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Invited review

Global synthesis of the classifications, distributions, benefits and issues of terracing

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ABSTRACT

For thousands of years, humans have created different types of terraces in different sloping conditions, meant to mitigate flood risks, reduce soil erosion and conserve water. These anthropogenic landscapes can be found in tropical and subtropical rainforests, deserts, and arid and semiarid mountains across the globe. Despite the long history, the roles of and the mechanisms by which terracing improves ecosystem services (ESs) remain poorly understood. Using literature synthesis and quantitative analysis, the worldwide types, distributions, major benefits and issues of terracing are presented in this review. A key terracing indicator, defined as the ratio of different ESs under terraced and non-terraced slopes (δ), was used to quantify the role of terracing in providing ESs. Our results indicated that ESs provided by terracing was generally positive because the mean values of δ were mostly greater than one. The most prominent role of terracing was found in erosion control (11.46 ± 2.34), followed by runoff reduction (2.60 ± 1.79), biomass accumulation (1.94 ± 0.59), soil water recharge (1.20 ± 0.23), and nutrient enhancement (1.20 ± 0.48). Terracing, to a lesser extent, could also enhance the survival rates of plant seedlings, promote ecosystem restoration, and increase crop yields. While slopes experiencing severe human disturbance (e.g., overgrazing and deforestation) can generally become more stable after terracing, negative effects of terracing may occur in poorly-designed or poorly-managed terraces. Among the reasons are the lack of environmental legislation, changes in traditional concepts and lifestyles of local people, as well as price decreases for agricultural products. All of these can accelerate terrace abandonment and degradation. In light of these findings, possible solutions regarding socio-economic changes and techniques to improve already degraded terraces are discussed.

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1. Introduction

Terraces are considered as one of the most evident anthropogenic imprints on the landscape, covering a considerable part of terrestrial landscapes (Krahtopoulou and Frederick, 2008; Tarolli et al., 2014). Generally, this human-created landscape is more ubiquitous on hillslopes and other mountainous regions, although it is used extensively across diverse landscapes such as in areas where severe drought, water erosion, mass movement and landslides from steep slopes threaten the security of land productivity, the local environment and human infrastructure (Lasanta et al., 2001). Terraced slopes even became the ideal sites for early human settlement and agricultural activities (Stanchi et al., 2012), with ancient agricultural terraces (e.g., in the central Negev highlands) serving as pronounced evidences of ancient human history, diverse cultures and civilizations (Pietsch and Mabit, 2012; Calderon et al., 2015).

Terracing, referred to as horizontal human-made spaces created to permit or facilitate cultivation on sloping terrains such as on hills and mountains (Petanidou et al., 2008), has been practiced as a key management strategy to minimize climate or human-induced disasters in those fragile landscapes (Chen et al., 2007; Andrew and James, 2011; Li et al., 2014). Since terraces reduce slope steepness by dividing them into short gentle sections (Morgan and Condon, 1986; Van Dijk and Bruijnzeel, 2004; Li et al., 2014), they strongly affect soil hydrology, vegetation growth and biogeochemical cycles (Moser et al., 2009). Terracing has been used to conserve water, alleviate flooding risks, reduce erosion, expand high-quality croplands and restore degraded habitats (Van Dijk and Bruijnzeel, 2004; Bruins, 2012). More recently, this practice has been found to improve other ecosystem services (ESs), such as carbon sequestration, food security as well as recreation (Ore and Bruins, 2012; Garcia-Franco et al., 2014).

Despite its long history, the fundamental roles and mechanisms of terracing on improving ESs and preventing land-degradation remain poorly understood (Frei et al., 2010; Li et al., 2014). At the same time, the specific size, appearance, choice of construction material (i.e., earth, stone or brick), age, land use/vegetation cover, and spatiotemporal distribution of terracing may differ across various ecosystems, resulting in the variability of ESs provided by terracing. In other words, the effects of terracing on ecosystems and human welfare can become very complex, particularly when different plant species, land uses, topographies, field treatments, and cultures are involved (Hill and Peart, 1998; He et al., 2009). Issues and problems regarding terracing (from design, construction, maintenance cost, to the actual outputs including ESs) also remain, highlighting the need for additional research. So far there has been no systematic synthesis regarding worldwide distribution of terracing and associated ESs with specific types of terracing. By developing a simple key indicator, utilizing data synthesis from the literature and quantitative analysis approaches, we summarize and discuss the multiple effects of terracing practices on ESs and human welfare. The major benefits of terracing to ESs are classified and examined, and problems regarding terracing are also discussed, highlighting the major directions for future efforts.

2. Data sources and analytical methods

2.1. Literature review and terrace mapping

In this study, three key words (i.e., land terracing, terracing, and terrace) were used to search the existing literature from two sources: Web of Science and Google Scholar. The latter served as a supplemental tool to elicit more information. We only recorded research articles that focused on man-made terraces while articles focusing on terraced landscapes formed by non-human forces (e.g., geological terraces) were removed from the database. Therefore, out of 437 articles found during our initial search, we used a final number of 300 publications to generate the geographical distribution of global terrace practice (Fig. 1). We specifically selected ancient terraces that appeared in the World Heritage List and some other historical terraces recorded in the literature to highlight their significance on human history and to distinguish them from modern terraces (Table 1).

2.2. Data extraction and indicator determination

Quantitative studies regarding each of our selected ecosystem services (ESs) associated with terracing were based on 300 selected publications. A key indicator (δ), defined as the ratio of different ESs under terraced and non-terraced slopes, was used to quantify terracing benefits. Non-terraced slopes were considered as controls, and from this point on, they will be referred to as “slopes”. A δ value of 1 (i.e., no difference between terraces and slopes) is used as the threshold to distinguish the impact of terracing. If the δ value is >1, terracing is considered to play a positive role. On the other hand, if the δ value is lower than 1, it is considered that terracing produces a negative impact. Scattered and frequency-distribution diagrams were then generated based on the values of δ for each ES. Similarly, the causes responsible for negative values were classified and plotted using bar chart and pie mapping methods based on the number of negative reports.

There were four major aspects of ESs that were characterized based on the aforementioned key indicator: (i) runoff reduction and water conservation parameters (e.g., runoff depth, runoff coefficient, soil moisture content, and water holding capacity), (ii) erosion and sediment yield (e.g., soil loss depth, erosion modulus, and sediment yield), (iii) soil nutrient variables (e.g., total N, total K, total P, available P, available K, NH_4, and organic matter), and (iv) carbon sequestration, biomass accumulation and agricultural production (e.g., plant survival rates, tree/crop height, DBH, crop yield, crop evapotranspiration, total plant dry matter, plant branch length, number of branches, canopy diameter, and aboveground or belowground biomass). While we also recorded soil physical parameters such as bulk density, pH, and porosity as proxies to soil health, we did not differentiate between different types of terraces because many of them play similar roles in providing ecosystem services. All of these data were classified according to each of the above-mentioned ESs and calculated using the following equations to examine the benefits of terracing:

$$\delta_{rr} = 1/\left[{}^{Rf_t}\!/_{Rf_s}\right], \quad (1)$$

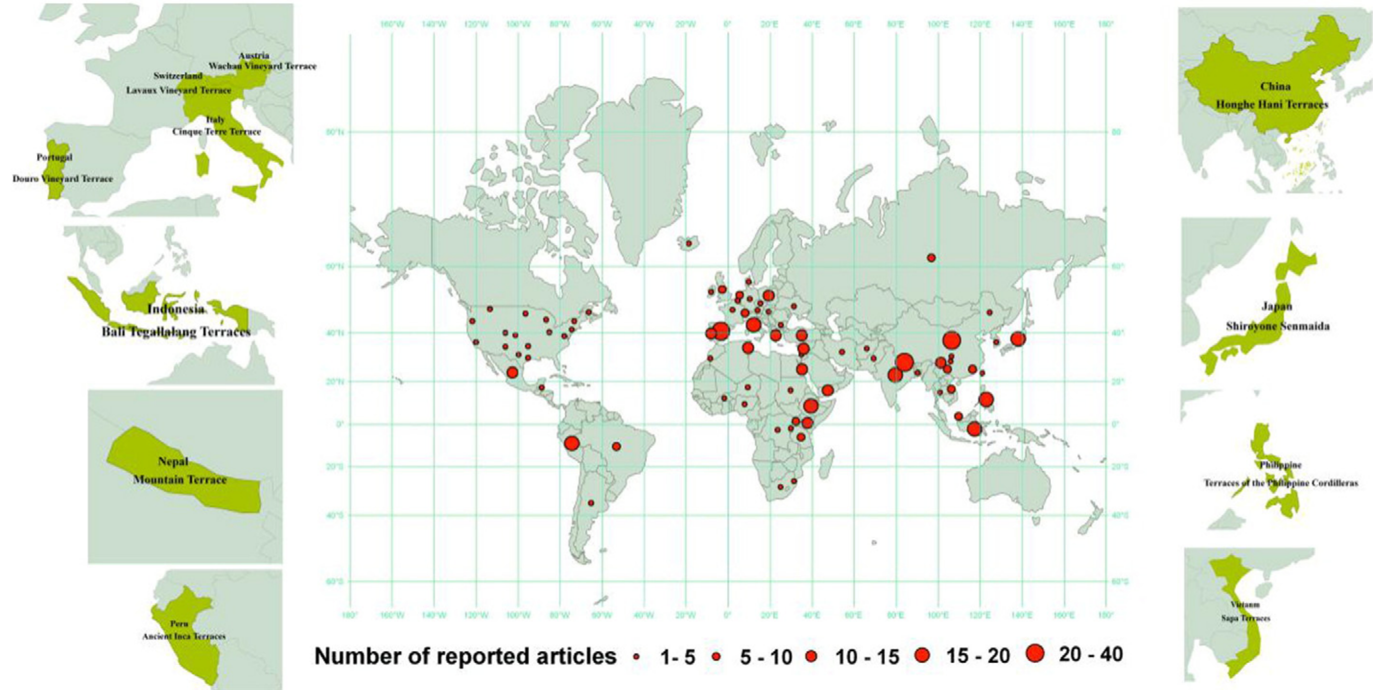

Fig. 1. Worldwide distribution of terracing. (Note: the most representative ancient terraces across the globe were especially extracted in both the left and right sides of the figure, based on the World Heritage List of UNESCO (United Nations Educational, Scientific and Cultural Organization) and GIAHS (Globally Important Agricultural Heritage Systems) as well as some other important historical terraces recorded in literature. They were used for distinguishing ancient terracing practices from modern terraces.)

