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An Assessment of Soil Loss by Water Erosion in No-Tillage and Mulching, China

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Abstract: Soil erosion poses a global threat to arable land and its sustainability, particularly in China, where the most severe soil erosion exists worldwide. No-tillage (NT) and mulching (NTS) are considered the most effective soil management techniques for reducing erosion, but only 10% of the global area utilizes them. Therefore, in comparison to conventional tillage (CT), we conducted a comprehensive national assessment of NT and NTS to evaluate their impact on water erosion across China's croplands for the period spanning 2000 to 2018, through using Revised Universal Soil Loss Equation (RUSLE); subsequently, we projected the temporal and spatial erosion distribution, and examined their effects of various underlying driving factors by using a random-forest model. Nationally, the average soil loss rates were 1085, 564, and 396 t km^{-2} a^{-1} for the CT, NT, and NTS, respectively, across the entire arable land over a span of 18 years. This represents a reduction of 48% and 64% in the NT and NTS, respectively, compared to CT. From 2000 to 2018, water erosion-induced soil loss exhibited a slightly increasing trend with a wavelike pattern in CT, NT, and NTS. The spatial distribution of water erosion in China's arable land was primarily influenced by local precipitation, accounting for 45% to 52% of the total impact on CT, NT, and NTS. Additionally, the soil slope degree played a role, contributing 29% to 36% of the erosion patterns. Overall, NT and NTS demonstrated superior performance in mitigating the soil erosion in the southern regions of China, including the Central South, Southwest, and East China, owing to the substantial local rainfall and steep terrain. In contrast, NT and NTS exhibited a lower but still significant reduction in soil loss in the northern regions of China due to the flat topography and limited rainfall. However, considering the trade-off between economic losses (yield) and ecosystem benefits (erosion control), we recommend implementing NT and NTS primarily in the northern parts of China, such as the Northeast, North China, and Northwest.

Keywords: soil erosion; water erosion; RUSLE; crop residue; conservation tillage

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1. Introduction

Soil erosion is a global threat to arable land and has been exacerbated by increasingly extreme climate events such as intense rainfall and drought accompanied by wind [1,2]. These factors have led to the degradation of various vital soil functions, including reduced stability, altered soil structure, limited biological growth, diminished water-holding capacity, and a loss of soil nutrients and organic carbon [3–6]. Globally, approximately 56% of arable land is affected by erosion [7], resulting in the loss of 75 Gt of soil [2], 1–5 Gt of soil organic carbon [8], and 23–42 Tg of soil nitrogen [9]. In China, the current soil erosion rates average 500 t km^{-2} a^{-1} [10], significantly exceeding the global average of 140 t km^{-2} a^{-1} [5].

Aside from climate change, anthropogenic activities such as deforestation, overgrazing, tillage, inappropriate agricultural practices, and urbanization contribute significantly to soil erosion, especially in arable land that undergoes more than one tillage annually [5,11,12]. Conventional tillage (CT), also referred to as traditional tillage, is the most widely practiced method that promotes extensive soil erosion. It involves inverting the soil using rotary tillers or mouldboard ploughs, which results in soil looseness, pulverization of clods, disruption of soil structure, displacement of surface soil, removal or burial of crop residue, and consequently, increased sheet erosion [13–15].

In contrast, no-tillage (NT), also known as zero tillage or direct seeding, represents the most effective management approach for reducing water-induced soil erosion in arable land [16]. Several plot studies have demonstrated the advantages of NT over CT. For instance, Madarasz et al. [17] observed a 75% reduction in soil surface runoff and a 95% decrease in soil loss in a silty loam Luvisol with low organic matter in the hilly region of southwest Hungary, comparing NT to CT on a slope of 10%. Chowaniak et al. [18] reported a 66.8% lower soil loss rate in NT compared to CT in an experiment station with a mixed soil of Eutric Cambisols and fluvioglacial sand, featuring a 9% gradient in Krakow. Similarly, Ryken et al. [19] found that soil erosion decreased from 6.1 kg under CT to 1.7 kg under NT in a small-scale plot (5 m^2) in central Belgium.

Furthermore, numerous studies have highlighted the effectiveness of no-tillage with straw mulching (NTS) in reducing overland runoff, sediment, and soil loss. McCool et al. (1997) [20] indicated that the presence of 30% surface residue cover led to only 26% soil loss compared to situations with no residue cover. Schuller et al. (2007) [21] revealed an 87% reduction in soil loss under NTS compared to CT. Prasuhn (2012) [22], based on a 10-year observation, reported that only 1% soil erosion occurred on NTS soils with over 30% surface residue, 9% on NT with less than 30% residue, and 88% on CT (plough-tilled land) soils out of a total soil loss of 1969 tons within a 263 ha catchment area. This finding illustrates the intricate relationship between soil loss and the quantity of crop residue.

Overall, previous studies have consistently demonstrated the enormous potential of NT and NTS in mitigating water-induced soil erosion in arable land, ranging from small-scale plots to field and watershed levels. However, despite these benefits, the adoption of NT globally is currently only 10% of the total cropland, and even lower in China [23]. Consequently, there is an urgent need for a large-scale assessment of soil erosion reduction achieved by NT and NTS on arable land. Such an assessment would assist policymakers and farmers in making informed decisions, selecting sustainable practices, and promoting the widespread implementation of NT and NTS.

Soil erosion, being influenced by multiple factors such as soil properties, local topography, climate conditions, vegetation cover, and human management [16], is often simulated using models at large scales due to the challenges associated with direct observation. Several models have been developed that consider the aforementioned factors. For instance, the Water Erosion Prediction Project (WEPP) is a highly accurate soil water erosion model utilized for slope landscapes and watershed scales, ranging from 1 m^2 to 1 km^2 [24]. Another model, the LImburg Soil Erosion Model (LISEM), demonstrates good compatibility with Geographic Information System (GIS) datasets, enabling effective assessment of water erosion [25]. The Universal Soil Loss Equation (USLE) is the most widely employed model for field-scale water erosion [26], along with its enhanced version, the Reversed Universal Soil Loss Equation (RUSLE) model [27]. The accuracy of these models has significantly increased due to the modern development of computer technology, the advancement of geographic information systems (GISs), and the availability of high-resolution images. In this study, we have chosen the RUSLE model to estimate the soil loss rate in NT and NTS practices at a national scale in China, considering that the WEPP model requires inaccessible datasets and LISEM's reliability is yet to be proven.

Consequently, we conducted an estimation of soil loss amounts in China's arable land under water erosion for the period from 2000 to 2018, comparing NT and NTS with conventional tillage (CT). Our specific objectives were as follows: (1) to quantitatively assess the overall potential reduction in the soil loss achievable through NT and NTS practices on a national scale in China; (2) to identify temporal variations and trends in the soil loss due to rainfall erosion under NT, NTS, and CT; and (3) to map the most effective areas for implementing NT and NTS practices to protect arable land, taking into account topographical features, climate conditions, soil characteristics, and existing management strategies.

