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Article

Farmers' Sustainable Strategies for Soil Conservation on Sloping Arable Lands in the Upper Yangtze River Basin, China

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Abstract: The Upper Yangtze River Basin comprises a densely-populated agricultural region with mountainous and hilly landforms. Intensive cultivation has been extended onto steep hillslopes, which constitute the principal source area for sediment production. Soil conservation on sloping arable lands is thus of utmost priority for persisting sustainable agricultural production and maintaining sound ecosystem services. Although there have been many soil conservation techniques, either promoted by the government or adopted by local farmers, the practiced area was very limited relative to the total area affected by soil erosion. This paper attempts to introduce four popular soil conservation measures on sloping arable lands in this region to enhance a broader scale of implementation, including hedgerow buffers, level trenches, sloping terraces and limited downslope tillage. These practices, although developed from local farmers' indigenous knowledge for productive purposes, have well conformed to our contemporary understanding of soil erosion processes on sloping landscape affected by human disturbances, were of sound suitability to regional manual tillage agriculture and more trade-off-efficient on rill prevention, runoff harvest and nutrient management.

Keywords: soil conservation; sloping arable land; hedgerow buffers; level trenches; conservative tillage; Upper Yangtze River Basin

1. Introduction

Global soil erosion has been greatly accelerated during the past centuries by the expansion and intensification of diverse human activities (e.g., land use change associated with agriculture expansion, land clearance and deforestation, mining, infrastructure construction, urbanization, *etc.*) [1–3]. The global soil erosion rate was estimated at 22 ± 6 Gt·year^{-1} [4] and 10%–20% of which has been delivered to downstream river channels [5]. In particular, in agricultural regions with a dense population, soil erosion rates are extremely high on agricultural lands due to intensive anthropogenic disturbances (e.g., land reclamation, grazing and tillage) [6]. Upland soil erosion and in-stream sediment redistribution can lead to a series of on-site problems, such as fertility depletion, land degradation and productivity reduction, and off-site environmental consequences, such as extreme floods, channel siltation, freshwater deterioration and aquatic habitat degradation. Upland soil conservation is increasingly recognized as one of the many effective mitigation measures, both by agricultural engineers to preserve precious land resources and maintain sustainable agricultural outputs and by river ecologists to maintain the sound ecological status of downstream freshwaters.

The Upper Yangtze River Basin in southwestern China comprises a densely-populated agricultural region with hilly and mountainous landforms. This region is affected by the many environmental and socioeconomic problems associated with severe soil erosion and high fluvial suspended sediment flux. Intensive cultivation has been extended onto steep hillslopes during the last century, due to the intense pressure of rapid population growth on land use. This region has thus been targeted as the principal provenance area for sediment production across the Yangtze River Basin, and a major proportion was produced from sloping arable lands due to regional extreme rainfall storms, the fragile landscapes and intensive human disturbances [7].

Soil conservation on sloping arable lands is thus of utmost priority, not only for sustainable agricultural productions, but also for the mitigation of the many off-site environmental consequences associated with sediment transport and the maintenance of the sound status of downstream freshwaters (e.g., alleviation of sedimentation in the Three Gorges Reservoir, reduction of the delivery of sediment-associated contaminants). There have been many soil conservation measures that have been either recommended by agricultural agencies or demonstrated by top-down government initiatives. Local farmers also persist in practicing many traditional techniques developed based on their own consciousness. The soil erosion rate is closely related to land use and field management [8]. Conservative farming techniques can contribute to soil conservation and increase crop yields [9]. There is a need to systematically understand the rationality and effectiveness of these measures to enhance a broader scale of implementation.

Optimum soil conservation strategies should follow the rule of balancing the cost-benefit efficiency through considering the suitability to the site-specific natural and socioeconomic conditions of the targeted area. Therefore, the present paper attempts to analyze the efficiency and rationality of common-practiced soil conservation measures. The specific objectives are to: (1) introduce popular soil conservation measures; (2) interpret the underlying rationality and suitability of these techniques through considering the specific social-natural status; and (3) summarize the cost-benefit efficiency through a literature review.

