MULTIPLE-SCALE SOIL MOISTURE DISTRIBUTION AND ITS IMPLICATIONS FOR ECOSYSTEM RESTORATION IN AN ARID RIVER VALLEY, CHINA

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ABSTRACT

The spatial distribution of soil moisture and its multiple-scale correlations to other environmental factors were examined along the Upper Minjiang River valley, China, a landscape subject to severe land degradation of soil and water erosion but also under investigation for potential ecosystem restoration. Results showed that: (1) Soil moisture was highest in the headwaters, and lowest in the arid valley, while moderate values characterized outside the arid valley. The polynomial model of soil moisture distribution on slopes was concave in the lightly disturbed headwaters, convex in the highly damaged arid valley, while convex on south facing slopes and concave on north facing slopes in highly damaged areas in better environmental condition. (2) Soil moisture was correlated with environmental factors at different scales, where elevation and air humidity were only correlated at the sample plot scale, light intensity and wind speed were found to be significant at both slope and site scales and slope and sample plot scales; while slope angle was correlated at all the three scales. From this we conclude that it is possible to improve soil moisture conditions in the arid valley by lowering slope angle and adding low-cost irrigation systems. (3) The practical threshold of soil moisture for growing meadows, shrubs, and forests were 11·800 per cent, 3·925 per cent, and 16·078 per cent respectively; the arid valley displayed soil-moisture conditions unfavourable to forest growth. The planned reforestation project is not ecologically reasonable. Reducing human disturbance and revegetating with natural shrubs and meadows may produce more effective results. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: ecosystem restoration; environmental factors; multiple scales; reforestation; soil moisture; Upper Minjiang River valley

INTRODUCTION

The negative impacts of land degradation are both ecological and socioeconomic. Human land use (such as deforestation, unsustainable agricultural practices, and overgrazing) often cause severe soil and water erosion in mountainous regions (Guan, 1996; Fu *et al.*, 2002), which lead to ecosystem degradation and environment deterioration (Wang, 1995). These may, in turn, influence river-water quality, cause floods, lower the productivity of farmland, and enlarge the arid area. Soil and water erosion thus can have a serious impact on the local economy and social development (Wang, 1995; Wang and Xie, 1997).

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There are several ecological and engineering ways to conserve soil and water (Wang, 1995; Guan, 1996). However, soil quality improvement has been paid more and more attention in recent years (Yang, 1993; Wang and Xie, 1997; Fu *et al.*, 2002; Cheng and Wan, 2002). In this regard, there have been abundant studies made on soil nutrients in small catchments in relation to land degradation and development (Fu *et al.*, 2002, and the references therein), but soil moisture has been largely neglected especially on a regional scale. This is surprising due to the fact that soil moisture is one of the most important factors in ecosystem structure and function, playing a unique role in many ecological processes. It determines tree and shrub establishment (Li and Wilson, 1998), plant canopy cover and species distribution (Barton, 1993; Duff *et al.*, 1997; Jacqumain *et al.*, 1999), species diversity and composition (Bratli and Myhre, 1999; Breshears and Barnes, 1999; Hutchinson *et al.*, 1999), and plant growth rate and biomass allocation (Wang *et al.*, 1998); it also has influence on the structure and function of microbial communities (Srivastava, 1992), as well as the function of some soil nutrients (Evans *et al.*, 1998).

The spatial variation of soil moisture is particularly important because it determines the regional distribution of ecosystems and must be considered an important factor in land-use planning and ecological restoration. Soil moisture can vary spatially in two ways: Soil moisture can be spatially autocorrelated, in which case regional patterns can be estimated through the statistical approach of spatial kriging (Bardossy and Lehmann, 1998; Fu *et al.*, 2002); soil moisture can also display scale variation, which becomes important when comparing local and regional distribution (Seyfried, 1998). The soil-moisture distribution is influenced by many environmental factors in a given area. These include precipitation, elevation, topographical settings, vegetation types, and other soil properties (Werling and Tajchman, 1984; Francis *et al.*, 1986; Wilson and Kleb, 1996; Gonzalez-Hidalgo and Bellot, 1997; Famiglietti *et al.*, 1998; Yeakley *et al.*, 1998; Yeh and Eltahir, 1998; Breshears and Barnes, 1999; Sulebak *et al.*, 2000; Salve and Allen-Diaz, 2001). Other climatic factors, such as wind speed and light, also influence the soil moisture although few studies have been carried out. Moreover, human land uses have the potential to affect soil moisture by altering the land cover (Fu *et al.*, 2000; Qiu *et al.*, 2001a,b). The spatial pattern of soil moisture is actually a result of the integration of these natural and anthropogenic factors at multiple scales.