2. Materials and Methods

2.1. Study Area

The study area specifically focuses on arable land in China for the year 2018 (Table 1), where areas not subjected to tillage practices or water erosion, including forestland, grassland, wetland, and paddy fields, were excluded from the analysis. The total area considered in the model amounts to 46.07 million ha, primarily dedicated to the cultivation of maize, wheat, and soybeans, with a limited presence of other dry cultivation species.

Table 1. The datasets used in this study.

Data Name	Description	Source
Precipitation	China daily precipitation in 0.1 degree resolution with the units of mm h^{-1} period 2000–2018	Resource and Environment Science and Data Center https://www.resdc.cn/Default.aspx. accessed on 10 February 2023.
Aridity index	Mean annual aridity from 1990 until now	Resource and Environment Science and Data Center https://www.resdc.cn/Default.aspx. accessed on 10 February 2023.
Digital elevation model (DEM)	Surface 30 m resolution digital elevation model	Geospatial Date Cloud: http://www.gscloud. accessed on 10 February 2023.
Site slope	Surface 30 m resolution land slope	Geospatial Date Cloud: http://www.gscloud. accessed on 10 February 2023.
Soil bulk density	An average of each grid cell (1 km × 1 km)	Institute of Soil Science, Chinese Academy of Sciences, Nanjing http://doi.org/10.11666/00073.ver1.db. accessed on 10 February 2023.
Soil sand content	An average of each grid cell (1 km × 1 km)	Institute of Soil Science, Chinese Academy of Sciences, Nanjing http://doi.org/10.11666/00073.ver1.db. accessed on 10 February 2023.
Soil silt content	An average of each grid cell (1 km × 1 km)	Institute of Soil Science, Chinese Academy of Sciences, Nanjing http://doi.org/10.11666/00073.ver1.db. accessed on 10 February 2023.

Table 1. *Cont.*

Data Name	Description	Source
Soil clay content	An average of each grid cell (1 km × 1 km)	Institute of Soil Science, Chinese Academy of Sciences, Nanjing http://doi.org/10.11666/00073.ver1.db. accessed on 10 February 2023.
Soil organic carbon	An average of each grid cell (1 km × 1 km)	Institute of Soil Science, Chinese Academy of Sciences, Nanjing http://doi.org/10.11666/00073.ver1.db. accessed on 10 February 2023.
Cropland	The agricultural upland soil areas of each grid cell (1 km × 1 km)	Institute of Soil Science, Chinese Academy of Sciences, Nanjing http://doi.org/10.11666/00073.ver1.db. accessed on 13 March 2022.
Maize cultivation	China maize cultivation areas in 2015 (1 km × 1 km)	https://www.nature.com/articles/s41597-022-01305-6#Sec14. accessed on 14 March 2022.
Soybean cultivation	China soybean cultivation areas in 2015 (1 km × 1 km)	https://www.nature.com/articles/s41597-022-01305-6#Sec14. accessed on 14 March 2022.
Conservation practices	Soil loss data of CT, NT, and NTS were collected from peer-reviewed literature	[28–58]

2.2. RUSLE Model

The estimation of soil loss rates in relation to different tillage practices, namely no-tillage (NT) and mulching (no-tillage with straw mulching, NTS), as compared to conventional tillage (CT), was conducted using the Revised Universal Soil Loss Equation (RUSLE):

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (1)$$

where A is the computed annual soil loss rate in t km^{-2} a^{-1}; R is the rainfall-runoff erosivity factor; K is a soil erodibility factor; LS is a topographical factor combining slope length, L, and slope steepness, S; C is a cover-management factor; and P is a supporting and conservation practices factor, i.e., mulching, no-tillage, and conventional tillage in this study.

2.3. R Factor

The R factor serves as a quantification of the driving force behind water erosion in cropland, derived precisely from climate data, specifically rainfall amount and intensity. In this study, the methods developed by Xie et al. (2000) [59] and Zhang et al. (2002 and 2003) [60,61] were employed to calculate the R factor, which is represented by the following equations:

$$Ri = a\sum^{n} Dj^{b} \quad (2)$$

$$a = 21.586b^{-7.1891} \quad (3)$$

$$b = 0.8363 + 18.144Dd12^{-1} + 24.455Dy12^{-1} \quad (4)$$

where Ri is the rainfall-runoff erosivity force in year i, in units of (MJ mm)/(ha^{-1} h^{-1} a^{-1}); Dj is the daily rainfall of day j with soil erosion threshold caused, mm; n is the days with rainfall $\geq$12 mm in each year, d; $Dd12$ is the average daily rainfall of several years with $\geq$12 mm required, mm; $Dy12$ is the average annual rainfall with daily rainfall above 12 mm, in units of mm; and a and b are the model parameters.

2.4. K Factor

The K factor is an indicator of the inherent soil erodibility, which is defined as the susceptibility of the soil to being eroded and affected by soil properties such as particle composition, structure, permeability, and the percent of organic matter. According to Williams [62], one approach to estimate the K value on a large scale is that:

$$K = (0.2 + 0.3\ \exp(-0.0256Sa(1 - \frac{Si}{100}))) \cdot (\frac{Si}{Ci - Si})^{0.5} \cdot (1 - \frac{0.25C}{C + \exp(3.72 - 2.95C)}) \cdot (1 - \frac{0.75Si}{Si +\ \exp\ (-5.51 + 22.95Si)}) \quad (5)$$

where Sa, Si, and Ci are the soil sand, silt, and clay content in %, respectively. The C is soil organic carbon content in %.

2.5. L and S Factors

The (dimensionless) LS factor represents the influence of the topography on the surface runoff and sediment transport capacity, which calculated as the following:

$$L = (l/22.13)^{\alpha} \quad (6)$$

$$\alpha = \beta/(\beta + 1) \quad (7)$$

$$\beta = (\sin\theta/0.0896)/\left[3.0(sin\theta)^{0.8} + 0.56\right] \quad (8)$$

$$S = \begin{cases} 10.8\ sin\theta + 0.03\ \theta < 9\% \\ 16.8sin\theta - 0.50\ 9\% < \theta < 14\% \\ 21.9\ sin\theta - 0.96\ \theta > 14\% \end{cases} \quad (9)$$

$$LS = L \times S \quad (10)$$

where L and S are the slope length and steepness factors; l is the slope length, m; α and β are the model parameter of slope length and steepness; and θ is the slope angle (gradient), in units of %.