2. Site Description

The Upper Yangtze River originates from the Qinghai-Tibetan Plateau, extends 4500 km to Yichang and covers a mountainous and hilly catchment of approximately one million km^2 (Figure 1). The Upper Yangtze River encompasses four major headwater tributaries of Jinsha, Jialing, Min and Wu. Regional landform comprises the four typical geomorphologic features of the Qinghai-Tibet Plateau, the Parallel Ridges and Valleys, the Yunnan-Guizhou Plateau and the Sichuan Plain [7]. The regional climate is principally influenced by local topography. The western part is dominated by an arid climate with average annual rainfall less than 400 mm, while the eastern part is dominated by a humid subtropical monsoon climate with annual average precipitation of more than 1200 mm, and a major proportion occurs during the rainy season from May to September. Extreme storms with a high intensity and short duration can cause large amounts of land erosion. The widely-distributed purple soils in the eastern part of the basin are developed from the purple rocks of the Trias-Cretaceous system and classified as Regosols in the FAO Taxonomy or Entisols in USDA Taxonomy [10]. The purple soils are characterized by rapid weathering, complexity in mineral composition, richness of nutrients and a loam texture. The land is of poor tolerance to drought and susceptible to erosion. Land use in the western highland is dominated by pasture and grazing, while in the eastern part mainly is farmland and cultivation. The area of dry farmland in this region is 15×10^4 km^2; 50% is sloping arable lands, and a large proportion is located on slopes with gradients over 25° [11,12]. The distribution of sloping arable lands with different slope gradients is summarized in Table 1. Previous studies have also documented the severity of soil erosion on the sloping agricultural landscape (Table 1). In this paper, we focused on four soil conservation measures on sloping arable lands in this region due to their popularity.

Figure 1. Geographical map of the Upper Yangtze River Basin.

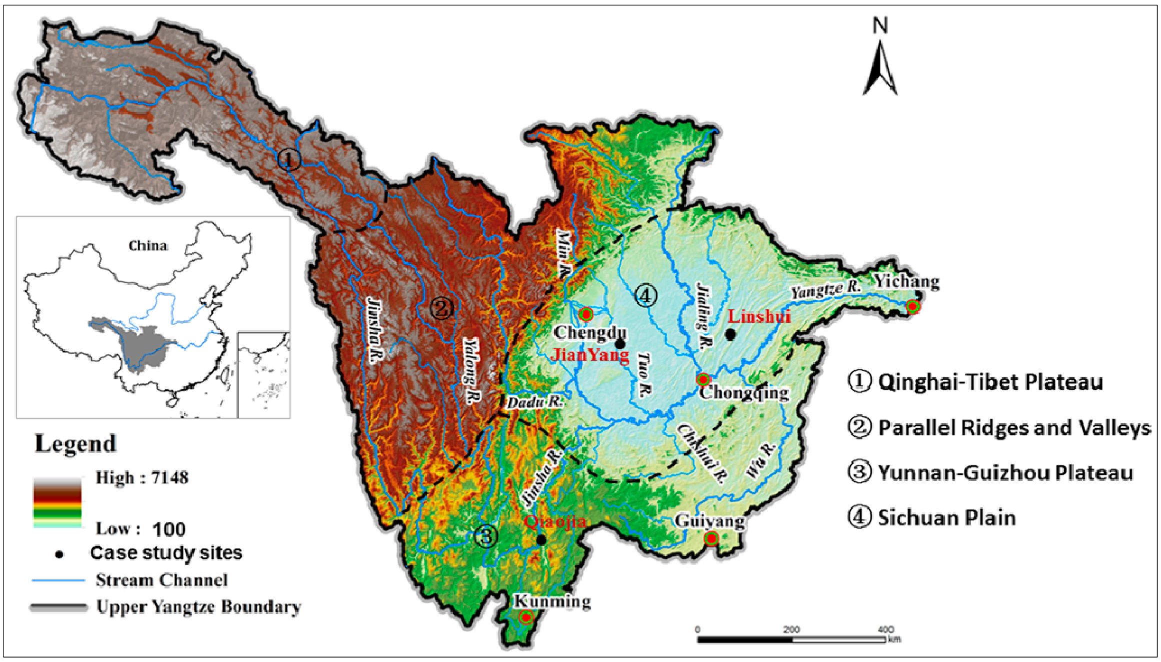


Table 1. Summary of soil erosion rates on sloping arable lands in the Upper Yangtze River Basin [11].