Knowing that soil moisture is crucial to ecosystem restoration and land development in arid regions, it is vital to clearly understand several key relationships: (1) how soil moisture varies at different scales; (2) what environmental factors determine the spatial distribution of soil moisture at a certain scale; (3) the soil moisture demand of a vegetation type; and (4) how to rehabilitate ecosystems by improving the influencing factors on soil moisture at different scales. All of these aspects are essential for effective ecological planning and ecosystem management projects in arid areas.

In this paper, we study the spatial variation of soil moisture along the mountainous arid Upper Minjiang River valley, an area suffering land degradation but also identified for potential ecosystem restoration. Soil and water erosion caused by vegetation damage is the most serious impact of land degradation along the Upper Minjiang River valley. Vegetation damage along the Minjiang River has taken place for at least a thousand years, mainly along the upper valley (Editorial Board of Sichuan Vegetation, 1980; Zhang, 1992). Forest cover has decreased from about 50 per cent in the 1800s to about 18 per cent at present, and deforestation is especially prevalent in the arid valley (Editorial Board of Sichuan Vegetation, 1980; Zhang, 1992). Consequently, serious soil erosion has occurred, further degrading soil water and nutrient conditions (He *et al.*, 1993; Lei and Huang, 1993). This has led to difficulty in recovering natural forests at most sites (Zhang, 1992), while increasing the silt content of the Minjiang River, and thus decreasing the water quality of the Yangtze River (He *et al.*, 1993).

Since topography, vegetation, soils, and climatic conditions are highly variable in river basins in mountainous regions (Gurtz *et al.*, 1999), the correlations of soil moisture to other important environmental factors were examined at the scales of site, slope, and sample plot. Physical properties studied included topographical settings, elevation, light intensity at the soil surface, wind speed, air humidity and vegetation types. The study was mainly aimed at two issues: (1) what environmental factors determined the soil moisture distribution at multiple scales in the arid valley; and (2) what implications could be concluded from the study to restore the degraded ecosystems through improving soil moisture conditions.

STUDY AREA AND METHODS

Study Area

The Minjiang River is a first-order branch of the Yangtze River (Figure 1). It is about 735 km in length and has an altitude range of 3560 m. The river is not only important economically, but also ecologically in southwestern China. It has been the main water resource of the Sichuan province, determining the production of agriculture and industry of the region. The watershed is inhabited by many rare species, such as the giant panda.

Located on the transition zone from the Tibetan Plateau to the Sichuan Basin, the Upper Minjiang River basin (102° 41'–103° 58' E; 30° 44'–32° 24' N) refers to the part up to Dujiangyan city (named after the great irrigation work), and is about 337 kilometers in length. It is normally incised to <1000 m in depth, which results in seven levels of terraces at 7 m, 15–20 m, 50–60 m, 100 m, 150–180 m, 370 m, and 460 m above water level. These terraces are fragmented and distributed in small areas (Zhang, 1992). The brown forest soils in the region are rich in lime (Bureau of Agriculture and Pasturage, Office of Soil Survey, Sichuan Province, 1997).

The mountainous topography results in a large degree of vertical variation in precipitation and air temperature. Incoming radiation is normally 4.5×10^9 – 5.5×10^9 J/m², and there are 1500–2000 sunshine hours per year. The mean temperature of the hottest month (August) is higher than 18°C, while that of the coldest month (January) is lower than 0°C. There are >180 days with temperature $\geq 10^\circ\text{C}$. Annual precipitation is between 500–850 mm.

