanchuanhe River	三川河	4,139
26	Hedi-Mutouyu	河底-木头峪	1,816
27	Chengjiazhuang	程家庄	295
28	Jinjiazhuang	靳家庄	461
29	Yanhe River	延河	7,712
30	Qingjianhe River	清涧河	4,074
31	Lijiashan-Yanchasi	李家山-眼岔寺	781
32	Quchanhe River	屈产河	1,227
33	Yonghe River	雍河	2,070
34	Xinshuihe River	昕水河	4,351
35	Anhe-Guandao	安河-关道	382
36	Fenchuanhe River	汾川河	1,880
37	Xigelou	西葛沟	331
38	Wencheng-Wangjiayao	文城-王家窑	495
39	Zhouchuan River	州川河	712
40	Shiwanghe River	仕望川	2,375
41	Ehe River	鄂河	1,023
42	Sili-Jiyizhen	寺里-集义镇	1,133
Total		**112,728 km^2**	

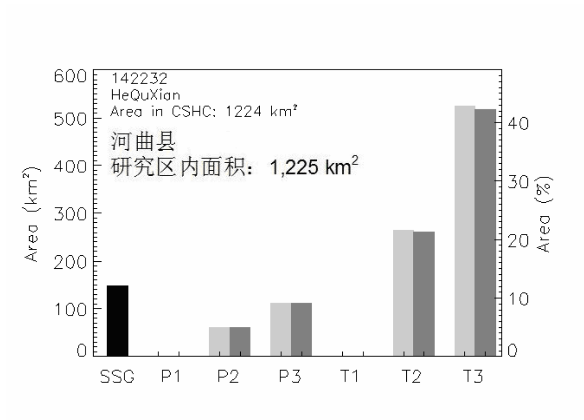
9 Appendix C: SSG, Target and Priority Areas by County

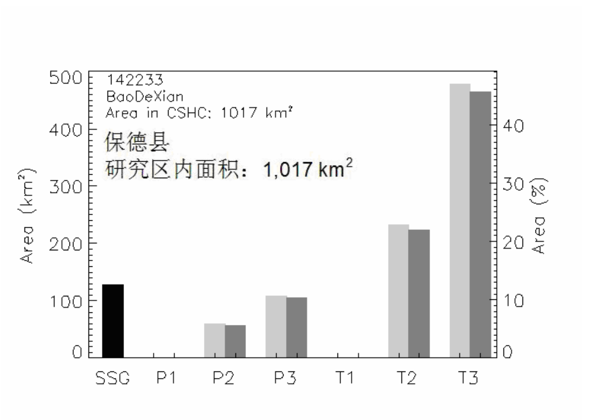
Only the 36 counties with greater than 90% of their area in the CSHC are included in this analysis; they are ordered by their county code. The meaning of the columns is described in Appendix B. County boundaries were provided at 1:500,000 scale for the 70 counties wholly or partially located in the CSHC, see Figure 10 and Table 13. There are 22 counties totally encompassed in the CSHC, another 14 counties have 90% or more of their area in the study site.