Study area	Precipitation (mm)	Slope gradient (°)	Slope length (m)	Soil erosion rates ($t \cdot km^{-2}$ $year^{-1}$)
Tianshui (Gansu)	606	19.3	20	4598
		18	19	5310
		12.8	34	2864
		31	15	8216
Zhenba (Sichuan)	1250	10	27	7467
		34	54	985
		7	8	4200
Nanchong (Sichuan)	1010	11	17	4663
		5	9	758
		14	24.7	6780
Kaixian (Chongqing)	1090	25	10	9452
		25	5	7481
		25	8	9854
Zigui (Chongqing)	1048	31	29	2059
Muding (Yunnan)	851	20	13	6271
Yiliang (Yunnan)	917	25	21	8543
Yuanmou (Yunnan)	614	15	25	2740
		5	70	1405

3. Materials and Methods

Mean annual soil erosion rates on cultivated sloping lands before and after soil conservation treatments were quantified using the ^{137}Cs tracing technique [11]. Soil redistribution rates can be estimated by comparing the reference value and the inventories for sampling sites using calibration models. Erosion is indicated in that ^{137}Cs inventories are depleted compared to the references value, while excess ^{137}Cs inventories indicate sedimentation [13]. Soil redistribution on cultivated sloping lands was also quantified by magnetic tracing [14]. The critical slope length for the initiation of rills on sloping arable lands was determined by repeated artificial rainfall simulations on experimental runoff plots with targeted gradients, and the results are statistical averages with the possibility of reoccurrence [15,16].

4. Results and Discussion

4.1. Marginal Hedgerows and Contour Buffering Strips

Converting the linear hillslopes to inconsecutive flat terraces was one of the many soil conservation measures under the national initiative of Soil Conservation in the Upper Yangtze River Basin, since the late 1980s. The project mainly focused on the four regions characterized by severe upland soil erosion and high fluvial suspended sediment yields (upper Jialing catchment, middle-lower Jialing catchment, Three Gorges Reservoir region and lower Jinsha catchment [9]. The regional soil erosion rate is closely related to local topography (*i.e.*, slope length and gradient) [17]. Terracing is proven to be effective in preventing sheet and rill erosion by shortening the slope length and decreasing the slope gradient [18].

However, regional extreme rainfalls during the summer season and concentrated runoffs tend to lead to the instability of the terrace structures (verging on collapse) and, consequently, results in a high amount of soil loss [19,20]. The maintenance of the terrace structure and its functions requires large amounts of constant labor and financial investment [17]. Installing marginal hedgerows mainly composed of woody species by local farmers was aimed originally to make full use of the marginal lands and obtain domestic fuels and additional economic outputs (e.g., harvest of leaves for silkworm breeding, Figure 2). However, marginal hedgerows may provide multiple ecological benefits to the local farming system. Well-maintained marginal plants enhanced the stability of the terrace structure by root consolidation and land coverage (Figure 2). Soil structure is improved such that water infiltration and holding capacity can be enhanced to reduce the denudation power of runoff on surface land.

Within-field contour hedgerows composed of woody plants and grass species were originally deployed on large sloping fields continuously along the slope, either as an inter-cropping system to obtained additional economic outputs or as a distinct boundary between subfields with different crops [21]. However, the ecological function of these components on agricultural landscape is increasingly recognized and evaluated. These act as buffer strips, which can physically retain upland sediment and agricultural contaminants, enhance the infiltration rate of surface runoff and reduce the surface sourcing process (Figure 3, Table 2). It was reported that compared with untreated fields, sediment yield on experimental sloping plots treated with contour buffer strips in the purple-soiled region under simulated rainfall condition was reduced by 82.2%, and runoff volume was reduced by 75.2% [22].