Regional vegetation mainly consists of small-leaf arid shrubs (elev. 1300–2200 m), broad-leaf and needle-leaf mixed forests and evergreen and deciduous broad-leaf mixed forests (elev. 2000–2800 m), *Picea* and *Abies* forests (elev. 2800–3600 m), and alpine shrubs and meadows (elev. >3600 m) (Zhang, 1992). The Upper Minjiang River valley is now dominated by some arid shrubs, especially *Caryopteris* spp., *Sophora vrsifolia*, *Bauhinia* spp., *Ajanía potaninii*, *Onosma* spp., *Selaginella pulvinata* and *Desmodium* spp. These are accompanied by some grasses and other plants, *Miscanthus sinensis*, *Themeda triandra*, *Asparagus filicinus*, *Setaria glauca*, *Aristida adscensionis*, and *Achnatherum inaequiglume* (Editorial Board of Sichuan Vegetation, 1980).

Methods

Considering the arid valley, which is about 108 km long, as the key part of the study area, six sites were chosen according to the degree of degradation in terms of vegetation damage. These sites were located approximately 500 m apart, from the highest elevation headwaters to the lower site (Yingxiu) along the Upper Minjiang River valley (see Figure 1). Three sites were located inside the arid valley, two sites outside the arid valley, and one site at the headwaters. More specifically, the headwaters Doujitai (Site 1), was mainly covered by alpine meadow and natural forests, and was only lightly disturbed by logging and grazing. The upper site outside the arid valley, Dsheng (Site 2), displayed the secondary needle-leaf forest after logging on north-facing slopes, and the dwarf dry shrubs on south-facing slopes. The upper end of the arid valley, Shidaguan (Site 3), upon which vegetation was seriously destroyed by logging and cultivation activities, had few vascular plant species, mainly short, dry grasses and dwarf, dry shrubs on both the north- and south-facing slopes. At the central part of the arid valley, Feihongguan (Site 4), vegetation consisted only of sparse dwarf, dry shrubs on the north-facing slopes and sparse vegetation on the south-facing slopes. On the lower portion of the arid valley, Wenchuan (Site 5), some trees occupied the north-facing slopes, but only sparse shrubs were present on the south-facing slopes. Finally, on the outside of the arid valley, Yingxiu (Site 6), was dominated by naturally recovering dense, small trees and high shrubs on slopes that had undergone forest cutting.

At each site, two transects were placed on the opposite south- and north-facing slopes, oriented towards the lower-elevation slope so as to make a 'V' shape. Sample plots were set up on each transect according to the vegetation types (forest, shrub, and meadow). Normally, three plots were set up in each vegetation type. However, occasionally only one or two plots were feasible, particularly when the vegetation type was narrowly distributed on slope. More than three plots were sampled if the vegetation area was large enough. Knowing that soil moisture varies over time, due to fluctuations in rainfall and plant water requirements in the summer season, soil-moisture sampling was carried out on sunny days within a two-week period in August 2001 (after 3 days of no rainfall; there was only one rain event at Site 2 during the field work), in order to keep the sampling conditions similar.

Figure 1. Location of the sample sites along the Upper Minjiang River, China. Where Sites 1 to 6 are Doujitai, Desheng, Shidaguan, Feihongguan, Wenchuan, and Yingxiu, respectively, starting from the headwaters.

Within each sample plot, the corresponding environmental factors, including elevation, topographical settings (slope, position, and aspect), light intensity at the soil surface, wind speed, and air humidity were measured when determining soil moisture. The elevation was measured using an altitude meter, the slope angle and aspect were measured using a clinometer and compass, the light intensity at the soil surface was measured using an illumination meter, wind speed was measured using an anemometer, and air humidity was measured using a psychrometer. All measurements were replicated three times. The moisture of surface soil (0–15 cm) was determined at nine points within each plot using a portable Time Domain Reflectometer (TDR). In total, data from 108 sample plots were collected in the field.

All the above parameters were averaged according to the 3 scales of sample plot, slope (aspects and positions), and site respectively. The soil-moisture variation of sample plots on slope was regressed using second-order polynomial models, because they provided the best fit of the data. Correlation analyses were performed between soil moisture and the other environmental factors at the three scales respectively. All the corresponding probabilities were examined according to a correlation coefficient table (Zar, 1999).

