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Estimation of soil loss by water erosion in the Chinese Loess Plateau using Universal Soil Loss Equation and GRACE

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SUMMARY

For the estimation of soil loss by erosion in the strongly affected Chinese Loess Plateau we applied the Universal Soil Loss Equation (USLE) using a number of input data sets (monthly precipitation, soil types, digital elevation model, land cover and soil conservation measures). Calculations were performed in ArcGIS and SAGA. The large-scale soil erosion in the Loess Plateau results in a strong non-hydrological mass change. In order to investigate whether the resulting mass change from USLE may be validated by the gravity field satellite mission GRACE (Gravity Recovery and Climate Experiment), we processed different GRACE level-2 products (ITG, GFZ and CSR). The mass variations estimated in the GRACE trend were relatively close to the observed sediment yield data of the Yellow River. However, the soil losses resulting from two USLE parameterizations were comparatively high since USLE does not consider the sediment delivery ratio. Most eroded soil stays in the study area and only a fraction is exported by the Yellow River. Thus, the resultant mass loss appears to be too small to be resolved by GRACE.

Key words: Satellite gravity; Gravity anomalies and Earth structure; Time variable gravity; Sedimentary basin processes; Asia.

1 INTRODUCTION

The Loess Plateau in China covers an area of approximately 600 000 km^2 (Shi & Shao 2000; Fu *et al.* 2011) and shows one of the highest erosion rates worldwide (Lal 2003). The consequences of soil erosion are loss of fertility and subsequent depletion of land resources affecting agriculture and industries in the region (Shi & Shao 2000). The situation exacerbated to a degree that conservation of agricultural soils became a matter of food security (Gates *et al.* 2011). The Loess Plateau lies in the middle reaches of the Yellow River, and eroded soil is the largest contributor to the river's sediment yield, which amounted to more than 1.6 Gt per year till 2002 (Giordano *et al.* 2004). A large amount of sediments deposits in the lower reaches of the Yellow River and causes a rising of the river bed accompanied by floods (Shi & Shao 2000).

There are multiple reasons for the strong erosion in the Loess Plateau where water erosion predominates over wind, freeze and thaw, or gravity erosion (Mou 1996; Miao *et al.* 2012). One reason is agriculture which started several thousand years ago and destroyed the protective natural vegetation (Fu 1989). Rapidly increasing population and involved human activities, such as cultivation, overgrazing, building of infrastructure or mining worsened the situation (Shi & Shao 2000). The loess soil itself has a porous and soft texture, thus it is easily washed away by runoff. Therefore, heavy rainfalls during the monsoon period from June to September are the major trigger for soil erosion in the area (Fu 1989). The severity of the situation has been recognized since the 1970s and the Chinese government implemented a number of practices of soil conservation in the Loess Plateau (Gates *et al.* 2011) including the Grain-to-Green Program launched in 1999 (Fu *et al.* 2011; Ostwald *et al.* 2011).

The aim of this research is to estimate soil loss caused by water erosion in the Loess Plateau by the Universal Soil Loss Equation (USLE) developed by Wischmeier & Smith (1978). The model has been used in previous studies in China (Zhang *et al.* 2004; Yue-Qing *et al.* 2008, 2005, 2008; Hu *et al.* 2010; Fu *et al.* 2011) since it allows consistent estimates over large areas. Maximum erosion rates from literature, e.g. up to 30 000 t km^{-2} and year (Wang *et al.* 2006; Fu *et al.* 2011), suggested that mass changes by soil erosion could be potentially seen in observations of the gravity field satellite mission GRACE (Gravity Recovery and Climate Experiment). GRACE is sensitive to the integral signal of mass redistributions in the Earth system, including hydrological and non-hydrological effects. We assume that non-hydrological mass changes within our study area are predominantly caused by soil erosion, and thus exclude other types of erosion as well as impacts of sand storms, afforestation, mining or oil production. In order to analyze if the signal of soil erosion can be resolved by GRACE, we estimated a linear trend for the GRACE data for the years 2003 to 2008 taking into account the standard deviations of monthly solutions. Subsequently, we compared the results of USLE and GRACE with those of observed sediment yield data of the Yellow River. In the following text we use the terms sediment yield and soil loss. While sediment yield is the total amount of erosional debris exported from a drainage basin, soil loss as simulated by USLE is the amount of soil eroded from the hillslopes and transported to the foot slopes or to the next channel. This material is not necessarily exported directly out of the river catchment, but parts of it may be temporarily stored within the catchment (such as foot slopes, inundation areas, lakes and reservoirs). Subsequent erosion processes may re-mobilize those sediments which will then contribute to sediment yield with some time delay. GRACE potentially sees sediment yield, i.e. the effective mass loss of the river basin by sediment export. Nevertheless, soil loss as simulated by USLE can be seen as an approximation of sediment yield at timescales that integrate over the temporary sediment storage processes within the river.

The paper first informs about the study area and introduces methods and data related to USLE and GRACE (Section 2). Section 3 provides numerical results and a critical discussion of error sources and related uncertainties before we conclude our paper with a summary and an outlook (Section 4).