Grasses proved to be more effective in trapping sediment and filtering runoffs than woody plants, but the latter were more efficient in preventing erosion through root consolidation [23]. Buffer strips can also change the sloping topography, due to constant sediment accumulation at the upper sides of the strips (Figure 3). Ma *et al.* [24] suggested the maximum inter-strip widths for the deployment of contour buffer strips on sloping arable land with gradients of 10° and 15° in the purple-soiled region to be 13.7 and 9.0 m, respectively. It was also documented that the application of fertilizers can obviously improve the performance of soil conservation, boosting production on sloping arable lands with contour vegetative barriers [25].

Figure 2. (**a**)–(**c**) Installing flat terraces with marginal hedgerows (*Morus alba L.*) in the Jinsha valleys (Qiaojia, Yunnan Province); (**d**) plant leaves harvested for silkworm breeding.

Figure 3. (**a)** Incorporating contour buffer strips composed of grass species into sloping arable land at the experimental plot scale (Zhong County, Three Gorges Reservoir region); (**b**) sediment fencing during a summer erosive rainfall event.

Table 2. Cost-benefit efficiency of multiple soil conservation practices [17,26].

Measures	Input	Runoff regulation	Soil loss	Agricultural output
Terraces	2.4 Yuan/m^2	−72%~−79%	−88%~−93%	+52%~+86%
Hedgerow buffers [a]	0.5 Yuan/m^2	−22%~−43%	−94%~−98%	+33%~+56%
Level trenches	0.8 Yuan/m^2	−8%~−47%	−7%~−80%	+3%~+26%

[a] Grass species.

4.2. Sediment Retaining Trenches

Soil loss on sloping farmlands is mainly conducted through sheeting and rilling processes. Preventing the formation and development of rills affords an effective way to reduce the total amount of soil erosion. A previous study demonstrated that there exists a critical slope length for rill formation on slopes with a fixed gradient (Table 3). The probability of rill formation on farmlands with a slope length larger than this critical value increases considerably compared with that on lands with a slope length shorter than this critical value. Previous studies have documented the critical slope lengths on experimental plots with various gradients under simulated rainfall conditions at two typical purple-soiled hilly environments (*i.e.*, Yanting in the central Sichuan Plain and Zhong in the Three Gorges Reservoir region) [15,16].

Table 3. Critical slope lengths corresponding to various slope gradients for the initiation of rills on experimental runoff plots under simulated rainfall conditions.

Slope gradient (°)	5	15	20	25	Study area	References
Critical length (m)	6.13	4.12	2.72	1.55	Zhong	Yang *et al.* 2010 [15]
	6.25	4.19	2.77	1.60	Yanting	Yang *et al.* 2010 [16]

The critical slope length theory is indicated by level trenches on sloping lands, which subdivide the entire field into numerous subfields for different cropping systems (Figure 4). The trenches are 30 cm-deep and connected to side permanent ditches. During a rainfall event, level trenches function in deviation of the flow path of surface runoff collected from the upland subfield from longitudinal flow to lateral flow and draining to the side ditches. Rills can rarely occur due to the shortened slope length. A proportion of eroded soils can be retained in the trenches, which subsequently is manually returned to the field. A field investigation was undertaken on a cultivated hillslopes with level trenches by using ^{137}Cs to calculate the medium-term annual average soil erosion rates. Results indicated that high soil erosion occurred at the utmost upper slope, and soil accumulation was observed at the areas upper from the level trenches (Figure 5), which should be ascribed to the manually return of sediment from the trenches [27].

Figure 4. (**a**) A view of sloping farmland subdivided by level trenches (Linshui, Sichuan Province); (**b**) illustration of the level trenches' deviating flow direction.