where δ_{rr}, Rf_t, and Rf_s represent terracing efficiency on runoff reduction, runoff loss under terraces, and runoff loss under slopes, respectively.

$$\delta_{sw} = {}^{SM_t}/_{SM_s}, \tag{2}$$

where δ_{sw}, SM_t, and SM_S represent terracing efficiency on soil water recharge, soil moisture under terraces and soil moisture under slopes, respectively.

$$\delta_{se} = 1/\left[{}^{ER_t}/_{ER_s}\right], \tag{3}$$

where δ_{se}, ER_t, and ER_s represent terracing efficiency on erosion and soil loss control, erosion under terraces, and erosion under slopes, respectively.

$$\delta_{sn} = {}^{SN_t}/_{SN_s}, \tag{4}$$

where δ_{sn}, SN_t, and SN_s represent terracing efficiency on soil nutrients and land productivity, soil nutrients under terraces, and soil nutrients under slopes, respectively.

$$\delta_{bm} = {}^{BM_t}/_{BM_s}, \tag{5}$$

where δ_{bm}, BM_t, and BM_s represent terracing efficiency on biomass accumulation/crop yield, biomass under terraces, and biomass under slopes, respectively.

3. Results and discussion

3.1. The historical distribution of terracing

While the distribution of terraces varied across continents (Fig. 1, Table 1), most often terracing practices were found in regions where agricultural civilization firstly developed. The earliest practices of terracing were recorded in Palestine and Yemen about 5000 years ago (Barker et al., 2000; Abu Hammad and Børresen, 2006). They appeared almost at the same time as the rise of agricultural civilization, and then spread to the drier regions of the Mediterranean (Price and Nixon, 2005; Galletti et al., 2013). While massive terracing practices in the Mediterranean region mainly began from the late 14th century during the Renaissance period in the Middle Ages (Nicod, 1990), older terracing practices recorded in the Alpine Region, the Maya Lowlands, the Middle East and sub-Mediterranean areas of Europe, dated back to the Iron Age or even earlier (Dunning and Beach, 1994; Beach et al., 2002; Kuijt et al., 2007; Stanchi et al., 2012). In old England, a terrace was commonly called a "lynch" (lynchet), such as the ancient Lynch Mill (Clark et al., 1967). In Asia, paddy terracing was largely developed in the Yangtze River Basin, spreading later to Southeast Asia (e.g., Philippines, Indonesia, Thailand and Vietnam) more than 5000 years ago (Chang, 1976; Chen et al., 2013; Yuan et al., 2014). Some of these practices remain until now, for example, the Hani Terraces (Fig. 2c), which are listed as a key pilot of GIAHS (Global Important Agricultural Heritage Systems) and play a key role in soil and biodiversity conservation, education, recreation, and aesthetic services.

3.2. Multiple concepts of terracing classification

Our review indicated that terracing has been and is very diverse in terms of geographical distribution, type, and structure. There are no fixed standards and, as a consequence, terracing largely reflects its specific purpose, the builders' culture and experience, available labor, and economic and political condition. Because the major functions and final services of different terraces may be quite similar, terraces are often built without necessarily following the local climate and geomorphological or social conditions (Cots-Folch et al., 2006; Ramos et al., 2007a).

Different classifications of terracing thus exist, based on different viewpoints or interests (Fig. 2, Table 2). From the structure and appearance standpoint, terraced landscapes can be classified into wave-like terraces, slope-separated terraces, level-benches, level-ditches, zig terraces, sloping terraces, half-moon terraces (also named fish-scale pits) and broad-base terraces (Sharda et al., 2002, 2013; Liu et al., 2013; Fig.

Table 1
The ancient terraces in different countries of the world.

Terraces	Country	Area (hm^2)	Building time	Terrace type	Current condition	Date of inscription	Functions and services
Battir hill terraces	Palestine	349	5000 years ago	Stone terraces	Badly maintained	UNESCO World Heritage Site, 2014	Orchards
Ibb terraces	Yemen	250,000	5000 years ago	Dryland terraces	Partially abandoned	–	Land degradation control, coffee cultivation, tourism
Ouadi Qadisha terraces	Lebanon	95,000	2500 years ago	Stone walled bench terraces	Severely degradation	UNESCO World Heritage Site, 1998	Grain cultivation, reducing erosion and water flow, increasing productivity
Rice terraces of the Philippine Cordilleras	Philippine	10,880	2000 years ago	Rice terraces	Partially collapsed	UNESCO World Heritage Site, 1995 GIAHS, 2002	Water storage, rice cultivation, sightseeing, cultural education
Hani terraces	China	16,603	1300 years ago	Rice terraces	Well maintained	UNESCO World Heritage Site, 2013 GIAHS, 2010	Rice cultivation, biodiversity, soil and water conservation, sightseeing, historical education, ethnic cultural value
Ziquejie terrace	China	1333	2000 years ago	Rice terrace	Well maintained	–	Rice cultivation, water management, ethnic cultural value
Terraces of the Bahá'í Faith	Israel	540,000	8th to 10th century	Dryland terraces	Well maintained	UNESCO World Heritage Site, 2012	Tourism, runoff retention
Cinque terre terraces	Italy	4689	8th century	Stone walled terraces	Partially abandoned	UNESCO World Heritage Site, 1997	Viticulture, olive groves
Wachau vineyard terraces	Austria	18,387	9th century	Vineyard terraces	Well maintained	UNESCO World Heritage Site, 2000	Viticulture, sightseeing
Bali Tegallalang terraces	Indonesia	19,520	9th century	Rice terraces	Well maintained	UNESCO World Heritage Site, 2012	Coffee plantation, soil and water conservation
Lavaux vineyard terraces	Switzerland	898	11th century	Stone walled terraces	Well maintained	UNESCO World Heritage Site, 2007	Viticulture, sightseeing
Serra de Tramuntana terraces	Spain	30,745	13th century	Stone walled terraces	Partially abandoned	UNESCO World Heritage Site, 2011	Orchards, vegetable gardens, olive groves
Machu Picchu terraces	Peru	2,471,053	13th to 14th century	Stone walled terraces	Abandoned	UNESCO World Heritage Site, 1983; GIAHS, 2011	Potato cultivation, climate regulation, water management
Noto Peninsula terraces	Japan	186,600	14th to 16th century	Stone walled rice terraces	Partially abandoned	GIAHS, 2011	Water retention, landslide prevention, ecosystem conservation, scenic value
Al Jabal Al Akhdar Aflaj and terraced fields system	Oman	160,000	500 years ago	Irrigated terraces	Badly maintained	–	Food security, soil and water conservation, climate regulation, carbon sequestration
Gudeuljangnon rice terraces	South Korea	4195	16th century	Stone rice terraces	Well maintained	GIAHS, 2014	Soil and water conservation, enrich biodiversity
Sukur terraces	Nigeria	764.40	16th century	Dry stone terraces	Well maintained	UNESCO World Heritage Site, 1999	Soil and water conservation, cultural education
Konso terraces	Ethiopia	23,000	400 years ago	Stone walled terraces	Well maintained	UNESCO World Heritage Site, 2011	Prevent erosion, collect water
Sapa terraces	Vietnam	N/A	18th century	Rice terraces	Well maintained	–	Reduce runoff and soil erosion, tourism
Douro vineyard terraces	Portugal	24,600	18th century	Vineyard terraces	Well maintained	UNESCO World Heritage Site, 2001	Viticulture, tourism

Note: UNESCO and GIAHS refer to "United Nations Educational, Scientific and Cultural Organization" and "Globally Important Agricultural Heritage Systems", respectively.

3). Based on the differences in building materials, these terraces can be divided into soil ridge terraces (Fig. 2 d and e), stone dike terraces (Fig. 2f), grass ridge terraces and soil–rock mixed terraces (Abu Hammad et al., 2004). Terraces in the Mediterranean region and South America (e.g., Colombia, Ecuador, Peru and Chile), for example, have mostly been constructed using dry-stone walls (Petanidou et al., 2008; Tarolli et al., 2014). Similar materials for terracing have also been found in China's Yungui Plateau and Three-Gorge Regions (Chen et al., 2007; Li et al., 2014) while terraces in North America, Vietnam, Thailand and NW China are mostly built of soil. According to rainfall availability and climatic zones, terracing generally can be divided into dryland terraces (e.g., Fig. 2d, e, f) and paddy terraces (e.g., Fig. 2a, b, c). Terraces can also be divided into embankment and non-embankment terraces based on the presence or absence of the embankment. Based on the differences in historical value or cultural landscape, they can be divided into ancient terraces (e.g., Fig. 2c, Table 2) and modern terraces (Fig. 2e, f). Terraces can be further divided into agricultural terraces (Fig. 2a–d), afforestation terraces (e.g., Fig. 2e), orchard terraces, tea-garden terraces, mulberry terraces, and rubber terraces based on their purposes (Cots-Folch et al., 2006; Li et al., 2014), which vary greatly across various regions and continents. For instance, terraces in the Asian humid regions are mainly used for rice cultivation, while terraces in Europe are used for grapevines and olive trees. In both of the semi-arid regions (e.g., western Kansas and Nebraska) and humid regions (e.g., Indiana and Kentucky) of North America, parallel terraces, bench terraces, contour terraces and parallel-tile-outlet terraces were mostly used for corn, soybean and wheat cultivation (Wheaton and Monke, 1981). The ancient Incan terraces (known as *andenes*) in Peru, Bolivia, Chile, Argentina and the South American Andes were once used to cultivate potato and maize, but then suffered from total abandonment about 500 to 700 years ago (Posthumus and Stroosnijder, 2010). Based on the specific location, terraces can also be divided into hillslope terraces and channel terraces. While the majority of terraces were built on hillslopes, in North America (i.e., New Mexico, Colorado Plateau, and Arizona), dry-stone walls related to ancient agricultural terraces were found on channels (Sandor et al., 1990). Similarly in Negev, Israel, due to the extremely dry climate, the ancient agricultural terraces here have existed as thousands of stone-walls in ephemeral stream valleys, where deep