2 METHODS AND DATA

2.1 Study area

The Loess Plateau in the middle reaches of the Yellow River is enclosed by the Taihang Mountains in the east, the Riyue-Helan Mountains in the west, the Qinling Mountains in the south and the Yinshan Mountains in the north (Shi & Shao 2000) (Fig. 1). The elevation ranges between 400 and 2400 m, and its topography is predominated by slopy landforms such as hills and low mountains, high and riverside plains, as well as ravine and gully (Fu 1989). With 600 000 km^2, the plateau stretches over the provinces Shanxi, Shaanxi, Gansu, partly Ningxia, Qinghai, Henan, Inner Mongolia and Hebei (Zhang *et al.* 2006). The climate varies from humid over semi-humid, semi-arid to arid running from southeast to northwest. Precipitation is the key factor of soil erosion with highest rates during the monsoon from June to September caused by rainstorms. 70 per cent of the annual precipitation of 300 to 500 mm falls during this period (Giordano *et al.* 2004; Tang *et al.* 2008). The generally sparse vegetation varies accordingly from a warm temperate deciduous broad-leaved forest zone, a temperate steppe zone to a desert vegetation zone (Shi & Shao 2000; Zhang *et al.* 2006). The main characteristic of the area is a thick layer of loess soil from less than 30 m to up to 200 m (Fu 1989). About 9 per cent of China's population lives in the Yellow River basin with strong urbanization and industrialization, however, the majority of the population still works in agriculture. On average, about 50 Gt of water are withdrawn from the river and groundwater per year (1998 to 2000) (Giordano *et al.* 2004). Because of this high water demand and a strong need for water and sediment regulation, China built over 3000 reservoirs with a total capacity of 57.4 Gt, the five largest ones in the last decades (Zhang *et al.* 2001; Wang *et al.* 2011). Our study area of 900 000 km^2 covers the catchment area upstream the Huayuankou gauge station (730 036 km^2) and comprises the entire Loess Plateau of 628 000 km^2 (Fig. 1).

2.2 USLE — model and input data

The USLE (Wischmeier & Smith 1978) calculates the annual amount of soil loss. Though it requires comparatively sparse input data, it is a difficult task to collect all parameters in the necessary temporal and spatial resolution. The soil loss in USLE is estimated as

$$A = R \times K \times LS \times C \times P\,, \qquad (1)$$

where A is soil loss (t ha^{-1} yr^{-1}), R is the rainfall and runoff factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the slope length and slope steepness factor (dimensionless), C is the cover and management factor (dimensionless) and P is support practice factor (dimensionless).

In our paper we applied two USLE approaches to estimate the soil loss in the Loess Plateau using different equations for the R-, K-

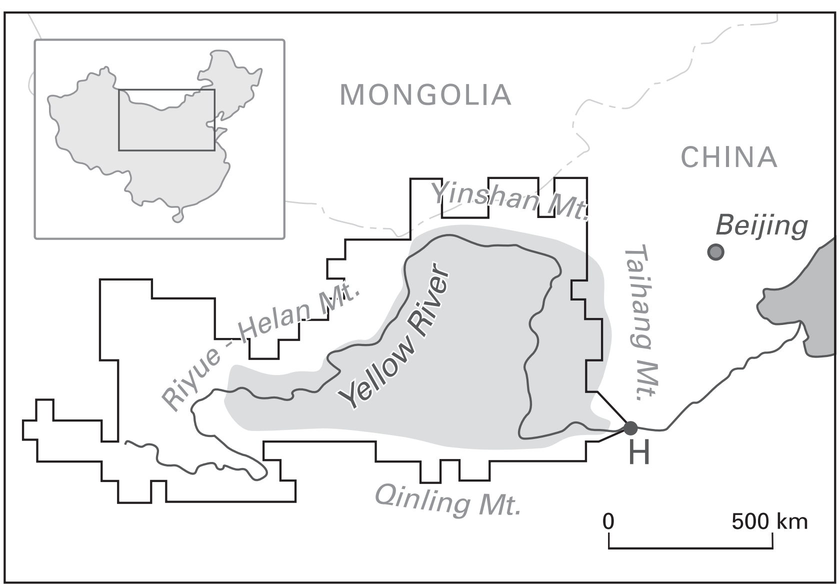

Figure 1. Map of study area. The black line shows the study area, the grey area represents the Loess Plateau. H = Huayuankou gauging station.

and *P*-factor; the factors *LS* and *C* were derived identically. The first approach — hereafter USLE1 — used equations from Schwertmann *et al.* (1990), the second approach (USLE2) applies equations used by Fu *et al.* (2011)/Zhang *et al.* (2004).

The required parameters were determined as follows:

R: Due to the lack of rain intensity data or ready isoerodent maps to use, we derived *R*-values from annual or monthly precipitation data. In USLE1, based on Schwertmann *et al.* (1990), *R* is assessed as

$$R = 0.083 \times P - 1.77\,, \tag{2}$$

where *P* is the annual precipitation (mm). In USLE2, *R* is calculated from monthly precipitation data as proposed by Fu *et al.* (2011):

$$R = \sum_{i=1}^{12} 1.735 \times 10^{(1.5\log_{10}(P_i^2/P)-0.08188)}\,, \tag{3}$$

where P_i are the monthly and *P* annual precipitation sums, both in mm. The used precipitation data from the Global Precipitation Climatology Centre (GPCC) had a spatial resolution of 1 degree.

K: Comparably to the *R*-factor, the *K*-factor was calculated using two different equations. The first one was proposed by Schwertmann *et al.* (1990):

$$K = 2.77 \times 10^{-6} \times M^{1.14} \times (12 - a) + 0.043 \times (b - 2) + 0.033 \times (4 - c)\,, \tag{4}$$

where *M* is the particle-size parameter derived from the ratio of silt, sand and clay (in per cent) of the soil top layer (0–30 cm), *a* is the organic matter (per cent), *b* is the soil structure code used in soil classification (dimensionless) and *c* represents the profile-permeability class (dimensionless). We used adequate values for *a*, *b* and *c* for the Loess Plateau following Zhang *et al.* (2004) (mean of four test sites: $a = 0.595$, $b = 2.25$, $c = 2.75$).

The second equation by Zhang *et al.* (2004) and Fu *et al.* (2011) was especially developed for the soil conditions of the Loess Plateau:

$$K = 0.031 - 0.0013 \times CL\,, \tag{5}$$

where *CL* is the clay content in per cent. In both approaches, the 2010 soil map of Beijing Normal University (Shangguan *et al.* 2012) was used as a basis for the soil erodibility factor *K*.

LS: The slope length and slope steepness factor was computed with the help of a DEM derived from a mosaic of SRTM data scenes with a resolution of 90 m. We used the hole-filled seamless SRTM data V4 of the International Centre for Tropical Agriculture (CIAT). The combined LS-factor was calculated with the software SAGA.

