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Degradation of cultivated bench terraces in the Three Gorges Area: Field mapping and data mining

Sarah Schönbrodt-Stitt[a,*], Thorsten Behrens[a], Karsten Schmidt[a], Xuezheng Shi[b], Thomas Scholten[a]

[a] University of Tübingen, Department of Geosciences, Chair of Physical Geography and Soil Science, Tübingen, Germany
[b] Institute of Soil Science, Department for Soil Resources and Remote Sensing Application, Chinese Academy of Sciences, Nanjing, People's Republic of China

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ABSTRACT

Due to resettlements, construction of new infrastructure, and new land reclamation the rapid agricultural changes in the Three Georges Area (TGA) in Central China are expected to force the degradation of the cultivated terraced landscape. Consequently, increased soil erosion can hamper a sustainable land management in the mountainous TGA. This paper presents the model framework *TerraCE* (Terrace Condition Erosion) for determining the causes for different terrace conditions and terrace degradation based on field surveys and spatial data mining. For a total of 987 bench terrace plots in the Xiangxi catchment we collected data on their state of maintenance and terrace design to account for terrace stability and thus capability of soil conservation. Assessing the driving factors of terrace degradation was done by embedding terrain-based predictors and distance-transforms of remote-sensing data as indicators of environmental and anthropogenic influences. Random forests classification and regression models were applied for data mining. Terrace degradation in the Xiangxi catchment is obvious. The sequence of degradation ranges from 'well maintained' (21%), 'fairly maintained' (44%), and 'partially collapsed' (23%) to 'completely collapsed' (11%) terraces. The cross-validation error of the supervised *TerraCE* model is below 8%, allowing for reasonable and valid interpretations of the causes of terrace degradation. Data mining reveals indicators for anthropogenic effects such as the distance to settlements or to roads as major drivers for the spatial distribution of terrace conditions. The effect of relief, which can be regarded as the major natural driver for terrace degradation by erosive action is tributary but altered and overlaid by land use dynamics associated with the Three Gorges Dam. An important indicator representing a combined effect of terrain and human activity is the distance to stream channels of different orders. Applying *TerraCE* we reveal mechanisms of terrace degradation in disturbed environments and present a framework for standardized mapping and analysis of terrace degradation under cultivation. The approach might also be used to develop guidelines for terrace planning in mountainous terraced landscapes of limited carrying capacity, with respect to socio-economic as well as environmental conditions.

1. Research background

1.1. Farming terraces and terrace degradation

Worldwide, estimated 75 billion tons of soil are eroded each year (Wachs and Thibault, 2009). Especially in mountain areas, soil erosion is one of the most pressing environmental problems affecting soil fertility, water availability, and farmland productivity (Posthumus and Stroosnijder, 2010; Montgomery, 2007). Here, the erosive effect of extreme climate and terrain triggering soil erosion processes by water can be most effectively alleviated by farming terraces (e.g., Hudson, 1981; Inbar and Llerena, 2000; Shi et al., 2004). Consequently, terracing serves as key technology for soil and water conservation and for a suitable land management (Shrestra et al., 2004; Cao et al., 2007).

Due to the terracing, steep slopes are converted into an artificial sequence of relatively flat surfaces (Montgomery, 2007). The erosive slope length and angle, and thus the runoff potential distinctly decrease resulting in a reduction of terrain-induced soil erosion and sediment yield (Arnaez et al., 2010; El Atta and Aref, 2010; Shi et al., 2012). Bench terraces (synonym for slope or stone terraces) are the major recommended type of terrace for steep sloping areas (Hudson, 1981; Shi et al., 2012). In order to stabilize the vertical terrace riser, dry-stone walling along the contour lines is largely applied (Hudson, 1981; Bellin et al., 2009; Shi et al., 2012).

* Corresponding author at: University of Tübingen, Department of Geosciences, Chair of Physical Geography and Soil Science, Rümelinstraße 19-23, D-72074 Tübingen, Germany. Tel.: +49 7071 29 74054.
E-mail address: sarah.schoenbrodt-stitt@uni-tuebingen.de (S. Schönbrodt-Stitt).