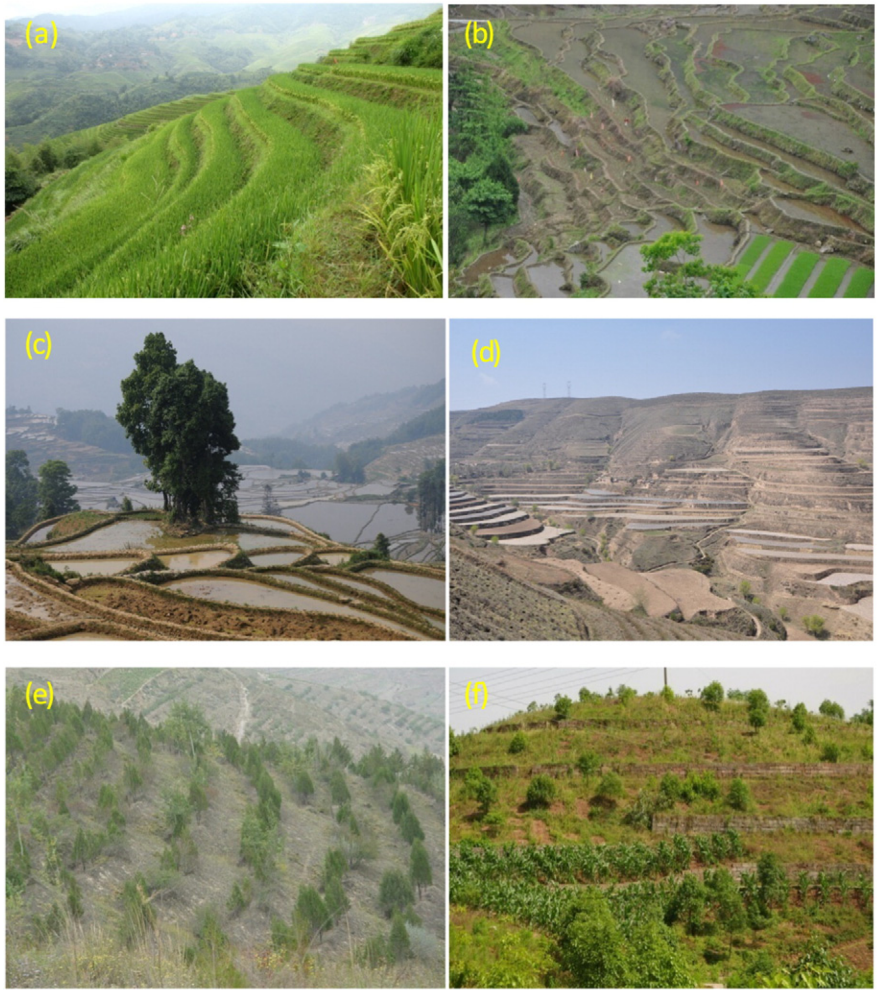

Fig. 2. Examples of diverse terracing types. (Note: terracing can be classified in different ways due to its diversity in practice. Taking China as an example: (a) paddy Longji bench terraces; (b) paddy terraces in Union County of Fujian; (c) Hani Heritage Terraced Landscape; (d) dryland broad-based terraces in the Loess Plateau for agricultural production and (e) zig terraces for ecosystem restoration with planted arborvitae; (f) sloping terraces in Chongqing: brick-wall construction for vegetation restoration in the upper hillslope and for crops in the lower position of hillslope.)

loess soil layers and abundant stored runoff-water occurred (Ore and Bruins, 2012).

3.3. Benefits of terracing

Incremental slope leveling is considered a normal adjunct to hillside farming, with agricultural practices and environmental constraints being the primary causes of terracing (Williams, 1990). Historically, terracing was regarded as a major adaptive strategy for land use in mountainous and hilly regions (Ramos et al., 2007b) and it performed multiple functions in improving environmental quality (Table 3), including the following ES provisions: (1) reduce runoff and conserve water, (2) control erosion and benefit soil conservation, (3) improve soil fertility and land productivity, (4) increase crop yield and ensure food security, (5) benefit vegetation restoration and enhance biodiversity, and (6) create aesthetic landscapes and enrich recreational options.

3.3.1. Terracing can boost the efficiency of runoff reduction and water conservation

Our results showed that the mean values of δ_{rr} and δ_{sm} were 2.6 and 1.2, respectively (Figs. 4 & 5; Table 3), indicating that the efficiency of terraced sites on reducing runoff and conserving soil water (e.g., soil moisture recharge) was greater than that of slopes. Out of the 105 cases extracted from 20 publications, 49 cases had δ_{rr} values between 1 and 2, 25 cases had δ_{rr} between 2 and 5, and 10 cases had $\delta_{rr} > 5$; only 21 cases were recorded having δ_{rr} values < 1 (Fig. 4). For δ_{sm}, only 31 cases had a mean value of 0.91 out of a total of 225 cases, while 189 cases had δ_{sm} values between 1 and 2, two cases had δ_{sm} between 2 and 3, and 3 cases had $\delta_{sm} > 5$ (Fig. 5).

There are two major reasons why terracing plays a key role in water conservation. First, terracing can directly reshape hillslope micro-topography and create many micro-watersheds across the whole slopes or within slope channels (Li et al., 2006; He et al., 2009; Courtwright and Findlay, 2011). These alterations can change the specific hydrological pathways and thus greatly increase the concentration, divergence, and efficiency of rainwater harvesting (Bergkamp, 1998; Appels et al., 2011; Adgo et al., 2013; Rockström and Falkenmark, 2015). Terracing in a sub-humid climate and a humid region, for example, was recorded to reduce runoff by 92.6% and 80%, respectively, compared to natural slopes (Sharda et al., 2002, 2013). Second, terracing can increase soil roughness and vertical surface relief, and decrease the connectivity of overland flow, both of which eventually alter raindrop penetration, and increase soil moisture and water holding capacity (Díaz et al., 2007; Thompson et al., 2010; Appels et al., 2011). Mean soil moisture could increase from 15.7% in the slopes to 29.4% in terraced slopes of the dryland of the Yun-Gui Plateau (Li et al., 2006). Indeed in one study, water holding capacity under terraces could reach 5.0–6.2 times higher than that of slopes (Hu et al., 2007).

Table 2
Worldwide research cases and major findings of terracing.

Study area		Methods/scale	Terracing type	Research purpose	Major findings and conclusions	References
Europe	Amalfi Coast, Italy	Data acquisition and analysis, questionnaire/regional scale	Stone-wall terraces	To analyze environmental factors which affect terrace stability	Fire, climate, vegetation dynamics, market demands and production costs govern the terrace system equilibrium. Landslides are more frequent where rainfall is high during winter.	Savo et al. (2014)*
	Murcia, Spain	Rainfall simulation/micro-plot	Bench terraces	To analyze factors contributing to piping process in abandoned terraces	The determinant factors that contribute to piping process were topographical characteristics, land-use, soil physiochemical properties and environmental conditions.	Díaz et al. (2007)
	Murcia, Spain	GIS/watershed	Stone-wall terraces	To assess the factors of terrace failure on abandoned fields	Terrace abandonment, steep slopes, loam texture, valley bottom position, and shrubs on terrace walls are factors that increase the risk of terrace failure. Terracing actually enhances erosion especially after abandonment	Lesschen et al. (2008)
	Granada and Malaga, SE Spain	Field experiment/plot	Dry-stone wall orchard terraces	To study the impact of soil erosion on the taluses of subtropical orchard terraces	Mean annual soil loss by erosion from the taluses of orchard terraces was 9.1 Mg ha^{-1} yr^{-1}, with a runoff of 100 mm $year^{-1}$ and a rain erosivity index (EI30) of 219.7 MJ mm ha^{-1} h^{-1}. The runoff coefficients ranged from 6 to 31%, depending on the intensity of rainfall events.	Zuazo et al. (2005)
	Catalonia, NE Spain	GIS/regional	Dry-stone wall terraces	To analyze land use change and terracing costs	Stimulated by received maximum EU subsidy, the transformation rate of modern terraces increased significantly from 7.5 ha yr^{-1} between 1986 and 1998 to 36.1 ha yr^{-1} in the 1998–2003 period. The costs of terracing represent 34% of the total costs for a new terraced vineyard.	Cots-Folch et al. (2006)*
	Sever do Vouga, Portugal	Plot experiment	Afforestation terraces	Effect of terracing on overland flow and associated sediment losses	Terracing increased runoff volumes and erosion rates, Eucalypt terraces produced 3 times more of sediments than Pine terraces.	Martins et al. (2013)
	Douro, Portugal	USLE, GIS/watershed	Stone dike vineyard terraces	Investigating land use conflicts	Water erosion is the major cause of hillside instability. Soil losses could be reduced by terracing management with covered crops.	Pacheco et al. (2014)
	Tuscany and Emilia Romagna, Italy	USLE/watershed	Dry-stone wall terraces	To evaluate the increasing degradation levels of stone wall terraces	The average soil loss ranged between 8640 and 23,040 t ha^{-1}, while it decreased to 260 and 537 t ha^{-1} after land leveling.	Bazzoffi et al. (2006)
	Lesvos Island, Greece	Field study/plot	Sloping terraces	Effects of slope gradient and terrace abandonment on sediment loss	When slope gradient reached 25%, soil erosion increased significantly after terrace abandonment due to changes in vegetation cover. When the slope gradient was 40% or higher, sediment loss remained stable after terrace abandonment	Koulouri and Giourga (2007)*
	Maltese islands	GIS/watershed	Stone dike terraces	To assess the possible erosion tracks	Cultivated terraces were protected by crops, farmer's care and rubble walls. Intensive soil erosion occurred once rubble walls collapsed.	Cyffka and Bock (2008)*
	Kislovodsk Depression, Russia	Field survey/slope	Ancient agricultural terraces	The origin of the terraces	Up to 60–70% of the sloping areas and inter fluvial plateaus at the heights of 900 to 1500 m a.s.l. were terraced during the Late Bronze–Early Iron ages (1200–600 BCE).	Borisov et al. (2012)*
	South Moravian, Czech Republic	Field survey/micro-habitat to landscape scale	Furrowed broad-base terraces	Key factors affecting the diversity of spiders in the terraces	Vineyard terraces created important refuges and replacement bio-topes through their heterogeneous mosaic of micro-habitats, thus increasing landscape biodiversity. Rare and endangered epigeic species were associated with terraces having sparse vegetation while rare epiphytic species were associated with terraces having dense vegetation.	Kosulic et al. (2014)
	Massif Central, France	GIS/watershed	Hedge-induced terraces	To quantify and explain the origin of the morphological and geo-chemical properties of terraces	The formation of the terraces was mainly due to soil redistribution through tillage. The stock of Ca, Mg, K, Fe and Cr mainly came from soil mechanical redistribution,while Mn and Co probably resulted from both mechanical and geochemical redistribution	Salvador-Blanes et al. (2006)
America	New Brunswick, Canada	Plot experiment	Terraces/grassed waterway systems	To quantify the benefits of terracing on soil and water conservation	Contour planting of potatoes associated with terracing will reduce runoff by as much as 150 mm of rainfall equivalent. Soil losses were reduced from 20 t/ha/yr to 1 t/ha/yr. Terracing also makes drainage basin hydrological characteristics less prone to ditch and stream flooding.	Chow et al. (1999)*
	New Brunswick, Canada	SWAT model/watershed	Grass ridge terraces	To estimate the efficacy of flow diversion terraces (FDT) on water and sediment yields	FDT reduced sediment and water yields by 4 t ha^{-1} yr^{-1} and 158 mm/yr on average, representing a total reduction of 56% and 20%, respectively.	Yang et al. (2009)*
	Kansas, America	SWAT model/watershed	Level benches	To test and validate the SWAT model on a terraced fields	Runoff and sediment were simulated with acceptable errors, predicting the multiple effects	Shao et al. (2013)