C: For the cover and management factor we used the GlobCover Land Cover product by the European Space Agency (ESA) from 2005 to 2006 with a spatial resolution of 300 m. The corresponding *C*-values of the 20 different cover classes were retrieved from Kim *et al.* (2007), Wischmeier & Smith (1978) and Fu *et al.* (2005). The resulting *C*-values range between 0.0 for water bodies and 1.0 for bare areas.

P: The support practice factor *P* represents measures to reduce soil erosion. Since it is not possible to access detailed, reliable data for the entire area of the Loess Plateau over a long time period, we used two approaches to estimate *P*. For USLE1, we implemented the information of Giordano *et al.* (2004) who report that in the Loess Plateau, terracing, strip farming, dams retaining sediment, afforestation, planting grasses and other measures have been applied on about one-third of the affected area. Considering a value range for *P* between 0.0 and 1.0 (between reducing and supporting soil erosion) (Wischmeier & Smith 1978), we assumed a *P*-value of 0.66 as reasonable, representing that two-third of the area are unprotected. In USLE2, we applied the slope-based approach of Wenner (1981) and Lufafa *et al.* (2003) which was also used by Fu *et al.* (2011) in the Loess Plateau:

$$P = 0.2 + 0.03 \times \alpha\,, \tag{6}$$

where α is the slope gradient in per cent.

All computation was done with ArcGIS where the thematic raster layers were stacked and calculated pixel-wise with a grid size of 100 m. The annual soil loss was estimated for the period 2002 to 2007. All data sets processed are freely available via the Internet.

2.3 GRACE

Previous studies have shown the potential of gravity field observations from the GRACE twin-satellite mission (Tapley 2004) for estimating hydrological storage variations in continental regions over areas larger than 200 000 km^2 and at a temporal resolution of approximately 1 month (e.g. Swenson & Wahr 2007; Ramillien *et al.* 2008; Schmidt *et al.* 2008; Seitz *et al.* 2008). Phenomena such as Earth and ocean tides, atmospheric pressure variations and ocean circulation are removed during pre-processing using respective background models described by Flechtner (2007). We compared the latest GRACE products of three different analysis centres, (1) the GFZ-RL05 solutions (Dahle *et al.* 2012) provided by the German Research Centre for Geosciences (GFZ), (2) the CSR-RL05 models (Bettadpur 2012) calculated by the Center for Space Research (CSR) and (3) the ITG-Grace2010 time-series (Mayer-Gürr *et al.* 2010) processed at the University of Bonn. The ITG-Grace2010 solutions are provided for the years September 2002 to August 2009. The GFZ and CSR RL05 models are currently available since 2004. Missing months (e.g. January 2011 and June 2011) were linearly interpolated. Each of the products is given in terms of quasi-monthly sets of spherical harmonic coefficients (SHC) of the Earth's gravity potential (GRACE level-2 data) which we used up to degree and order 60. As GRACE is not able to obtain information on geocentre motion, we substituted the coefficients of degree one by a time-series based on a joint inversion of GRACE, GPS and ocean bottom pressure data, see Rietbroek *et al.* (2012). The SHC were analyzed for a geographical $1^\circ \times 1^\circ$ grid of equivalent water height (EWH) variations relative to a mean over the GRACE period and smoothed using a 300 km Gaussian filter. The observations were corrected for leakage effects and rescaled in order to compensate the loss of signal as a consequence of spherical harmonic truncation and filtering (Swenson & Wahr 2007). For the ITG-Grace monthly solutions there are full variance-covariance matrices publicly available (http://www.igg.uni-bonn.de/apmg/index.php?id = itg-grace2010), which we used for a realistic GRACE error assessment.

3 RESULTS AND DISCUSSION

3.1 USLE

The USLE approaches, USLE1 based on Schwertmann *et al.* (1990) and USLE2 based on Fu *et al.* (2011)/Zhang *et al.* (2004) led to different results for the rainfall and runoff factor *R* and the soil erodibility factor *K* (Fig. 2). The mean *R* in USLE1, based on annual precipitation sums, amounted to 324.2 MJ mm ha^{-1} h^{-1} yr^{-1}, whereas the inclusion of monthly precipitation data in USLE2,

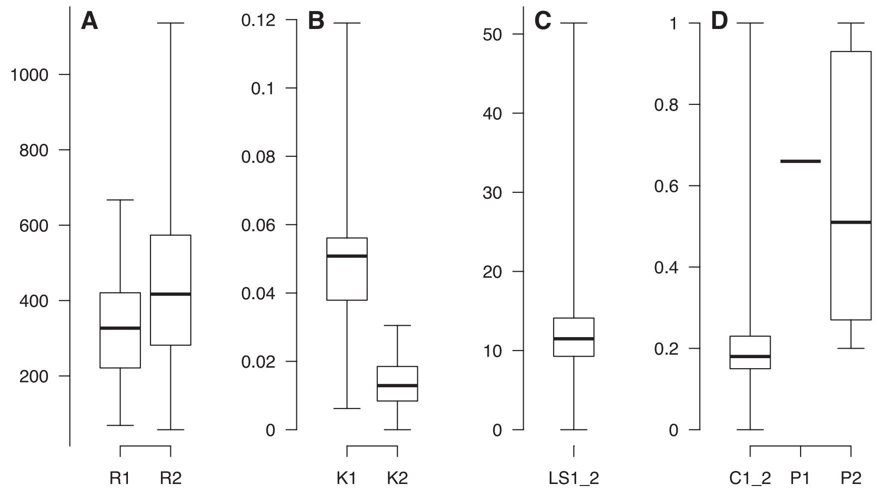

Figure 2. Box plots showing the range of the determined factors of the USLE models (2002–2007, approx. 90 million pixel of 100 m × 100 m in the study area). The factors are named after their USLE approach: R1, K1 and P1 were used in USLE1, R2, K2 and P2 in USLE2. LS1_2 and C1_2 were applied in both approaches. A: R1, R2 in (MJ mm ha^{-1} h^{-1} yr^{-1}), B: K1, K2 in (t ha h ha^{-1} MJ^{-1} mm^{-1}), C and D: dimensionless.

