Progress in Dust Modelling, Global Dust Budgets, and Soil Organic Carbon Dynamics

Weixiao Chen¹,²,³, Huan Meng¹,⁴,*, Hongquan Song¹,⁵ and Hui Zheng¹,⁴,*

¹ Key Laboratory of Geospatial Technology for Middle and Lower Yellow River Regions, Ministry of Education, Henan University, Kaifeng 475004, China; wxchen@niglas.ac.cn (W.C.); menghuan@henu.edu.cn (H.M.); hqsong@henu.edu.cn (H.S.)
² Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
³ University of Chinese Academy of Sciences, Beijing 100049, China
⁴ Institute of Urban Big Data, College of Geography and Environmental Science, Henan University, Kaifeng 475004, China
⁵ Henan Key Laboratory of Integrated Air Pollution Control and Ecological Security, Kaifeng 475004, China
* Correspondence: zhenghui@vip.henu.edu.cn
† These authors contributed equally to this work.

Abstract: Dust emission is an important corollary of the soil degradation process in arid and semi-arid areas worldwide. Soil organic carbon (SOC) is the main terrestrial pool in the carbon cycle, and dust emission redistributes SOC within terrestrial ecosystems and to the atmosphere and oceans. This redistribution plays an important role in the global carbon cycle. Herein, we present a systematic review of dust modelling, global dust budgets, and the effects of dust emission on SOC dynamics. Focusing on selected dust models developed in the past five decades at different spatio-temporal scales, we discuss the global dust sources, sinks, and budgets identified by these models and the effect of dust emissions on SOC dynamics. We obtain the following conclusions: (1) dust models have made considerable progress, but there are still some uncertainties; (2) a set of parameters should be developed for the use of dust models in different regions, and direct anthropogenic dust should be considered in dust emission estimations; and (3) the involvement of dust emission in the carbon cycle models is crucial for improving the accuracy of carbon assessment.

Keywords: dust emission; wind erosion; dust models; dust cycle; carbon cycle

1. Introduction

The aeolian and fluvial processes play a fundamental role in earth systems and have important environmental and ecological effects at both local and global scales [1]. Wind erosion is a natural geological process involving the detachment, transport, and deposition of soil particles by strong winds [2–5], and it is a key soil degradation process in arid and semi-arid areas worldwide [6–9]. In contrast to water erosion, where the eroded material follows determined paths, wind-eroded material is widely dispersed over the landscape [10]. The mineral dust generated by soil particle emissions, in turn caused by wind erosion, is considered the most important source of atmospheric aerosols [11]. The global annual emission amount of mineral dust due to wind erosion is estimated to be around 1 to 5 billion (10⁹) tons [11–14], which account for approximately 30–50% of the total aerosol introduced into the atmosphere [15]. Dust aerosols play important roles in regulating the Earth’s radiation budget, climate, global biogeochemical cycles, terrestrial soil formation, air quality, and human health [16–30].

To assess the socio-economic and environmental effects of dust processes, it is essential to quantify the dust emission rates at different spatial and temporal scales. Dust emission involves complex interactions among soil properties, climate, vegetation, and land use regimes. The understanding of dust processes and the capability of dust emission models...
have improved considerably over the past five decades. Based on the measured physical properties of dust emission at the field scale, several approaches have been adopted to estimate dust emission rates, such as mathematical simulation using data on the relationships between meteorological records and interacting surface parameters [31], remote sensing [32,33], and using geographic information systems (GIS) [34–37]. Numerous dust models have been developed to quantify dust emission rates and soil losses in the field [38,39], regional [40,41], continental, and global scales [42,43].

Soil is the main terrestrial reservoir of organic carbon and contributes substantially to the global carbon cycle [1,44]. Small changes in the soil organic carbon (SOC) stock may result in large changes in atmospheric carbon dioxide (CO₂) concentration [4,45]. Dust emission is an essential component of the carbon budget; it removes carbon from vast areas and, if the wind is strong enough, readily transports carbon dust offshore [46,47]. Thus, soil redistribution through dust mobilisation is an important mechanism underlying carbon cycling in terrestrial ecosystems, the atmosphere, and oceans. The active component of SOC and the organic carbon combined with the fine fraction of the soil are easily removed from terrestrial ecosystems via dust emission [48]. Wind-driven mobilisation of carbon augments the net loss of carbon from terrestrial systems.

In this review, we discuss empirical and physical dust models at multiple spatial scales, developed worldwide over the past five decades; the effects of dust emission on global dust budgets and SOC dynamics; and the link between dust processes and the global carbon cycle.

2. Dust Models Adopted Worldwide
2.1. Factors Influencing Dust Emissions at Multiple Scales

Dust emission is a dynamic natural process regulated by complex interactions among the climate, soil properties (grain size, aggregation, structure, moisture, and surface roughness), vegetation (cover, distribution, and height), and land use at different spatial and temporal scales [3,34,49–54]. This process is recognised as a major source of uncertainty in climate models [55,56].

Dust emission is essentially a flow process in which soil is detached from an erodible surface and transported in various ways (surface creep, saltation, and suspension) in response to wind shear stress (Figure 1) [57]. Dust transport mechanisms redistribute soil and associated nutrients and organic materials at different spatial scales (Figure 1). The mechanism by and the distance to which soil particles are transported are determined by their size. Large (>500 µm) and medium-sized (100–500 µm) particles are more likely to be transported via surface creep and saltation, respectively, over relatively short distances; smaller particles (<100 µm) can be transported via suspension over longer distances, across regions, continents, and the world [32,57–61].
The development of dust models requires an understanding of the factors affecting dust emission at different spatial scales. At the grain scale (<$10^{-2}$ m), dust emission is controlled by wind shear speed and the structure, texture (particle size distribution), moisture content, mineral composition, electrostatic forces, chemistry, and microbiota composition of the soil (Figure 1) [57,62–70]. Together, these factors determine the weight, drag, and interparticle cohesion of soil aggregates and threshold friction velocity ($u^*$) [57]. The $u^*$, which controls both frequency and intensity of erosion events, is the minimum friction velocity required to initiate the movement of soil particles, representing the strength of forces among the soil particles and the capacity of an aeolian surface to resist wind erosion [60,71–73]. This crucial parameter controls the frequency and intensity of dust emission. Soil erodibility is defined as the susceptibility of soils to detach and transport by erosive agents, namely water or wind. Soil erodibility is also dependent on the intrinsic properties of soils (include texture, mineralogy, chemistry, and organic matter content) and the combined influence of temporal soil properties, namely moisture, aggregation, surface crusting, and the availability of loose erodible material [57,66,68,69,74–77]. At the field scale, the grain-scale conditions of soil texture, soil moisture, and inter-particle bonding control soil aggregation and crusting, and thus, influence soil particle movement and the potential for dust emission [74,75]. Aggregation and crusting affect soil surface roughness, $u^*$, and the availability of loose erodible soil particles. The latter parameters affect soil erodibility at the landscape ($10^3$ m) scale [62].

At the landscape scale, dust emission is determined by soil type, vegetation cover, cultivation practices, soil surface roughness, $u^*$, and the availability of loose erodible material [57]. However, at the regional to global scales (>10$^4$ m), the transport, transformations, and deposition of dust particles, and their chemical reaction with air pollutants are affected by soil type, landforms, climate, ecoregional environmental conditions, and practices of land use and land management [76]. Together, these factors determine the
relative influence of soil moisture, aggregation, and crusting on the soil surface, as well as the spatial and temporal variations in soil erodibility at the field scale. The regional climate, other ecoregional conditions, and land use practices may, in turn, be affected by dust transport and deposition. This interdependence generates feedback that affects soil erodibility at various scales, from the landscape to the microscopic [57].

2.2. Dust Models at Multiple Spatial and Temporal Scales

To understand the role of dust in the earth system, numerous models that simulate dust emission at various spatial and temporal scales have been developed since the 1960s [38,78–81]. Most of these models are used to predict dust emission rates. Dust models can be divided into empirical and physical types [7]. Empirical models are based on functions derived from field or wind tunnel experiments under a wide variety of soil types and soil surface roughness conditions. Physical dust models focus largely on the physical mechanisms of dust movement and predict patterns of dust emission, transport, and deposition driven by climate, land use, and/or the land management measures being employed. The evolution of the dust models reviewed in this study is illustrated in Figure 2. We systematically reviewed a representative selection of 18 dust models developed over the past 60 years.