(continued on next page)

Table 2 (*continued*)

Study area		Methods/scale	Terracing type	Research purpose	Major findings and conclusions	References
					of terraces on runoff, sediment, nutrient transport, and groundwater recharge.	
	Nebraska, America	Plot experiment	Agricultural terraces	To evaluate the effects of agricultural terraces on the reestablishment of grasslands	It is advisable to remove terraces and redistribute terrace soil prior to seeding cultivated land to native grasses	Bragg and Stephens (1979)
	Illinois, America	Model simulation/watershed	Level benches	To calculate incident solar radiation falling on terraced and un-terraced fields in steep slope environments	The SOLARCAL model shows that a terraced hillslope receives a significantly different amount of direct solar radiation compared to an un-terraced hillslope. This difference is a function of latitude, slope aspect, slope angle, and seasonality.	Evans and Winterhalder (2000)
	North Dakota, America	Plot experiment	Level benches	The effect of terraces on moisture storage and spring wheat yields	Level bench increased moisture storage by 1.3 in. and wheat yields by 4.7 bushels per acre. The cost of construction may limit bench installation, and such cost may be as high as 15 cents per lineal foot for a bench 50 ft wide.	Haas et al. (1966)*
	Rio Grande do Sul, Brazil	State-space approach/watershed	Level benches	Effects of land leveling on spatial relationships of soil properties	Land leveling induced negative effects on soil quality since it decreased the water contents at field capacity and permanent wilting point, soil organic carbon, cation exchange capacity and soil bulk density.	Aquino et al. (2015)
	Minas Gerais State, Brazil	Plot experiment	Level and graded terraces	To carry out a comparative analysis between mixed terraces and level and graded terraces	Mixed terraces have a lower height than level terraces and a higher level than the graded terraces, resulting in direct consequences for the soil movement for the terrace construction.	de Oliveira et al. (2012)
	Southeast Brazil	Plot experiment	Level terraces	To evaluate the hydrological functioning of terraces under different management systems	The highest volumes and flux densities of water in the terrace canal occurred in the treatments with lowest soil cover. The increase of runoff also enhances the soil deposition in the terrace canal.	Castro et al. (2002)
	Tlaxcala, Mexico	Field measurement	Agricultural terraces	To examine the key roles of terrace in repairing degraded agricultural land	Methods of wildland restoration and agricultural restoration may differ in the degree to which the latter must plan for and facilitate a sustained human involvement	LaFevor (2014)*
	Mixteca Alta region, Mexico	Data intergradation/regional scale	Agricultural terraces	To document the history of terracing	Different stages in the history of terracing show parallels with the adaptive cycles of a resilient system	Rodriguez and Anderson (2013)*
	Tlaxcala, Mexico	Field survey and radiocarbon dating techniques/regional scale	Agricultural terraces	To date the construction of terraces	Stone-walled terraces were built in 1150 to 1520. Renewed reclamation has been undertaken since the Colonial period, eventually taking the form of sloping-field terraces with berms planted in maguey.	Borejsza et al. (2008)*
	Peruvian Andes	Plot experiment	Bench terraces	The short-term impact of bench terraces on soil properties and crop response	Bench terraces did not result in any short-term change in soil properties, but resulted in 20% higher biomass yields, due to a higher planting density.	Posthumus and Stroosnijder (2010)*
	Mantaro Valley, Peru	Model simulation/watershed	Level benches	To simulate the impact of C contracts on the adoption of terraces and agroforestrypractices	Terrace and agroforestry adoption and C sequestration have the potential to raise per capita incomes by up to 15% on farms with steeply sloped fields, and reduce poverty by as much as 9%.	Goodman-Elgar (2008)*
Asia	Negev highland, Israel	Plot experiments	Bench terraces	To determine terracing effect on vegetation productivity and soil quality	Terraces increase geodiversity and soil compaction, decrease vegetation production, adversely affects soil quality in a short term, but will improve soil quality and increase land productivity from a long-term run.	Stavi et al. (2015)
	Yura Peninsula, Japan	Regional multivariate analyses	Stone-walled terraces	To elucidate how land-use legacy and site conditions influence re-vegetation processes	Stone-walled terracing influences re-vegetation process of abandoned mountain slopes, fern species adapted to inhabiting the stone-wall structures, and common weed species of arable land occurred more frequently in former stonewalled terraced fields than in former un-walled terraced fields.	Tokuoka and Hashigoe (2015)*
	West Java, Indonesia	Modelling/plot and sub-watershed scales	Bench terraces	To analyze temporal dynamics of the hillside sediment budget	Runoff was 3.0–3.9% of rainfall and sediment yield was 11–30 t ha^{-1} yr^{-1}. Terrace Erosion and Sediment Transport (TEST) model overestimates runoff and underestimates sediment concentration.	Van Dijk et al. (2005)*
	Asir, Saudi Arabia	Plot experiments	Afforestation terraces	Effect of terraces on rainwater harvesting and *Juniperus procera* growth	Maintained terraces served as key means for rainwater harvesting, whereas abandonment of terraces resulted in increased soil loss, surface runoff, bulk density, and reduced infiltration rates. DBH, height, basal area, volume, number of trees, crown coverage and regeneration/ha of *J. procera* were significantly ($P < 0.001$) higher in maintained terraces compared with abandoned terraces.	El Atta and Aref (2010)*

Table 2 (*continued*)