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Under optimum conditions, these engineering structures form a 'hydraulic equilibrium' state between the geomorphic settings and anthropogenic use (Brancucci and Paliaga, 2006; Chemin and Varotto, 2008). From the Mediterranean, for instance, Hammad et al. (2004) report a decrease of average soil loss on bench terraces compared to non-terraced plots by factors up to 20. In the highly vulnerable Chinese Loess region, decreases of soil loss of average 49% were observed (Li and Nguyen, 2008). Applying the WATEM/SEDEM erosion and sediment transportation model for a small watershed sloping in average with 23° in Central China, Shi et al. (2012) report a reduction of soil loss and sediment yield by approximately 17% and 32% for bench terraces combined with furrow-ridge tillage. Terraces are further likely to favor the interception of overland flow and to enhance the infiltration in the long-term (e.g., Bellin et al., 2009; El Atta and Aref, 2010; Shi et al., 2012), to reduce the erosion-induced nutrient loss (Damene et al., 2012), to promote agricultural productivity (Posthumus and Stroosnijder, 2010), and to expand available land for cultivation (Zhang, 2008).

In contrast to the above benefits, numerous studies such as from Saudi Arabia (El Atta and Aref, 2010), the Andes in Peru (Inbar and Llerena, 2000), from the Chinese Loess region (e.g., Li and Lindstrom, 2001), from Italy (e.g., Bazzoffi and Gardin, 2011), from Greece (e.g., Koulouri and Giourga, 2007), from Spain (e.g., Bellin et al., 2009), Indonesia (Van Dijk, 2002), Thailand (Sang-Arun et al., 2006), and the Yemen Highlands (Pietsch and Mabit, 2012) have proven that despite terracing, soil erosion can be a serious problem.

Particularly, inadequate terrace design and mismanagement strongly affect the stability of bench terraces and favor soil erosion (e.g., Sang-Arun et al., 2006; Koulouri and Giourga, 2007; Lesschen et al., 2008; Bellin et al., 2009). Causes for this phenomenon are seen in a lack of local knowledge of adequate terracing (e.g., Esteve et al., 2004), in a lack of individual farmers' motivation and uncertainty regarding tenure (Williams, 1990; Deininger and Jin, 2006), in a shortage of labor and investments (Inbar and Llerena, 2000), a shift of production (Bellin et al., 2009; Bevan et al., 2012), and land shortage and fragmentation (Corbeels et al., 2000). Mostly, these causes interact with each other and are discussed to result from an agricultural abandonment (e.g., Koulouri and Giourga, 2007; Lesschen et al., 2008; El Atta and Aref, 2010) due to social, economic and/or political upheavals such as rural-urban migration (e.g., Aw-Hassan et al., 2000; Inbar and Llerena, 2000; Koulouri and Giourga, 2007).

According to Inbar and Llerena (2000) who studied erosional processes on bench terraces in Peru, the supporting terrace wall mainly determines the terrace stability. Typically, walls of bench terraces left to degrade exhibit bulges and upsetting by erosive action followed by more intense wall disorders such as breaches that further lead to complete collapses (Inbar and Llerena, 2000; Lasanta et al., 2001; Brancucci and Paliaga, 2006; Lesschen et al., 2008; Bellin et al., 2009). The natural geomorphic system will progressively annul the former balanced terraced system (Brancucci and Paliaga, 2006; Bazzoffi and Gardin, 2011). This will increase the slope length and slope gradient, followed by an acceleration of runoff (e.g., El Atta and Aref, 2010; Koulouri and Giourga, 2007). Consequently, the capability of a terrace to protect the soil against surface erosion by water is reduced, defined as terrace degradation by Bazzoffi and Gardin (2011).