better mirroring the monsoon period in the Chinese Loess Plateau, led to higher *R* factors (mean of 433.8). In contrast, the soil erodibility factor *K* was much higher in USLE1 with a mean of 0.0461 t ha h ha^{-1} MJ^{-1} mm^{-1}, ranging from 0.0061 to 0.119 t ha h ha^{-1} MJ^{-1} mm^{-1}. This corresponds quite well to the mean *K* of 0.065 given in Schwertmann *et al.* (1990) for luvisol out of loess in Germany. The USLE2 approach resulted in a mean *K*-value of 0.0135 t ha h ha^{-1} MJ^{-1} mm^{-1} (from 0.00003 to 0.0305). The underlying equation of Zhang *et al.* (2004) relies on the clay content *CL*, and was parameterized on four samples only. Thus, there are no valid *K*-values for *CL* higher than 23.85 per cent.

The slope length and slope steepness factor *LS* and cover and management factor C were identical for both USLE estimations (Fig. 2). The calculated *LS*-values were based on a DEM and gave a mean *LS*-factor of 11.9. For our study area the mean slope was 8.5° with most slopes ranging between 0.58° and 17.46°. Fu *et al.* (2011) presented similar slope gradients with about 75 per cent of the area of the Loess Plateau lying between less than 5° and 15°.

Our *C*-factors derived from literature based on the GlobCover data set ranged from 0.0 and 1.0 with a median of 0.18 and was applied for the entire time period. In contrast, Fu *et al.* (2011) used the NDVI (normalized difference vegetation index) derived from remote sensing data to estimate annual *C*-values, thus considering the interannual vegetation changes in the study area. Here, the dominating land cover type was grassland (41 to 45 per cent) followed by farmland. Their observed land use/land cover changes suggest that grassland increased by 6.6 per cent and farmland decreased by 10.8 per cent. Though our *C*-values did not represent the vegetation changes over time, the distribution of vegetation types was about the same as reported in Fu *et al.* (2011) with dominating grassland (over 30 per cent) and farmland (over 25 per cent).

The support practice factor *P* was, similarly to the factors *R* and *K*, estimated with two different methods. In USLE1, *P* was set to a constant value of 0.66 for the whole study area reflecting soil conservation measures taken in the Loess Plateau on one-third of the affected area (see Section 2.2). In USLE2, the approach based on the slope gradient was applied and resulted in *P*-values between 0.2 and 1.0 with a mean of 0.57 (Fig. 2) which was very close to the constant value of 0.66 used in USLE1.

The modelled annual soil loss by water erosion for the study area of 900 000 km^2 amounted up to 4.32 and 1.45 Gt for USLE1 and USLE2, respectively, with some variations between the years depending on the annual precipitation sums (Table 1). Corresponding numbers for observed sediment yield in the catchment area of 730 036 km^2 (Yellow River Conservancy Commission 2005; Wu *et al.* 2007, 2008a,b; Wu 2011, personal communication) of on average 0.129 Gt (2002-2007) revealed that both USLE approaches, also with coarse input data, were in principle acceptable for estimating soil loss on the large scale of the Chinese Loess Plateau, however the total soil erosion modelled was larger by a factor of less than 10 (USLE2) compared to the observed sediment yield. Two possible reasons may explain this obvious discrepancy. First, the sediment delivery ratio has not been considered in our soil loss estimations. In reality, a large amount of sediments stays in the region of the Loess Plateau after the erosion process and does not reach the Yellow River (Giordano *et al.* 2004; Wu *et al.* 2005). Additionally, the reservoirs along the Yellow River, capture large amounts of sediment. After Giordano *et al.* (2004) 1 Gt of sediment yield is transported into the Yellow River every year, but only 200 million tons are transported to the lower reaches or to the sea; thus, 800 million tons or 80 per cent stay along the river or pile up in reservoirs. The figures in Table 1 reveal a similar ratio between observed sediment yield data and USLE2. For USLE1 though, the results are roughly 25 times higher than the measured sediment data in the Yellow River.

The second reason may be due to the coarse input data sets as well as poor parameterizations of the factors used in both USLE approaches. For the *R*-factor the annual precipitation data implemented in the German USLE1 approach does not represent the characteristic seasonal rain fall pattern with heavy rainstorms in the monsoon season from June to September and hardly any precipitation during the rest of the year. This deficit has been improved in the second USLE estimation applying monthly and annual precipitation data based on Chinese field data of the Loess Plateau. This feature can be recognized in the (temporal and spatial) standard deviation of *R* in USLE1 and USLE2 (SD of $R = 127.2$ versus 189.6). Moreover, the data used for the *K*-factor do not meet the accuracy of required field data for parameterization. The equation for *K* in USLE1 is well elaborated based on the original Wischmeier & Smith (1978) publication, however the model is fitted to German conditions. In contrast, the equation used by Fu *et al.* (2011) was developed for Chinese settings, however, would need a broader

Table 1. Observed sediment yield, USLE results [USLE1: approach of Schwertmann *et al.* (1990); USLE2: approach of Fu *et al.* (2011)], USLE results estimated by Fu *et al.* (2011) and runoff data (after Wu *et al.* 2007, 2008a; Yellow River Conservancy Commission 2005; Wu, personal communication) .