Dust models usually concentrate on smaller (<100 µm in diameter) soil particle emissions, as such particles can be suspended in the atmosphere and transported over long distances [61]. One such model is the wind erosion equation (WEQ) developed by Woodruff and Siddoway [38] from empirical functions that describe the effects of environmental factors on the rate of soil loss. Physical models were developed mainly in the 1980s (Figure 2). As shown in Figure 2, before 2000, dust models mainly constituted dust emission modules at the field scale (e.g., WEQ, wind erosion prediction system (WEPS), Texas erosion analysis model (TEAM), revised wind erosion equation (RWEQ), wind erosion assessment model (WEAM), and wind erosion stochastic simulator (WESS)) [38,39,82–85]. With increasing awareness of the role of dust at regional scales, regional dust emission models were developed and forced by climate datasets (e.g., wind erosion on European light soils (WEELS) and Australian land erodibility model (AUSLEM)) or dust transport models were developed by integrating dust emission modules with regional- to global-scale climate models (e.g., integrated wind erosion modelling system (IWEMS), computational fluid dynamics wind erosion model (CFD-WEM), computational environmental management system (CEMSYS), global ozone chemistry aerosol radiation and transport (GOCART), GOCART-Air Force Weather Agency (GOCART-AFWA), GOCART—University of Cologne (GOCART-UoC), dust entrainment and deposition (DEAD), community aerosol research model (CARMA-MM5), and global transport model of dust (GMOD), and Lund-Potsdam-Jena dynamic global vegetation model–dust (LP-J-Dust)) [11,40–43,53,86–91].
To account for the complex interaction between the physical processes and anthropogenic factors of wind erosion, dust models are drawn from field and laboratory measurements. Owing to the differences in model complexity, required inputs, and outputs [61], these models provide variable dust process simulations at specific spatial and temporal scales. The spatio-temporal scales, input parameters, and outputs of the dust models reviewed in this study are summarised in Table 1. The early dust models are mainly focused on the development of dust emission models at a field scale. However, dust models after 2000 have mainly concentrated on dust transport models at the regional and global scales. Field-scale dust models can be used to assess soil losses due to wind erosion under different land management regimes. Physical models require more detailed inputs and are difficult to implement owing to the lack of soil and land-surface parameters. In addition, these emission models are mainly applied at a field scale and usually cannot estimate spatial variations of dust emissions for a region. Regional and global-scale dust models integrated
into dust emission modules and climate models should be employed to predict spatial and temporal variations of dust processes, such as dust emission, transport, and deposition.

Table 1. Summary of reviewed dust models, including spatial scale, inputs, and outputs.

| Reference | Model Name | Category | Spatial Scale | Input Data                                                                 | Output Data                                                                 |
|-----------|------------|----------|---------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| [92]      | DENAPAP    | Emission | R             | Soil roughness, probability density function for wind speed, threshold wind velocity, field length | Dust emissions                                                              |
| [38]      | WEQ        | Emission | F             | Soil surface, ridges, surface roughness, climate, field length, wind, vegetation cover | Soil loss rates                                                             |
| [39]      | WEPS       | Emission | F             | Weather conditions, soils properties, management, management decisions, threshold wind velocity | Soil loss rates                                                             |
| [85]      | WEAM       | Emission | F             | Climate, soil types, vegetation cover                                        | Dust emissions, dust depositions                                            |
| [84]      | TEAM       | Emission | F             | Wind, relative humidity, clay content, particle size distribution, surface cover factor, soil erodibility, soil bulk density, length of the erosion segments | Soil loss rate, dust concentration, dust emission, dust deposition           |
| [82]      | RWEQ       | Emission | F             | Weather factor, percentage dry aggregation, soil crust factor, soil roughness, vegetation cover | Dust emissions, dust depositions                                            |
| [83]      | WESS       | Emission | F             | Wind, soil surface, ridge height                                              | Dust emissions, dust deposition                                              |
| [40]      | IWEMS      | Transport | R             | Soil properties (strength, fine content, bulk density, particle size distribution), surface characteristics (land use, frontal area index, vegetation height), climate (rainfall, evaporation, wind velocity) | Dust emissions, dust trajectories                                           |
| [41]      | WEELS      | Emission | R             | Soil moisture, soil erodibility, soil surface roughness, land use             | Wind erosion risk                                                           |
| [42]      | DEAD       | Transport | C, G          | Vegetation cover, surface soil moisture, soil texture, threshold wind velocity, particle size distributions, optical properties, land surface and geographic constraints | Dust emissions, dry depositions, wet depositions                            |
| [93]      | DPM        | Emission | C, G          | Soil particle size distribution, surface roughness, threshold wind velocity  | Dust emissions                                                              |
| [86]      | CARMA-Dust | Transport | C, G          | MM5 forecast data                                                            | Dust concentrations                                                         |
| [91]      | AUSLEM     | Emission | R             | Rainfall, soil moisture, evaporation, vegetation cover, percentage of sand, silt and clay in topsoil | Wind erosion hazards                                                        |
| [87]      | CEMSYS     | Transport | R, C          | Soil texture, soil type, vegetation, roughness, soil moisture, land surface, atmospheric data | Soil losses, dust concentrations                                             |
| [43]      | GMOD       | Transport | C, G          | Meteorological conditions, wind friction speed, relative humidity of the surface air, threshold wind velocity, densities of mineral dust and dry air, effective radius of the particles | Dust concentrations, dust depositions, dust optical thickness, particle size distributions |
#### Table 1. Cont.

| Reference | Model Name | Category | Spatial Scale | Input Data | Output Data |
|-----------|------------|----------|---------------|------------|-------------|
| [53]      | CFD-WEM    | Transport | R             | Digital elevation model (DEM), surface roughness length, land uses, threshold wind velocities | Sensitive areas to wind erosion |
| [95]      | LPJ-dust   | Transport | C, G          | Vegetation cover, soil texture, soil moisture, snow depth, threshold wind velocity, temperature, wind speed | Dust sources, dust emissions, dust trajectories, dust depositions |

Note: F, R, C, and G represent field, regional, continental, and global, respectively.

Evidently, u*t is the key factor affecting dust emission simulations. Dust emission will occur when the wind friction velocity over the land surface (u*) exceeds u*t. Generally, there are two approaches for representing the factors that influence the soil’s susceptibility to wind erosion in dust models: (1) constructing empirical relationships between soil surface conditions, soil moisture, and vegetation cover to predict rates of soil loss (e.g., models WEQ and RWEQ); and (2) integrating physical processes and theoretical relationships among soil properties, land surface conditions, and u*t (e.g., models CFD-WEM, GMOD, TEAM, and WEAM). Empirical models can account for dynamic variations in soil erodibility [96], but they largely depend on field measurements, which are not available at large spatial scales [38]. Physical models enable the inclusion of large-scale spatial inputs and are not restricted to specific environments [40,42]. The complexity of the description of u*t and dust emission has increased as the development of dust models progressed over the past five decades (Table 1). The definitions of u*t and the soil’s susceptibility to wind erosion differ between these models; therefore, calculations and predictions obtained from different models are not directly comparable. Thus, there is a need to integrate the two types of models to reduce the uncertainty of dust models overall.

Precisely modelling the spatial and temporal variability of dust emissions is a prerequisite to estimate and forecast atmospheric dust concentrations and their effects. Current dust emission models mostly include main physical processes of dust production, which can reproduce the spatial and temporal variability of dust emissions if the model inputs are accurately described. Studies have confirmed that the accuracy of ground surface condition data is the key determinant of spatial and temporal variability accuracy of dust emissions models [9,77,97]. In addition, the accuracy of temporal variability of dust emission models is also determined by specific model parameter values, such as the Kawamura coefficient value in a dust scheme [90] and the roughness correction factor to u*t in the dust schemes of the Community Earth System Model (CESM) [77]. However, it is difficult to define or customise these values owing to the spatial heterogeneity of ground surface conditions and the dearth of dust observations. To evaluate and improve the performance of temporal variations of dust emission models, it is essential to improve the accuracy of surface parameters in dust emission models and strengthen the collection of dust observation globally.

Dust models are important tools to account for the complex interaction between the physical processes and anthropogenic factors of wind erosion. However, there are no universally accepted parameters for these models in different regions/countries. Therefore, most of these models have to be parameterised before they can be applied to other regions. For example, models IWEMS and CFD-WEM have been successfully applied to the simulation of dust emissions in Asia after calibration of their parameters [9,96,98–101]. Model parameterisation is essential to ensure the accuracy of the estimation results. Dust models can be evaluated using in-situ measurements of dust and other required inputs. To ensure the accuracy of the simulation, before the application of a dust model in a region, the model’s empirical variables can be adjusted by comparing the model’s predictions with field measurements [101]. However, this comparison is challenging because of the difficulty in obtaining dust data. Several studies have attempted to validate dust model predictions against measured and observed data. The performance of some of the selected dust models
in Europe, Australia, and China (Table 2) have shown considerable differences in the accuracy among different dust models and among estimations in different regions using the same model. This also proved that the localisation of model parameters is important for the simulation accuracy of dust models.