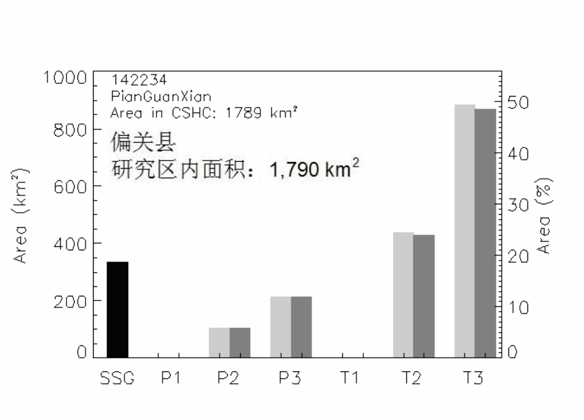


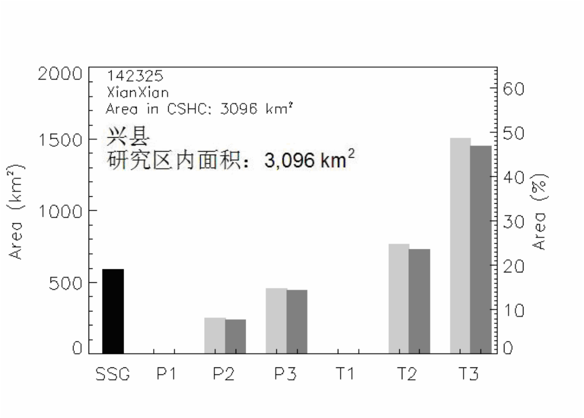


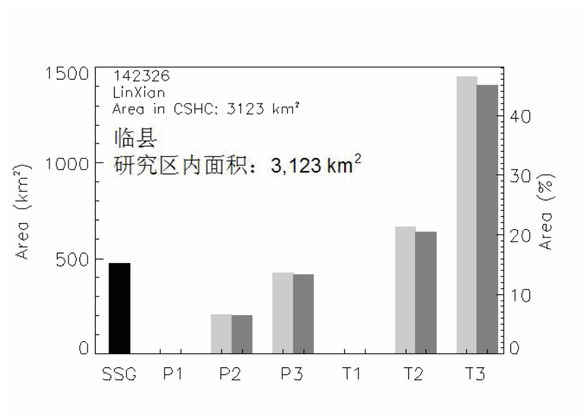


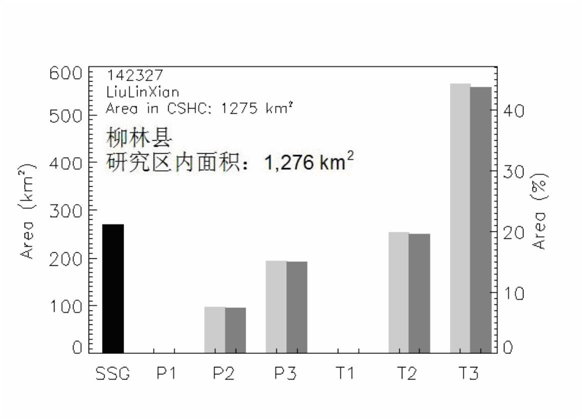


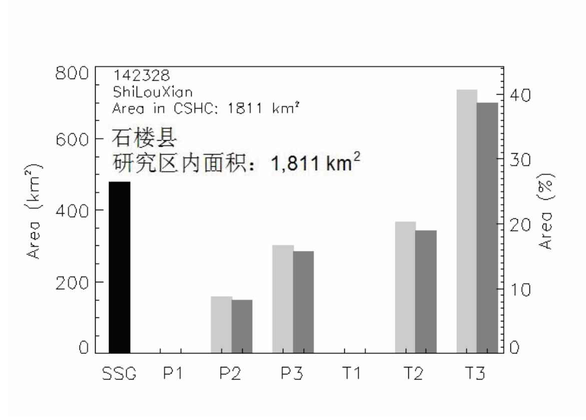


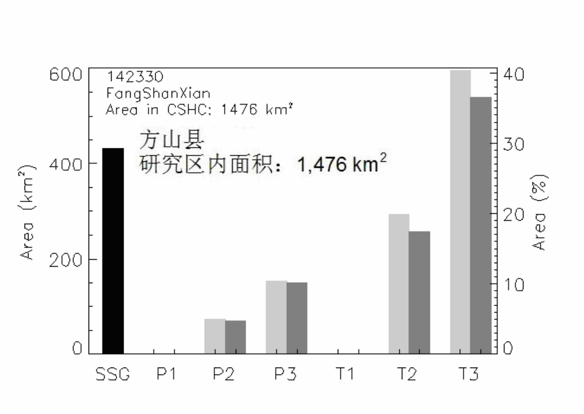


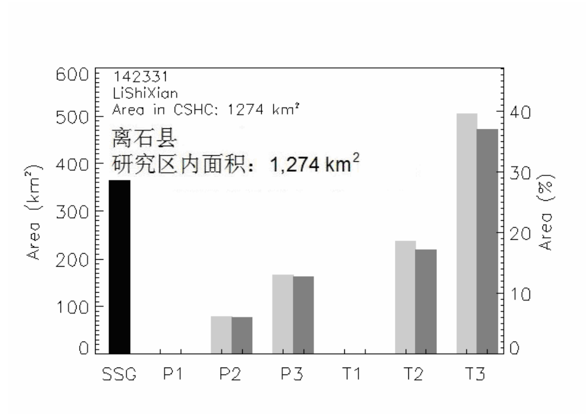

142325
XianXian
Area in CSHC: 3096 km²
兴县
研究区内面积：3,096 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

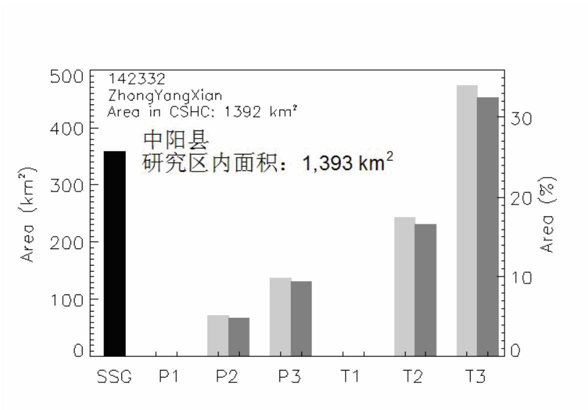

142326
LinXian
Area in CSHC: 3123 km²
临县
研究区内面积：3,123 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

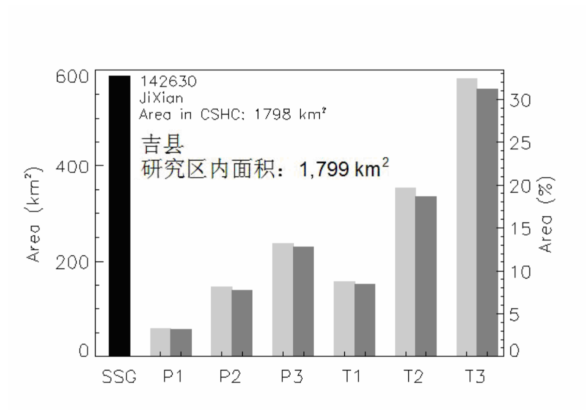

142327
LiuLinXian
Area in CSHC: 1275 km²
柳林县
研究区内面积：1,276 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

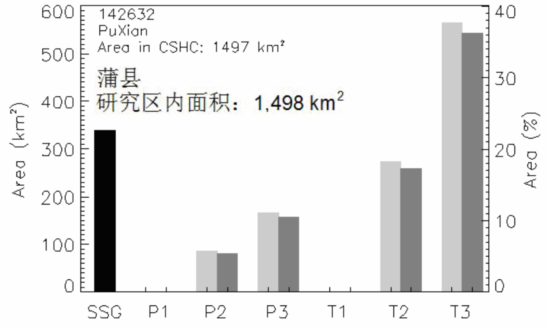

142328
ShiLouXian
Area in CSHC: 1811 km²
石楼县
研究区内面积：1,811 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