Study area	Methods/scale	Terracing type	Research purpose	Major findings and conclusions	References
Loess Plateau, China	Field experiments/hillslope	Dryland terraces	The variation of soil moisture and crop production potentials in slope and terraces	Terraces tend to store much more water, promote more favorable interactions between water and fertilizer. Crop yields of 3-year-old terrace were 27% higher than that of the slopes >10°, and can increase by 52.78% in the following years.	Liu et al. (2011)
Three Georges Area, China	Field survey and spatial data mining/watershed	Bench terraces	To analyze the causes of different terrace conditions and terrace degradation	The sequence of degradation ranges from 'well maintained' (21%), 'fairly maintained' (44%), and 'partially collapsed' (23%) to 'completely collapsed' (11%) terraces. Anthropogenic effects such as the distance to settlements or to roads are major drivers for the spatial distribution of terrace conditions.	Schonbrodt-Stitt et al. (2013)
Honghe, China	Field surveys/regional scale	Paddy terraces	To find out the standard of eco-compensation for the rice-fish eco-agriculture system	The government should pay farmers 7462 yuan ha^{-1} yr^{-1} to meet their willingness, but the ecological benefit was only 7393 yuan ha^{-1} yr^{-1}. If rice price increases 1 yuan kg^{-1}, the government just has to pay farmers 4062 yuan ha^{-1} yr^{-1} and the surplus will be 3331 yuan ha^{-1} yr^{-1}.	Liu et al. (2014)*
Taiwan, China	Field experiment/plot	Flooded paddy terraces	To determine soil erosion in terraced paddy fields	Terraced paddy fields retained the highest percentages of clay, silt, and organic matter, meaning that topsoil was less susceptible to erosion under flooded conditions. Soil and water conservation in terraced paddy fields can be further increased by maintaining embankments more effectively and raising the height of bunds.	Chen et al. (2012)
Chungju dam, South Korea	SWAT model/watershed	Broad earthen embankment terraces	To evaluate which BMP scenarios are proper for present and future watershed conditions	Terracing was the best choice to reserve total P by 69.8%, and remained the highest efficiency for sediment and total N by 97.2% and 75.4%, respectively.	Park et al. (2014)
ChiangRai, Thailand	Rainfall simulation/hillslope	Bench terraces	To detect the impact of bench terracing on soil erosion	Erosion severity varies with the structures of bench terraces and the ground cover conditions, plots covered by weeds and residues had less runoff, soil and nutrient losses than bare terraces.	Sang-Arun et al. (2006)*
Ifugao, Philippines	GIS /regional	Rice terraces	To evaluate the extent of irrigated rice terraces (IRT) and the currently unproductive IRT	There are almost 11,000 ha of rice terraced fields, and the total damage is about 4.4% to 12.2%.	Bantayan et al. (2012)*
Ifugao, Philippines	Questionnaire and interview/watershed	Rice terraces	To examine the damaging extent of golden apple snail (GAS) in the terraces	Farmers ranked GAS as their main pest after earthworms and rats. Farmers perceived a yield loss of 41–50% caused by GAS.	Joshi et al. (2001)
Dehradun, India	Plot experiments	Bench terraces	To evaluate the function of a conservation bench terrace (CBT) system	The CBT system was effective in reducing runoff and soil loss by over 80% and 90% respectively, and was about 19.5% more productive in terms of maize-equivalent yields over the conventional system.	Sharda et al. (2002)*
Tam Duong, Vietnam	Field measurements/plot, sub-watershed, watershed	Paddy terraces	To measure erosion at field, small-watershed (SW), and main watershed (MW) scales	Runoff volume and sediment yield from the SW were 75% and 88% lower than that at plot scale respectively; runoff from MW was higher than that from SW, because of the rice fields with their temporary storage and releasing effects.	Mai et al. (2013)*
Malaysia	Field observation and samples analysis/hillslope	Bench terraces	To determine the quality of terraced-saprolite	The saprolite materials were unsuitable for oil palm cultivation. The root permeability, moisture availability, poor drainage, compaction, crust formation and runoff are the potential problems of saprolites that limit soil quality and crop productivity.	Hamdan et al. (2000)
Yemen Highlands	^{14}C and ^{137}C isotope/watershed	Dryland terraces	Ascertain the agricultural suitability and vulnerability to degradation of terracing systems	Terrace soils in the Yemen Highlands are threatened by soil erosion, but they are still agriculturally suitable, whatever they are ancient terraced soils, eroded or cultivated modern soils.	Pietsch and Mabit (2012)*
Dhading, Nepal	Field monitoring/plot	Outward sloping agricultural terraces	To analyze the efficacy of reduced tillage and crop pattern on soil conservation	Soil loss from agricultural terraced land (1.3 Mg ha^{-1} yr^{-1}) was higher than that in forested terraces (0.3 Mg ha^{-1} yr^{-1}), while reduced tillage can decrease runoff by 11% and soil loss by 28%.	Tiwari et al. (2009)
Jabal Akhdar, Oman	Tracer experiment (KBr)/hillslope	Dryland terraces	To examine how terrace structure and water management maintain agricultural productivity and soil quality	High quality irrigation water, the elaborately built soil structure of the terraces, a system of water distribution designed to match crop needs during their different growth stages and adequate drainage are the main factors explaining the lack of salinization in ancient mountain oases of Oman.	Luedeling et al. (2005)*
Petra, Jordan	Radiocarbon dating techniques/hillslope	Agricultural terraces	To determine the phases of the construction, use and	Runoff terrace systems in the Petra region started around the beginning of the Common Era, while	Beckers et al. (2013)*

(continued on next page)

Table 2 (*continued*)

Study area		Methods/scale	Terracing type	Research purpose	Major findings and conclusions	References
				abandonment of the terraces	construction, use and maintenance lasted at least until 800 CE.	
	Palestine	Field experiment and questionnaire/watershed	Stonewall terraces	To study the socioeconomic impacts of soil erosion on local farmers and their adoption of terracing	Those areas with terracing practices had 3.5–6 times higher of net profits than the areas without terracing. Farmers' incentives and willingness to adopt terraces were highly affected by the perceptions, land ownership, and geomorphology.	Abu Hammad and Børresen (2006)
	The Gareh Bygone Plain, Iran	Modelling/watershed	Level ditches	To analyze groundwater recharge and the increased crop transpiration on terraces	Groundwater recharge on the terrace increased on average by four-fold. In a dry year, 27% of the infiltrated rain and floodwater percolates on average to the aquifer and the recharge increases up to 69% in a humid year. Without ditches, the transpiration rate of crops and biomass production were seriously limited.	Raes et al. (2008)
	Guilan, Iran	Samples analysis/slope	Level benches, paddy terraces	To evaluate the impacts of land leveling on soil properties	Compared to traditional sites, land leveling had negative effects on soil properties: increased soil bulk density by about 20%, and reduced the number and species diversity of bacteria, fungi, actinomycetes, and nematodes in the soils.	Sharifi et al. (2014)
Africa	Amrich jessr, Tunisia	Rainfall simulation/micro-catchment	Dryland terraces	To examine the impact of terraces on water availability for crop production	The ratio "impluvium area/terrace area" (CCR) should be at least 7.4 in order to provide sufficient water for olive cultivation, taking into account an average annual precipitation of 235 mm.	Schiettecatte et al. (2005)
	Lushoto, Tanzania	Plot experiment	Bench terraces	Impact of Sustainable Land Management (SLM) measures on soil degradation and crop productivity	SLM stabilized slope and reduced soil losses by erosion. The use of high amounts of farmyard manure (>6.0 ton ha^{-1} yr^{-1}) on terraces resulted in an up to 4 times and 7 times higher yields of maize and beans, respectively.	Wickama et al. (2014)
	Taroudannt, Morocco	Rainfall simulation/plot	Bench terraces	The influence of land leveling on infiltration rates	Infiltration rates were very low on terraces due to the soils are sealed by crusting.	Peter and Ries (2013)
	Wello, Ethiopia	Plot experiment	Stone wall Bench terraces	The role of farmland terracing in maintaining soil fertility	Farmland terracing contributes greatly to the reduction of soil erosion and nutrient loss, reduced fertility gradient between erosion and deposition zone across the terrain.	Shimeles et al. (2012)
	Tigray, Ethiopia	Plot experiment	Stone wall terraces, bench terraces	To evaluate the effectiveness of soil conservation measures	After terracing, sediment yield was reduced from 14.3 t ha^{-1} yr^{-1} to 9 t ha^{-1} yr^{-1}, and the deposition of sediment increased from 5.8 t ha^{-1} yr^{-1} to 7.1 t ha^{-1} yr^{-1}.	Nyssen et al. (2009)
	Amhara, Ethiopia	Data collection, field observation and questionnaire/watershed	Stone wall terraces	To quantify terraces and other soil conservation initiatives on crop productivity and profitability returns	In terraces, the average yields of teff, barley and maize were 0.95 t ha^{-1} (control 0.49), 1.86 t ha^{-1} (control 0.61), and 1.73 t ha^{-1} (control 0.77), respectively. The net benefit was significantly higher on terraces, recording US$ 20.9 (US$ − 112 control) for teff, US$ 185 (US$ − 41 control) for barley and US$ − 34.5 (US$ − 101 control) ha^{-1} yr^{-1} for maize, respectively.	Adgo et al. (2013)
	Buberuka, Rwanda	Plot experiment	Hedge-induced terraces	Effect of soil erosion on the soil fertility gradient and crop yields on the slow-forming terraces	Grass strips alone or combined with infiltration ditches reduced soil loss by 43% and 57%, respectively. The soil in the lower parts of the terraces showed 57% more organic carbon content and 31% more available P than the soil in the upper terraces. Potato and maize yields were 60% greater on the lower parts than on the upper terraces.	Kagabo et al. (2013)
	Machakos, Kenya	Plot experiment	Bench terraces	Offer an approach to the design of bench terraces	Terrace banks should be raised periodically to maintain adequate storage capacity and the method will be the most effective where slopes are <15%.	Thomas et al. (1980)

* Note: the cited literature with an asterisk (*) represents ancient terraces, while those without refer to modern terrace cases.

3.3.2. Terracing can help to control erosion and benefit soil conservation

Our results suggested that terracing can play a positive role in minimizing erosion and soil loss (Table 3) as indicated by the number of studies with δ_{se} values >1 (Fig. 6). The mean efficacy of terracing in controlling erosion was 11.46 times higher than that of the control. Out of the 154 available cases drawn from 26 research articles, 79 cases had δ_{se} values between 1 and 6, 23 cases had δ_{se} between 6 and 10, 24 cases had δ_{se} between 10 and 20, and 16 cases had δ_{se} >20. In contrast, terraces failed to reduce erosion and soil loss in only 13 cases, with an average δ_{se} value of 0.79 (Fig. 6). Our results were thus in line with many other studies stressing the benefits of terracing on soil conservation (Nyssen et al., 2004; Hu et al., 2007; Hallema and Moussa, 2014; Zhang and Li, 2014). An appreciable erosion reduction could be achieved if terraces covered over 40% of the total hillslope (et al. et al., 2008). Other studies even reported that terracing could reduce over 90% of the total soil loss (He et al., 2009; Zhang et al., 2010). Studies in Thailand and the Czech Republic indicated that terracing could markedly increase soil conservation provided that weed cover and furrow management were also available (Sang-Arun et al., 2006; Dumbrovsky et al., 2014). Montgomery (2007) found that rice terracing systems produced

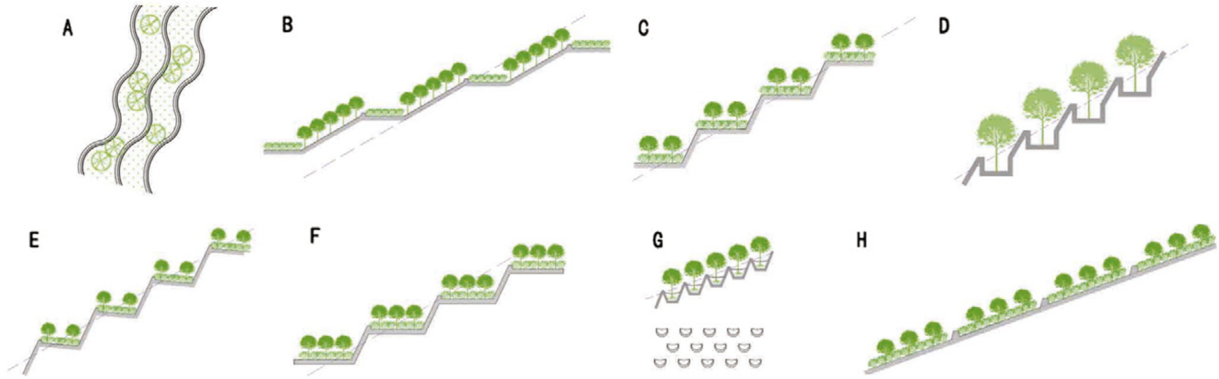

Fig. 3. Some typical terracing types based on the differences in structure and appearance. (Note: A: wave-like terraces; B: slope separated terraces; C: level benches/level terraces without embankments; D: level ditches; E: zig terraces; F: broad-based terraces with embankments; G: half-moon terraces/fish-scale pits; H: natural slope).

very low erosion rates (<10^{-4} to 0.01 mm/yr, close to geological erosion rates), while other agricultural practices (e.g., conventional tillage) produced far higher erosion rates (0.1 to >10 mm/yr), inducing unsustainable consequences on soil resources.