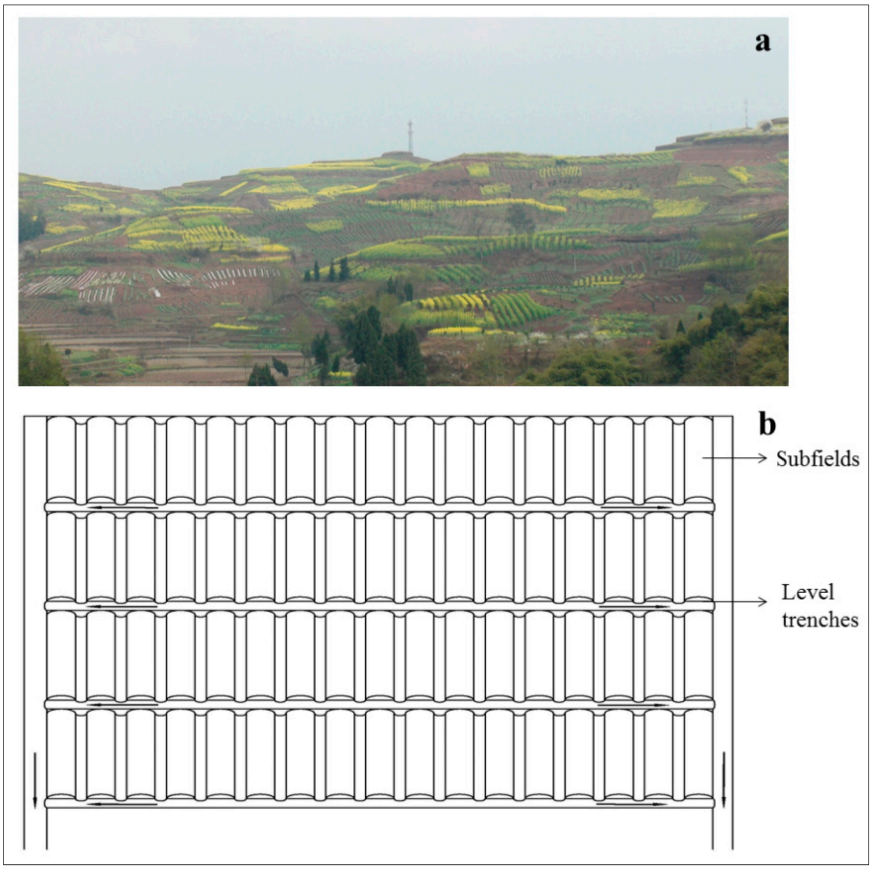
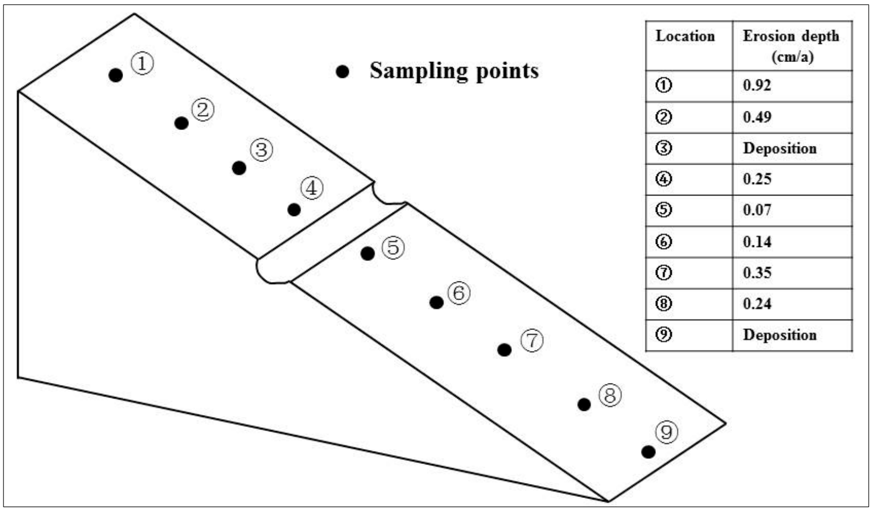


Figure 5. Distribution of soil erosion depth on a sloping farmland with level trenches and managed with a sediment return practice [27].