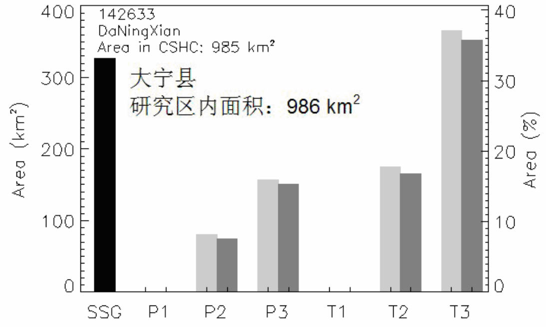

142330
FangShanXian
Area in CSHC: 1476 km²
方山县
研究区内面积：1,476 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

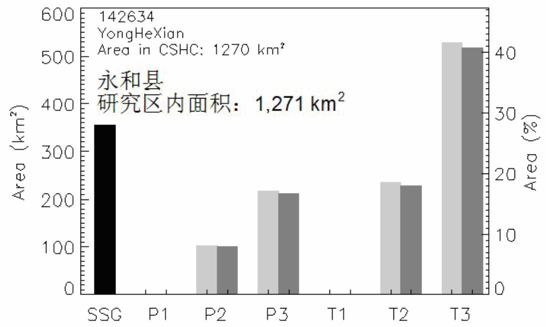

142331
LiShiXian
Area in CSHC: 1274 km²
离石县
研究区内面积：1,274 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

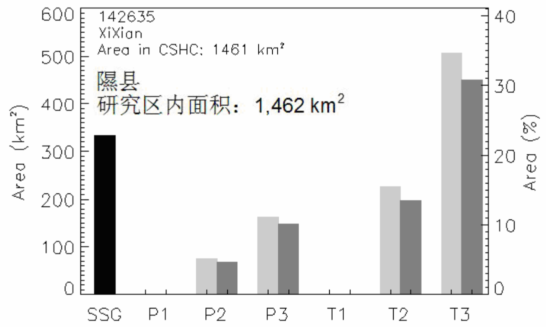

142332
ZhongYangXian
Area in CSHC: 1392 km²
中阳县
研究区内面积：1,393 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

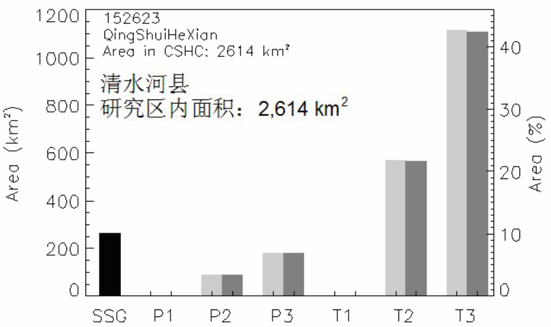

142630
JiXian
Area in CSHC: 1798 km²
吉县
研究区内面积：1,799 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

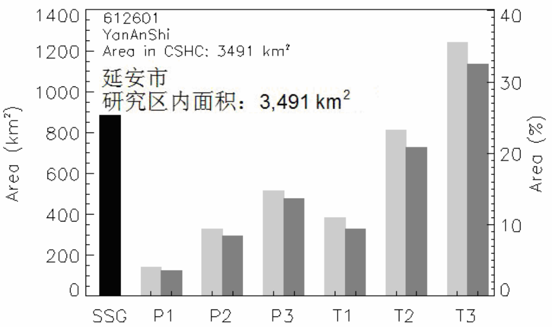

142632
PuXian
Area in CSHC: 1497 km²
蒲县
研究区内面积：1,498 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

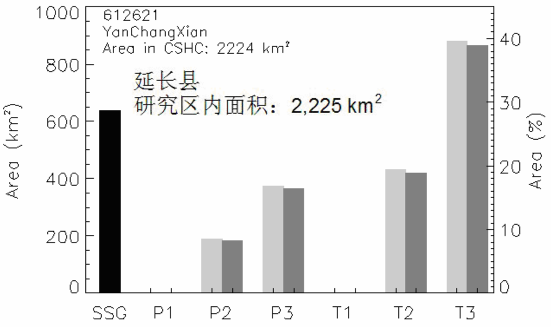

142633
DaNingXian
Area in CSHC: 985 km²
大宁县