The reasons why terracing can control erosion are straightforward. First, terracing can markedly weaken rainfall–runoff erosivity (Chen et al., 2012) by reducing the velocity and total amount of overland flow (Section 3.3.1). Second, terracing can conserve abundant rainwater and increase soil moisture availability as well as nutrients and land productivity (which will be discussed in the next section), benefiting plant growth and increasing canopy coverage. Increasing biomass and surface cover significantly decrease raindrop energy, creating a positive feedback by reducing splash, rill, and inter-rill erosion (Zhang and Cao, 2008). Third, terracing often has specific measures (e.g., ridges or embankments), which contributes greatly to soil conservation. Terraces with embankments mainly generated tillage erosion (accounting for 65%–71% of the total erosion), with a minor degree of water erosion (Zhang and Li, 2014). In contrast, terracing without embankments in tilled soils generated both severe tillage erosion and water erosion, inducing more substantial soil loss. In the dryland loess area of China, for example, terraces with ridges could conserve all of the runoff and sediment, while terraces without ridges only conserved 82% overland flow and 95% sediment, respectively (Jiao and Wang, 1999).

3.3.3. Terracing can improve soil fertility and land productivity

Our results showed that in most cases, terracing could improve soil nutrient flux, although a few negative reports were also found (i.e., 18 out of 108 cases) (Fig. 7). The remaining 89 cases had δ_{sn} values between 1 and 2, and two cases had δ_{sn} between 2 and 3, with mean δ_{sn} values of 1.23 and 2.47, respectively (Table 3 and Fig. 7). As most nutrients are dissolved in water or attached to soil particles, terracing can directly improve soil nutrient status by minimizing water erosion, particularly when barren slope practice is coupled with irrigation and fertilizer (Ramos et al., 2007a, 2007b; Wen et al., 2009; Shimeles et al., 2012). Compared with barren slopes, available P/K, total N, and soil organic matter in the first 0–60 cm soil layers under level ditches, zig terraces and half-moon terraces increased by up to 30%, 28.1% and 41.7%, respectively (Hu et al., 2007; Zhang and Cao, 2008). Terracing with supplemental treatments (e.g., terraced orchards with grass cover and contour hedgerows), rather than sloping orchards, could markedly improve hydraulic conductivity, aggregate soil stability, soil organic matter and available N, P, and K, while decreasing soil bulk density (Xu et al., 2012). With fertilizer and plant litter inputs and root recycling, long-

Table 3
Descriptive δ features of terracing by collected case studies.

δ	Range	Minimum	Maximum	Sum	Mean	Variance	C.V.	N
δ_{rr}	45.25	0.02	45.27	273.16	2.60	21.68	1.79	105
δ_{sm}	5.52	0.70	6.22	269.34	1.20	0.33	0.48	225
δ_{se}	275.86	0.14	276	1764.17	11.46	719.71	2.34	154
δ_{sn}	1.70	0.80	2.50	129.81	1.20	0.08	0.23	108
δ_{bm}	6.15	0.69	6.83	147.44	1.94	719.71	0.59	76

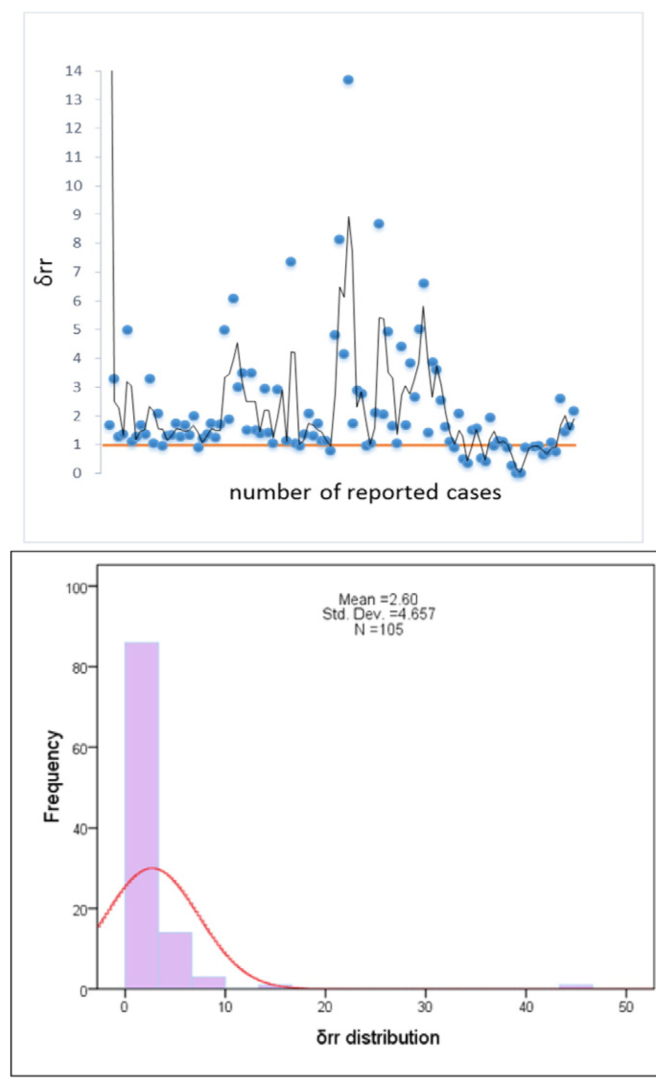

Fig. 4. The terracing efficiency on runoff reduction.

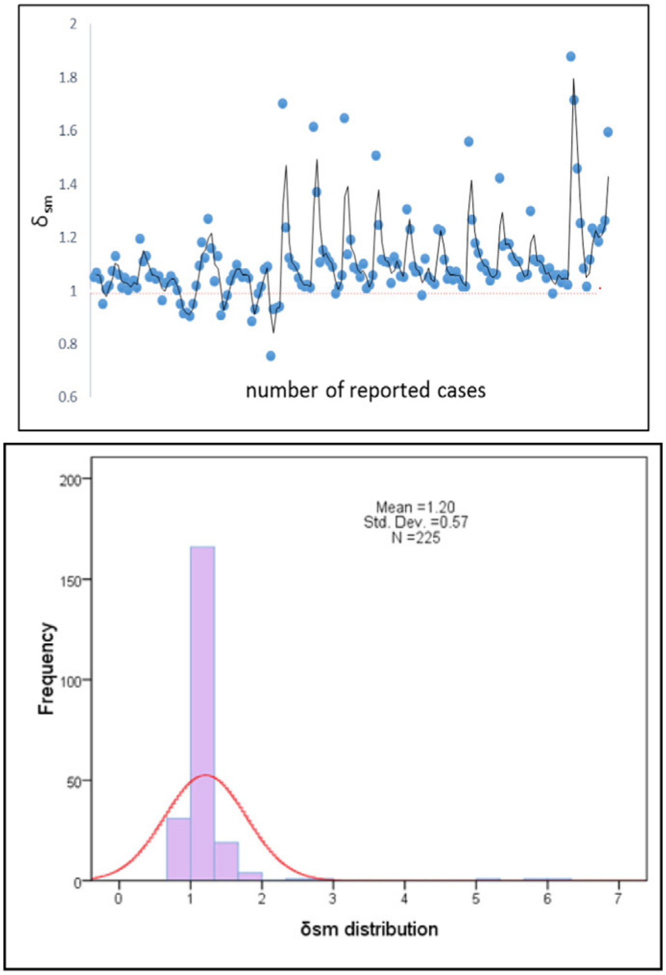

Fig. 5. The terracing efficiency on soil water recharge.

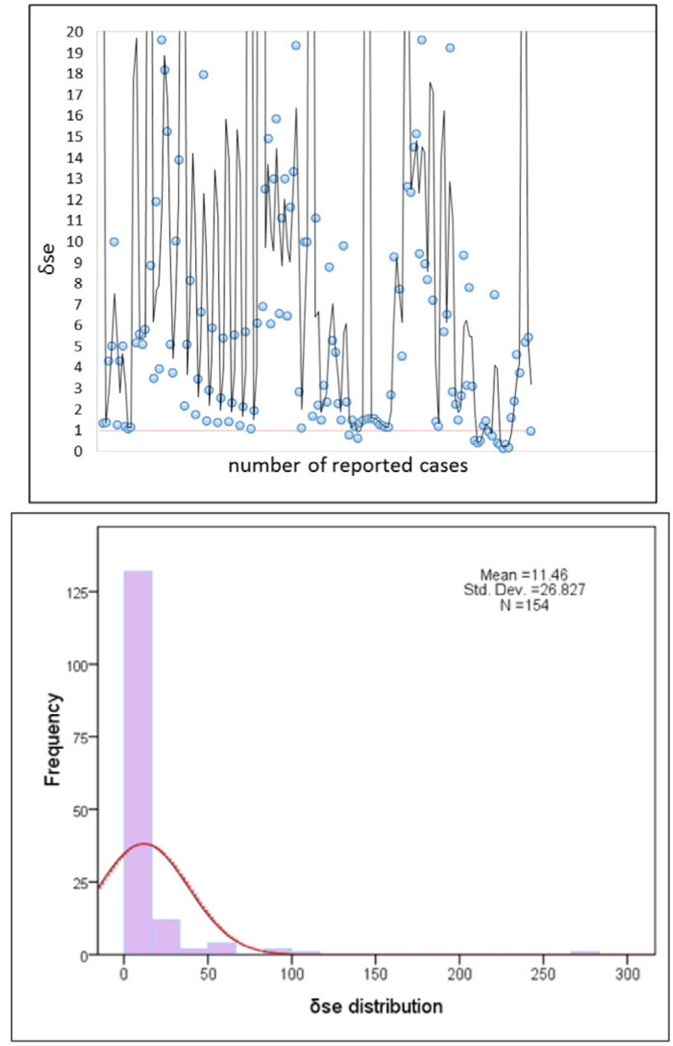

Fig. 6. The terracing efficiency on erosion control and soil conservation.

term cultivation and field managements from ancient terraces were found to accelerate soil genesis and accumulate more nutrients (Homburg and Sandor, 2011).

