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Abstract

While it is known that soil erosion by wind in drylands results in soil loss and redistribution and changes the texture of topsoil, there is little information about how these changes in the topsoil might affect the productivity of vegetation and if they result in degradation of the grasslands in wind-eroded regions such as Mongolian grasslands. In this study, we compared two different scenarios of vegetation growth, namely a wind-eroded scenario and an actual field condition, on two different grasslands in Mongolia (steppe and desert steppe) using an ecosystem model. The simulations of the wind-eroded scenario were based on a topsoil (0–0.1 m depth) with 1% clay and 99% sand, designed to represent an extremely wind-eroded soil surface that had permanently lost the fine clay particles and had gained sand particles. The effects of temperature, nutrient and water stresses on plant production were quantitively estimated. The model gave reasonably good simulations of the vegetation and soil water dynamics during the growing seasons (April–September) from 2002–2011. The simulation results showed that water had more effect on plant production than nitrogen and temperature at the two sites, and stresses because of a lack of water and nutrients generally affected plant production in the wind-eroded coarse-textured topsoil. Plant production was 20.2% lower in the wind-eroded scenario than in the actual field condition in the desert steppe under water-stressed conditions but plant production was slightly higher (5.0%) in the wind-eroded

scenario on the steppe that received more rainfall, because of a reverse texture effect, where water continues to infiltrate from the coarse topsoil (0–0.1 m depth) to the deeper root-zone (0.1–0.3 m depth) because of lower evapotranspiration from soil, and facilitates growth. When this happens, there is enough soil moisture in the root-zone, and plant growth is mostly affected by the nitrogen supply.

Keywords

DAYCENT ecosystem model, Mongolian grasslands, Nitrogen stress, Plant production, Soil texture change, Temperature stress, Water stress, Wind erosion

Introduction

The area of degraded land in dryland areas is increasing at an alarming pace, threatening food security and environmental quality (UNCCD, 1994). Soil erosion, mainly by wind and water, is the main driver of land degradation. Wind erosion of soil is a global phenomenon that occurs in arid and semi-arid regions worldwide (Shao, 2008; Shinoda et al., 2011). Soil that is eroded by strong wind causes aeolian dust events that threaten human and livestock health, present risks to life, and cause environmental problems, such as land degradation and air pollution, and economic losses in both the source and downwind areas. These phenomena have also triggered changes in global energy and carbon cycling in recent decades (Reichstein et al., 2013; Shao et al., 2011). Over recent decades, aeolian dust events have become increasingly severe globally, including those on temperate grasslands (Shinoda et al., 2011; Shao and Dong, 2006; Chimgee et al., 2010). Of the total land area affected by wind erosion worldwide, 549 million hectares are in major dust source regions (Middleton and Thomas, 1997), some of which are in northeastern Asia (Shinoda et al., 2014; Nandintsetseg and Shinoda, 2015).

These phenomena affect ecosystems at different scales and facilitate important biophysical feedbacks between biotic and abiotic components of Earth systems (Ravi et al., 2010; Shao et al., 2011), particularly the interactions between wind erosion and vegetation dynamic processes in dryland. Plant growth is generally affected by environmental factors such as temperature, light, water, and nutrients, which, when they deviate from the optimal intensity or quantity for the plant, are called stress factors (Schulze et al., 2005). Water is the factor that most limits plant productivity, and studies have shown that growth rates are proportional to water availability when the temperature is suitable for plant growth in arid and semi-arid regions (Noy-Meir, 1973; Pugnaire et al., 1999). Furthermore, productivity may be limited under temperature extremes and low soil nutrient contents (Fischer and Turner, 1978). During wind erosion, fine particles (<125 μm) in the topsoil are permanently removed from the parent soil surface and are redistributed elsewhere by aerodynamic lift, saltation bombardment, and disaggregation (Shao et al., 1993; Shao, 2008; Kok et al., 2012; Újvári et al., 2016; Zhang et al., 2016). At the same time, the texture of the topsoil becomes increasingly coarse (Li et al., 2009; Yan et al., 2018) because of the accumulation of large amounts of sand-sized particles that hop along the topsoil by saltation (Shao, 2008) from the windward side. Consequently, when topsoil is eroded by strong wind, the texture, and also the soil water status and nutrients content are changed, and may cause plant productivity to decrease (Kirchner 1977; Larney et al., 1998; Hooper and Johnson., 1999; Okin et al., 2004; Harpole et al., 2007) or increase (Alizai and Hulbert, 1970; Noy-Meir, 1973; Sala et 1998). However, there is little information about how wind erosion accelerates land degradation in drylands through interactions with vegetation.