研究区内面积：986 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

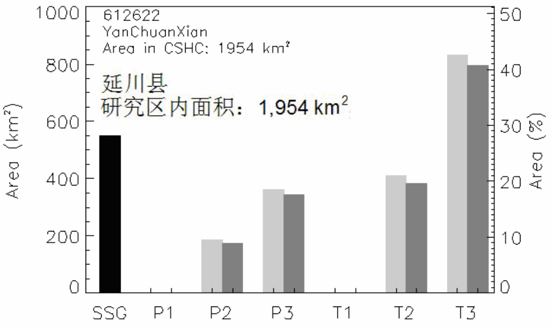

142634
YongHeXian
Area in CSHC: 1270 km²
永和县
研究区内面积：1,271 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

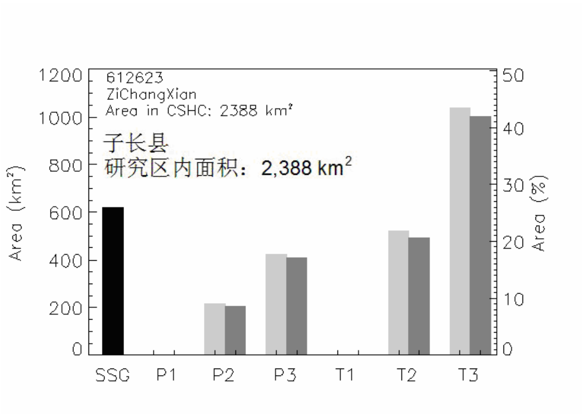

142635
XiXian
Area in CSHC: 1461 km²
隰县
研究区内面积：1,462 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

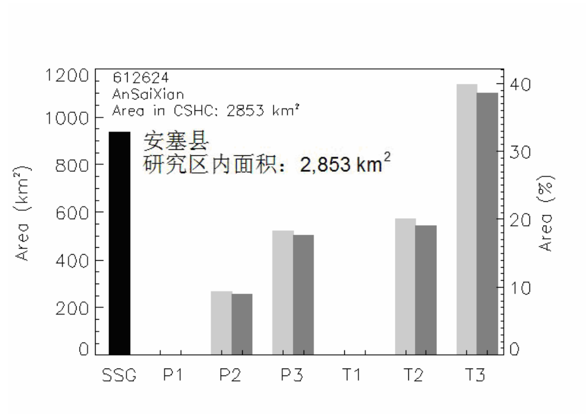

152623
QingShuiHeXian
Area in CSHC: 2614 km²
清水河县
研究区内面积：2,614 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

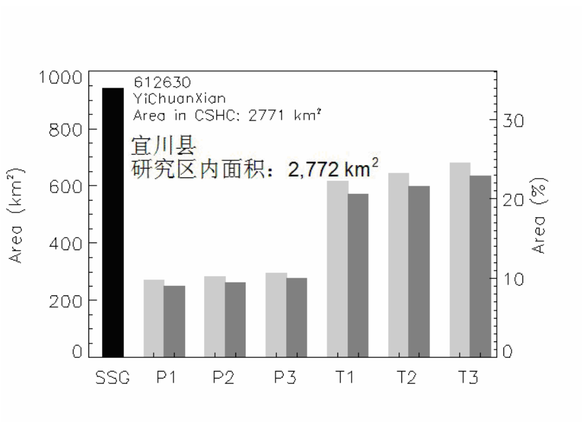

612601
YanAnShi
Area in CSHC: 3491 km²
延安市
研究区内面积：3,491 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

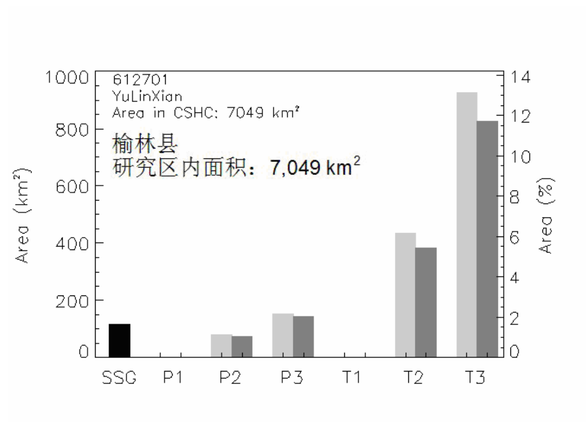

612621
YanChangXian
Area in CSHC: 2224 km²
延长县
研究区内面积：2,225 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

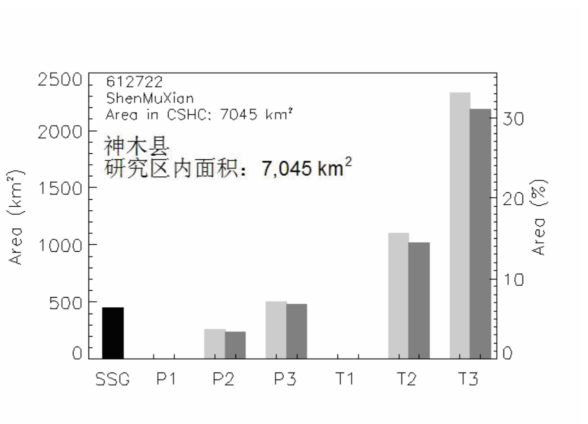