RESULTS

Soil Moisture Variation along the Valley at Different Scales

At the site-level, soil moisture was the highest at the headwaters of Site 1, and lowest in the arid valley from Sites 3 to 5, while moderate values were found outside the arid valley at Sites 2 and 6 (Figure 2a). The soil moisture within

Figure 2. Soil moisture variation along the Upper Minjiang River valley at different scales. The sample sites are the same as shown in Figure 1. (a) The total averages at each site. (b) The averages on south- and north-facing slopes of each site. (c) The averages at higher elevation, intermediate elevation and lower elevation slopes of each site. (d) The averages at different slope positions on the south-facing slopes of each site. (e) The averages at different slope positions on north-facing slopes of each site.

the arid valley was about two-times lower than those of the outside parts, and about four-times lower than recorded at the headwaters, indicating a water shortage in the arid valley.

At slope-level, soil-moisture distributions were similar to that of the site average along the upper valley, but some slight differences were observed: (1) Although soil moisture on the south-facing slopes was less than the north-facing slopes at all sites (Figure 2b), these differences were not statistically different. Slope aspect only weakly influenced soil-moisture distribution along the arid valley at the slope-level. (2) For different slope positions, the soil moisture showed an exception of lower values for the higher elevations at the headwaters (Figure 2c), which might be explained by the lower vegetation cover and stronger wind on the mountain tops. (3) Both south- and north-facing slopes showed spatial trends at all sites similar to that of the site average (Figure 2d,e). However, values further down the slope were lower than those noted at the intermediate and higher elevations on south-facing slopes. This same pattern was not found at the headwaters, Site 1, where lower

Table I. The polynomial models of the soil moisture variation of sample plots along the slopes at the six sites along the Upper Minjiang River valley. The analysis was performed from the top to the foot of each mountain

Site	Model of south-facing slope	Response type	Model of north-facing slope	Response type
1	$y = 0.446x^2 - 3.176x + 43.661^*$	Concave	$y = 0.389x^2 + 6.382x + 2.049^{***}$	Concave
2	$y = -0.365x^2 + 4.513x + 4.244^{**}$	Convex	$y = 3.650x^2 - 16.561x + 34.600^{***}$	Concave
3	$y = -0.134x^2 + 2.059x + 8.326^{***}$	Convex	$y = 0.067x^2 - 0.837x + 15.980$	Concave
4	$y = 0.225x^2 - 2.364x + 10.876^*$	Concave	$y = -0.299x^2 + 2.090x + 6.024^{**}$	Convex
5	$y = -0.011x^2 - 0.288x + 7.467^{**}$	Convex	$y = -0.109x^2 + 1.904x + 1.768^{***}$	Convex
6	$y = -1.172x^2 + 6.150x + 12.378^{***}$	Convex	$y = 0.342x^2 - 1.208x + 18.917^{***}$	Concave

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

elevations produced higher moisture values. Similar trends were found on north-facing slopes at all sites, with the exception of lower elevations yielding higher moisture content at the headwaters. This could indicate that the combination of slope aspect and position greatly affected soil moisture on the north-facing slope of the headwaters, but it had little influence in the arid valley.

At sample plot scale, the second-order polynomial models fitted to soil-moisture distribution along the slopes were all statistically significant except on the north-facing slope at Site 3 (Table I). This suggested a regularity that soil moisture response was concave at the headwaters, convex in the arid valley (except the south-facing slope at Site 4), convex on south-facing slopes and concave on north-facing slopes in both sites outside the arid valley. This could indicate that the soil-moisture distribution was concave on slopes in the lightly disturbed area (i.e. headwaters), but convex on slopes in the highly damaged arid valley, while convex on south-facing slopes and concave on north-facing slopes in highly damaged areas with better environmental conditions (i.e. sites outside the arid valley). The soil-moisture distribution was thus closely related to disturbance intensity and soil-moisture conditions.