2.6. C Factor

The C factor represents the extent to which erosion is reduced by human management in upland soils, specifically referring to the ratio of soil loss between a plot with a specific crop cover and an uncovered plot. For China upland, the C factor for major crops is determined based on long-term experiments spanning seven years, as reported by Zhang et al. (1992) [63]. The measured C factors were as follows: maize 0.2578, wheat 0.0704, soybean 0.2626, upland rice 0.2772, and sorghum 0.3295. To incorporate the C factor values for different crops in upland China, we utilized ArcMap 10.8 software and considered their respective distributions in the year 2019 (Table 1).

2.7. P Factor

The conservation practice factor (P) in the Revised Universal Soil Loss Equation (RUSLE) model represents the ratio of soil loss achieved with a specific conservation practice compared to the soil loss resulting from traditional up and down cultivation methods. It serves as a measure of the effectiveness of conservation practices in reducing water runoff and erosion rates [64]. In this study, the P factors for no-tillage (NT) and no-tillage with straw mulching (NTS) were computed by comparing the soil loss amounts between NT and conventional tillage (CT), as well as between NTS and CT, using the following equation:

$$P_i = \frac{A_i}{B_i} \quad (11)$$

where Pi represents the P factor of NT or NTS, Ai denotes the soil loss amount of NT or NTS, Bi represents the soil loss amount of CT. The subscript i corresponds to the number of the experiments.

Subsequently, the distribution patterns of the P factor were analyzed for different tillage practices across mainland China.

2.8. Tillage Datasets

In the present study, a comprehensive search of peer-reviewed literature was conducted to gather data on the soil loss amount for calculating the P factors of NT, NTS, and CT. Web of Science, Google Scholar, Springer Link, Scopus, and China Knowledge Resource Integrated Database (CNKI) were searched by using the scientific terms related to no-tillage, conservation tillage, conservation agriculture, straw return and/or mulching, soil water erosion, and the runoff, spanned from 1980 to March 2023. Several criteria were used to select and choose relevant publications, including the following: (1) the article should be formatted in English and Chinese; (2) laboratory-simulated tests were excluded, and only field experiments were considered; (3) studies comparing at least one pair of NT to CT, or NTS to CT were required, with CT commonly referred to as ploughing, rotary tillage, rotary hoe, disc harrow, or mouldboard ploughing; (4) soil loss amounts resulting from water erosion had to be measured and easily accessible; (5) the experiments had to be conducted within mainland China, with a minimum of three replications for each experiment; (6) equal management practices were applied to each treatment, including the same crop species, fertilizers, pesticides, machinery operations, and weed control. The screening process yielded 183 matched experiments from 31 papers as references (Table 1).

The average amounts of soil loss in NT, NTS, or CT were collected from paper tables by hand-reading, or figures by using a software named Get Data Graph Digitizer (version 2.26).

2.9. Other Datasets

Other datasets used in the study to support the estimating model were collected from various sources, see details in Table 1. The daily precipitation from 2000 to 2018 was obtained from the Resource and Environment Science and Data Center, through accessing the internet website with the link of https://www.resdc.cn/Default.aspx on 10 February 2023, for example. Similarly, aridity index, digital elevation model (DEM), site slope, soil bulk density, sand, clay, silt, and organic carbon contents, wheat and maize cultivated areas, as well cropland areas were collected (Table 1). All these datasets, formatted with various resolutions, were normalized into a standard resolution of 1 km^2 by using the "GeoPandas" package from the python software with the version of 37, for further computing.

2.10. Model Accuracy and Validation

To assess the performance of our model, we compared the simulation results with a previous study by Li et al. (2021) [65] published in the Journal of Global Change Data and Discovery. They reported estimated national-scale water erosion of soils under various land types, including forestland, grassland, wetland, paddy soil, and arable land. For our evaluation, we randomly selected 5000 grid cells of arable land at a scale of 1000 m $\times$ 1000 m from their dataset for the years 2000, 2010, and 2015, compared with a corresponding 5000 cells in our result. However, since we lacked the NT and NTS soil erosion data, we could only compare the conventional tillage (CT) treatment between their results and ours. Subsequently, we tested the linear regression relationship between their results and our simulations, and calculated the correlation coefficient (r), mean absolute error (MAE), and root mean square error (RMSE) using the following equations:

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n} |x_1 - x_2|}{n} \quad (12)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (x_1 - x_2)^2}{n}} \quad (13)$$

where x_1 and x_2 were the annual soil loss rates in the research conducted by Li et al. (2021) [65] and our simulation, respectively; while n denotes the total number of pared sites.

3. Results

3.1. Soil Erosion Factors

The results depicting the soil erosion factors for different tillage practices are illustrated in Figure 1. The rainfall erosivity factor (R) exhibited a wide range of values, ranging from 0 to 27,694.3 (MJ mm)/(hm^2 ha), across the Chinese mainland in 2010. The highest R values were observed in the southern region, while the lowest values were observed in the northern region (Figure 1A). In the Northwest, characterized by an arid climate with infrequent precipitation, a no-data area was identified. Overall, there was a noticeable increase in R values from south to north and from west to east in China (Figure 1A).

The soil erodability factor (K) exhibited minimal variation across the entire mainland, except in the Northwest region where water erosion caused more pronounced soil displacement potential (Figure 1B). In the eastern part of China, particularly in the Northeast plain, North China plain, and the Yangtze plain—regions that contribute significantly to China's food production—the slope length (L), steepness (S), and their combined factor remained consistently small and stable (Figure 1C). The crop covering factor (C), ranging from 0.0704 to 0.2897 without dimension, displayed a strong correlation with the spatial distribution of wheat and maize, which are the primary cultivated crops in China (Figure 1D). The conservation practice factor (P) was used to illustrate the potential soil loss by water under different tillage practices. In this context, Figure 1E represents conventional tillage (CT) with a fixed value of 1, Figure 1F represents no-tillage (NT) with values ranging from 0.21 to 1.01, and Figure 1G represents no-tillage with straw mulching (NTS) varied from 0.042 to 0.8.

3.2. Soil Amount of Water Erosion as Affected by NT and NTS

3.2.1. Temporal Variation

The modeling results indicate a significant reduction in average soil loss rates under NT and NTS across the entire arable land of China from 2000 to 2018. Specifically, the NT exhibited a 48% decrease in soil loss rates (564 t km^{-2} a^{-1}), while the NTS demonstrated an even greater reduction of 64% (396 t km^{-2} a^{-1}) when compared to CT, which had a rate of 1085 t km^{-2} a^{-1} (Figure 2). In 2000, the national average soil loss rate for CT was 1048 t km^{-2} a^{-1}, slightly lower than the mean of CT over the 18-year period (1085 t km^{-2} a^{-1}), but higher than both NT (557 t km^{-2} a^{-1}) and NTS (396 t km^{-2} a^{-1}) within that same year. The rates for CT were nearly two and two-and-a-half times greater than those of NT and NTS, respectively (Figure 2).