The coarser eroded soil in the top layer has less ability to retain water because of a decrease in the water-holding capacity (Saxton et al., 1986; Saxton and Rawls., 2006; Zhao et al., 2006) and an increase in the saturated hydraulic conductivity of the soil (Yao et al., 2013). This means that the water supply to the plant may be limited, causing an increase in water stress and effects on plant production (Pugnaire et al., 1999; Porporato et al., 2001). Conversely, previous field studies reported that there was more evaporation from fine-textured than from coarse-textured soils in arid and semi-arid areas (Alizai and Hulbert, 1970; Noy-Meir, 1973). This effect may effectively trigger competition for moisture in the root-zone and lead to a decrease in the effect of water stress on plant production (Noy-Meir, 1973). In addition, some recent field studies and simulations have shown that wind erosion plays an important role in the depletion and redistribution of soil organic carbon (SOC) and a variety of soil nutrients (Wang et al., 2006; Li et al., 2007, Li et al 2009; Hoffmann et al., 2008; Yan et al., 2018). For example, large nutrient losses and decreases in soil quality were observed in wind-eroded areas when nutrient-rich topsoil was removed (Li et al., 2004, Ikazaki et al., 2012). Wind erosion may cause the soil organic matter (SOC) to decline gradually with potential detrimental effects on nutrient availability and soil moisture (Lyles and Tatarko, 1986). Therefore, when SOC and nutrients (e.g. nitrogen) are irreversibly removed by wind erosion, the productivity or fertility of the parent soil declines (Lal et al., 2001; Ravi et al., 2010) and the demand for nutrients stress from plant production increases (LeBauer and Treseder, 2008; Li et al., 2009).

In the 2000s, the frequency of severe dust events has increased in dust source areas in Asia, particularly in the Mongolian temperate grasslands, because of an increase in dryness (drought stress) and human interference (e.g. overgrazing) (Kurosaki et al., 2011; Shinoda et al., 2011; Hoffmann et al., 2008; Nandintsetseg et al., 2018). An assessment of the Mongolian grasslands suggested that 78.2% of the territory had been degraded because of soil erosion (Mandakh et al., 2007), triggered by climate change and overgrazing (Nandintsetseg et al., 2018). Indeed, the situation is so serious that the Mongolian grasslands are recognized as one of the most vulnerable terrestrial ecosystems to wind erosion worldwide under a changing climate (Kassas, 1995; Lal, 2003; Shinoda et al., 2011; Abulaiti et al., 2014).

In this study, we examined how plant productivity differed between wind-eroded coarse-textured topsoil (0–0.1 m depth) and actual field conditions on two different Mongolian grasslands (steppe and desert steppe). To do this, we simulated and compared the growth on the potentially wind-eroded coarse-textured topsoil (referred to as the wind-eroded scenario) and the actual field condition (referred to as the actual condition). We therefore used an ecosystem model (DAYCENT) to study the daily vegetation dynamics for both conditions at these two grasslands, and quantitatively estimated how much of the change in plant production was attributable to the limited supplies of water and nutrients (nitrogen).