Table 2. Performance of selected dust models.

| Model Name | Validation Region | Observed Parameter          | R Square (R²) | References |
|------------|-------------------|-----------------------------|---------------|------------|
| WEQ        | Argentina         | Average annual soil loss    | R² = 0.96     | [8]        |
| WEAM       | Inner Mongolia, China | Vertical dust flux          | R² = 0.87     | [102]      |
|            | Wind tunnel Experiments at Loxton and Borrika, Australia | Saltation flux             | R² = 0.66     | [85]       |
| TEAM       | U.S.A.            | Horizontal dust flux        | R² = 0.71 to 0.82 | [6]       |
| RWEQ       | Egypt             | Saltation flux              | R² = 0.96     | [8]        |
|            | China and U.S.A.  | Saltation flux              | R² = 0.91     | [103]      |
|            |                   | Saltation flux              | R² = 0.02 to 0.81 | [70]     |
| WEPS       | U.S.A.            | Amount of suspended material | R² = 0.71     | [65]       |
| DPM        | Mu Us Desert, China | Saltation flux             | R² = 0.83     | [104]      |
| WEELS      | 25 member states of the European Union | Wind-erodible fraction of the soil | R² = 0.50 | [105] |
| Shao dust scheme | Japan–Australia Dust Experiment (JADE) | Vertical dust flux | R² = 0.89     | [89,90]    |

3. Global Dust Budgets

3.1. Dust Sources and Sinks

Global dust source regions have been identified using different approaches, such as information gathering from dust weather records [99], remote sensing [32,100], dust monitoring networks [106], and dust models [42,55,86,107]. The seven main dust source regions of the world are North Africa, Middle East/Central Asia, East Asia, North America, South America, South Africa, and Australia (Figure 3).

Some studies simulated the global dust emission, deposition, and budgets over the past three decades (Table 3). The map of global dust emission and deposition in different regions (Figure 3) generated based on the data from previous studies represented in Table 4 shows that North Africa is the largest dust source region in the world. Because of the Sahara, the world’s largest desert, North Africa accounts for approximately 60% of the global dust emissions and approximately 65% of the global atmospheric dust load [55,108]. The second largest dust source region is Asia, comprising Arabia, Central Asia, and East Asia. Dust emissions and atmospheric dust loads in Asia account for approximately 30% of the global values [42,43,55]. Specifically, the dust emission and atmospheric dust load in East Asia are approximately 214 and 1.1 Tg yr⁻¹, respectively [55]. Australia is the largest contributor to dust emissions in the Southern Hemisphere, accounting for approximately 6% of the global dust emissions [33,42,55,108–110] and 5% of the global atmospheric dust load [43,55]. The smallest dust source regions are North and South America, accounting for 0.3% and 2.5% of the global dust emissions, respectively [33,42,55,109].
Table 3. Research periods of global dust emission, deposition, and budgets in several studies.

| Reference | Research Period | Reference | Research Period |
|-----------|-----------------|-----------|-----------------|
| [111]     | 1981–1989       | [110]     | 31 years        |
| [112]     | 1981–1990s      | [18]      | 1980–1990       |
| [94]      | 1987–1997       | [55]      | 1990–1995       |
| [113]     | 1990            | [43]      | 20 years        |
| [114]     | 1990, 1996, 1997| [13]      | 1996–2006       |
| [115]     | 1982–1993       | [14]      | 1960–2018       |
| [109]     | 1979–1988       | [116]     | 1950–2014       |
| [108]     | 1979–2000       | [117]     | 2000–2014       |
| [42]      | 1990–1999       | [80]      | 2004–2008       |
| [33]      | 1981–1996       |           |                 |

Table 4. SOC erosion associated with dust emission in major regions of the world.

| Region      | Min-Max Dust Emission (t ha⁻¹ yr⁻¹) | SOC Erosion Flux (t C ha⁻¹ yr⁻¹) | Wind Eroded Area (× 10⁶ ha) | Total SOC Erosion (Tg C yr⁻¹) | Oxidation at 20% SOC Erosion (Tg C yr⁻¹) |
|-------------|-------------------------------------|---------------------------------|-----------------------------|-------------------------------|------------------------------------------|
| Africa      | 2.8–7.7                             | 0.06–0.16                       | 186                         | 11.1–29.1                     | 9–23                                     |
| Asia        | 1.2–2.6                             | 0.03–0.06                       | 222                         | 5.7–12.3                      | 5–10                                     |
| South America| 0.8–1.3                             | 0.02–0.03                       | 42                          | 0.8–1.2                       | 1–1                                      |
| North America| 0.1–1.5                            | 0.00–0.03                       | 35                          | 0.1–1.2                       | 0–1                                     |
| Europe      | 0                                   | 0                               | 42                          | 0                             | 0–0                                     |
| Oceania     | 2.3–9.3                             | 0.05–0.19                       | 16                          | 0.8–3.0                       | 1–2                                     |
| Global      | 1.6–4.2                             | 0.03–0.09                       | 543                         | 18.6–47.4                     | 15–38                                    |

The amount of dust deposition over land is around three orders of that deposition over oceans [52]. Although dust deposition measurements are relatively scarce and incomplete worldwide, existing dust deposition rates records show large variations on land and oceans [52]. The estimates of dust deposition on the ocean shown in Figure 3 illustrate a considerable discrepancy among different studies. Nevertheless, according to most estimates, the region of maximum dust deposition is the North Atlantic due to the Saharan dust, which accounts for nearly 43% of the total dust deposited worldwide [18]. The second largest deposition centre is the Indian Ocean, receiving dust from North Africa, Arabia, Central Asia, and Australia, accounting for approximately 25% of the total dust deposition worldwide. Dust deposition in the North Pacific, South Pacific, South Ocean, and South Atlantic is 15%, 6%, 6%, and 4% of the global total, respectively.

3.2. Dust Budgets

The estimated global dust emission ranges from 895 to 8079 Tg yr⁻¹, and the global atmospheric dust load is estimated to be between 8 and 41.65 Tg yr⁻¹ (Figure 4). Similarly, there is uncertainty regarding the lifetime of the global atmospheric dust load and the ratio of dry to wet deposition. Evidently, there are large discrepancies among the dust models. These discrepancies can be attributed to the following: differences in the description of dust processes in different dust models; different particle size ranges utilised in each model (particle size is a fundamental parameter for simulating soil particle processes and estimating the effect of dust particles on radiation and cloud processes); and different meteorological/climatic data that form a part of the model input.
Figure 3. Map of global (a) dust emissions, deposition, and (b) dust budgets at different regions, estimated by several dust models. Grey and black arrows in (a) denote dust emission and deposition (percent of the total dust deposition worldwide), respectively. Horizontal and vertical bars in (b) denote annual dust emission (from land regions) and deposition (in oceans), respectively, estimated by different studies. The particle size ranges (r) of dust emissions are Werner et al. [109], 0.1 ≤ r ≤ 219 μm; Luo et al. [108], 0.1 ≤ r ≤ 10 μm; Zender et al. [42], 0.1 ≤ r ≤ 10 μm; Ginoux et al. [33], 0.1 ≤ r ≤ 6 μm; Miller et al. [110], r < 10 μm; Tanaka and Chiba [55], 0.2 ≤ r ≤ 20 μm; Kok et al. [80], 0.2 ≤ r ≤ 20 μm; Checa-Garcia et al. [117] and Aryal et al. [116], multi-model with different maximum dust particle size.
4. Dust Emission and SOC Dynamics

4.1. Loss of SOC Due to Dust Emission

Generally, SOC storage represents the net long-term balance between photosynthesis and respiration in terrestrial ecosystems [29,119]. The global SOC storage is estimated to be approximately 1550 Pg of carbon; this accounts for nearly 54% of the terrestrial carbon pool and is twice the magnitude of the atmospheric carbon pool (760 Pg) [48]. Soil erosion by wind, and the transport and deposition of the eroded material, redistribute SOC across landscapes and regions [20,120]. These physical processes substantially affect the biological mediation of carbon mineralisation in the soil system. Erosion and mobilisation of mineralised carbon could result in a net release of carbon from the soil system to the atmosphere, which may offset carbon sinks in vegetation [120–127]. The fraction of soil carbonates in SOC entering the atmosphere may reduce the intensity of terrestrial carbon sequestration and further increase the CO₂ concentration in the atmosphere, which has a positive feedback effect on climate warming [123,124,128].