From 2000 to 2018, soil water erosion exhibited a fluctuating tend in CT, NT, and NTS across China, with a slight overall increase. The highest erosion values were observed in 2003 and 2016, while the lowest values occurred in 2004 and 2011 (Figure 2). Ultimately, the average soil erosion rates in 2018 were 1122, 573, and 410 t km^{-2} a^{-1} for CT, NT, and NTS, respectively. These rates were similar to those recorded in 2017 (Figure 2).

3.2.2. Spatial Variation

According to the spatial distribution of average soil loss rates per grid cell in CT, NT, and NTS (Figure 3A–C show 2000; Figure 4A–C show 2018), the intensity of soil erosion in China's cropland was highest in the south, followed by the northeast region. Interestingly, the reduction rates of soil loss by NT and NTS were also highest in these regions. Despite having smaller cropland areas, the gross soil loss amount, which represents the total annual mass of soil loss in regional arable land (based on the regions shown in Figure 1H), was the highest in the south of China, including the Central South (CS) and Southwest (SW), under CT, NT, and NTS from 2000 to 2018 (Figure 2D for 2000, Figure 3D for 2018; other years not shown). Specifically, the CS and SW regions had soil loss amounts of 29.2 and 24.5 million tons (Mt) in 2000, and 23.8 and 22.8 Mt in 2018, respectively, under CT (Figures 3D and 4D). These amounts were reduced by 28% to 51% under NT, and by 54% to 62% under NTS.

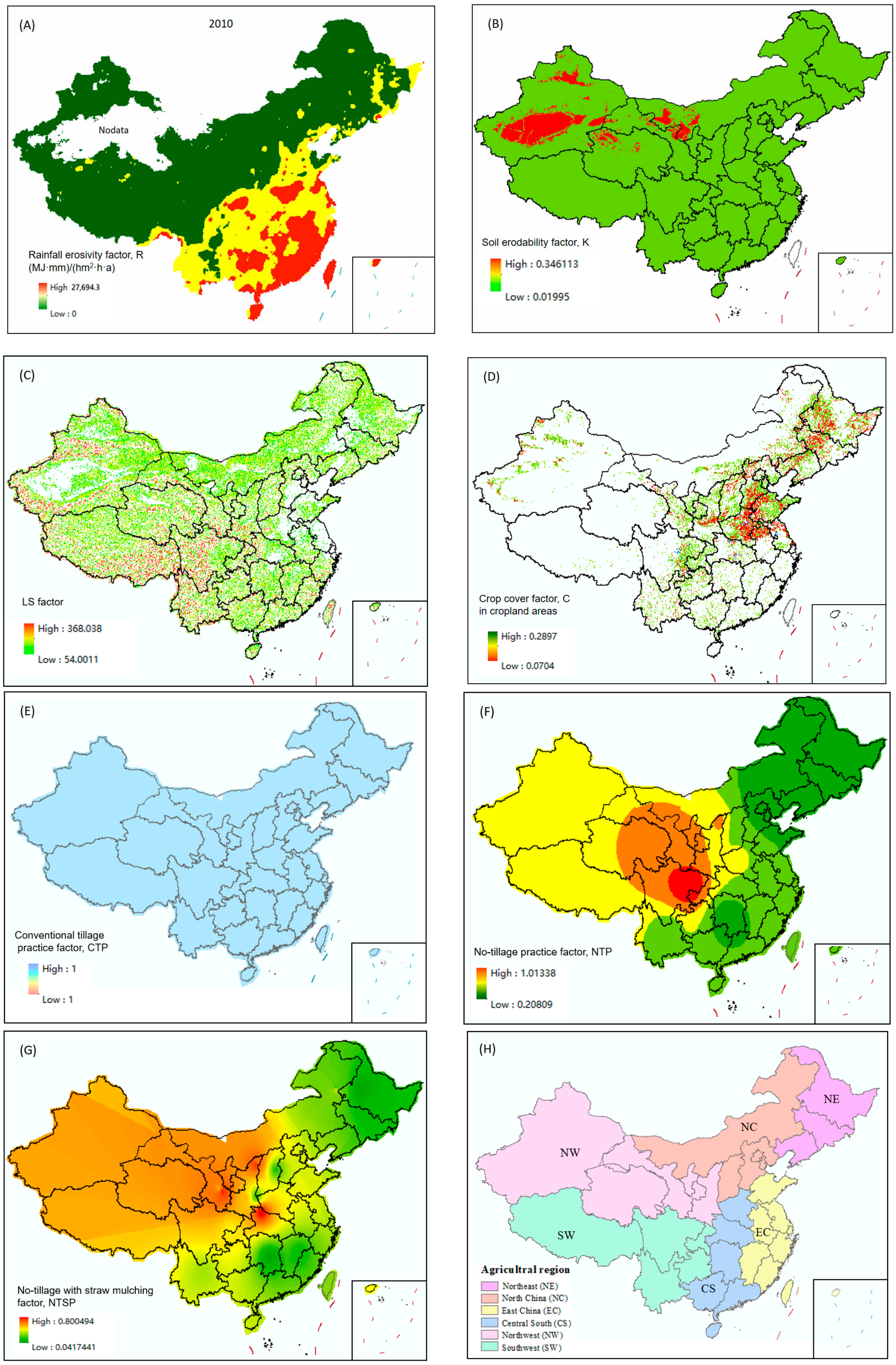

Figure 1. Spatial distributions of driver factors from model calculating. They are rainfall-erosivity factor (**A**), soil erodability factor (**B**), slope length and steepness factor (**C**), crop covering factor (**D**), and tillage practice factors of the conventional tillage (**E**), no-tillage (**F**), and no-tillage with straw mulching (**G**). Figure (**H**) is the major regions of China mainland used in this analysis.