Materials and methods

Study area description

The two study sites are on the Mongolian grasslands (Fig. 1). One site, Bayan-Unjuul (BU: 47.04°N, 105.95°E), is on the steppe and has a semi-arid climate while the other, Tsogt-Ovoo (TsO: 44.42ºN, 105.39ºE) is on the desert steppe and has an arid climate. The two sites are in the north (BU) and the middle (TsO) of a major dust source area (Shinoda et al., 2011; Kurosaki et al., 2007; Kurosaki et al, 2011), respectively. It was assumed that vegetation was critical for dust emissions in temperate grasslands, so the Dust-Vegetation Interaction Experiment (DUVEX) was established at BU in 2007 to gain insights into the relationships between dust emissions and ecosystem processes (e.g. vegetation, soil moisture, and grazing) on vegetated land surfaces (Shinoda et al., 2010; Nandintsetseg and Shinoda, 2015). The DUVEX project was extended to include a dust observation site at TsO (Ishizuka et al., 2012; Abulaiti et al., 2014). Weather information was obtained from the Mongolian Institute of Meteorology, Hydrology, and the Environment (IRIMHE) for the period from 2002–2011 at BU and from 2002–2017 at TsO. The average annual precipitation at BU and TsO amounted to 145.1 and 85.3 mm, with 116.9 and 71.5 mm occurring between May and September, respectively. The annual mean temperatures at BU and TsO were 0.86°C and 5.1°C, respectively. At both sites, the soil is frozen during winter (October–March), and the growing season generally begins in late April and lasts until mid-September. The Mongolian grasslands are generally dominated by the C3 vegetation type (Nandintsetseg and Shinoda, 2015). At BU, natural perennial grasses (*Stipa krylovii*, *Stipa grandis*, and *Cleistogenes squarrosa*), forbs (*Artemissia spp.*), and small shrubs (*Caragana spp.*) dominate, while desert shrubs (*Reaumuria soongolica* and *Salsola passerine*) dominate at TsO (Hilbig, 1995; Ishizuka et al., 2012).

Simulations for the actual and wind-eroded scenarios

The aim of the simulations was to examine how the plant productivity changed in the wind-eroded coarse-textured topsoil in the Mongolian grasslands. For the wind-eroded scenario, a topsoil (0–0.1 m depth) that comprised 1% clay and 99% sand was used. This represented a soil had permanently lost most of the fine clay particles from its surface because of dust emissions by aerodynamic entrainment, saltation bombardment and aggregate disintegration (Shao, 2008; Kok et al., 2012; Újvári et al., 2016; Zhang et al., 2016), leaving coarse sandy particles that were supplemented through saltation (Shao, 2008) from the windward side. This type of texture may be common in topsoils in severely degraded grasslands, particularly these Mongolian grasslands, that eroded by wind. The simulations of the actual field condition were based on the observed data of the soil texture at the steppe and desert steppe field sites (Table 1).

Meteorological data and land surface measurements

The meteorological (daily maximum and minimum air temperatures, and daily precipitation) data from the IRIMHE monitoring stations at BU (1980–2011) and TsO (1980–2016) were used as model inputs. The above-ground mass (AGM) (live plus standing dead grasses) in the grazing areas of BU was measured approximately monthly in June, July, and August (mostly August) from 2003 to 2010 (Nandintsetseg and Shinoda, 2015). Measurements of AGM (2002–2015) in the grazing areas at the TsO IRIMHE monitoring station were also obtained. Plants in 1 × 1 m quadrants that were randomly distributed throughout the grazing areas were clipped (Nandintsetseg and Shinoda, 2010). The stocking rates (number of animals per hectare) at BU and TsO were classified as light grazing (Sugita et al., 2007) and heavy grazing, respectively. Soils at BU and TsO are mostly Kastanozems and Kastannozem calcic skelectic (Kinugasa et al., 2012; Dordjgotov, 2003). The texture and bulk densities of the topsoils at BU and TsO are shown in Table 1. The volumetric soil moisture content was measured hourly at depths of 0.1 and 0.2 m at BU from 2004 to 2008 (Shinoda et al., 2010; Nandintsetseg and Shinoda, 2015) and at TsO from 2012 to 2015 (Ishizuka et al., 2012) using time-domain reflectometry. The field-measured data were used for the DAYCENT model validations and simulations.