Multiscale Correlations of Soil Moisture with Environmental Factors

Environmental factors were correlated with soil-moisture variation along the Upper Minjiang River valley at multiple scales (Table II). At the site scale, slope angle was correlated with soil moisture negatively ($p < 0.01$) and light intensity at the soil surface was correlated with soil moisture positively ($p < 0.05$) among all the environmental factors. At the slope scale, three environmental factors were correlated with soil moisture. These

Table II. The correlations of soil moisture to environmental factors along the Upper Minjiang River valley at multiple scales

Scale	Slope	Elevation	Light intensity	Wind speed	Air humidity
Site	-0.9355**	0.7190	0.8167*	0.6900	0.6721
Slope aspects					
South-facing	-0.6782	0.7190	0.3679	0.6990	0.6721
North-facing	-0.7774	0.7896	0.8628*	0.6670	0.5674
Slope positions					
Highest elevation	-0.5782	0.7423	0.6872	-0.2638	0.7970
Intermediate elevation	-0.6374	0.7072	0.5522	0.8210*	0.7888
Lower elevation	-0.9872***	0.7638	0.6636	0.8608*	0.3497
South-facing slope					
Highest elevation	-0.5635	0.6917	0.5723	-0.0666	0.6049
Intermediate elevation	-0.1149	0.6886	0.2638	0.7793	0.7837
Lower elevation	-0.9334**	0.7375	-0.0296	0.8384*	0.3449
North-facing slope					
Highest elevation	-0.3585	0.4499	0.2829	-0.5140	0.8030
Intermediate elevation	-0.6507	0.7227	0.8921*	0.8523*	0.7880
Lower elevation	-0.9390**	0.7751	0.8638*	0.8722*	0.3511
Plot	-0.7540***	0.6902***	0.1972	0.4176**	0.5261***

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

were slope angle, light intensity at the soil surface, and wind speed. The slope angle at lower elevations ($p < 0.001$) was the reason for its effect at the site scale and, similarly, the north-facing intermediate and lower elevation light intensities (both $p < 0.05$) affected the light intensity influence at the site scale. Wind speed was also correlated with soil moisture distribution at slope scale. The south-facing lower elevations and the north-facing intermediate and lower elevations correlated well ($p < 0.05$), but this factor failed to influence soil moisture at the site scale. At sample plot scale, all the environmental factors were statistically significant correlated to soil moisture, except light intensity at the soil surface. We can summarize two facts from the above results. (1) The number of correlated environmental factors increased as the scale was decreased in the upper valley. There were two, three, and four factors correlated at the site, slope, and sample plot scales respectively. (2) The environmental factors influenced soil moisture at different scales. Two factors, elevation and air humidity, were only effective at the sample plot scale. Two factors were statistically significant at two scales, light intensity at slope and site scales and wind speed at slope and sample plot scales. Slope angle was statistically significant at all three scales. Interestingly, wind speed and light intensity at the soil surface were both positively correlated with soil moisture in the upper Minjiang River, indicating that the stronger the wind or light, the wetter the soil. This seems counterintuitive, but may be explained in this arid valley as a result of the föhn effect combined with the influence of elevation.

Soil Moisture Distribution in Different Vegetation Communities

Vegetation pattern is not only a result of soil-moisture distribution, it could also affect the soil moisture regime in an arid region. Important features from the mutual relationship between vegetation type and soil moisture can be utilized to restore the degraded ecosystem in the arid valley. The soil-moisture conditions were different in forests, shrublands, and meadows at site and slope (aspect and position) scales. At the site scale, shrublands had lower values than the other two, while forests and meadows were similar (Figure 3a). At the slope scale, results were variable. (1) Patterns were different on south- and north-facing slopes (Figure 3b). The soil-moisture regime was shrublands < forests < meadows on south-facing slopes, and meadows < shrublands < forests on north-facing slopes. (2) At different slope positions, the soil-moisture regime was meadows < shrublands < forests at higher elevations, shrublands < meadows < forests at intermediate elevations, and shrublands < forests < meadows at lower elevations (Figure 3c). There was no explicit pattern in the soil-moisture conditions in different vegetation communities at the slope scale.

