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Vegetation cover and topography rather than human disturbance control gully density and sediment production on the Chinese Loess Plateau

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ABSTRACT

The factors controlling topsoil erosion rates on the Chinese Loess Plateau (CLP) are currently relatively well understood and topsoil erosion rates can now be relatively accurately estimated. This is, however, not the case for non-topsoil erosion (sediment production by gullying and landslides): while it is well known that these processes produce significant amounts of sediment, the factors controlling their intensity and spatial distribution on the CLP are less well understood.

In this study we quantified the contribution of non-topsoil erosion to total sediment production on the CLP and investigated which factors control spatial and temporal variations in non-topsoil erosion. We estimated non-topsoil erosion rates (E_{NT}) by comparing the measured average sediment yields of 46 gauged catchments for the 1950–1970 period, when soil conservation measures were nearly absent in the area, with predicted topsoil erosion rates (using a recently developed empirical model). In addition, gully density was estimated in each catchment using Google Earth data. Our results showed that the area-weighted average catchment erosion rate (E) and E_{NT} were 58.60 ± 51.80 and 48.68 ± 49.78 t ha^{-1} yr^{-1} respectively for the studied catchments. The sediment contribution of non-topsoil erosion to total sediment production ranged between ca. 0 and 97% with a mean of 70 ± 25%. Both E and E_{NT} were significantly correlated to longitudinal river slope, land use, *NDVI*, and gully density. However, gully density was the only variable explaining a major part of the variance in both E (60%) and E_{NT} (57%). Gully density itself was significantly related to topography and vegetation cover but not to rainfall erosivity. Importantly, gully density was not only related to overall slope steepness, but also to the longitudinal slope of the river network and the hypsometric integral, suggesting that not only land cover disturbance but also tectonic uplift controls gully density and erosion rates. The absence of a clear climate signal, both with respect to the variation in gully density and in E, can be explained by the overwhelming effect that climate has on vegetation cover. Our research showed that non-topsoil erosion processes are the dominant sediment sources on the CLP and are strongly controlled by natural factors. The effect of human disturbance on non-topsoil erosion processes is far less important than its effect on topsoil erosion. Given the dominance of non-topsoil erosion processes on the CLP, this suggests that the high sediment production of the CLP is mainly attributable to natural factors.

1. Introduction

Understanding the mobilisation, transport and deposition of sediment at the Earth's surface is highly important, since sediment transfers are a key component of the link between terrestrial and marine ecosystems (Walling and Webb, 1996; Saito et al., 2001; Lal, 2003) and affect various biogeochemical cycles (Van Oost et al., 2007; Quinton et al., 2010). Sediment mobilisation and transport is also highly relevant to a more applied perspective as they have important consequences for river navigability, reservoir sedimentation and water pollution (Pimentel et al., 1995; Owens, 2005; Blanco-Canqui and Lal, 2008; Vanmaercke et al., 2011). While the processes that contribute to sediment production are well known, the quantification of their relative contribution to total sediment mobilisation in a given area is much more problematic (Walling, 2005; Vanmaercke et al., 2012; De Vente et al., 2013). Over the past decades considerable efforts have been made to quantify topsoil erosion by water (sheet and rill as well as ephemeral gully erosion) and it is now possible to assess topsoil erosion rates over large areas with an acceptable accuracy using models that account for the most important controls and that are calibrated using field observations (Renard et al., 1997; Cerdan et al., 2010). However, quantifying the contribution of non-topsoil erosion (i.e. sediment mobilisation by processes such as deep gullying, deep-seated landslides and river bank erosion) is more difficult (Wasson, 2002; Ndomba et al.,

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2009; De Vente et al., 2013). Indeed, the large spatial and temporal variability that characterizes these processes as well as the scale at which they occur hitherto preclude an approach whereby the factors controlling these processes are systematically studied and integrated into a modelling framework that can be applied at the regional scale.

Different alternative strategies can be used to assess the contribution of non-topsoil erosion to sediment production. A simple approach to assess the contribution of non-topsoil erosion processes can be followed if (i) the total amount of sediment mobilised within a catchment is accurately known and (ii) the contribution of topsoil erosion by water to total sediment production can be quantified. One can then simply derive the contribution of non-topsoil erosion to total erosion as the difference between total and topsoil erosion. However, total erosion cannot always be equalled to a basin's sediment yield. In most environments a significant part of the sediment that is mobilised by erosion is stored within the catchment, sometimes for very long time spans (Walling and Webb, 1996; Hoffmann et al., 2007; Wittmann and von Blanckenburg, 2009). As these sediment stores are generally not in equilibrium, there is often no direct link between current total erosion within the basin and the sediment export from the basin (De Vente et al., 2008; Hoffmann, 2015). Thus, directly estimating non-topsoil erosion from current sediment export and topsoil erosion is only possible when no significant sediment stores are present within the basin or when it can be reasonably assumed that sediment stores are in equilibrium (i.e. total sediment storage does not change over time): the latter is, however, difficult to assess.

When sediment storage within a basin is significant, the relative importance of different processes can be quantified through the establishment of sediment budgets by combining different techniques (Dietrich and Dunne, 1978; Nyssen et al., 2008). The establishment of a detailed sediment budget is labour intensive and costly as intensive field work is required to assess the magnitude of the different sediment sources and stores (Notebaert et al., 2009). This explains why detailed budgets are most often established for catchments smaller than 1000 km^2.