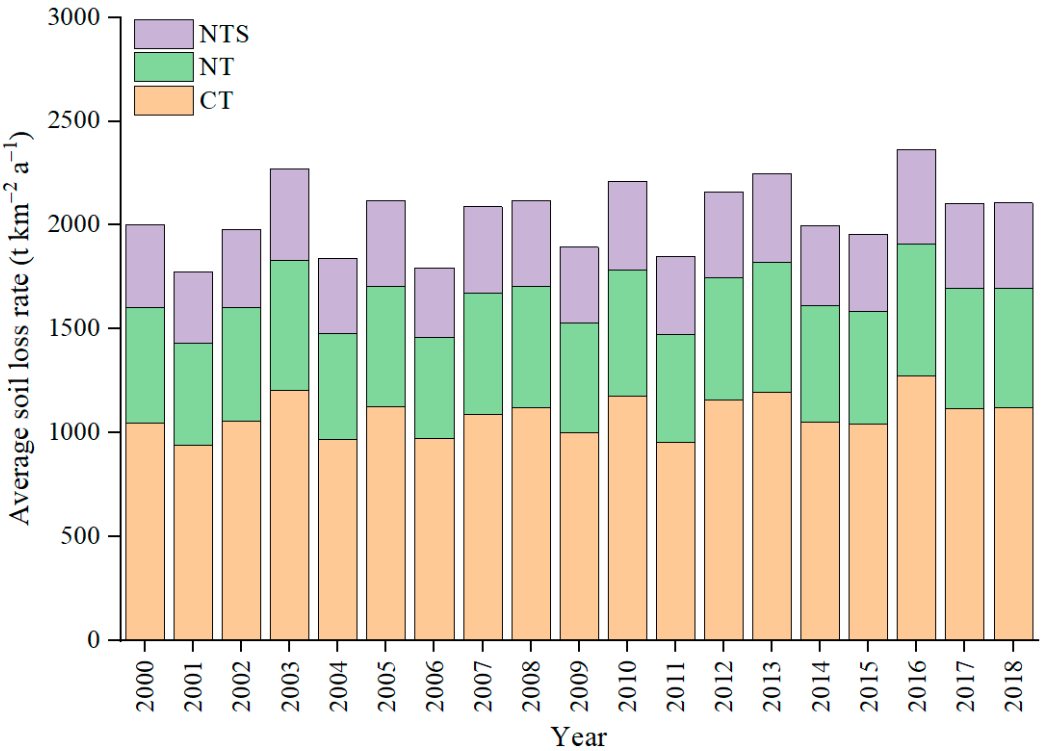

Figure 2. Annual average soil loss rate in different tillage practices in China from 2000 to 2018.

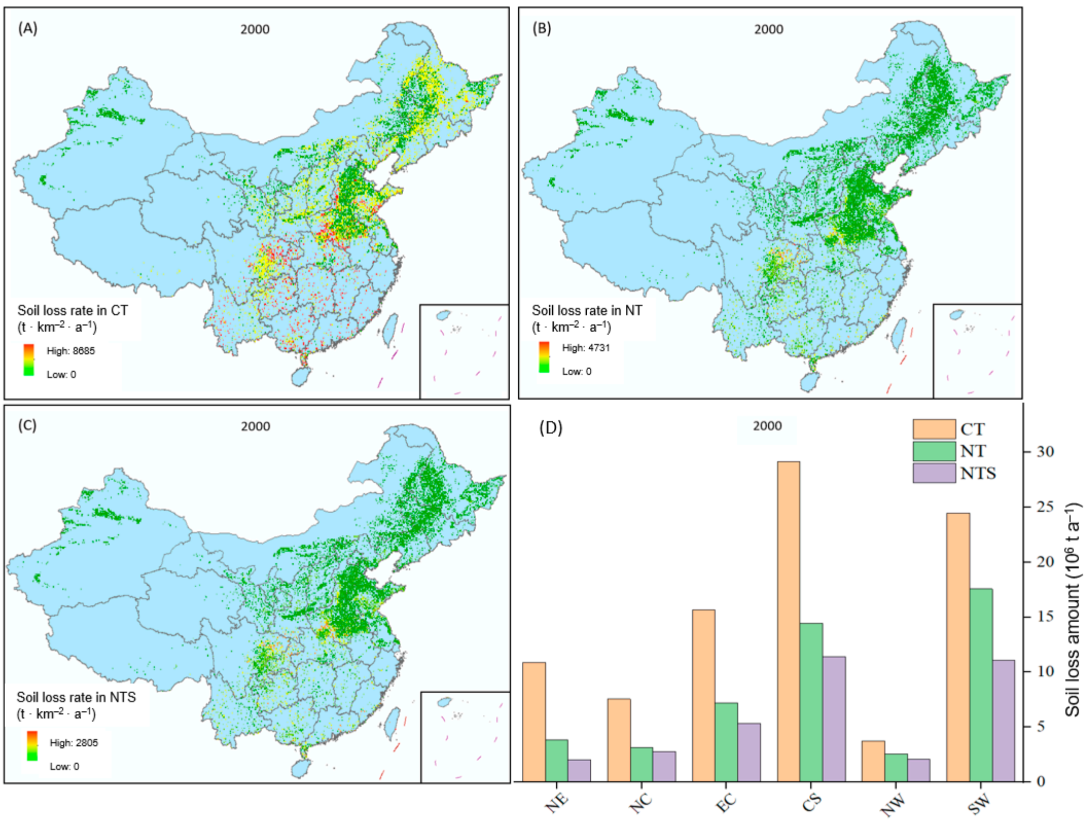

Figure 3. Soil loss amount in CT (**A**), NT (**B**), and NTS (**C**), and their total loss amount (**D**) in areas of the Northeast (NE), North China (NC), East China (EC), Central South (CS), Northwest (NW), and the Southwest (SW). All from 2000.