Dust emission affects SOC by selectively removing fine particles from the soil surface. In this way, the soil evolves toward a coarser texture [119]. Fine soil particles have a high content of stable SOC [122], which directly affects plant growth and soil biological activities,
soil air CO$_2$ concentration, soil water regimes, temperature, and respiration, and, therefore, carbon flux to the atmosphere [119,128]. Studies have shown that the SOC loss caused by wind erosion is mainly the active component of SOC and the organic carbon components combined with the soil fine-grained particles [48,54,119,129–131]. Dust emissions can affect soil reflectivity, and thus, soil moisture and temperature, thereby accelerating the in-situ mineralisation of residual SOC [48]. Soil desertification and dust emission reduce the soil’s water-holding capacity, root depth, and the efficiency of water and nutrient uptake by plants, thus reducing organic matter returning to the soil, and the rate of POC formation [24,132]. Moreover, severe dust emission removes the topsoil and exposes the calcium carbonate-rich subsurface soil horizon. This can result in increased emission of CO$_2$ into the atmosphere due to carbon oxidation [48,128].

Despite the significance of dust in the global carbon cycle, wind erosion-induced carbon emissions remain a poorly understood, unquantified component of the global carbon budget. The SOC erosion associated with dust emission in major regions of the world is presented in Table 4 [24,45,120,131]. The difference in an order of magnitude in total min-max dust emission, wind-eroded area, and total SOC erosion across different regions is shown in Table 3. Although several studies have attempted to estimate SOC losses due to dust emission in specific regions, such as China (75 Tg C yr$^{-1}$ [7]), Australia (1.59 Tg C yr$^{-1}$) [46], the United States (34 Tg C yr$^{-1}$), a small arable catchment in Germany (4.4 g C m$^{-2}$ yr$^{-1}$) [133], and a dryland farming system in Western Australia (3.6 t C ha$^{-1}$ yr$^{-1}$) [134], there is significant inconsistency among these results.

4.2. Fate of SOC in Dust

Soil losses due to wind erosion do not amount to a net loss of SOC; it is a process of SOC migration, in other words, a non-source and non-sink process [135,136]. The fate of the SOC involved in dust dynamics is determined by a series of complex interactions. As these interactions constitute a dynamic process, it is difficult to accurately estimate the ultimate fate of wind-eroded SOC. In general, the fate of the SOC is mobilised, as dust may include [134]: (1) proximal deposition, from creep and saltation, in the range of tens of meters; (2) deposition in lakes and rivers; (3) transport, in the form of dust, to a distant system; (4) release to the atmosphere by oxidation; and (5) variation in SOC with dust size.

The net change in SOC stocks reflects the balance between carbon sequestration and soil carbon emission. Some studies have indicated that the main losses in the process of dust emission are mainly the active organic carbon of SOC and the organic carbon combined with soil fine-grained components [137–140]. Soil active organic matter components are the habitat and survival matrix of soil microorganisms. Therefore, the loss of SOC caused by dust emission can significantly reduce soil biological activity. The decrease in soil biological activity and the change in soil structure and water-holding capacity caused by wind erosion can significantly change the biological process of carbon mineralisation and result in the net release of carbon from the soil system to the atmosphere. Therefore, from the perspective of the global carbon balance, more attention should be paid to the loss of mineralised SOC due to wind erosion. The mechanisms of carbon mineralisation during the migration and deposition of wind-eroded material are yet to be determined. This raises the question of how to estimate the effect of dust emissions on the global carbon balance. The current estimates of SOC loss usually ignore the redistribution of SOC generated by dust emissions; consequently, they overestimate the contribution of SOC erosion to atmospheric CO$_2$. The fate of wind-eroded SOC is still discussed in merely qualitative terms. Quantitative analysis is limited to smaller space-time scales. In-depth study and quantification of SOC in dust, especially the fate of wind-eroded SOC in the global dust cycle, is essential to quantify the release of CO$_2$ from SOC dust to the atmosphere, the contribution of SOC deposition to downwind carbon sinks, and the effect of dust processes on the global carbon balance.
5. Conclusions

Advances in dust modelling in the past five decades have changed the requirements for input data, and increased model complexity and the availability of model outputs. Owing to the diversity of the required inputs, hybrid observation methods (integrating multiple observation methods) should be adopted to provide dust models with input data. Although the development of dust models has progressed considerably over the past 30 years, the model simulation results are still replete with uncertainties. Dust models developed in a specific region require careful calibration when used to other regions. It is only possible to simulate dust processes in an area after the model’s parameters have been localised with the use of observation data. There are no universally accepted parameters for dust models in different regions/countries. Therefore, it is necessary to develop a set of parameters for different regions. It is recognised that anthropogenic activities can also induce dust emissions; as such, they are non-negligible contributors to global dust concentrations [140–145]. However, all models reviewed in this study simulated ‘natural’ or indirect anthropogenic (e.g., cropland and pastureland) dust processes, neglecting the contribution of direct anthropogenic dust (e.g., city construction and transportation). This leads to considerable uncertainties in estimating dust emissions. Therefore, to improve the accuracy of dust emission simulations, the consideration of anthropogenic dust emissions is imperative [146].

SOC loss due to wind erosion is a key component of the global carbon cycle. A better understanding of the role of dust processes in the global SOC flux and carbon budget is needed. Although it is recognised that SOC is transported and redistributed by dust processes, SOC cycling schemes used in land surface models (LSMs) typically only consider the effects of net primary production and heterotrophic respiration. Current estimates of SOC loss results in significant underestimations due to the omission of the effects of dust emission. Moreover, the dust emission flux observation does not include the measurement of SOC concentrations; there is a lack of SOC concentration in different dust sizes, and how dust emission is directly linked to SOC erosion is not well represented. It is necessary to explore the various effects of dust processes on SOC pools, mineralisation rates, and SOC emission to the atmosphere in dust source regions, and on the enrichment of SOC in deposition regions. Currently, although some Earth System Models have the ability to simulate the effects of mineral dust deposition on biogeochemistry [78,147,148], most dust models are limited to estimating dust emission and deposition and do not consider the effects of dust on the global carbon cycle. Similarly, the current carbon cycle models ignore the effects of SOC movement caused by dust processes. Therefore, representing the linkages between dust processes and the carbon cycle in both dust and carbon cycle models is essential.

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References

1. Belnap, J.; Munson, S.M.; Field, J.P. Aeolian and fluvial processes in dryland regions: The need for integrated studies. *Ecological Engineering* 2011, 4, 615–622. [CrossRef]

2. Li, J.; Oki, G.S.; Alvarez, L.; Epstein, H. Quantitative effects of vegetation cover on wind erosion and soil nutrient loss in a desert grassland of southern New Mexico, USA. *Biogeochemistry* 2007, 85, 317–332. [CrossRef]

3. Hoffmann, C.; Funk, R.; Reiche, M.; Li, Y. Assessment of extreme wind erosion and its impacts in Inner Mongolia, China. *Aeolian Res.* 2011, 3, 343–351. [CrossRef]

4. Pokharel, A.K.; Kaplan, M.L.; Fiedler, S. Subtropical dust storms and downslope wind events. *J. Geophys. Res. Atmos.* 2017, 122, 10191–10205. [CrossRef]

5. Pokharel, A.K.; Kaplan, M.L.; Fiedler, S. The role of jet adjustment processes in subtropical dust storms. *J. Geophys. Res. Atmos.* 2017, 122, 12122–12139. [CrossRef]

6. Gregory, J.M.; Wilson, G.R.; Singh, U.B.; Darwish, M.M. TEAM: Integrated, process-based wind-erosion model. *Environ. Modell. Softw.* 2004, 19, 205–215. [CrossRef]

7. Webb, N.P.; Mcgowan, H.A. Approaches to modelling land erodibility by wind. *Prog. Phys. Geol.* 2009, 33, 587–613. [CrossRef]

8. Buschiazzo, D.E.; Zobeck, T.M. Validation of WEQ, RWEQ and WEPS wind erosion for different arable land management systems in the Argentinian Pampas. *Earth Surf. Proc. Land* 2010, 33, 1839–1850. [CrossRef]

9. Song, H.; Zhang, K.; Piao, S.; Wang, S. Spatial and temporal variations of spring dust emissions in northern China over the last 30 years. *Atmos. Environ.* 2016, 126, 117–127. [CrossRef]

10. Buschiazzo, D.E.; Funk, R. Wind erosion of agricultural soils and the carbon cycle. In *Soil Carbon Science Management & Policy for Multiple Benefits*; CABI: Egham, UK, 2014; pp. 161–168.