In order to determine the practical threshold of soil moisture for forests, shrublands, and meadows in the upper valley, we summarized the field data of the sample plots by finding the lowest soil moisture for each vegetation type. This showed that the practical threshold of soil moisture were 11.800 per cent for meadows, 3.925 per cent for shrublands, and 16.078 per cent for forests respectively. Compared with the soil-moisture regimes from each site and slope scale (Figure 2), vegetation types likely to regenerate can be suggested for each location (Table III). (1) All vegetation types can be grown in Site 1 on all slopes except that the north-facing, higher elevations could not support forest growth. (2) Site 2 can support all vegetation types, however forests may not be supported on the north-facing intermediate elevation and south-facing slopes. (3) Meadows and shrublands can probably be grown in Site 3, except that the south-facing lower elevation slope can only support the growth of shrublands, and forests could not be grown at this site. (4) Sites 4 and 5 can only support growth of shrublands. (5) Site 6 can support all vegetation types.

This indicates that the arid valley (Sites 3 to 5) was too dry to grow meadows and forests, with the exception of Site 3, which usually can support meadows. The headwaters and the site outside the arid valley had abundant soil moisture for growing all vegetation types, except that forests could not be supported on the north-facing, highest elevation slope in the headwaters, which could be due to high elevation and strong winds. Site 2 was an intermediate site, but could not support forest growth on the north-facing intermediate elevation and south-facing slopes.

DISCUSSIONS AND RECOMMENDATIONS

Ecosystem restoration has been very much needed for preserving soil and water along the upper Minjiang River valley, especially in the arid valley, although it is very difficult. The arid valley is an area where evaporation

Figure 3. Soil moisture of different vegetation types in the Upper Minjiang River valley. (a) The soil moistures of meadows, shrublands and forests averaged across the sample plots within a certain vegetation type in the valley. (b) The averaged values of meadows, shrublands and forests on south- and north-facing slopes. (c) The averaged values of meadows, shrublands and forests on higher, intermediate and lower elevation slopes.

(>1500 mm yr⁻¹) greatly exceeds precipitation (500 mm yr⁻¹). Meanwhile, the climate in the arid valley, as a result of the föhn effect, results in lower areas of the valley becoming even drier than the higher slopes. This has become a further impediment to forest recovery in the lower areas. Many zonal species are difficult to establish under the insufficient water conditions present following forest clear-cutting, especially on the steep south-facing slopes, which are mainly covered by sparse, dwarf shrublands with small, hard or needle leaves. Meanwhile, species sensitive to the disturbances in the region also led to habitat fragmentation and the endangerment of rare species such as the giant panda (Liu *et al.*, 2001; Loucks *et al.*, 2001). Hence, the Minjiang River has been considered one of the most important watersheds in China for ecological restoration and biological conservation under the background of land degradation. In recent years, the Chinese Government has made great efforts in facing these problems (Zhang *et al.*, 2000).

This empirical study showed that soil moisture is an important factor to characterize land degradation, and a crucial factor in ecosystem restoration and reforestation in the arid valley of the Minjiang River, its multiple-scale distribution and correlation to other environmental factors provided some valuable implications for regional reforestation and land development. These could also be significant in other places experiencing similar problems throughout the world.

Table III. Vegetation types that can be supported along the Upper Minjiang River valley under given soil-moisture thresholds. The practical thresholds of soil moisture are 11.800 per cent for meadows (M), 3.925 per cent for shrublands (S), and 16.078 per cent for forests (F)

Scale	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Site	M, S, F	M, S, F	M, S	S	S	M, S, F
Slope aspects						
South facing	M, S, F	M, S	M, S	S	S	M, S, F
North facing	M, S, F	M, S, F	M, S	S	S	M, S, F
Slope positions						
Highest elevation	M, S, F	M, S, F	M, S	S	S	M, S, F
Intermediate elevation	M, S, F	M, S	M, S	S	S	M, S, F
Lower elevation	M, S, F	M, S, F	S	S	S	M, S, F
South facing slope						
Highest elevation	M, S, F	M, S	M, S	S	S	M, S, F
Intermediate elevation	M, S, F	M, S	M, S	S	S	M, S, F
Lower elevation	M, S, F	M, S	S	S	S	M, S, F
North facing slope						
Highest elevation	M, S	M, S, F	M, S	S	S	M, S, F
Intermediate elevation	M, S, F	M, S	M, S	S	S	M, S, F
Lower elevation	M, S, F	M, S, F	M, S	S	S	M, S, F