612622
YanChuanXian
Area in CSHC: 1954 km²
延川县
研究区内面积：1,954 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

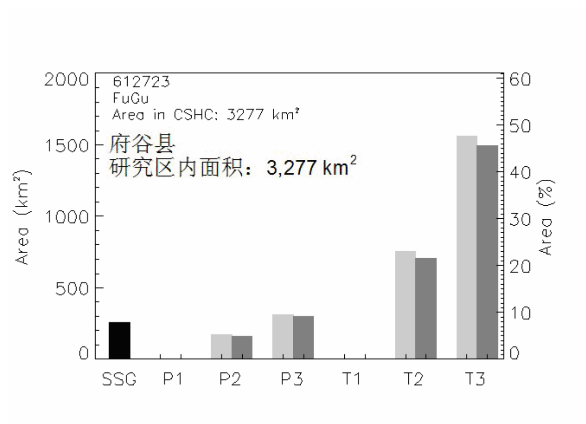

612623
ZiChangXian
Area in CSHC: 2388 km²
子长县
研究区内面积：2,388 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

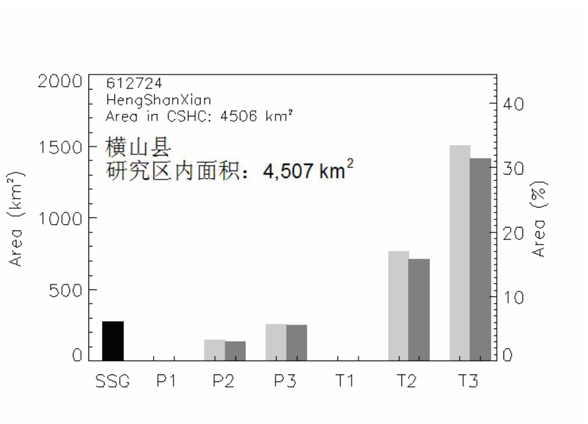

612624
AnSaiXian
Area in CSHC: 2853 km²
安塞县
研究区内面积：2,853 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

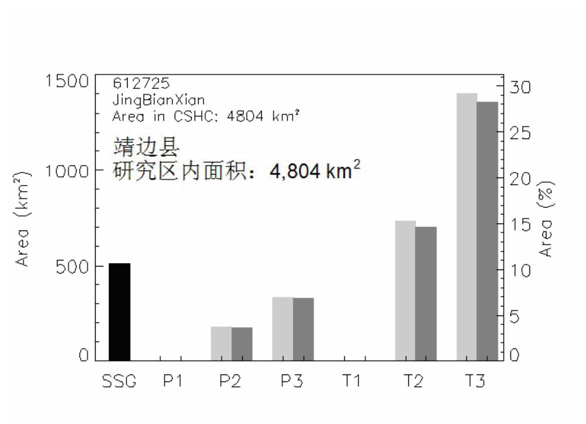

612630
YiChuanXian
Area in CSHC: 2771 km²
宜川县
研究区内面积：2,772 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

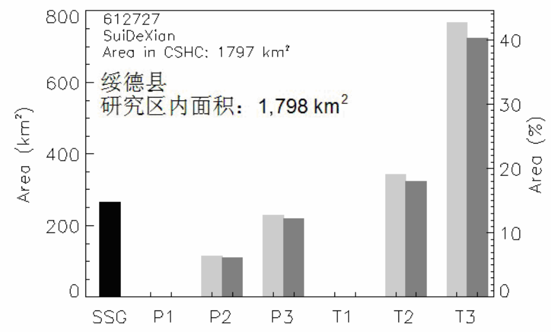

612701
YuLinXian
Area in CSHC: 7049 km²
榆林县
研究区内面积：7,049 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

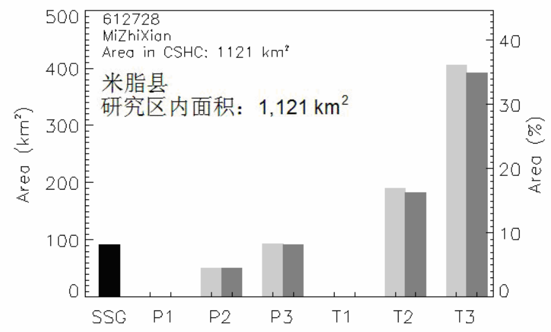

612722
ShenMuXian
Area in CSHC: 7045 km²
神木县
研究区内面积：7,045 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