11. Shao, Y. A model for mineral dust emission. *J. Geophys. Res. Atmos.* 2001, 106, 20239–20254. [CrossRef]

12. Wang, X.; Onema, O.; Hoogmoed, W.B.; Perdok, U.D.; Cai, D. Dust storm erosion and its impact on soil carbon and nitrogen losses in northern China. *Catena* 2006, 66, 221–227. [CrossRef]

13. Huneeus, N.; Schulz, M.; Balkansky, Y.; Griesfeller, J.; Prospero, M.J.; Kinne, S.; Bauer, S.; Boucher, O.; Chin, M.; Dentener, F.; et al. Global dust model intercomparison in AeroCom phase I. *Atmos. Chem. Phys.* 2010, 10, 7781–7816. [CrossRef]

14. Wu, C.; Li, Z.; Liu, X. The global dust cycle and uncertainty in CMIP5 (Coupled Model Intercomparison Project phase 5) models. *Atmos. Chem. Phys.* 2020, 20, 10401–10425. [CrossRef]

15. Tegen, I.; Werner, M.; Harrison, S.P.; Kohfeld, K.E. Relative importance of climate and land use in determining present and future global soil dust emission. *Geophys. Res. Lett.* 2004, 31, 325–341. [CrossRef]

16. Chadwick, O.A.; Derry, L.A.; Vitousek, P.M.; Huebert, B.J.; Hedin, L.O. Changing sources of nutrients during four million years of ecosystem development. *Nature* 1999, 397, 491–497. [CrossRef]

17. Reynolds, R.; Belnap, J.; Reheis, M.; Lamothe, P.; Luiszler, F. Aeolian dust in Colorado Plateau soils: Nutrient inputs and recent change in source. *Proc. Natl. Acad. Sci. USA* 2001, 98, 7123–7127. [CrossRef]

18. Pickrell, T.D.; An, Z.S.; Andersen, K.K.; Baker, A.R.; Bergametti, G.; Brooks, N.; Cao, J.J.; Boyd, P.W.; Duce, R.A.; Hunter, K.A.; et al. Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science* 2005, 308, 67–71. [CrossRef][PubMed]

19. Alfaro, S.C. Influence of soil texture on the binding energies of fine mineral dust particles potentially released by wind erosion. *Geomorphology* 2008, 93, 157–167. [CrossRef]

20. Chappell, A.; Sanderman, J.; Thomas, M.; Read, A.; Leslie, C. The dynamics of soil redistribution and the implications for soil organic carbon accounting in agricultural south-eastern Australia. *Glob. Chang. Biol.* 2012, 18, 2081–2088. [CrossRef]

21. Song, H.; Wang, K.; Zhang, Y.; Hong, C.; Zhou, S. Simulation and evaluation of dust emissions with WRF-Chem (v3.7.1) and its change in source. *Atmos. Environ.* 2017, 167, 511–522. [CrossRef]

22. Li, L.; Sokolik, I.N. Analysis of dust aerosol retrievals using satellite data in Central Asia. *Atmosphere* 2018, 9, 288. [CrossRef]

23. Wang, K.; Zhang, Y.; Zhang, X.; Fan, J.; Leung, L.R.; Zheng, B.; Zhang, Q.; He, K. Fine-scale application of WRF-CAM5 during a dust storm episode over East Asia: Sensitivity to grid resolutions and aerosol activation parameterizations. *Atmos. Environ.* 2018, 176, 1–20. [CrossRef]

24. Song, H.; Zhang, K.; Piao, S.; Liu, L.; Wang, Y.-P.; Chen, Y.; Yang, Z.; Zhu, L.; Wan, S. Soil organic carbon and nutrient losses resulted from wind erosion in Inner Mongolia. *Atmos. Environ.* 2019, 213, 585–596. [CrossRef]

25. Hashizume, M.; Kim, Y.; Ng, C.F.S.; Chung, Y.; Madaniyazi, L.; Bell, M.L.; Guo, Y.L.; Kan, H.D.; Honda, Y.; Yi, S.M.; et al. Health effects of asian dust: A systematic review and meta-analysis. *Environ. Health Perspect.* 2020, 128, 66001. [CrossRef][PubMed]

26. Wang, L.; Cai, K.; Si, Y.; Yu, C.; Zheng, H.; Li, S. Evaluation of Himawari-8 version 2.0 aerosol products against AERONET ground-based measurements over central and northern China. *Atmos. Environ.* 2020, 224, 117357. [CrossRef]

27. Liu, X.; Song, H.; Lei, T.; Liu, P.; Xu, C.; Wang, D.; Yang, Z.; Xia, H.; Wang, T.; Zhao, H. Effects of natural and anthropogenic factors and their interactions on dust events in Northern China. *Catena* 2021, 196, 104919. [CrossRef]

28. Yang, L.; Ren, Q.; Zheng, K.; Jiao, Z.; Ruan, X.; Wang, Y. Migration of heavy metals in the soil-grape system and potential health risk assessment. *Sci. Total Environ.* 2022, 806, 150646. [CrossRef][PubMed]

29. Wang, T.; Zhang, L.; Zhou, S.; Zhang, T.; Zhai, S.; Yang, Z.; Wang, D.; Song, H. Effects of ground-level ozone pollution on yield and economic losses of winter wheat in Henan, China. *Atmos. Environ.* 2021, 262, 118654. [CrossRef]