3.3.4. Terracing can increase crop yield and ensure food security

Terrace farming has long been considered an ancient indigenous model to ensure food security (Wheaton and Monke, 1981; Williams, 1990). It can increase crop yield and help to fight famine, particularly when water scarcity and soil erosion become the main concerns in many mountainous regions (Rockström and Falkenmark, 2015). Terracing can mitigate drought by facilitating soil moisture conservation (Fig. 5) and accumulating nutrients for crops (Fig. 7), thus increasing their production potential (Fig. 8). A more favorable interaction between water and fertilizer also can occur with terracing since soil water retention improved under terracing (Liu et al., 2011). Average crop yields on terraced teff (*Eragros ticabyssinica* L.), barley (*Hordeum vulgare* L.) and maize (*Zea mays* L.) in China and Palestinian fields were at least two-times greater than that on slopes (Liu et al., 2011; Abu Hammad and Børresen, 2006).

Compared with slopes, the net benefits of crop yields on terraced fields were also greater (Adgo et al., 2013). The yields of maize and wheat under terraces could increase 3–4 times and 6–7 times than when grown on slopes, respectively, under same input costs (Wickama et al., 2014; Abu Hammad and Børresen, 2006). In Peru, 2 to 4-year old bench terraces resulted in 20% greater yields than adjacent sloping fields (Posthumus and Stroosnijder, 2010), potentially increasing per capita incomes by up to 15% and reducing poverty by 9% (Antle et al., 2007). Cultivated bench terrace systems, rather than conventional systems (i.e., sloping cultivation), were more effective in improving land productivity by over 19% in terms of maize-equivalent yields (Sharda et al., 2002). In Africa, terracing combined with other conservation means (e.g., grass strips) has been implemented extensively to control land degradation and improve crop productivity (Adgo et al., 2013).

3.3.5. Terracing can benefit vegetation restoration and enhance biodiversity

In many degraded or water-limited ecosystems, the success of an afforestation or reforestation program will be difficult to achieve without other vital measures because of poor existing site conditions and a harsh climate (Wang et al., 2011; Groninger, 2012). Terracing, as an additional measure or approach, can play a key role in re-constructing and improving habitats, thus benefiting ecosystem restoration and enhancing biodiversity (Wei et al., 2012; Armitage et al., 2014). Several points help to understand the roles of terracing in improving vegetation survival. First, terracing can decrease the mortality of plant seedlings, particularly in regions where rainfall is scarce. In Northern China, for example, the survival values for locust trees (*Robinia pseudoacacia* L.) were recorded at 89.5%, 81.3%, and 75.6% in broad-base terraces, level ditches, and half-moon terraces, respectively, compared to only 34.7% on slopes (Hu et al., 2007; Zhu and Fang, 2009). Second, plant growth can be improved by terracing as water and nutrients become more available. Compared to slopes, mean stem diameter, branch length, branch number and leaf

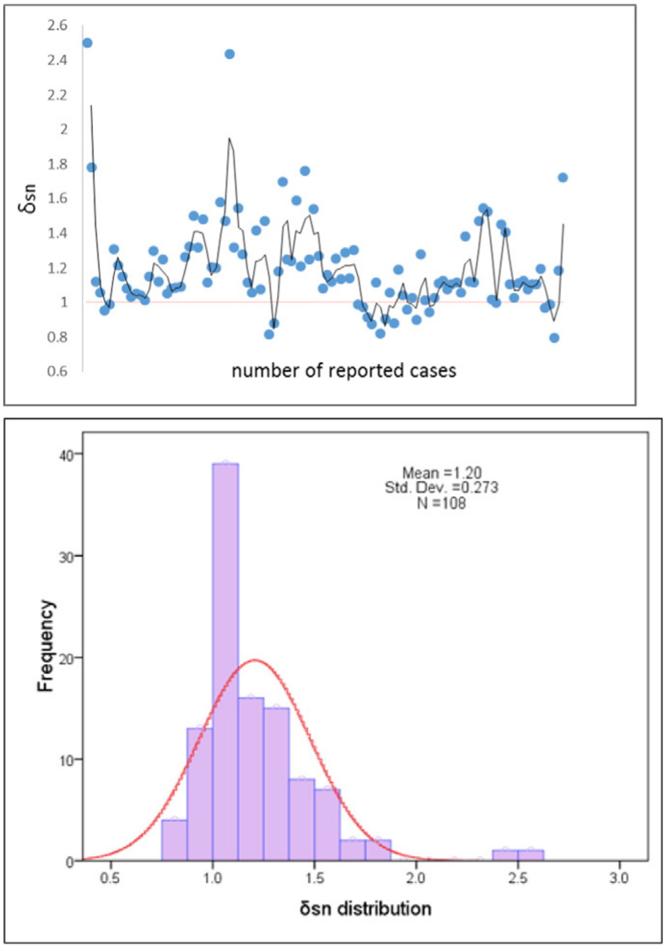

Fig. 7. The terracing efficiency on soil nutrients and land productivity.

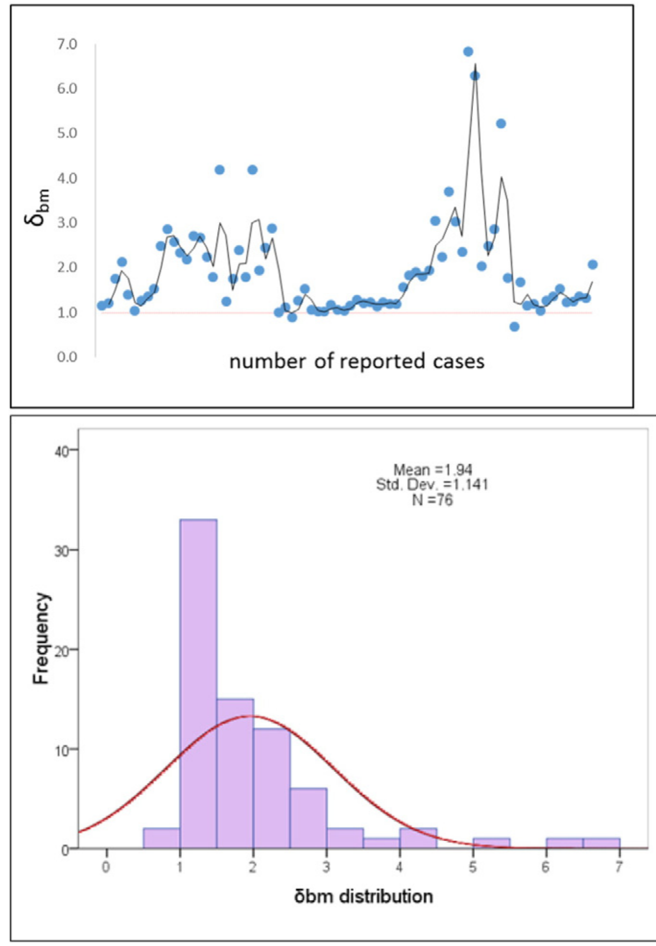

Fig. 8. The terracing efficiency on crop yields and biomass accumulation.

yields per plant of mulberry trees (*Fructus mori*) grown on zig terraces versus on slopes improved by 120%, 125%, 175% and 240%, respectively (Zhang and Cao, 2008). Compared to controlled sites, terraced fields had greater plant growth through rainwater interception and site improvements in Spain, China, and Afghanistan (Yang and Ma, 2004; Zhao and Cai, 2012; Shi, 2013; Garcia-Franco et al., 2014). Third, terracing may help to increase the diversity of plant species by improving the growing conditions for different species. In Japan, the diversity of weed species in stone-walled terraces was recorded to be higher than that in sloping forests (Tokuoka and Hashigoe, 2015).

3.3.6. Terracing creates aesthetic landscapes and enriches recreational options

Extensive terracing projects have markedly re-shaped landscapes, increasing their geo-diversity (Hobbs et al., 2014) and attracting thousands of visitors each year. Many terraces were even identified as "cultural landscape" heritages, expressing harmony between humans and the environment (UNESCO, 2008). Cultural landscapes, defined as "distinctive geographical areas or unique properties that represent the combined work of nature and of man" by the World Heritage Committee, play crucial roles in aesthetic appreciation, recreation and spiritual enrichment (UNESCO, 2008; Fig. 1; Table 1). There are over tens of famous terraced landscapes in China and many other countries chosen by public appraisals (Table 1; Hill and Peart, 1998; Lu and Stocking, 2000; Sun et al., 2013), which are highly praised as productive, harmonious, clean, and sustainable landscapes (Paoletti, 1999). Some of them (e.g., the terraced agricultural landscape created by Hani ethnic groups) have even been declared as an UNESCO World Heritage site. All these terraced landscapes contribute ecosystem services including cultural and spiritual values (UNESCO, 2008).