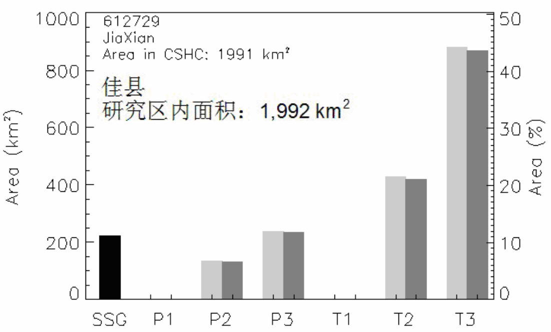

612723
FuGu
Area in CSHC: 3277 km²
府谷县
研究区内面积：3,277 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

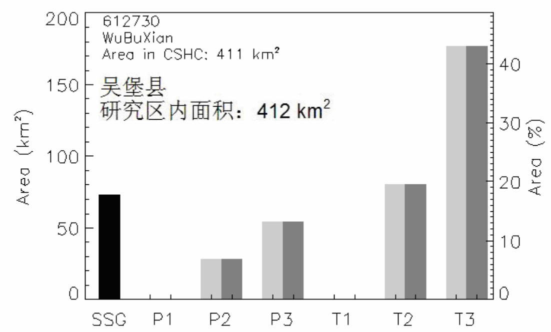

612724
HengShanXian
Area in CSHC: 4506 km²
横山县
研究区内面积：4,507 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

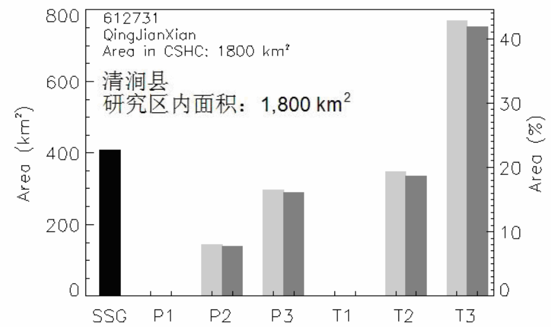

612725
JingBianXian
Area in CSHC: 4804 km²
靖边县
研究区内面积：4,804 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

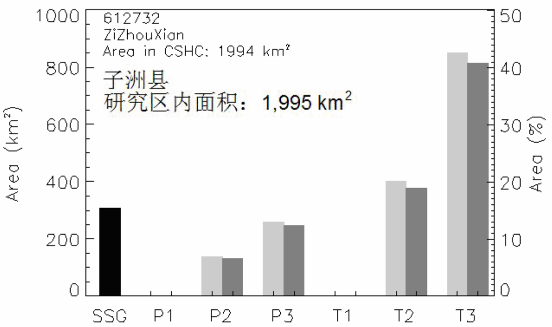

612727
SuiDeXian
Area in CSHC: 1797 km²
绥德县
研究区内面积：1,798 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


612728
MiZhiXian
Area in CSHC: 1121 km²
米脂县
研究区内面积：1,121 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


612729
JiaXian
Area in CSHC: 1991 km²
佳县
研究区内面积：1,992 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


612730