30. Zhang, T.; He, W.; Zheng, H.; Cui, Y.; Song, H.; Fu, S. Satellite-based ground PM$_{2.5}$ estimation using a gradient boosting decision tree. *Chemosphere* 2021, 268, 128801. [CrossRef][PubMed]
31. McTainsh, G.; Lynch, A.; Tews, E. Climatic controls upon dust storm occurrence in Eastern Australia. *J. Arid Environ.* 1998, 39, 457–466. [CrossRef]
32. Prospero, J.M.; Ginoux, P.; Torres, O.; Nicholson, S.E.; Gill, T.E. Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Rev. Geophys.* 2002, 40, 1002. [CrossRef]
33. Ginoux, P.; Prospero, J.M.; Torres, O.; Chin, M. Long-term simulation of global dust distribution with the GOCART model: Correlation with North Atlantic Oscillation. *Environ. Modell. Softw.* 2004, 19, 113–128. [CrossRef]
34. Zobeck, T.M.; Parker, N.C.; Haskell, S.; Guo, K. Scaling up from field to region for wind erosion prediction using a field-scale wind erosion model and GIS. *Agric. Ecosyst. Environ.* 2000, 82, 247–259. [CrossRef]
35. Maman, S. The Central Asian ergs: A study by remote sensing and geographic information systems. *Aeolian Res.* 2012, 3, 353–366. [CrossRef]
36. Guo, J.; Tao, N.; Fu, W.; Deng, M.; Wang, Y. Integration of multi-source measurements to monitor sand-dust storms over North China: A case study. *Acta Meteorol. Sin.* 2013, 27, 566–576. [CrossRef]
37. Borrelli, P.; Lugato, E.; Montanarella, L.; Panagos, P. A new assessment of soil loss due to wind erosion in European agricultural soils using a quantitative spatially distributed modelling approach. *Land Degrad. Dev.* 2017, 28, 335–344. [CrossRef]
38. Woodruff, N.P.; Siddoway, F. A wind erosion equation. *Soil Sci. Soc. Am. J.* 1965, 29, 602–608. [CrossRef]
39. Fryrear, D.; Stout, J.; Hagen, L.; Vories, E. Wind erosion: Field measurement and analysis. *Trans. ASAE* 1991, 34, 155–0160. [CrossRef]
40. Lu, H.; Shao, Y. Toward quantitative prediction of dust storms: An integrated wind erosion modelling system and its applications. *Environ. Modell. Softw.* 2001, 16, 233–249. [CrossRef]
41. Böhner, J.; Schäfer, W.; Conrad, O.; Gross, J.; Ringeler, A. The WEELS model: Methods, results and limitations. *Catena* 2003, 52, 289–308. [CrossRef]
42. Zender, C.S.; Bian, H.; Newman, D. Mineral Dust Entrainment and Deposition (DEAD) model: Description and 1990s dust climatology. *J. Geophys. Res. Atmos.* 2003, 108, 4416. [CrossRef]
43. Yue, X.; Wang, H.; Wang, Z.; Fan, K. Simulation of dust aerosol radiative feedback using the Global Transport Model of Dust: 1. Dust cycle and validation. *J. Geophys. Res. Atmos.* 2009, 114, D10202. [CrossRef]
44. Webb, N.P.; Chappell, A.; Strong, C.L.; Marx, S.K.; McTainsh, G.H. The significance of carbon-enriched dust for global carbon accounting. *Glob. Chang. Biol.* 2012, 18, 3275–3278. [CrossRef]
45. Chappell, A.; Baldock, J.A. Wind erosion reduces soil organic carbon sequestration falsely indicating ineffective management practices. *Aeolian Res.* 2016, 22, 107–116. [CrossRef]
46. Chappell, A.; Webb, N.P.; Butler, H.J.; Strong, C.L.; McTainsh, G.H.; Leys, J.F.; Rossel, R.V. Soil organic carbon dust emission: An omitted global source of atmospheric CO₂. *Glob. Chang. Biol.* 2013, 19, 3238–3244. [CrossRef] [PubMed]
47. Chappell, A.; Baldock, J.; Sanderman, J. The global significance of omitting soil erosion from soil organic carbon cycling schemes. *Nat. Clim. Chang.* 2016, 6, 187. [CrossRef]
48. Lal, R. Soil erosion and the global carbon budget. *Environ. Int.* 2003, 29, 437–450. [CrossRef]
49. Lancaster, N.; Baas, A. Influence of vegetation cover on sand transport by wind: Field studies at Owens Lake, California. *Earth Surf. Proc. Land.* 1998, 23, 69–82. [CrossRef]
50. Baas, A. Complex systems in aeolian geomorphology. *Geomorphology* 2007, 91, 311–331. [CrossRef]
51. Bauer, B.O. Contemporary research in aeolian geomorphology. *Geomorphology* 2009, 105, 1–5. [CrossRef]
52. Shao, Y.; Wyrwoll, K.H.; Chappell, A.; Huang, J.; Lin, Z.; Tainsch, M.; Mikami, M.; Tanaka, T.Y.; Wang, X.; Yoon, S. Dust cycle: An emerging core theme in Earth system science. *Aeolian Res.* 2011, 2, 181–204. [CrossRef]
53. Zhang, Z.; Wieland, R.; Reiche, M.; Funk, R.; Hoffmann, C.; Li, Y.; Sommer, M. Wind modelling for wind erosion research by open source computational fluid dynamics. *Ecol. Inform.* 2011, 6, 316–324. [CrossRef]
54. Webb, N.P.; Strong, C.L.; Chappell, A.; Marx, S.K.; McTainsh, G.H. Soil organic carbon enrichment of dust emissions: Magnitude, mechanisms and its implications for the carbon cycle. *Earth Surf. Proc. Land.* 2013, 38, 1662–1671. [CrossRef]
55. Tanaka, T.Y.; Chiba, M. A numerical study of the contributions of dust source regions to the global dust budget. *Glob. Planet. Chang.* 2006, 52, 88–104. [CrossRef]
56. Neff, J.C.; Ballantyne, A.P.; Farmer, G.L.; Mahowald, N.M.; Conroy, J.L.; Landry, C.C.; Overpeck, J.T.; Painter, T.H.; Lawrence, C.R.; Reynolds, R.L. Increasingolian dust deposition in the western United States linked to human activity. *Nat. Geosci.* 2008, 1, 189–195. [CrossRef]
57. Webb, N.P.; Strong, C.L. Soil erodibility dynamics and its representation for wind erosion and dust emission models. *Aeolian Res.* 2011, 3, 165–179. [CrossRef]
58. Stout, J.E.; Zobeck, T.M. The Wolfforth field experiment: A wind erosion study. *Soil Sci.* 1996, 161, 616–632. [CrossRef]
59. Field, J.P.; Bareshears, D.D.; Whicker, J.J. Toward a more holistic perspective of soil erosion: Why aeolian research needs to explicitly consider fluvial processes and interactions. *Aeolian Res.* 2009, 1, 9–17. [CrossRef]
60. Li, J.; Okin, G.S.; Herrick, J.E.; Belnap, J.; Munson, S.M.; Miller, M.E. A simple method to estimate threshold friction velocity of wind erosion in the field. *Geophys. Res. Lett.* 2010, 37, L10402. [CrossRef]
61. Jarrah, M.; Mayel, S.; Tatarko, J.; Funk, R.; Kuka, K. A review of wind erosion models: Data requirements, processes, and validity. *Catena* 2020, 187, 104388. [CrossRef]
62. Zobeck, T.M. Soil properties affecting wind erosion. J. Soil Water Conserv. 1991, 46, 112–118.
63. Belnap, J.; Gillette, D.A. Disturbance of biological soil crusts: Impacts on potential wind erodibility of sandy desert soils in southeastern Utah. Land Degrad. Dev. 1997, 8, 355–362. [CrossRef]
64. Cornelis, W.; Gabriels, D. The effect of surface moisture on the entrainment of dune sand by wind: An evaluation of selected models. Sedimentology 2003, 50, 771–790. [CrossRef]
65. Hagen, L.J. Evaluation of the Wind Erosion Prediction System (WEPS) erosion submodel on cropland fields. Environ. Modell. Softw. 2004, 19, 171–176. [CrossRef]
66. Nickovic, S.; Vukovic, A.; Vujadinovic, M.; Djurdjevic, V.; Pejanovic, G. High-resolution mineralogical database of dust-productive soils for atmospheric dust modeling. Atmos. Chem. Phys. 2012, 12, 845–855. [CrossRef]
67. Jourret, E.; Balkanski, Y.; Harrison, S.P. A new data set of soil mineralogy for dust-cycle modeling. Atmos. Chem. Phys. 2014, 14, 3801–3816. [CrossRef]
68. Perlwitz, J.; Perez Garcia-Pando, C.; Miller, R. Predicting the mineral composition of dust aerosols—Part 1: Representing key processes. Atmos. Chem. Phys. 2015, 15, 11593–11627. [CrossRef]
69. Perez Garcia-Pando, C.; Miller, R.L.; Perlwitz, J.P.; Rodriguez, S.; Prospero, J.M. Predicting the mineral composition of dust aerosols: Insights from elemental composition measured at the Izaa Observatory. Geophys. Res. Lett. 2016, 43, 10520–10529. [CrossRef]
70. Pi, H.; Sharratt, B.; Feng, G.; Lei, J. Evaluation of two empirical wind erosion models in arid and semi-arid regions of China and the USA. Environ. Modell. Softw. 2017, 91, 28–46. [CrossRef]
71. Batt, R.G.; Peabody, S.A., II. Threshold friction velocities for large pebble gravel beds. J. Geophys. Res. Atmos. 1999, 104, 24273–24279. [CrossRef]
72. Marticorena, B.; Bergametti, G.; Gillette, D.; Belnap, J. Factors controlling threshold friction velocity in semiarid and arid areas of the Unite States. J. Geophys. Res. Atmos. 1997, 102, 23277–23287. [CrossRef]
73. Shao, Y.; Lu, H. A simple expression for wind erosion threshold friction velocity. J. Geophys. Res. Atmos. 2000, 105, 22437–22443. [CrossRef]
74. Gillette, D.A.; Stockton, P.H. The effect of nonerodible particles on wind erosion of erodible surfaces. J. Geophys. Res. Atmos. 1989, 94, 12885–12893. [CrossRef]
75. Rice, M.; Mcewan, I.; Mullins, C. A conceptual model of wind erosion of soil surfaces by saltating particles. Earth Surf. Process. Land. 1999, 24, 383–392. [CrossRef]
76. Okin, G.; Gillette, D.; Herrick, J. Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments. J. Arid Environ. 2006, 65, 253–275. [CrossRef]
77. Wu, C.; Lin, Z.; He, J.; Zhang, M.; Liu, X.; Zhang, R.; Brown, H. A process-oriented evaluation of dustemission parameterizations in CESM: Simulation of a typical severe duststorm in East Asia. J. Adv. Modeling Earth Syst. 2016, 8, 1432–1452. [CrossRef]
78. Wu, C.; Lin, Z.; Liu, X.; Li, Y.; Lu, Z.; Wu, M. Can climate models reproduce the decadal change of dust aerosol in East Asia? Geophys. Res. Lett. 2018, 45, 9953–9962. [CrossRef]
79. Wu, M.; Liu, X.; Zhang, L.; Wu, C.; Lu, Z.; Ma, P.L.; Wang, H.; Tilmes, S.; Mahowald, N.; Matsui, H.; et al. Impacts of aerosol dry deposition on black carbon spatial distributions and radiative effects in the Community Atmosphere Model CAM5. J. Adv. Modeling Earth Syst. 2018, 10, 1150–1171. [CrossRef]
80. Kok, J.F. A scaling theory for the size distribution of emitted dust aerosols suggests climate models underestimate the size of the global dust cycle. Proc. Natl. Acad. Sci. USA 2021, 108, 1016–1021. [CrossRef]
81. Kok, J.F.; Adebiyi, A.A.; Albani, S.; Balkanski, Y.; Checa-Garcia, R.; Chin, M.; Colarco, P.R.; Hamilton, D.S.; Huang, Y.; Ito, A.; et al. Contribution of the world’s main dust source regions to the global cycle of desert dust. Atmos. Chem. Phys. 2021, 21, 8169–8193. [CrossRef]
82. Fryrear, D.; Saleh, A.; Bilbro, J. A single event wind erosion model. Trans. ASAE 1998, 41, 1369. [CrossRef]
83. Potter, K.; Williams, J.; Larney, F.; Bullock, M. Evaluation of EPIC’s wind erosion submodel using data from southern Alberta. Can. J. Soil Sci. 1998, 78, 485–492. [CrossRef]
84. Singh, U.B.; Gregory, J.M.; Wilson, G.R. Texas erosion analysis model: Theory and validation. In Proceedings of the Wind Erosion: An International Symposium/Workshop, Manhattan, KS, USA, 3–5 June 1997.
85. Shao, Y.; Raupach, M.R.; Leys, J.F. A model for predicting aeolian sand drift and dust entrainment on scales from paddock to region. Soil Res. 1996, 34, 309–342. [CrossRef]
86. Barnum, B.H.; Winstead, N.S.; Wesely, J.; Hakola, A.; Colarco, P.R.; Toon, O.B.; Ginoux, P.; Brooks, G.; Hasselbarth, L.; Toth, B. Forecasting dust storms using the CARMA-dust model and MM5 weather data. Environ. Modell. Softw. 2004, 19, 129–140. [CrossRef]
87. Butler, H.J.; Shao, Y.; Leys, J.F.; Mctainsh, G. Modelling Wind Erosion at National and Regional Scale Using the CEMSYS Model: National Monitoring and Evaluation Framework, Prepared for the National Land & Water Resources Audit; Technical Report; National Land and Water Resources Audit: Canberra, Australia, 2007.
88. LeGrand, S.L.; Polashenski, C.; Letcher, T.W.; Creighton, G.A.; Peckham, S.E.; Cetola, J.D. The AFWA dust emission scheme for the GOCART aerosol model in WRF-Chem v3. 8.1. Geosci. Model Dev. 2019, 12, 131–166. [CrossRef]
89. Shao, Y.P. Simplification of a dust emission scheme and comparison with data. J. Geophys. Res. Atmos. 2004, 109, D10202. [CrossRef]
90. Shao, Y.; Ishizuka, M.; Mikami, M.; Leys, J. Parameterization of size-resolved dust emission and validation with measurements. *J. Geophys. Res. Atmos.* 2011, 116, D08203. [CrossRef]