Model description

The DAYCENT model is a process based terrestrial ecosystem model that simulates how fluxes of carbon, nutrients (e.g., nitrogen, phosphorus and sulfur), and trace gases in the atmosphere, soil, and plants, change in response to human activities, such as fire and grazing (Del Grosso et al., 2001; Parton et al., 1998). This model is the daily time-step version of the CENTURY biogeochemical model (Parton et al., 1994), and includes routines for simulating the movement of nutrients and water through soil layers, plant growth, and many other ecosystem components. The model input variables include (1) climate variables (daily maximum and minimum air temperature, and daily precipitation), (2) site-specific variables such as soil properties (texture, depth, pH, bulk density, and field capacity) (Table 1), and (3) land management (e.g., cultivation or grazing).

The plant production sub-model of DAYCENT (Parton et al., 1993, Kelly et al., 2000, and Del Grosso et al., 2011) can simulate a variety of ecosystems, including grasslands (Gilmanov et al., 1997; Nandintsetseg and Shinoda., 2015; Chang et al., 2015), by altering various plant-specific parameters so that different herbaceous crops (corn, wheat, etc.) and plant communities (C3, C4, etc.) are represented. This sub-model considers plant productivity as a function of genetic potential, phenology, nutrient availability, water/temperature stress, and solar radiation. Biomass can be removed or transferred to the litter pool by disturbances such as grazing. The effect of grazing pressure on plant production was represented by the models of Holland et al. (1992), Ojima et al. (1993), and Ojima and Correll (2009).

The widely-used soil water sub-model can simulate the soil moisture content and water fluxes through the canopy, surface runoff, leaching, evaporation and transpiration for each horizon throughout the defined depth of the soil layers (Parton et al., 1998, Eitzinger et al., 2000; Del Grosso et al., 2011, Nandintsetseg and Shinoda, 2015). The amount of water in the soil that is available for plant growth depends on the current soil water, precipitation, and potential evapotranspiration (Parton et al., 1998). Precipitation intercepted by vegetation and litter is evaporated at the PET rate calculated by the Penman equation (1948). The amount of water intercepted is a function of the plant biomass and the amount of rainfall (Parton, 1978). When the daily air temperature is below freezing, precipitation is assumed to fall as snow and is accumulated in the snowpack.

In addition, the soil organic matter and nutrient sub-models represent the flow of carbon (C), nitrogen (N), phosphorus (P), and sulfur (S) in plant litter, and different organic and inorganic soil pools (Parton et al., 1988). The N sub-model, which has the same structure as the soil C sub-model (Parton et al., 1994), was the focus of this study. The N flows are equal to the product of the C flows and the C/N ratio of the state variable that receives the C. The inputs of N can be calculated using equations for atmospheric deposition, and soil and plant N fixation. The N losses due to leaching are related to the soil texture and the amount of water moving through the soil profile (Parton et al., 1994, 1996, 2001; Del Grosso et al., 2000).