WuBuXian
Area in CSHC: 411 km²
吴堡县
研究区内面积：412 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


612731
QingJianXian
Area in CSHC: 1800 km²
清涧县
研究区内面积：1,800 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3


612732
ZiZhouXian
Area in CSHC: 1994 km²
子洲县
研究区内面积：1,995 km²
Area (km²)
Area (%)
SSG P1 P2 P3 T1 T2 T3

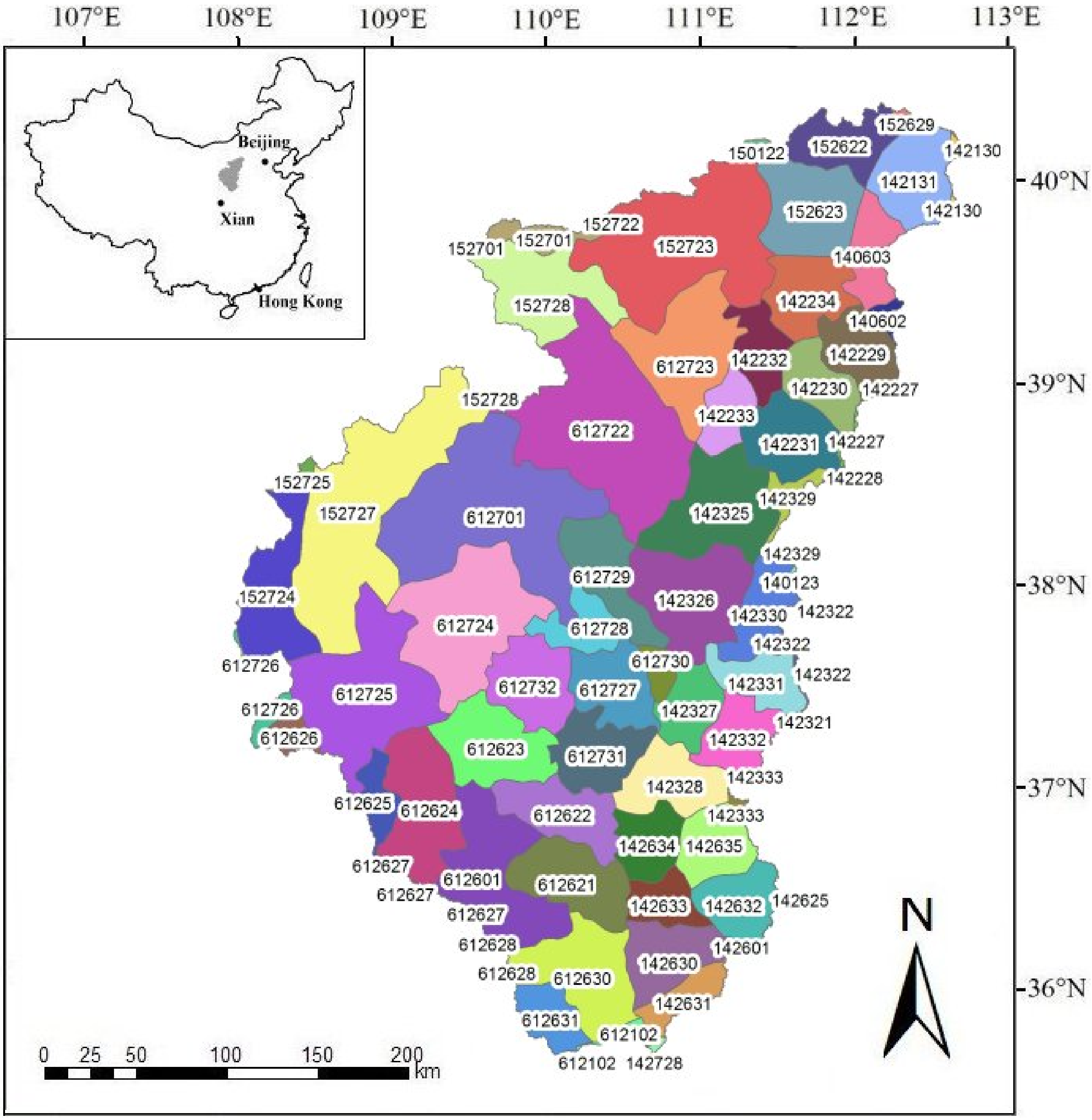


Figure 10. Locations and county codes of the 70 counties either wholly or partially located in the CSHC. The different colours are only used to distinguish the counties from each other. The inset map shows the location of the CSHC in all China.

Table 13. Counties fully or partly within the CSHC are shown. The table is primarily sorted by column labeled 'Area in CSHC (%)' and then secondarily by the column labeled 'County Code' in which the Chinese Central Government County Code are recorded.