91. Webb, N.P.; Megowan, H.A.; Phinn, S.R.; Metainsh, G.H. AUSLEM (AUstralian Land Erodibility Model): A tool for identifying wind erosion hazard in Australia. *Geomorphology* 2006, 78, 179–200. [CrossRef]

92. Gillette, D.A.; Passi, R. Modeling dust emission caused by wind erosion. *J. Geophys. Res. Atmos.* 1988, 93, 14233–14242. [CrossRef]

93. Gomes, L.; Rajot, J.; Alfaro, S.; Gaudichet, A. Validation of a dust production model from measurements performed in semi-arid agricultural areas of Spain and Niger. *Catena* 2003, 52, 257–271. [CrossRef]

94. Ginoux, P.; Chin, M.; Tegen, I.; Prospero, J.M.; Holben, B.; Dubovik, O.; Lin, S.J. Sources and distributions of dust aerosols simulated with the GOCART model. *J. Geophys. Res. Atmos.* 2001, 106, 20255–20273. [CrossRef]

95. Shannon, S.; Lunt, D. A new dust cycle model with dynamic vegetation: LPJ-dust version 1.0. *Geosci. Model Dev.* 2011, 4, 85–105. [CrossRef]

96. Hagen, L. A wind erosion prediction system to meet user needs. *J. Soil Water Conserv.* 1991, 46, 106–111.

97. Flaounas, E.; Kotroni, V.; Lagouvardos, K.; Klose, M.; Flamant, C.; Giannaros, T.M. Sensitivity of the WRF-Chem (V3.6.1) model to different dust emission parametrisation: Assessment in the broader Mediterranean region. *Geosci. Model Dev.* 2017, 10, 2925–2945. [CrossRef]

98. Shao, Y.; Yang, Y.; Wang, J.; Song, Z.; Leslie, L.M.; Dong, C.; Zhang, Z.; Lin, Z.; Kanai, Y.; Yabuki, S. Northeast Asian dust storms: Real-time numerical prediction and validation. *J. Geophys. Res. Atmos.* 2003, 108, 4691. [CrossRef]

99. Kurosaki, Y.; Mikami, M. Regional difference in the characteristic of dust event in East Asia: Relationship among dust outbreak, surface wind, and land surface condition. *J. Meteorol. Soc. Jpn.* 2005, 83A, 1–18. [CrossRef]

100. Koven, C.D.; Fung, I. Identifying global dust source areas using high-resolution land surface form. *J. Geophys. Res. Atmos.* 2008, 113, D22204. [CrossRef]

101. Gregorich, E.; Greer, K.; Anderson, D.; Liang, B. Carbon distribution and losses: Erosion and deposition effects. *Soil Till. Res.* 1998, 47, 291–302. [CrossRef]

102. Fratini, G.; Santini, M.; Ciccioli, P.; Valentini, R. Evaluation of a wind erosion model in a desert area of northern Asia by eddy covariance. *Earth Surf. Proc. Land.* 2009, 34, 1743–1757. [CrossRef]

103. Fryrear, D.; Wassif, M.; Tadrus, S.; Ali, A. Dust measurements in the Egyptian northwest coastal zone. *Trans. ASABE* 2008, 51, 1255–1262. [CrossRef]

104. Fan, S.; Moxim, W.; Levy, H. Aeolian input of bioavailable iron to the ocean. *Atmos. Chem. Phys. Discuss.* 2003, 3, 2887–3014. [CrossRef]

105. Werner, M.; Tegen, I.; Harrison, S.; Kohfeld, K.; Balkanski, Y.; Rodhe, H.; Roelandt, C. Seasonal and interannual variability of the mineral dust cycle under present and glacial climate conditions. *J. Geophys. Res. Atmos.* 2002, 107, 4744. [CrossRef]

106. Holben, B.N.; Tanre, D.; Smirnov, A.; Eck, T.; Slutsker, I.; Abuhassan, N.; Newcomb, W.; Schafer, J.; Chatenet, B.; Lavenue, F. An emerging ground-based aerosol climatology: Aerosol optical depth from AERONET. *J. Geophys. Res. Atmos.* 2001, 106, 12067–12097. [CrossRef]

107. Zhao, A.; Ryder, C.; Wilcox, L. How well do the CMIP6 models simulate dust aerosols? *Atmos. Chem. Phys. Discuss.* 2021. [CrossRef]

108. Luo, C.; Mahowald, N.M.; Del Corral, J. Sensitivity study of meteorological parameters on mineral aerosol mobilization, transport, and distribution. *J. Geophys. Res. Atmos.* 2010, 108, 4447. [CrossRef]

109. Werner, M.; Tegen, I.; Harrison, S.; Kohfeld, K.; Prentice, I.; Balkanski, Y.; Rodhe, H.; Roelandt, C. Seasonal and interannual variability of the mineral dust cycle under present and glacial climate conditions. *J. Geophys. Res. Atmos.* 2002, 107, 4744. [CrossRef]

110. Miller, R.; Tegen, I.; Perlwitz, J. Surface radiative forcing by soil dust aerosols and the hydrologic cycle. *J. Geophys. Res. Atmos.* 2004, 109, D04203. [CrossRef]

111. Duce, R.A.; Tindale, N.W. Atmospheric transport of iron and its deposition in the ocean. *Limnol. Oceanogr.* 1991, 36, 1715–1726. [CrossRef]

112. Prospero, J.M. The atmospheric transport of particles to the ocean. *Part. Ocean Sci.* 1996, 57, 19–52.

113. Takemura, T.; Okamoto, H.; Maruyama, Y.; Numaguti, A.; Higurashi, A.; Nakajima, T. Global three-dimensional simulation of aerosol optical thickness distribution of various origins. *J. Geophys. Res. Atmos.* 2000, 105, 17853–17873. [CrossRef]

114. Chin, M.; Ginoux, P.; Kinne, S.; Torres, O.; Holben, B.N.; Duncan, B.N.; Martin, R.V.; Logan, J.A.; Higurashi, A.; Nakajima, T. Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and Sun photometer measurements. *J. Atmos. Sci.* 2002, 59, 461–483. [CrossRef]

115. Tegen, I.; Harrison, S.P.; Kohfeld, K.; Prentice, I.C.; Coe, M.; Heimann, M. Impact of vegetation and preferential source areas on global dust aerosol: Results from a model study. *J. Geophys. Res. Atmos.* 2002, 107, 4576. [CrossRef]

116. Aryal, Y.N.; Evans, S. Global dust variability explained by drought sensitivity in CMIP6 models. *J. Geophys. Res. Earth Syst. Sci.* 2021, 126, e2020JD033173. [CrossRef]

117. Checa-Garcia, R.; Balkanski, Y.; Albani, S.; Bergman, T.; Carslaw, K.; Cozic, A.; Dearden, C.; Maticorena, B.; Michou, M.; van Noije, T.; et al. Evaluation of natural aerosols in CRESSCENDO Earth system models (ESMs): Mineral dust. *Atmos. Chem. Phys.* 2021, 21, 10295–10335. [CrossRef]