Year	Observed sediment yield in Gt from literature	Estimated soil loss in Gt from USLE1	Estimated soil loss in Gt from USLE2	Estimated soil loss in Gt by Fu *et al.* (2011)	Observed runoff in Gt from literature
Area in km^2	730 036	900 000	900 000	628 000	730 036
2000	—	—	—	2.11	—
2002	0.100	3.28	1.18	—	19.50
2003	0.197	4.32	1.40	2.54	27.27
2004	0.201	3.44	1.25	—	24.08
2005	0.105	3.52	1.11	—	25.70
2006	0.084	3.35	1.19	—	28.11
2007	0.084	3.97	1.45	1.67	26.97
2008	—	—	—	1.51	—
Mean	0.129	3.65	1.26	1.96	25.27

observational input data set than four samples. The better representation of spatial variability is again mirrored by higher standard deviation of K in USLE1 (0.0168) than in USLE2 (0.0076). The calculation of the LS-factor based on SAGA standard procedures for a 90-m grid resolution from SRTM data does not give much room for improvements. An intrinsic obstacle of both USLE approaches are the constant C- and P-factors over time. China has been working hard to improve the soil conservation measures (Ostwald *et al.* 2007; Fu *et al.* 2011; Wu, personal communication), and the result can be seen in the decreasing sediment yield observed (Table 1). In both USLE approaches though, we used one data set from 2005 to 2006 representing the C-factor for the whole time period neglecting the progress made during time. Also, due to lack of data, we applied a constant P-value of 0.66 in USLE1 and a slope-based approach in USLE2 (mean 0.57) for the entire period and study area. This low quality of the input data may also explain the smaller interannual variations of the USLE results in comparison to the observed data. Nevertheless, the mean annual soil loss of 1.96 Gt per year (2000, 2003, 2007, 2008) calculated by Fu *et al.* (2011) for the area of the Loess Plateau (*ca.* 628 000 km^2) lies between our results of USLE1 and USLE2 with a mean annual soil loss of 1.26 Gt per year and 3.65 Gt per year for our study area of 900 000 km^2. Data used in Fu *et al.* (2011) for R were monthly precipitation data from 107 weather stations provided by China Meteorological Administration. For K they implemented data of the Soil Survey Office of Shaanxi Province from 1992 and additional information about soil content in the Loess Plateau from literature.

In order to assess the uncertainty of the data, we estimated the annual soil loss (A) with minimum and maximum values for each USLE factors to determine a spatially explicit minimum and maximum sum for the study area. Taking the uncertainties of observed precipitation data of about 30 per cent into account, we reduced the monthly and annual precipitation sums of the driest year 2002 by 30 per cent and increased the respective values of the wettest year 2003 also by 30 per cent. For K we determined the range of uncertainty in two different ways. In USLE1, we used the most frequently existing high value of 0.052 as the maximum value and most frequently existing low value of 0.016 as the minimum value. The mean 0.046 and median 0.051 of K are close to the maximum value of 0.052. In USLE2, we estimated K applying the approach based on the clay content in the soil. Therefore we assume a lab error in soil type by 20 per cent. Since high-clay content makes the soil more resistant against water erosion (Zhang *et al.* 2004), we decreased the clay content by 20 per cent for the maximum K-values and increased the clay content by the same amount for the minimum K-values. For the assessment of minima and maxima C-values, 30 per cent of all pixels were reclassified, first from C-values of 1, corresponding to bare soil, to proportionately all other classes (minimum values for C) and second vice-versa, the low values for C were equally reclassified to C-values of 1. The increase in numbers of the C-values of 1 by 30 per cent corresponds to the situation in the 1960s before China had started to plant trees and grasses to preserve the soil from erosion (Giordano *et al.* 2004). Additionally, classification errors caused by limited classes and spatial resolution of the input data increase the uncertainties. The factors P and LS were not modified. The results of USLE1 and USLE2 for the minimum and maximum annual soil loss in the study area show a range from 0.75 to 7.92 Gt per year and from 0.46 to 2.88 Gt per year, respectively.

3.2 GRACE

Fig. 3 shows the total mass changes from GRACE for each of the three GRACE solutions. For the overlapping time span it can be observed that even though there are differences between the individual monthly solutions, the general evolution of the time-series shows a reasonable agreement. The standard deviations for the mass variations obtained by rigorous error propagation using the full ITG-Grace2010 variance–covariance matrices are displayed in Fig. 4 and are also illustrated as error bars in Fig. 5. Months with poor GRACE data coverage (e.g. 2003–01, 2003–06, 2004–01 and 2004–09) due to instrument problems or a repeat orbit configuration are clearly indicated by larger standard deviations. For the rest of the time-series the error level is around 8 to 15 Gt. The GRACE curves feature intra-annual variability with maximum storage in the second half of the year as well as signatures of specific events such as, e.g. in the beginning of 2003 a minimum due to extremely low precipitation and a maximum related to a flood during August/September 2003 or a minimum due to a drought in mid-2007 when about 11 million people were short of drinking water (see NOAA's State of the climate 2003 and State of the climate 2007). The linear trend for the ITG-Grace2010 time-series was calculated for the years 2003 to 2008 taking into account the standard deviations of the monthly solutions. It is plotted as a blue line in Fig. 5 and amounts to an (insignificant) positive mass trend of 0.61 Gt per year with a standard deviation of 2.24 Gt. It was tested if the inclusion of ten years of GRACE data (i.e. the full GRACE era) would allow for a significant determination of the trend. Assuming an invariable standard deviation at the level of 12.5 Gt (compare Fig. 4) after 2008 until

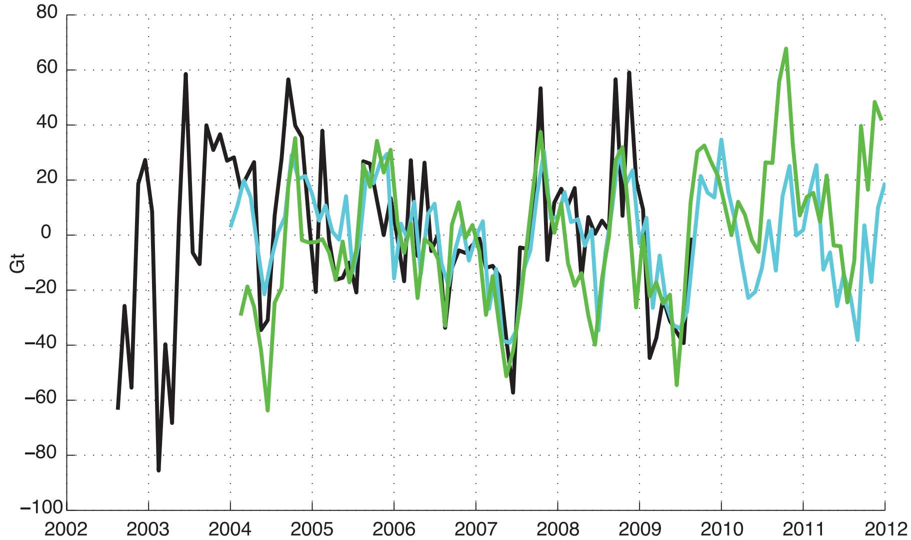

Figure 3. Mass variations from GRACE for the study area from three different GRACE products: ITG-GRACE2010 (black), CSR (blue), GFZ (green) both RL05.