By evaluating the potential of the terrace design to reduce soil erosion and applying flow traces, Bellin et al. (2009) proved that terraces that were not longer maintained do not longer retain water and promote an increased contribution of runoff from cropland to the drainage network. Within 50 years, the portion of runoff was observed to increase from 9% to 31%. According to Sidle et al. (2006) and Bazzoffi and Gardin (2011) poorly designed and maintained terraces represent significant sediment sources.

As an answer on the increasing interest on terraced landscapes, several studies within the European Cross Compliance Framework and the Interregional ALPTER project focused on varying conditions of terraces and their degradation (e.g., Comolli, 2005; Scaramellini and Varotto, 2008; Bazzoffi and Gardin, 2011). All studies have in common to especially account for the condition of the supporting walls of bench terraces and the terraced sloped instability, since the terrace' 'state of maintenance' (Bellin et al., 2009) strongly controls the soil erosion. However, by now, no standard on the assessment and evaluation of terrace degradation and its effects exists. Whereas Bellin et al. (2009) differentiate between intact or leaking terrace walls, Comolli (2005), Brancucci and Paliaga (2006), and Bazzoffi and Gardin (2011) apply a higher grade of differentiation for terraces in North Italy. By mapping different percentages of abandonment or degradation of terraces from 'conserved' to 'removed' (Bazzoffi and Gardin, 2011), respectively, 'well maintained' to 'completely collapsed' (Comolli, 2005), they classified terraces in terms of their condition.

While much is known about terrace degradation due to agricultural abandonment, until now no attention was paid to terrace degradation in areas experiencing agricultural intensification and rapid ecosystem changes. Since the reservoir of the Three Gorges Area (TGA) in China currently belongs to the most dynamic large-scale anthropogenic influenced regions in the world (e.g., Yang et al., 2002; Cui et al., 2011), rapid land use changes in this widely terraced landscape (Shi et al., 2012) are expected to likewise impact terracing.

1.2. The Three Gorges Area

Due to the river impoundment by the Three Gorges Dam (TGD), the TGA is largely characterized by resettlements, construction of new infrastructure, and new land reclamation for agricultural cultivation (Cui et al., 2011). Combined with the mountainous topography accounting for 90% of the TGA, abundant precipitation, highly erodible soils (Cui et al., 2011), and population pressure (Zhang, 2008), the land use changes occur in a region exhibiting a low environmental carrying capacity (Heggelund, 2006; Zhang, 2008) and the highest soil erosion rates in China (Zhou, 2008). Estimations on annual soil loss based on empirical modeling, remote sensing, and radionuclides inventory account for an average soil loss from 32.8 to 45 t ha^{-1} and a total amount of annual soil loss of 1.891×10^8 t mainly caused by water (Lu and Higgitt, 2000; Zhang, 2008; Wu et al., 2011). According to the Chinese Soil Erosion Rate Standard almost 77% of the total soil loss occurs in areas of high to extreme erosion grades (Wu et al., 2011).

Along with the soil erosion, manifold environmental and socio-economic threats occur such as reservoir siltation with threat to the long-term safe operation of the TGD (Shi et al., 2004; Zhang, 2008) and deterioration of the aquatic systems (Ponseti and López-Pujol, 2006). For instance, the farmland supply of suspended material is estimated to be 90% (Cui et al., 2011). Thus, discharge of sediment and associated contamination of adjacent waterbodies (e.g., Liu et al., 2003; Cui et al., 2011), are expected to further boost the ecological degradation in this strongly manufactured landscape (Zhang, 2008).

The reclamation of steep slopes, their destabilization due to artificial fluctuations of the reservoir's water level, and the increasing number of landslides (Ehret et al., 2010; Cui et al., 2011) still might accelerate the soil erosion potential. Zhang (2008) concerns an already serious soil erosion problem causing a latent crisis of the agricultural environment which can likely been aggravated by the conflict potential between relocates from the resettlements and agricultural land.

This is especially true against the background of soil erosion being strongly related to cultivated slopes (Lu and Higgitt, 2000;