Simulating water, temperature, and nitrogen stresses with the DAYCENT model

In the DAYCENT grassland sub-model, plant production is controlled by initially having soil moisture and temperature at a maximum, and then decreased if the soil nutrient supply is insufficient. The grassland model also includes the effect of shading from dead vegetation, while the forest model includes the effect of live leaf area on plant production (Parton et al., 1993). During the simulation processes, the maximum potential (or genetic maximum) above-ground plant production (AGP_{max}), not limited by temperature, water, or nutrient stresses, is primarily determined by the level of photosynthetically active radiation, the maximum net assimilation rate of photosynthesis, the efficiency at which carbohydrates are converted into plant constituents, and the rate at which respiration is maintained (van Heemst, 1986). Thus, the parameter for AGP_{max} has both genetic and environmental components. The potential production (AGP_{pot}) is a function of the AGP_{max} for grassland and 0–1 environmental scalars depending on soil temperature, soil water status, shading from dead vegetation, and seedling growth (Parton et al., 1993). Here, seedling growth and shading from dead vegetation will have a negligible effect on AGP_{pot}, because the seedling growth for grass is not limited (Parton et al., 1992). Also, the shading effect on AGP_{pot} is a response surface that depends on the amount of live and dead vegetation. We found that amounts of observed above-ground live and dead vegetation in the Mongolian grasslands (Fig. 2) were lower than the threshold values at which shading occurs and shoot senescence increases (150 and 60 g m^{-2}, respectively) (Parton et al., 1992). Therefore, we assumed that the soil water status and temperature were the main controls on the AGP_{pot} in the Mongolian grasslands (Eq. 1). The effects of soil water availability and temperature on plant production (Water stress, W_{stress}; Temperature stress, T_{stress}) were calculated as shown in Eq. (2) and Eq. (3).

$$AGP_{pot} = AGP_{max} \times S_T \times S_w \quad (1)$$

$$T_{stress} = 1 - S_T \quad (2)$$

$$W_{stress} = 1 - S_w = 1 - \frac{\mathrm{AGP_{pot}}}{\mathrm{AGP_{max}} \times S_T} \quad (3)$$

Where S_T is an environmental scalar of soil temperature, which is calculated as a function of air temperature and the optimum plant temperature. S_w is an environmental scalar of soil moisture statue, which is identified by the soil-water sub-model (Parton et al., 1993). The values of T_{stress} and W_{stress} are both range from 0 to 1, and the values close to 1 indicate the maximum stress on plant production.

The plant production also decreases if there is insufficient mineral nutrient for uptake and to satisfy the C/N ratio for producing plants. The actual production (AGP_{act}) is limited to what can be achieved with the nutrient supply available at the time with plant nutrient concentrations Eq. (4). We assumed how the AGP_{act} was affected by the lack of nitrogen (nitrogen stress, N_{stress}) as shown in Eq. (5).

$$AGP_{act} = AGP_{pot} \times S_N \quad (4)$$

$$N_{stress} = 1 - S_N = 1 - \frac{AGP_{act}}{AGP_{pot}} \quad (5)$$

Where S_N is an environmental scalar of nitrogen insufficiency, which is identified by the soil organic matter and nutrient sub-models.

In this study, we mainly focused on the changes in the effects of W_{stress} and N_{stress} on AGP_{act} for the actual condition and the wind-eroded scenario during the critical growing season (June–August). Eq. (6), Eq. (7) and Eq. (8) were therefore proposed to examine coarse-textured topsoil impacts on AGP_{act}:

$$\Delta AGP_{act} = (AGP_{act})_{eroded} - (AGP_{act})_{actual} \quad (6)$$

$$\Delta W_{stress} = (W_{stress})_{eroded} - (W_{stress})_{actual} \quad (7)$$

$$\Delta N_{stress} = (N_{stress})_{eroded} - (N_{stress})_{actual} \quad (8)$$

Where ΔAGP_{act}, ΔW_{stress}, and ΔN_{stress} are the differences in the actual plant production, water stress, and nitrogen stress between the actual condition and the wind-eroded scenario. The subscripts "*actual*" and "*eroded*" denote the actual condition and the wind-eroded scenario, respectively.

The changes in the plant production between the actual condition and wind-eroded scenario (ΔAGP_{act}) were examined. For example, when $\Delta AGP_{act} < 0$, the AGP_{act} in the actual condition was higher than in the wind-eroded scenario. The reasons for the changes in ΔAGP_{act} from the ΔW_{stress} and the ΔN_{stress} were also analyzed. When $\Delta W_{stress} > 0$ and $\Delta N_{stress} \leq 0$, plant production is mainly limited by water, while when $\Delta W_{stress} < 0$ and $\Delta N_{stress} > 0$, plant growth is limited by nitrogen.