118. Mahowald, N.M.; Baker, A.R.; Bergametti, G.; Brooks, N.; Duce, R.A.; Jickells, T.D.; Kubilay, N.; Prospero, J.M.; Tegen, I. Atmospheric global dust cycle and iron inputs to the ocean. *Glob. Biogeoc. Cycles* 2005, 19, GB4025. [CrossRef]
119. Yan, H.; Wang, S.; Wang, C.; Zhang, G.; Patel, N. Losses of soil organic carbon under wind erosion in China. Glob. Chang. Biol. 2005, 11, 828–840. [CrossRef]
120. Chappell, A.; Webb, N.; Leys, J.; Waters, C.; Orgill, S.; Eyres, M. Minimising soil organic carbon erosion by wind is critical for land degradation neutrality. Environ. Sci. Policy 2019, 93, 43–52. [CrossRef]
121. Pimentel, D.; Kounang, N. Ecology of soil erosion in ecosystems. Ecosystems 1998, 1, 416–426. [CrossRef]
122. Lobe, I.; Amelung, W.; Du Preez, C.C. Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African Highveld. Eur. J. Soil Sci. 2001, 52, 93–101. [CrossRef]
123. Van Oost, K.; Quine, T.; Govers, G.; De Gryze, S.; Six, J.; Harden, J.; Ritchie, J.; Mccarty, G.; Heckrath, G.; Kosmas, C. The impact of agricultural soil erosion on the global carbon cycle. Science 2007, 318, 626–629. [CrossRef]
124. Yang, Y.; Fang, J.; Ji, C.; Ma, W.; Mohammadi, A.; Wang, S.; Wang, S.; Datta, A.; Robinson, D.; Smith, P. Widespread decreases in topsoil inorganic carbon stocks across China’s grasslands during 1980s–2000s. Glob. Chang. Biol. 2012, 18, 3672–3680. [CrossRef]
125. Duan, K.; Caldwel, P.V.; Sun, G.; Menuly, S.G.; Zhang, Y.; Shuster, E.; Liu, B.; Bolstad, P.V. Understanding the role of regional water connectivity in mitigating climate change impacts on surface water supply stress in the United States. J. Hydrol. 2019, 570, 80–95. [CrossRef]
126. Du, H.; Li, S.; Webb, N.; Zuo, X.; Liu, X. Soil organic carbon (SOC) enrichment in aeolian sediments and SOC loss by dust emission in the desert steppe, China. Sci. Total Environ. 2021, 798, 149189. [CrossRef] [PubMed]
127. Ren, Z.; Zheng, H.; He, X.; Zhang, D.; Shen, G.; Zhai, C. Changes in spatio-temporal patterns of urban forest and its above-ground carbon storage: Implication for urban CO₂ emissions mitigation under China’s rapid urban expansion and greening. Environ. Int. 2019, 129, 438–450. [CrossRef] [PubMed]
128. Lal, R. Accelerated Soil erosion as a source of atmospheric CO₂. Soil Till. Res. 2019, 188, 35–40. [CrossRef]
129. Du, H.; Wang, T.; Xue, X.; Li, S. Estimation of soil organic carbon, nitrogen, and phosphorus losses induced by wind erosion in Northern China. Land Degrad. Dev. 2019, 30, 1006–1022. [CrossRef]
130. Lei, L.; Zhang, K.; Zhang, X.; Wang, Y.; Xia, J.; Piao, S.; Hui, D.; Zhong, M.; Ru, J.; Zhou, Z.; et al. Plant feedback aggravates soil organic carbon loss associated with wind erosion in Northwest China. J. Geophys. Res. Biogeoosci. 2019, 124, 825–839. [CrossRef]
131. Zou, X.; Zhang, Z.; Zhou, Z.; Qui, Q.; Luo, J. Landscape-scale spatial variability of soil organic carbon content in a temperate grassland: Insights into the role of wind erosion. Catena 2021, 207, 105635. [CrossRef]
132. Webb, N.P.; Gowan, M.; Phinn, S.R.; Leys, J.F.; Tainsh, M. A model to predict land susceptibility to wind erosion in western Queensland, Australia. Environ. Modell. Softw. 2009, 24, 214–227. [CrossRef]
133. Dlugoss, V.; Fiener, P.; Van Oost, K.; Schneider, K. Model based analysis of lateral and vertical soil carbon fluxes induced by soil redistribution processes in a small agricultural catchment. Earth Surf. Proc. Land. 2012, 37, 193–208. [CrossRef]
134. Harper, R.; Gilkes, R.; Hill, M.; Carter, D. Wind erosion and soil carbon dynamics in south-western Australia. Aeolian Res. 2010, 1, 129–141. [CrossRef]
135. Óskarsson, H.; Arnalds, Ö.; Gudmundsson, J.; Gudbergsson, G. Organic carbon in Icelandic Andosols: Geographical variation and impact of erosion. Catena 2004, 56, 225–238. [CrossRef]
136. Van Oost, K.; Verstraeten, G.; Doetterl, S.; Notebaert, B.; Wiaux, F.; Broothaerts, N.; Six, J. Legacy of human-induced C erosion and burial on soil–atmosphere C exchange. Proc. Natl. Acad. Sci. USA 2012, 109, 19492–19497. [CrossRef]
137. Su, Y.Z.; Zhao, W.Z. Soil organic carbon dynamics: Wind erosion effect. Acta Ecol. Sin. 2005, 25, 2049–2054.
138. Mahowald, N.; Albani, S.; Kok, J.F.; Engelstaeder, S.; Scanza, R.; Ward, D.S.; Flanner, M.G. The size distribution of desert dust aerosols and its impact on the Earth system. Aeolian Res. 2014, 15, 53–71. [CrossRef]
139. Li, X.; Song, H.; Zhai, S.; Lu, S.; Kong, Y.; Xia, H.; Zhao, H. Particulate matter pollution in Chinese cities: Areal-temporal variations and their relationships with meteorological conditions (2015–2017). Environ. Pollut. 2018, 246, 11–18. [CrossRef]
140. Li, P.; Liu, L.; Wang, J.; Wang, Z.; Wang, X.; Bai, Y.; Chen, S. Wind erosion enhanced by land use changes significantly reduces ecosystem carbon storage and carbon sequestration potentials in semiarid grasslands. Land Degrad. Dev. 2018, 29, 3469–3478. [CrossRef]
141. Ward, D.S.; Mahowald, N.M.; Kloster, S. Potential climate forcing of land use and land cover change. Atmos. Chem. Phys. 2014, 14, 12701–12724. [CrossRef]
142. Ginoux, P.; Prospero, J.M.; Gill, T.E.; Hsu, N.C.; Zhao, M. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. Rev. Geophys. 2012, 50, 1–36. [CrossRef]
143. Li, Z.; Wang, Y.; Guo, J.; Zhao, C.; Cribb, M.; Dong, X.; Fan, J.; Gong, D.; Huang, J.; Jiang, M.; et al. East Asian Study of Tropospheric Aerosols and their Impact on Regional Clouds, Precipitation, and Climate (EAST-AIRCPC). J. Geophys. Res.-Atmos. 2019, 124, 13026–13054. [CrossRef]
144. Chen, S.; Jiang, N.; Huang, J.; Xu, X.; Zhang, H.; Zhang, Z.; Huang, K.; Xu, X.; Wei, Y.; Guan, X. Quantifying contributions of natural and anthropogenic dust emission from different climatic regions. Atmos. Environ. 2018, 191, 94–104. [CrossRef]
145. Chen, S.; Jiang, N.; Huang, J.; Zhang, Z.; Guan, X.; Ma, X.; Luo, Y.; Li, J.; Zhang, X.; Zhang, Y. Estimations of indirect and direct anthropogenic dust emission at the global scale. Atmos. Environ. 2019, 200, 50–60. [CrossRef]
146. Chen, S.; Huang, J.; Qian, Y.; Zhao, C.; Kang, L.; Yang, B.; Wang, Y.; Liu, Y.; Yuan, T.; Wang, T.; et al. An overview of mineral dust modeling over East Asia. J. Meteorol. Res. 2017, 31, 633–653. [CrossRef]
147. Mahowald, N.; Lindsay, K.; Rothenberg, D.; Doney, S.C.; Moore, J.K.; Thornton, P.; Randerson, J.T.; Jones, C.D. Desert dust and anthropogenic aerosol interactions in the Community Climate System Model coupled-carbon-climate model. *Biogeosciences* **2011**, *8*, 387–414. [CrossRef]

148. Mahowald, N.M.; Scanza, R.; Brahney, J.; Goodale, C.L.; Hess, P.G.; Moore, J.K.; Neff, J.C. Aerosol deposition impacts on land and ocean carbon cycles. *Curr. Clim. Chang. Rep.* **2017**, *3*, 16–31. [CrossRef]