Past efforts at ecosystem restoration and reforestation were not satisfactory, because soil moisture as a critical variable was not taken into account. The ecological principle of 'restoring suitable vegetation in the right place' has been put forward for the reforestation in the arid valley for many years (The Integrated Investigation Group for Upper Minjiang River, 1979, unpublished work), and the central government conceived this idea before implementing its 'Green for Grain' policy (Li, 2001). Historically, many places inside the arid valley have been reforested, even in recent years after the 'Green for Grain' policy was put in place. Under these circumstances, two kinds of problem occurred. (1) Reforestation in the arid valley was very costly. More money was invested in planting tree seedlings, and irrigation became necessary for the seedlings to obtain water upslope from the Minjiang River to ensure that the moisture demands of the plants could be met. (2) Tree seedlings that have survived may die in the future due to low soil moisture. Trees in other arid areas have been found to overuse soil water in the deep layers (Lu, 1997). This not only slows down the growth of the trees, but also can lead to mortality and the inability to revegetate the site in the future. Therefore, we urgently need to change the present manner of reforestation techniques towards that of natural recovery.

Specifically, soil moisture has been considered the most limited factor in the ecosystem restoration along the Upper Minjiang River valley (He *et al.*, 1993). Our study showed that soil moisture was very low in the arid valley (Sites 3–5) and sufficient for recovering natural forests outside the area (Sites 1, 2 and 6) (Figure 2). We can restore forests in all the disturbed sites outside the arid valley except on the south-facing slopes in Site 2, but we may only be able to restore shrublands and some meadows rather than forests inside the arid valley (as a result of the soil-moisture conditions). Our results strongly support the notion that we should implement ecosystem restoration strictly according to the soil-moisture distribution in the region. This would be necessary for two reasons: (1) Recovering shrublands and meadows in the arid valley would be at a lowest cost, since it is a natural process; and (2) as the goal of ecological restoration has been changed from forestry production to environmental improvement in the region, we need not reforest in a single step. The shrub and meadow restoration could more effectively prevent the soil and water losses in the region (Liu, 2003), which would gradually improve the physical conditions for future forest planting and recovery as implied by this study. Moreover, the regional ecosystem restoration along the arid valley should be planned according to the multiple-scale distribution of soil moisture, as shown in this study, which would be more effective in regional land-development practice as well.

Besides strictly implementing the principle of 'restoring suitable vegetation in the right place' in the ecological restoration along the arid valley under natural environmental conditions, we may also be able to accelerate

ecosystem restoration directly by improving the soil moisture in some possible sites through engineering methods. Among all the correlated environmental factors at different scales, lowering slope would be the only possible way for increasing soil moisture. This can be accomplished by altering the shape of the steep slope to terrains and dams (Bao and Chen, 1999). Contour planting on slopes can also be useful in aiding soil and water conservation, and this has often been employed in mountainous farming practices (Chow *et al.*, 1999). Irrigation is probably the best way of improving soil moisture conditions for vegetation recovery and restoration, however it can only be implemented when water resources are convenient (i.e. close) and the cost is low.

Knowing that land degradation is not only an ecological, but also an economic and social problem, some relevant conservation policies are needed to reduce human disturbance on these lands. These policies could include forbidding forest clear-cutting, returning farmland in unsuitable places to natural vegetation, and preventing other activities that might cause vegetation damage and soil and water loss. Actively, some alternative industries also need to be established in the region. Small water power plants and ecological tourism are examples of industries that have been developed with success in recent years (Lü, 2003).

However, this empirical study was only concerned with the spatial pattern of soil moisture, since we were interested in the spatial scales of moisture distribution. Of course, the temporal variation of soil moisture is equally important to ecosystem restoration, and further study on spatiotemporal soil-moisture distribution, while much more intensive, may be needed to supply a better answer to the questions surrounding regional ecological restoration in the arid river valley.

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