County Code	County Name in Chinese	County Name in English	County Area (km^2)	County Area in CSHC (km^2)	County Area in CSHC (%)
142231	岢岚县	KeLanXian	1,960	1,960	100.00
142232	河曲县	HeQuXian	1,225	1,225	100.00
142233	保德县	BaoDeXian	1,017	1,017	100.00
142234	偏关县	PianGuanXian	1,790	1,790	100.00
142325	兴县	XingXian	3,096	3,096	100.00
142326	临县	LinXian	3,123	3,123	100.00
142327	柳林县	LiuLinXian	1,276	1,276	100.00
142630	吉县	JiXian	1,799	1,799	100.00
142633	大宁县	DaNingXian	986	986	100.00
142634	永和县	YongHeXian	1,271	1,271	100.00
612621	延长县	YanChangXian	2,225	2,225	100.00
612622	延川县	YanChuanXian	1,954	1,954	100.00
612623	子长县	ZiChangXian	2,388	2,388	100.00
612701	榆林县	YuLinXian	7,049	7,049	100.00
612723	府谷县	FuGuXian	3,277	3,277	100.00
612724	横山县	HengShanXian	4,507	4,507	100.00
612727	绥德县	SuiDeXian	1,798	1,798	100.00
612728	米脂县	MiZhiXian	1,121	1,121	100.00
612729	佳县	JiaXian	1,992	1,992	100.00
612730	吴堡县	WuBuXian	412	412	100.00
612731	清涧县	QingJianXian	1,800	1,800	100.00
612732	子州县	ZiZhouXian	1,995	1,995	100.00
142328	石楼县	ShiLouXian	1,812	1,811	99.96
142230	五寨县	WuZhaiXian	1,334	1,334	99.94
612630	宜川县	YiChuanXian	2,774	2,772	99.90
152623	清水河县	QingShuiHeXian	2,618	2,614	99.85
142331	离石县	LiShiXian	1,278	1,274	99.72
612601	延安市	YanAnShi	3,506	3,491	99.58
612624	安塞县	AnSaiXian	2,865	2,853	99.57
142330	方山县	FangShanXian	1,504	1,476	98.13
142332	中阳县	ZhongYangXian	1,423	1,393	97.85
142632	蒲县	PuXian	1,547	1,498	96.81
142229	神池县	ShenChiXian	1,498	1,440	96.12
142635	隰县	XiXian	1,521	1,462	96.12
612725	靖边县	JingBianXian	5,075	4,804	94.67
612722	神木县	ShenMuXian	7,794	7,045	90.39
142131	右玉县	YouYuXian	2,328	2,038	87.52
152723	准格尔旗	ZhunGeErQi	7,493	6,244	83.33
152727	乌审旗	WuShenQi	11,127	6,998	62.89
140603	平鲁区 [1]	PingLuQu	2,150	1,272	59.17
152728	伊金霍洛旗	YiJinHuoLuoQi	5,680	2,807	49.42
152622	和林格尔县	HeLinGeErXian	3,308	1,596	48.24
142631	乡宁县	XiangNingXian	2,198	940	42.76
612631	黄龙县	HuangLongXian	2,795	1,041	37.23
152701	东胜市	DongShengShi	2,192	696	31.76
142329	岚县	LanXian	1,477	445	30.16
612625	志丹县	ZhiDanXian	3,689	776	21.04
152724	鄂托克前旗	ETuoKeQianQi	12,561	2,328	18.53

County Code	County Name in Chinese	County Name in English	County Area (km^2)	County Area in CSHC (km^2)	County Area in CSHC (%)
140602	朔城区 [2]	ShuoChengQu	1,932	239	12.40
150122	托克托县	TuoKeTuoXian	1,394	164	11.74
612626	吴旗县	WuQiXian	3,838	391	10.18
612102	韩城市	HanChengShi	1,578	152	9.65
142728	河津县	HeJinXian	549	41	7.47
142333	交口县	JiaoKouXian	1,148	82	7.16
612726	定边县	DingBianXian	7,241	424	5.86
142130	左云县	ZuoYunXian	1,251	73	5.80
142227	宁武县	NingWuXian	1,962	106	5.38
152629	凉城县	LiangChengXian	3,380	93	2.74
142322	文水县	WenShuiXian	1,725	46	2.64
142601	临汾市	LinFenShi	1,285	32	2.52
140123	娄烦县	LouFanXian	1,329	33	2.45
142321	汾阳县	FenYangXian	1,367	24	1.76
612627	甘泉县	GanQuanXian	2,290	38	1.67
142228	静乐县	JingLeXian	2,045	32	1.56
152725	鄂 托克旗	ETuoKeQi	20,787	198	0.95
142324	孝义县	XiaoYiXian	1,022	8	0.75
142625	洪洞县	HongDongXian	1,502	7	0.48
612628	富县	FuXian	4,330	13	0.30
152722	达拉特旗	DaLaTeQi	8,343	21	0.25
612629	洛川县	LuoChuanXian	1,728	4	0.23

[1],[2]:1988 年设朔州市,朔县和平鲁县改称朔城区和平鲁区. Renamed in 1988 after merging.