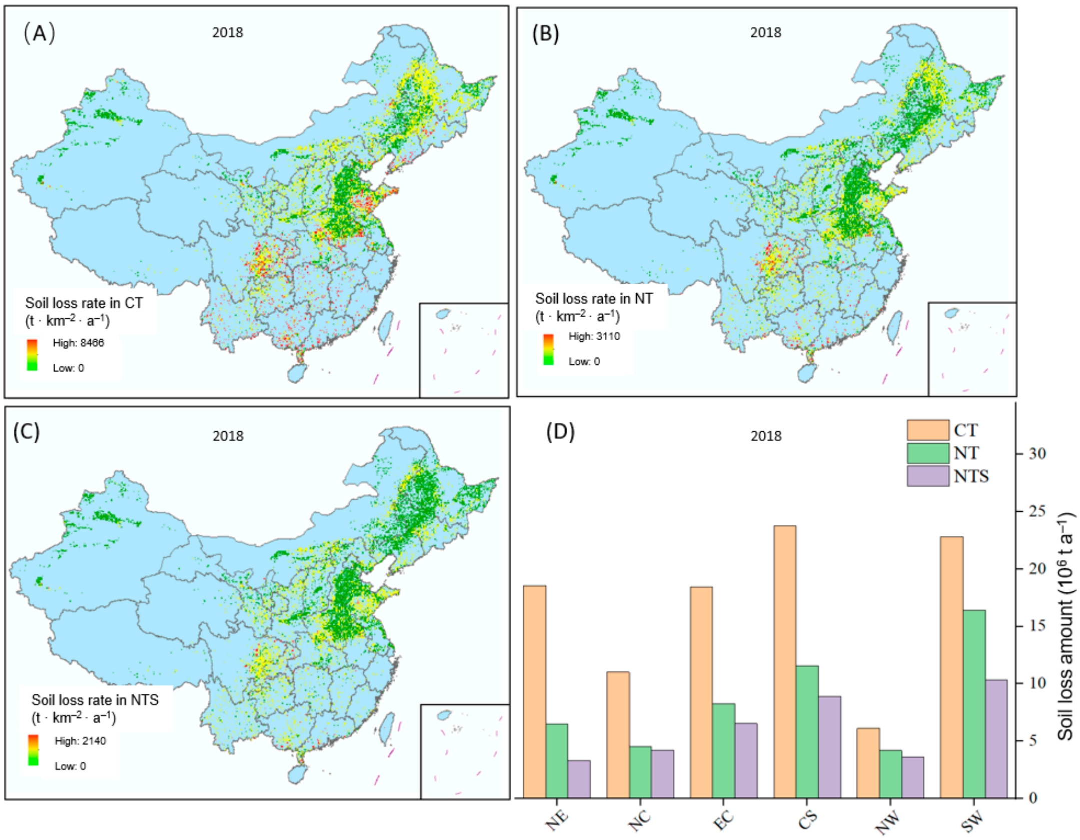

Figure 4. Soil loss amount in CT (**A**), NT (**B**), and NTS (**C**), and their total loss amount (**D**) in areas of the Northeast (NE), North China (NC), East China (EC), Central South (CS), Northwest (NW), and the Southwest (SW). All from 2018.

Conversely, the Northwest area exhibited the lowest soil loss amount (Figures 3D and 4D) due to the lack of arable land in that region. Moderate and relatively similar levels of soil erosion were observed in the major food production regions of China, namely the Northeast plain (NE) and the East China (EC) area (Figures 3 and 4). In CT, the total soil loss amount in 2000 was 10.8 Mt a^{-1} for NE and 15.7 Mt a^{-1} for EC. By 2018, these value had increased to 18.6 Mt a^{-1} for NE and 18.4 Mt a^{-1} for EC (Figures 3D and 4D), indicating a significant regional increase in soil loss over time. The total soil loss amount in the NE and EC regions declined by 54% to 65.8% under NT and by 64.6% to 82.2% under NTS compared to CT during the period from 2000 to 2018 (Figures 3D and 4D).

3.3. Soil Areas of Water Erosion as Affected by NT and NTS

To assess erosion risks, we classified soil loss amounts into six categories based on the Soil Erosion Classification Standard (SL190-2007) from the People's Republic of China. These categories included tolerable, slight, moderate, severe, very severe, and destructive erosion defined by thresholds of 0–200, 200–2500, 2500–5000, 5000–8000, 8000–15,000, and (>15,000) t km^{-2} a^{-1}, respectively.

In CT, NT, and NTS, a significant portion of Chinese arable land was found to experience tolerable (class 1) to slight (class 2) erosion (Table 2). In the NE region, for example, 92% of the 24,796 ha of arable land experienced tolerable and slight erosion in CT, with 8924 and 14,000 ha affected, respectively (Table 2). This percentage increased to 96% in both NT and NTS when implemented as replacements. Notably, there was a clear trend of increasing areas of tolerable and slight erosion from CT to NT and NTS. The proportions of these erosion classes varied from 81% to 82% in the North China (NC), 79% to 95% in the EC, 71% to 88% in the CS, and 48% to 64% in the SW (Table 2).

Table 2. Soil erosion areas in various regions under CT, NT, and NTS, in the year 2018.

Region	Cropland	Tillage	Tolerable	Slight	Moderate	Severe	Very Severe	Destructive
NE	24,796	CT	8924	14,000	697	90	0	0
		NT	13,974	9738	0	0	0	0
		NTS	19,205	4507	0	0	0	0
NC	27,505	CT	10,771	11,520	271	0	13	0
		NT	15,046	7517	0	13	0	0
		NTS	15,240	7323	0	13	0	0
EC	18,528	CT	8459	6148	2428	646	77	0
		NT	9958	7258	517	26	0	0
		NTS	10,319	7310	129	0	0	0
CS	18,479	CT	5838	7297	2415	775	387	39
		NT	6897	8705	943	168	39	0
		NTS	7375	8898	439	39	0	0
NW	23,433	CT	7878	5851	220	77	13	13
		NT	8627	5256	129	26	13	0
		NTS	9105	4817	116	0	13	0
SW	19,735	CT	1550	7891	3061	542	103	13
		NT	2015	9376	1485	271	13	0
		NTS	2583	10,074	478	13	13	0

Note: The unit of numbers in table was 10^3 ha.

Conversely, the areas affected by moderate (class 3), severe (class 4), very severe (class 5), and destructive (class 6) erosion were decreased when CT was replaced by NT or NTS (Table 2). The areas of moderate erosion in the NE (697,000 ha) and the NC (271,000 ha), severe erosion in the NE (90,000 ha), EC (646,000 ha), and NW (77,000 ha), very severe erosion in the NC, EC, and CS, as well as destructive erosion in the CS, NW, and SW, all dropped to zero ha when CT was changed to NT and NTS (Table 2). Although there were extreme declines in these erosion classes, other high erosion areas in CT were reduced by NT and NTS. For instance, the moderate erosion areas in the EC of CT, which covered 2,428,000 ha, decreased to 517,000 and 129,000 ha in the NT and NTS, respectively (Table 2). Similar patterns were observed in the CS, NW, and SW regions (Table 2). In general, in areas with low erosion the severity increased with the implementation of NT and NTS, while in areas with high erosion the severity decreased.

3.4. Soil Water Erosion under NT and NTS as Affected by Different Factors

To evaluate the relative importance of natural drivers such as topographical features, climate factors, and soil properties, on simulated soil loss rates due to water erosion under CT, NT, and NTS, we conducted a multivariate random forest model analysis. The analysis showed that precipitation played a significant role in all three treatments, with contributions of 45% for CT, 52% for NT, and 49% for NTS (Figure 5A). The slope of the field was also found to be particularly important in explaining soil erosion variations under CT (36% contribution), NT (29% contribution), and NTS (34% contribution). The combined influence of precipitation and slope varied between 79% and 83%. Soil properties, including sand, silt, clay, and soil organic carbon (SOC), also influenced the soil erosion rates, although their contributions were relatively lower compared to the aforementioned factors (Figure 5A).