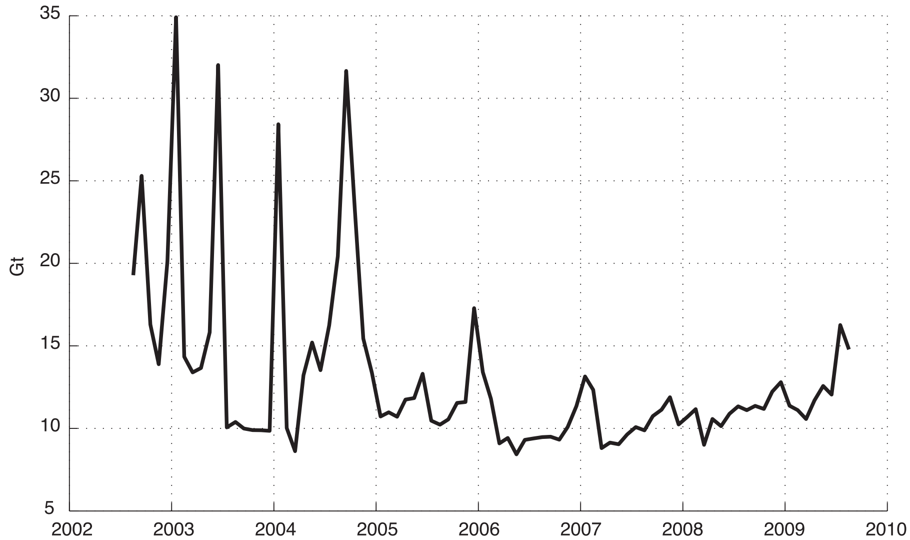

Figure 4. Standard deviation of ITG-Grace2010 solutions.

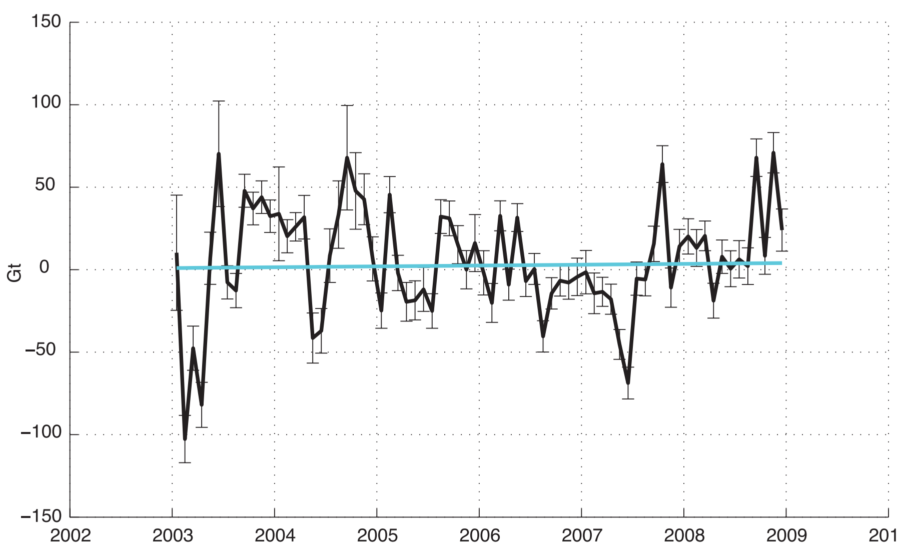

Figure 5. ITG-Grace2010 solutions and the resulting linear trend of 0.61 Gt per year with a standard deviation of 2.24 Gt for the period 2003–2008.

2012, the uncertainty of the estimated trend would be reduced by a factor of two. Even though this still means insignificance, the experiment indicates the potential of GRACE to become a useful tool for studying small but ongoing mass effects as the observation period increases (this holds in particular in the light of the GRACE Follow-on mission, scheduled for launch in 2017).

Regarding the standard deviation of the trend from 2003 to 2008, the amount of soil loss in the study area has to reach about 6 Gt per year to reveal a significant result in GRACE. For the trend's time span of 6 years this accumulates in soil losses of 36 Gt. Our two USLE models estimated maximum erosion rates of 4.32 Gt per year and 1.45 Gt per year, respectively. Maximum soil losses calculated in the uncertainty analysis described in Section 3.1 for both USLE approaches were 7.92 and 2.88 Gt per year, respectively. Observed sediment values are even smaller with a mean of 0.129 Gt per year from 2002 to 2007 (Table 1), though before 2002, sediment yield of 1.6 Gt per year have been recorded (Wu *et al.* 2008b). Fu *et al.* (2011) and Wang *et al.* (2006) report annual erosion rates of 30 000 t km^{-2} resulting in 19 Gt for the area of the Loess Plateau per year. Over 6 years, these losses above accumulate to about 26 and 9 Gt for USLE1 and USLE2, respectively. According to our uncertainty analysis, the maximum annual soil losses accumulate to 47 Gt (USLE1) and 17 Gt (USLE2). Sediment yield recorded before 2002 adds up to 10 Gt over 6 years and Fu *et al.* (2011) reports 19 Gt per year. While some of these amounts of soil loss might be captured by a long-term trend in GRACE with significance, the current rate of effective soil loss to lower reaches or to the sea due to water erosion is not strong enough to be detectable by present-day satellite gravity field observations, although the erosion rates in our study area are among the highest in the world. However, mass changes detected by GRACE show all mass variations including water storage changes. These may include about 50 Gt of water withdrawn from the river and groundwater mainly for irrigation (Giordano *et al.* 2004), large amounts of runoff (Table 1) and around 57 Gt of water stored in over 3000 reservoirs to control water supply in the region (Zhang *et al.* 2001). These hydrological mass changes have to be considered if the effects of soil erosion should be verified in the GRACE signal. For instance by subtracting water storage changes derived by a hydrological model from the GRACE data. However, uncertainties of hydrological models in simulating water storage variations, in particular long-term trends, are high (Steffen *et al.* 2009; Werth *et al.* 2009). The prospect of achieving improved estimates of non-hydrological trends by this approach is thus limited.