The fact that quantitative studies on non-topsoil erosion rates are generally limited to relatively small areas implies that the impact of regional variations (at a scale >10,000 km^2) in controlling factors such as climate, land cover and tectonics on non-topsoil erosion rates is not assessed. This fundamentally limits our understanding of sediment fluxes in large basins where such regional variations occur and where non-topsoil erosion often mobilises more sediment than topsoil erosion (Wasson et al., 2002; Nagle and Fahey, 2007). It also implies that it remains difficult to assess the overall impact of human activities on overall sediment mobilisation. While several studies have clearly shown that human activities may increase topsoil erosion rates by over two orders of magnitude (Montgomery, 2007; Zhao et al., 2016), the impact of human activities on non-topsoil erosion is much less clear. Human activities have a much smaller effect on the overall sediment transfer from the land to the ocean than on topsoil erosion: studies suggest that the land–ocean sediment transfer would have increased from ca. 14 to 16.2 Gt yr^{-1} (i.e. only by ca. 16%) due to human impact if no sediment would be retained in river reservoirs (Syvitski et al., 2005). The dramatic effect of scale on the magnitude of human impact may be partly explained by the strong buffering of sediments mobilised by topsoil erosion on land (Wilkinson and McElroy, 2007). However, it may also be the case that non-topsoil erosion is far less affected by human activity than topsoil erosion, thereby limiting the overall impact of humans on sediment export. Our lack of knowledge has also practical implications. As we do not know the impact of humans on non-topsoil erosion, we cannot reliably assess how different management strategies may affect total erosion and/or sediment fluxes in large basins. Furthermore, we cannot reliably quantify the impact of humans on the lateral transport of soil carbon and soil nutrients, as the carbon and nutrient content of topsoil is different from that of the deeper soil horizons/sediments mobilised by non-topsoil erosion processes (Han et al., 2010).

The Chinese Loess Plateau (CLP, ca. 640,000 km^2) is located in the northwest of China. The climate on the CLP varies from arid to semi-arid with total annual precipitation amounts ranging from 300 to 600 mm; 90% of the rainfall occurs from July to September (Takayama et al., 2004; Xin et al., 2011). Soils are loess-derived, containing a large amount of silt (41–64%) and relatively small amounts of clay (15–26%) and sand (9–42%) (Liu et al., 1991). They are therefore very suitable for arable agriculture, yet at the same time they are very erodible (Liu et al., 1991). Topography is variable, but large areas of the CLP are characterised by very steep slopes which are the result of strong river incision, especially during the Quaternary (Craddock et al., 2010). The combination of all these factors make the CLP a hotspot area of severe erosion where different erosion processes, such as rill and sheet erosion, gully erosion and landsliding combine, leading to very high erosion rates which may exceed 100 t ha^{-1} yr^{-1} on arable land (Tang et al., 1991; Zhang et al., 1997). Before the implementation of reservoirs, the Yellow River annually exported ca. 1.37 Gt of sediments to the Bohai Sea, which was ca. 9% of the total global land to sea export: over 90% of these sediments were coming from the CLP (Shi and Shao, 2000; Syvitski et al., 2005; Zhao et al., 2016).

As the CLP is a rapidly uplifting area (Pan et al., 2009; Wang et al., 2010), where rivers are strongly incised in relatively narrow valleys, very little sediment storage occurs under natural conditions (Craddock et al., 2010). There is a consensus that, before check dams and reservoirs were implemented since 1970 (Chen et al., 2007; Zhang et al., 2008), most of the sediment mobilised in the area was leaving the catchment quickly, resulting in sediment delivery ratios close to 1 (Zheng et al., 2014, 2015).

Recently, Zhao et al. (2016) developed a modelling procedure to estimate topsoil erosion rates on the CLP based on erosion plot data documenting the variation of topsoil erosion rates with topography, land use and land management practices. Validation of the model using ^{137}Cs inventories showed that topsoil erosion rates were predicted with an acceptable accuracy (<25% uncertainty). A first comparison of estimated topsoil erosion rates with total sediment yield from the CLP showed that, over the whole CLP, sediment production by non-topsoil erosion was far more important than topsoil erosion: under current conditions, ca. 60% of the total sediment export is derived from non-topsoil erosion.

In summary, sediment storage on the CLP was very limited before 1970 and topsoil erosion rates can now be reliably estimated. Furthermore, the CLP is characterised by strong gradients in land cover and climate, while variations in soil properties are limited. Finally, detailed sediment export data are available for a large number of catchments for an extended time period. The combination of all these factors make the CLP an interesting case study area to study non-topsoil erosion. Here, we combine data on measured gully densities, information on historical sediment yields and the topsoil erosion model developed by Zhao et al. (2016) to (i) quantify the contribution of non-topsoil erosion to total sediment production for a number of catchments on the CLP; (ii) investigate the link between estimated non-topsoil erosion and gully density; and (iii) assess the importance of various anthropogenic and natural factors that may control the variation of gully density and non-topsoil erosion.

2. Materials and methods

2.1. Sediment export and catchment erosion rate

Daily sediment concentrations (S_c, t m^{-3}) and discharges (Q, m^3 s^{-1}) were measured in 120 gauging stations on the CLP between 1950 and 2010 (Fig. 1). These data are provided by the National Science & Technology Infrastructure of China, Data Sharing Infrastructure of Earth System Science (http://www.geodata.cn). In order to minimize the impact of human measures such as the implementation of terraces and check-dams and the construction of reservoirs, we only used