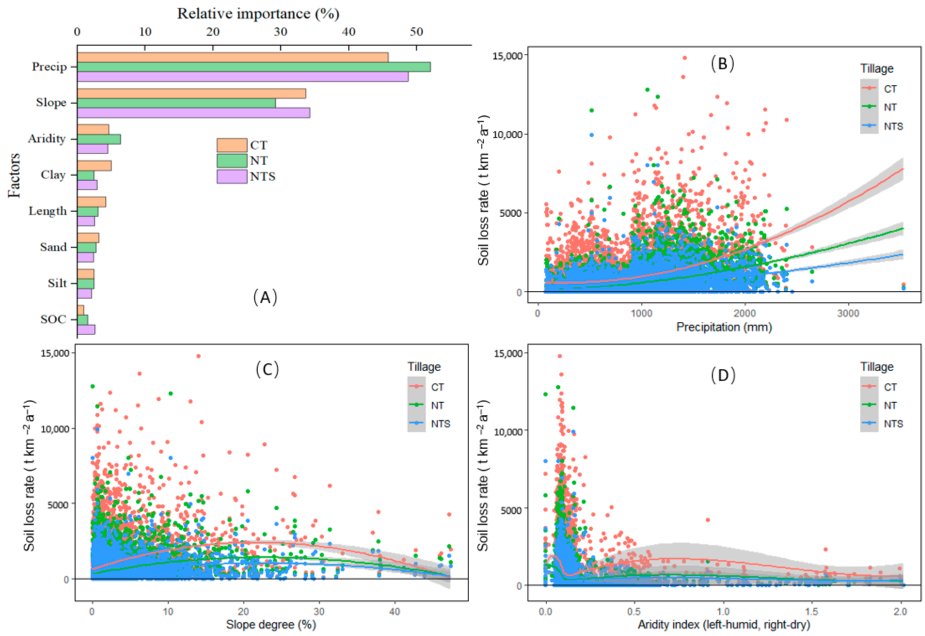

Figure 5. Soil erosion as affected by different factors (**A**), and their variations under precipitation (**B**), slope degree (**C**), and aridity index (**D**).

In particular, the soil loss rates due to water erosion increased significantly with precipitation, following an exponential function. The highest increase was observed under CT, especially in areas with annual precipitation exceeding 1000 mm (Figure 5B). Additionally, the soil loss amounts increased from zero to a peak within a slope range of 0 to approximately 20% for all treatments (CT, NT, and NTS), and then steadily decreased to zero t km^{-2} a^{-1} as the slope increased from 20% to 48% (Figure 5C). However, it is worth noting that most of the research sites were located within the initial slope range of 0 to 20% (Figure 5C, left).

4. Discussion

4.1. Validation of Model Results

Although the RUSLE model has been widely utilized to study water erosion at a global scale [2,5,12,66] and in mainland China [10,67–69], its application in assessing soil loss under NT and NTS at a large scale is limited. In this study, we compared the soil loss rates under CT in 2000, 2010, and 2015 with similar field soil loss data published by Li et al. (2021) [65] to validate our models. The selection of this dataset was based on the good correspondence between our results and those of Li et al. [65] in terms of spatial and temporal scales, as well as the high quality of their data (which is published in the Journal of Global Change Data and Discovery). Our model results were credible in large areas of simulation, according to the RMSE (353, 447, and 259), MAE (233, 298, 186), and the r (0.56, 0.49, 0.63) for years 2000, 2010, and 2015 (Figure 6). Furthermore, it is worth noting that the correlation of soil loss rates indicated that our model results were slightly lower than those of Li et al. [65], as evident from the linear regression relationship of y = 0.6x + 90, y = 0.57x + 178, and y = 0.62x + 60 in 2000, 2010, and 2015, respectively (Figure 6). One possible explanation for this discrepancy is that we used a value of 1 to represent the P factor for CT (Figure 1), which may underestimate the soil loss rates caused by tillage disturbance under CT.

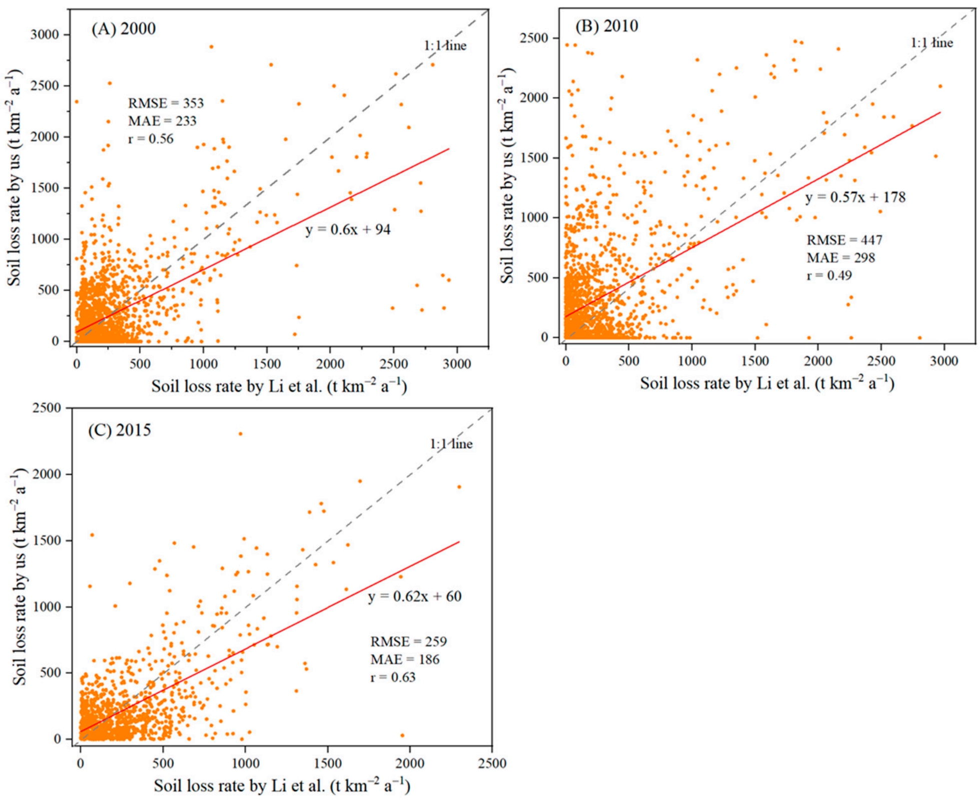

Figure 6. RUSLE model performance evaluated by the correlation between the soil loss rate from our calculation and Li et al. [65] in 2000 (**A**), 2010 (**B**), and 2015 (**C**), respectively. For each year, 2000 sites were selected randomly from the erosion areas under CT treatment.