4 CONCLUSION

The aim of our research was to estimate soil loss by water erosion in the Loess Plateau in China using the USLE and the gravity satellite mission GRACE. The Loess Plateau is characterized by the highest mass changes due to soil loss worldwide (Lal 2003). The USLE models, based on freely available environmental monitoring data sets but of much coarser resolution than required, proved to deliver reasonable results as compared to those given by Fu *et al.* (2011) with a mean of 1.96 Gt per year. Our two USLE approaches estimated a mean soil loss of 3.65 and 1.26 Gt per year, respectively (Table 1). GRACE indicates an insignificant accumulating mass trend of 0.61 Gt per year ($\pm$2.24 Gt), representing not only non-hydrological mass changes such as soil erosion but also hydrological mass changes. Mean observed sediment yield data were 0.129 Gt per year (Table 1). According to Fu *et al.* (2011), maximum annual erosion rates reached up to 30 000 tons per km^2 in the Loess Plateau itself. Maximum soil losses estimated in our first USLE approach reaches 4.32 Gt per year which would be almost enough to be detected by GRACE. However, the rates of lost soil leaving the Loess Plateau completely turned out to be too small to be resolved in the observations of the gravity field satellite mission. This effect reveals also the success of soil conservations programs carried out in the area of the Loess Plateau, such as the Grain-to-Green Program. Nevertheless, the USLE2 approach could further be improved if the necessary input data should become accessible with higher accuracy in future. In this way, the model may contribute to a better understanding of the processes in the region and provide more reliable estimates of the actual soil loss due to water erosion.

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REFERENCES

Bettadpur, S., 2012. Insights into the Earth System mass variability from CSR-RL05 GRACE gravity fields, in *Presented at the EGU General Assembly Conference Abstracts,* vol. 14 of EGU General Assembly Conference Abstracts, p. 6409.

Dahle, C., Flechtner, F., Gruber, C., König, D., König, R., Michalak, G. & Neumayer, K.-H., 2012. GFZ GRACE level-2 processing standards document for level-2 product release 0005a, *Scientific Technical Report - Data,* 12/02.

Flechtner, F., 2007. Gravity recovery and climate experiment AOD1B product description document for product releases 01 to 04. technical report GRACE327-750, rev. 3.1.

Fu, B., 1989. Soil erosion and its control in the Loess Plateau of China, *Soil Use Manag.,* **5**(2), 76–82.

Fu, B., Liu, Y., Lü, Y., He, C., Zeng, Y. & Wu, B., 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China, *Ecol. Complex.,* **8**(4), 284–293.

Fu, B.J., Zhao, W.W., Chen, L.D., Zhang, Q.J., Lü, Y.H., Gulinck, H. & Poesen, J., 2005. Assessment of soil erosion at large watershed scale using RUSLE and GIS: a case study in the Loess Plateau of China, *Land Degrad. Dev.,* **16**(1), 73–85.

Gates, J.B., Scanlon, B.R., Mu, X. & Zhang, L., 2011. Impacts of soil conservation on groundwater recharge in the semi-arid Loess Plateau, China, *Hydrogeol. J.,* **19**(4), 865–875.

Giordano, M., Zhu, Z., Cai, X., Hong, S., Zhang, X. & Xue, Y., 2004. *Water management in the Yellow River Basin background, current critical issues and future research needs,* International Water Management Institute, Colombo, Sri Lanka.

Hu, L., Yang, H., Yang, Q. & Li, R., 2010. A GIS-based modeling approach for fast assessment of soil erosion by water at regional scale, Loess Plateau of China, *Chinese Geogr. Sci.,* **20**(5), 423–433.

Kim, S.M., Im, S.J., Park, S.W., Lee, J.J., Benham, B.L. & Jang, T.I., 2007. Assessment of wastewater reuse effects on nutrient loads from paddy field using Field-Scale water quality model, *Environ. Model. Assess.,* **13**(2), 305–313.

Lal, R., 2003. Soil erosion and the global carbon budget, *Environ. Int.,* **29**(4), 437–450.

Lufafa, A., Tenywa, M.M., Isabirye, M., Majaliwa, M.J.G. & Woomer, P.L., 2003. Prediction of soil erosion in a Lake Victoria basin catchment using a GIS-based Universal Soil Loss model, *Agric. Syst.,* **76**(3), 883–894.

Mayer-Gürr, T., Kurtenbach, E. & Eicker, A., 2010. *ITG-Grace2010 gravity field model*. Available at: http://www.igg.uni-bonn.de/apmg/index.php?id = itg-grace2010. Last accessed: 11/02/2013.

Miao, C.Y., Yang, L., Chen, X.H. & Gao, Y., 2012. The vegetation cover dynamics (1982-2006) in different erosion regions of the Yellow River basin, China, *Land Degrad. Dev.,* **23**(1), 62–71.

Mou, J., 1996. Recent studies of the role of soil conservation in reducing erosion and sediment yield in the Loess Plateau area of the Yellow River basin, *Int. Assoc. Hydrol. Sci. (IAHS Publications-Series of Proceedings and Reports),* **236,** 541–548.

Ostwald, M., Simelton, E., Chen, D. & Liu, A., 2007. Relation between vegetation changes, climate variables and Land–use policy in Shaanxi Province, China, *Geogr. Ann.: Series A, Phys. Geogr.,* **89**(4), 223–236.