4.3. Sloping Terraces

Although terracing is an effective measure for soil conservation, the construction of a flat terrace requires a large labor investment to change the land topography. Sloping terraces are constructed at a broad scale in the region. Earth ridges are preliminarily constructed along the contour lines (Figure 6).

Eroded sediment can be deposited above the ridges, and the slope gradient can be decreased due to constant sediment redistribution. Sloping terraces are thus formed without the involvement of human force. The occurrence of rills can be reduced due to the relatively shorter slope length.

Figure 6. Sloping land management with terraces, side drainage ditches and sediment tanks (Linshui, Sichuan Province).

4.4. Limited Downslope Tillage

Tillage on sloping farmland is a predominant anthropogenic force leading to the spatially (both laterally and longitudinally) displacement of soil particles. Conventional tillage turns the soil patches downslope with pulling. The rate of tillage translocation is closely related to tilling methods and the slope gradient. The widely-practiced animal-traction and hoeing tillage on sloping arable lands in this region contribute substantially to the total amount of soil erosion [28,29]. It was estimated that tillage erosion (hoeing tillage) on sloping lands with gradients from 4%–43% at Jianyang (central Sichuan Plain) were 4800–15,100 $t{\cdot}km^{-2}{\cdot}a^{-1}$ [30]. Specifically, these tillage practices can lead to the depletion of soil depths on the concave upper slope positions and soil accretion on the convex lower slope positions [31]. Additionally, the contrasting behavior of the change of soil organic carbon and phosphorus is associated with the change of soil profiles at different positions of the slope by tillage [32–34].

A conservation tillage method termed "non-overturning hoeing tillage" reduces the translocation rate through slightly pulling soil patches downslope and the avoidance of turning the downslope soils over [16]. By a comparative experimental plot study at Zhong County in the Three Gorges Reservoir region, the tillage erosion rate was estimated at 28 $Mg{\cdot}ha^{-1}{\cdot}year^{-1}$, which was reduced by 63% compared with that under conventional tillage (Table 4) [14].

Table 4. Summary of soil translocation and tillage erosion rates by conventional and conservation tillage [14].

Conventional tillage			
Translocation distance (m)	Tillage depth (m)	Translocation rate ($kg \cdot m^{-1}$ $tillage \cdot pass^{-1}$)	Erosion rate ($Mg \cdot ha^{-1}$ $tillage \cdot pass^{-1}$)
0.3268	0.17	77.87	77.87
Conservation tillage			
Translocation distance (m)	Tillage depth (m)	Translocation rate ($kg \cdot m^{-1}$ $tillage \cdot pass^{-1}$)	Erosion rate ($Mg \cdot ha^{-1}$ $tillage \cdot pass^{-1}$)
0.1105	0.19	28.44	28.44

5. Conclusions

This study introduced four commonly-practiced soil conservation measures on sloping arable lands in the Upper Yangtze River Basin, which were promoted by the government and resilience scientists and improved based on local farmers' indigenous knowledge. These practices appear to conform well to our contemporary knowledge of the individual soil erosion processes (sheeting and rilling) on sloping cultivated lands, demonstrating high suitability to regional natural (sloping topography, concentrated summer rainfalls) and socioeconomic condition (regional agriculture-dominated undeveloped economy, manual tillage agriculture) and are more trade-off-efficient on soil conservation, sediment reuse, rainfall harvest or drainage, nutrient management and maintaining a diversified cropping system. Although these measures are practiced at the field scale, they serve as effective supplementary measures for sustainable sloping land management. These practices also demonstrated a specific suitability to fields with different slope gradients.

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Author Contributions

Qiang Tang, Yuhai Bao and Ronghua Zhong performed the data assemblage and manuscript preparation. Xiubin He, ChanSheng He and Anbang Wen contributed to the development of the idea, result interpretation and manuscript preparation.

Conflicts of Interest

The authors declare no conflict of interest.

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