4.2. Soil Water Erosion as Affected by NT and NTS

From 2000 to 2018, soil loss amounts were reduced by NT and NTS by 48% to 64% compared to CT (1058 t km^{-2} a^{-1}) across the entire arable land of China (Figure 2). This finding aligns with numerous previous studies conducted at smaller scales such as plots, watersheds, slope landscapes, and concrete boxes [1,13,16,18]. However, to the best of our knowledge, our study represents the first national-scale assessment of NT and NTS erosion in China. The underlying mechanisms have been well described in these smaller-scale studies. The reduction in soil loss under no-tillage (NT) can primarily be attributed to the improved soil structure. In conventional tillage (CT), extensive soil surface disturbance leads to the breakdown of soil aggregates, resulting in the generation of erodible particles [19]. This, in turn, increases the soil's detachment capacity and roughness, while decreasing its resistance to erosion by the concentrated runoff [70,71]. Additionally, the exposed and drier aggregates in CT are susceptible to slaking (re-breakdown) during initial rainstorms [72]. In contrast, under NT, the soil surface structure remains undisturbed due to the absence of mechanical tillage (only a narrow hole or furrow strip, approximately 20–30 mm wide, is required for seeding) [73]. Consequently, inter-particle consolidation, higher soil strength, increased bulk density, higher biomass content, improved infiltration, and enhanced water retention capacity are observed in NT [74,75]. Compared to CT, NT exhibits reduced runoff due to higher infiltration, thereby reducing soil and sediment transportation. Furthermore, the soil detachment capacity is decreased by the greater strength and consolidation observed in NT, and the slaking of aggregates is eliminated due to the presence of moisture in the soil prior to rainfall, as well as the avoidance of direct raindrop impact. This is a key reason why some literature reports lower soil and sediment loss rates in NT, despite runoff being equal to or less than CT [18].

Moreover, NTS (no-tillage with mulching) is even more effective in reducing soil erosion due to its greater crop residue cover. In addition to the structural improvements offered by NT, NTS involves the application of at least 30% crop residue mulching, which significantly reduces the soil surface runoff (as evidenced by a 71% reduction in a global meta-analysis [76]). This mulching serves to protect the soil surface from the energy of the raindrop impact and surface flow, thus reducing aggregate breakdown, surface sealing and crusting, and the clogging of wormholes or voids between structural units.

4.3. The Variation of Water Erosion as Affected by NT, NTS, and Natural Factors

4.3.1. Temporal Variation

Our simulation revealed a slight increase in the annual average soil loss amount in China's arable land from 2000 to 2018 (Figure 2), which aligns well with a previous study by Li et al. (2021) [65]. According to their findings, the average soil loss amount due to water erosion was 3863, 3735, 4903, and 4784 t km^{-2} a^{-1} for the years 2000, 2005, 2010, and 2015, respectively, indicating a rising trend. Although our study identified a significant effect of precipitation amount on water erosion spatial patterns in arable land (Figure 5B), the observed increase in soil erosion over time may not be solely driven by changes in precipitation amount. This is because the annual average precipitation during the study period (2000 to 2018) did not show a clear increase based on our datasets. However, it is important to note that the average intensity of rainfall, particularly during heavy storms, experienced a significant increase and exhibited fluctuations that correlated with the fluctuation in soil loss rates during these years [31]. Therefore, we believe that the increased frequency and magnitude of extreme rainfall events were the primary factors contributing to the observed increase in erosion. Nevertheless, multiple studies have indicated that extreme climate events, including higher temperatures, heavy storms, and drought conditions, are expected to occur more frequently in the near future [77–79].

4.3.2. Spatial Variation

In China's arable land, the distribution of soil loss amounts under CT, NT, and NTS was initially well correlated with local precipitation (contributions of 45% to 52%). Subsequently, it varied with the slope degree (contributions of 29% to 36%; Figure 4). Specifically, the implementation of no-tillage (NT) and mulching (NTS) demonstrated notable efficacy in reducing soil water erosion in the southern regions, namely the Central South (CS), East China (EC), and Southwest (SW) areas. This resulted in a reduction in annual soil loss amounts by 28% to 62% between 2000 and 2018 (Figures 3 and 4). Additionally, NT and NTS significantly mitigated the soil erosion intensity in these areas. A clear decline in erosion areas was observed, transitioning from moderate (class 3), severe (class 4), very severe (class 5), and destructive (class 6) erosion to significantly lower levels as slight erosion (Table 2). However, caution is warranted when considering the widespread adoption of NT and NTS in these regions, as the substantial reduction in erosion was primarily achieved at the expense of potential crop yield (economic) loss [23]. It is worth noting that no-tillage has been associated with significant yield decreases in humid areas globally [37], and the southern part of China experiences high humidity [80]. Moreover, the soil in these areas tends to have a high bulk density, greater soil strength, and low soil organic carbon content, further limiting the potential yield under NT. Therefore, we suggest that no-tillage may not be the optimal method for water erosion control in South China.

Conversely, NT and NTS may be suitable for implementation in the Northeast (NE), North China (NC), and Northwest (NW) regions, although their soil loss trend were less than CS and SW regions (Figures 3 and 4). In the NE region, where the most fertile and flat soil, i.e., the black soil, is predominantly found, with a high soil organic content, low soil strength and bulk density, and favorable precipitation patterns, NT has the potential to maintain comparable or slightly reduced yields; it has even been particularly effective in increasing yields in major crop plantation areas such as the Songnen and Liao River Plain [81]. Additionally, the reduction ratios of NT and NTS compared to CT were high in the NE region, at 54% and 64.6% in 2000 and 2018, respectively (Figures 3 and 4). In the NC and NW regions, the total soil loss was relatively low due to the limited arable land area and scarce rainfall (Figures 3 and 4, Table 2). Once again, no-tillage appears to be a suitable practice in these regions due to its enhanced soil water retention capabilities.

5. Conclusions

In China's arable land, the estimated soil loss rates due to water erosion were 1085 t km^{-2} a^{-1} under conventional tillage (CT). Furthermore, these rates were reduced by 48% and 64% under no-tillage (NT) and mulching (NTS) practices, respectively, from 2000 to 2018. The spatial distribution of soil loss was primarily influenced by annual precipitation and local slope, contributing together to 79% to 83% of the variations observed. While NT and NTS demonstrated excellent performance in the southern regions of Central South (CS), East China (EC), and Southwest (SW), it is not advisable to widely implement these practices in these areas due to limitations in soil structure and the potential for economic losses. Conversely, taking into account both soil and climatic conditions, NT and NTS practices are recommended for extensive adoption in the northern regions, including the Northeast (NE), North China (NC), and Northwest (NW).

Author Contributions: F.J. and S.H. proposed the research concept; S.Z., Y.W. and Y.G. collected the data from papers and other sources; F.D. and J.W. ran the model, and produced figures and tables; Z.C. and G.C. wrote the initial manuscript; F.J. and S.H. reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: We collected data from various resources, all of them are stated in Table 1.

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