3.4. Issues of terracing: facing the challenges

Although the majority of collected terracing cases resulted in positive outcomes, there were negative cases (Fig. 9), partly due to the diversity of terracing types and histories, socioeconomic factors,

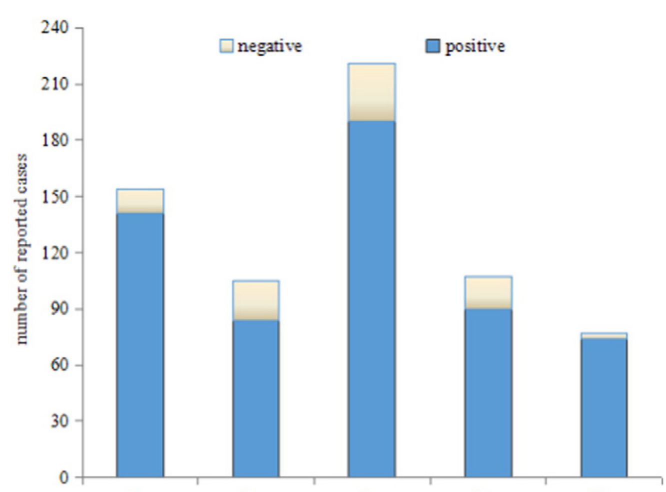

Fig. 9. Number of reports on the negative and positive effects of terracing.

techniques and knowledge levels, personal concepts and ideas as well as interactions of these factors. Our analysis from 60 negative reports on terracing suggested that there were at least four major reasons contributing to terrace failures in providing ESs (Posthumus and de Graaff, 2005; Sang-Arun et al., 2006; Tarolli et al., 2014; Fig. 10) and these were (1) terrace abandonment, (2) inappropriate management of terraces, (3) lack of appropriate regulations regarding the design of terraces, and (4) the insufficient transfer of knowledge regarding terrace construction.

3.4.1. Terrace abandonment

Based on our literature search and analysis, one of the key issues associated with terracing is their abandonment, accounting for about 49% of terrace failures (Fig. 10). Such abandonments generally equal to a total lack of maintenance, which in the long run can accelerate the formation of existed rills, interrills, gullies, gravitational erosion, piping and landslides on marginal slopes (Lasanta et al., 2001; Koulouri and Giourga, 2007; Garcia-Ruiz et al., 2013). Without adequate maintenance, various natural or other human-generated forces will gradually damage the structure and strength of terrace walls and risers, leading to a complete terrace failure. In Northern China, at least 40% of the Dazhai Terraces constructed in the late 1960s were damaged due to long-term degradation and poor management (Peng and Zhang, 2005). In the Mediterranean regions, over 50% of abandoned terraces were vulnerable to gully erosion and landslides, causing collapse of the dry-stone terrace walls (Lesschen et al., 2008; Bellin et al., 2009). Once collapsed, the reconstruction costs will be very high, which exacerbates the status of terracing and eventually leads to more severe land degradation.

There are multiple drivers of terrace abandonments. One of the most common reasons is the absence of labor and a rural population where those terraces exist. Poverty as well as changes in the traditional values and lifestyle of rural communities (Posthumus and de Graaff, 2005) result in the majority of young residents leaving their own land and migrating to big cities where economic and work conditions are perceived superior (Lasanta et al., 2001; Tarolli et al., 2014), leaving behind old farmers (Garcia-Ruiz et al., 2013; Qiu et al., 2014). Meanwhile, slumps in agriculture prices and high maintenance costs reduce the economic returns of terracing (Antle et al., 2007; Qiu et al., 2014). As terracing costs increased with increasing slope gradients (Table 4), terrace profitability decreased faster than once believed by farmers and stakeholders as indicated by a cost–benefit analysis from 11 cases in Peru (Posthumus and de Graaff, 2005; Bizoza and de Graaff, 2012). Limited accessibility (e.g., poor road condition, steep topography and remote marginal areas) of some terraces also contributed to the large-scale abandonment of old terraced olive orchards in Europe, inducing a productivity decline and thus economic losses (Duarte et al., 2008).

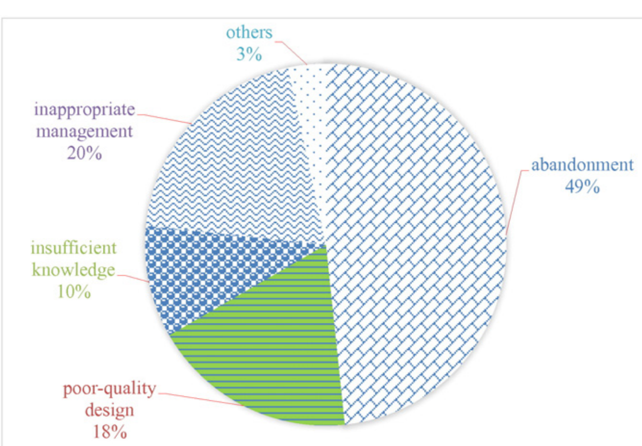

Fig. 10. Major reasons responsible for the negative effects of terracing.

Table 4
Example of terracing costs.
(Based on Yang et al. (2014)).

OTSG (°)	TTW (m)	Earthwork (m^3/ha)	Terracing costs (US$/ha) MC	AC	SEC	Total
5	14	1613	1209	387	322	1918
10	10	2454	1491	483	475	2450
15	8	3170	1773	580	629	2981
20	6	3456	2055	677	782	3513
25	4	3191	2337	774	935	4045

Note: OTSG, TTW, TBH, MC, AC and SEC refer to original terrain slope gradient, terrace trend width, the economic cost by mechanization, economic cost by manpower and labor, and socioeconomic cost, respectively.

3.4.2. The inappropriate management of terraces

Inappropriate terrace management was the second major reason of terrace failures, contributing to about 20% of the reported terrace failures (Fig. 10). In upland Java, there was about 2.8-times greater runoff from the riser than from the terrace beds (Purwanto and Bruijnzeel, 1998; Van Dijk and Bruijnzeel, 2004). Better management should therefore focus on the more fragile and sensitive parts of the terraces (e.g., risers and bunds) as the intensity of erosion on terrace risers is often greater than that on terrace beds. Additional treatments such as mulching and vegetation cover are often necessary to protect the risers and bunds as degraded earth bunds and barren risers often became significant sediment sources (e.g., in the Mediterranean regions) (Bellin et al., 2009). As another example, stone terraces in Ethiopia that were not protected by effective vegetation cover led to widespread land degradation and water erosion (Taddese, 2001).

3.4.3. The lack of appropriate regulations regarding the design of terraces

Our analysis suggested that poor-quality terracing design ranked third (18%) among the reasons of terrace failures (Fig. 10). Evidence indicates that the ratio between riser gradient and height is important in determining the strength and durability of a terrace (Díaz et al., 2007). Yet many terraces (with some exceptions such as the one in the Negev highland; Ore and Bruins, 2012) did not take advantage of this knowledge, inducing unstable terraced slopes. So far, subjective factors (e.g., the ease to run agricultural machinery, field size, bund height, and the locations of outlet within the bund) largely determined terrace structure (Chen et al., 2014), making some terraces prone to severe failures (Ramos and Porta, 1997). Local farmers or their contractors often randomly determine the height and outlet location of paddy terraces in many Asian countries (Chen et al., 2014). The absence of environmental legislation on terracing (Cots-Folch et al., 2006) further exacerbates the risks of terrace failure, even for modern terraces. Poorly-structured terraces of the Priorat vineyards in Spain, for example, was recorded to induce severe landslides affected by only a single rainstorm, causing substantial damage to plants and drainage systems (Ramos et al., 2007b). Stone terraces in Guangxi of China were also developed with a much higher riser than those built from soils, trapping thick sediments and raising the risks of gravitational erosion and slope failure (McConchie and Ma, 2002).

3.4.4. The insufficient transfer of knowledge regarding terrace construction

Currently, detailed knowledge and skills on how to better protect the existing terraces or on how to develop well-designed terraces are still lacking, particularly at the farmer-level. These may include but is not limited to the lack of knowledge transfer from academia and policymakers to farmers. When knowledge is not transferred or is poorly transferred, misunderstandings are created. When bench terraces needed to be covered by weed to reduce erosion, the majority of farmers (over 70%) in Northern Thailand had no willingness to grow weeds in their farmlands due to concern about potential nutrient competition (Sang-Arun et al., 2006). Yet rill erosion, which could develop into gullies running from the upper to the lower terraces, was very common on bare bench terraces in this region (Sang-Arun et al., 2006).

Other factors, such as the specific land use and external field choices, may also add to the complexity of terracing knowledge. For example, erosion rates declined sharply from 4.15 ton ha^{-1} yr^{-1} to 0.77 ton ha^{-1} yr^{-1} when land use in the same terraced sites was transformed from green manure into rice (Chen et al., 2012). Adding trenches in Indian paddy terraces could increase soil moisture and productivity by 58%–64% (Kumar et al., 2014). The cutting sections of new terraces reduce crop yields as a result of the removal of fertile soil and the compaction of the remaining soil. Understanding these outcomes, by the appropriate transfer of knowledge, to farmers may assist them in taking measures (e.g., soil backfill and loosening) to avoid unnecessary economic losses (Liu et al., 2008; de Blécourt et al., 2014). One particularly effective way to transfer knowledge is to use one farmer, who already is using the transferred knowledge, to demonstrate the approach and its advantages to other nearby farmers.

4. Concluding remarks and suggestions

Our global synthesis suggested that diverse terracing practices played a positive role in ES provisions, particularly erosion control, followed by runoff reduction, biomass accumulation, soil water recharge, and nutrient enhancement. Despite their importance, terracing failures still occur in many regions, resulting from agricultural abandonment, the lack of an appropriate design, environmental legislation, and the insufficient knowledge regarding design, construction and maintenance alternatives. More importantly, changes in the traditional concept and lifestyle, as well as price slumps of agricultural products have caused severe losses of local labor, which directly resulted in induced widespread terrace abandonment.

In light of these results, we make several recommendations to better manage terracing practices. First, the scientific criteria for terracing designs should be developed, including the associated environmental legislations. Here it is important to understand that no one design criteria will meet all of the climate, crop, cultural and geographic opportunities and constraints. Second, terraces need to be built in conjunction with other water recycling techniques and field treatments such as vegetation cover and riser protection, to ensure the security of terraces, the efficiency of rainwater harvesting and land productivity. Lastly, there is an urgent need to transfer knowledge from academia or policy makers to local farmers regarding terracing and sustainable land management. The potential damage and risks of agricultural terraces should be better evaluated to protect both the farmer and the greater watershed interests. Special funds and economic subsidies regarding terracing should be considered in order to achieve better management from farmers, which may help with the goals of environmental protection and land sustainability.

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