Ostwald, M., Moberg, J., Persson, M. & Xu, J., 2011. The Chinese Grain for Green Program—assessing the sequestered carbon from the land reform, *in Proceeding of the World Renewable Energy Congress* 2011, Linköping, Sweden, pp. 2517–2522.

Ramillien, G., Famiglietti, J.S. & Wahr, J., 2008. Detection of continental hydrology and glaciology signals from GRACE: a review, *Surv. Geophys.,* **29**(4–5), 361–374.

Rietbroek, R., Fritsche, M., Brunnabend, S.-E., Daras, I., Kusche, J., Schröter, J., Flechtner, F. & Dietrich, R., 2012. Global surface mass from a new combination of GRACE, modelled OBP and reprocessed GPS data, *J. Geodyn.,* **59–60,** 64–71.

Schmidt, R., Flechtner, F., Meyer, U., Neumayer, K., Dahle, C., König, R. & Kusche, J., 2008. Hydrological signals observed by the GRACE satellites, *Surv. Geophys.,* **29**(4–5), 319–334.

Schwertmann, U., Vogl, W. & Kainz, M., 1990. *Bodenerosion durch Wasser. Vorhersage des Abtrags und Bewertung von Gegenmassnahmen,* 2nd edn, Ulmer (Eugen). Stuttgart, Germany.

Seitz, F., Schmidt, M. & Shum, C.K., 2008. Signals of extreme weather conditions in Central Europe in GRACE 4-D hydrological mass variations, *Earth planet. Sci. Lett.,* **268**(1–2), 165–170.

Shangguan, W., Dai, Y., Liu, B., Ye, A. & Yuan, H., 2012. A soil particle-size distribution dataset for regional land and climate modelling in China, *Geoderma,* **171–172,** 85–91.

Shi, H. & Shao, M., 2000. Soil and water loss from the Loess Plateau in China, *J. Arid Environ.,* **45,** 9–20.

Steffen, H., Petrovic, S., Müller, J., Schmidt, R., Wünsch, J., Barthelmes, F. & Kusche, J., 2009. Significance of secular trends of mass variations determined from GRACE solutions, *J. Geodyn.,* **48**(3), 157–165.

Swenson, S. & Wahr, J., 2007. Multi-sensor analysis of water storage variations of the Caspian Sea, *Geophys. Res. Lett.,* **34**(L16401), L16401, doi: 10.1029/2007GL030733.

Tang, Q., Oki, T., Kanae, S. & Hu, H., 2008. A spatial analysis of hydro-climatic and vegetation condition trends in the Yellow River basin, *Hydrol. Proc.,* **22,** 451–458.

Tapley, B.D., 2004. GRACE measurements of mass variability in the earth system, *Science,* **305,** 503–505.

Wang, H., Saito, Y., Zhang, Y., Bi, N., Sun, X. & Yang, Z., 2011. Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia, *Earth-Sci. Rev.,* **108,** 80–100.

Wang, L., Shao, M., Wang, Q. & Gale, W.J., 2006. Historical changes in the environment of the Chinese Loess Plateau, *Environ. Sci. Pol.,* **9**(7–8), 675–684.

Wenner, C.G., 1981. *Soil conservation in Kenya: especially in small-scale farming in high potential areas using labour intensive methods,* Ministry of Agriculture, Soil Conservation Extension.

Werth, S., Güntner, A., Schmidt, R. & Kusche, J., 2009. Evaluation of GRACE filter tools from a hydrological perspective, *Geophys. J. Int.,* **179**(3), 1499–1515.

Wischmeier, W.H. & Smith, D.D., 1978. Predicting Rainfall Erosion Losses - A Guide to Conservation Planning, *U.S. Department of Agriculture,* Agriculture Handbook Number 537. Washington, D.C., USA.

Wu, B., Wang, G. & Xia, J., 2007. Case study: delayed sedimentation response to inflow and operations at Sanmenxia Dam, *J. Hydraul. Eng.,* **133**(5), 482–494.

Wu, B., Wang, G., Xia, J., Fu, X. & Zhang, Y., 2008a. Response of bankfull discharge to discharge and sediment load in the Lower Yellow River, *Geomorphology,* **100**(3–4), 366–376.

Wu, B., Xia, J., Fu, X., Zhang, Y. & Wang, G., 2008b. Effect of altered flow regime on bankfull area of the Lower Yellow River, China, *Earth Surf. Proc. Land.,* **33**(10), 1585–1601.

Wu, S., Li, J. & Huang, G., 2005. An evaluation of grid size uncertainty in empirical soil loss modeling with digital elevation models, *Environ. Model. Assess.,* **10**(1), 33–42.

Yellow River Conservancy Commission, V., 2005. *Yellow River sediment bulletin 2005 (in Chinese)*.

Yue-Qing, X., Jian, P. & Xiao-mei, S., 2008. Assessment of soil erosion using RUSLE and GIS: a case study of the Maotiao River watershed, Guizhou Province, China, *Environ. Geol.,* **56**(8), 1643–1652.

Zhang, G.H., Nearing, M.A. & Liu, B.Y., 2005. Potential effects of climate change on rainfall erosivity in the Yellow River basin of china., *Trans. ASAE,* **48**(2), 511–517.

Zhang, J.T., Ru, W. & Li, B., 2006. Relationships between vegetation and climate on the Loess Plateau in China, *Folia Geobot.,* **41**(2), 151–163.

Zhang, K., Li, S., Peng, W. & Yu, B., 2004. Erodibility of agricultural soils on the Loess Plateau of China, *Soil Till. Res.,* **76**(2), 157–165.

Zhang, K.L., Shu, A.P., Xu, X.L., Yang, Q.K. & Yu, B., 2008. Soil erodibility and its estimation for agricultural soils in China, *J. Arid Environ.,* **72**(6), 1002–1011.

Zhang, X., Wang, L. & Si, F., 2001. Prediction water consumption in the Huanghe River basin., *Water Resour. Hydropower Technol.,* **6,** 8–13.