Site-level model parameterization

Previous studies have shown that global grassland ecosystems can be simulated using relatively few data of site-specific parameters that change as the circumstances change (Parton et al., 1995; 1998). The DAYCENT model was parameterized and calibrated with the field experiment data (soil physical and chemical properties, and vegetation) at BU (Nandintsetseg and Shinoda, 2015) and TsO (Table. 1). AGP_{max}, and the optimum and maximum temperatures for production were parameterized using information from the agrometeorological database for the Mongolian grasslands (IMH, 1996).

The soil and vegetation were in equilibrium for the actual condition and wind-eroded scenario at BU and TsO, historical simulations were processed in DAYCENT for 1980 years by repeating the long-term climate averages over 32 years (1980–2011) for BU and 37 years (1980–2016) for TsO. The actual daily meteorological data sets were then used to run the model for the actual grazing condition (light grazing for BU from 1980 to 2011 and heavy grazing for TsO from 1980 to 2016). The model performance was assessed from the mean absolute deviation (D_{abs}) and the slope coefficient (b) from the regression equation of the observations versus the corresponding simulations (Gilmanov et al., 1997).

Results

Model performance

The model performance of the actual condition was validated using observations of daily soil moisture and above-ground mass (AGM) from April to September at BU and TsO. The daily precipitation, and the daily observed and simulated soil moisture and AGM from 2002 to 2011 at BU and from 2002 to 2017 at TsO are shown in Fig. 2. In general, the model gave reasonably good simulations of the daily variations in the soil moisture at both stations (r = 0.80, $p < 0.05$ for BU, and r = 0.56, $p < 0.05$ for TsO) (Figs. 2−a1 and 2−a2). These simulations of soil moisture at both sites showed a similar seasonal pattern as was observed in a previous study of the Mongolian grasslands. There were three seasonal phases of soil moisture, as follows: the spring drying between April and May until the onset of the rainy season, the summer recharge between late May and late July from summer precipitation, and autumn drying in August–October prior to the soil freezing because of the decrease in precipitation (Nandintsetseg and Shinoda, 2011). The D_{abs} and b of the observed soil moisture data from these simulations were 1.8% and 1.2 at BU, and 2.6% and 0.9 at TsO, respectively. Comparison of the measured and simulated values shows that the model performed well using the available observed data even though the observed and simulated soil moisture data were from slightly different depths. The model gave a reasonable simulations of soil carbon and total nitrogen at BU with $r = 0.94$ ($p < 0.05$) and $r = 0.55$ ($p < 0.05$) but the soil total nitrogen was underestimated (6.8%).

As shown in Figs. 2–b1 and 2–b2, there was good agreement between the daily simulated and observed AGM at both sites ($r = 0.77$, $p < 0.05$ for BU, and $r = 0.60$, $p < 0.05$ for TsO). The simulations of the seasonal dynamics in AGM showed the timings of the onset of spring growth (May), a summer peak (July–August), and decay (September). The D_{abs} and b of the observed data from these simulations were 21.7 g m^{-2} and 1.5 at BU, and 1.3 g m^{-2} and 0.7 at TsO, respectively. The model underestimated the peak production in the years when the measured production at BU was high (2003, 2008, and 2010) and following drought years at TsO (2008), perhaps reflecting changes in the plant species composition during those years (Nandintsetseg and Shinoda, 2015). Previous observed studies showed that annual plant species increased more after drought years than perennial species (Shinoda et al., 2014).

Numerous studies have shown that the grassland degradation has increased (Mandakh et al., 2007; Nandintsetseg and Shinoda, 2013) and the plant species composition has decreased; moreover, because of drought (Shinoda et al., 2014) and overgrazing in the Mongolian grasslands in recent decades (e.g., Jigmed, 2006; Hilker et al., 2014; Nandintsetseg et al., 2017), perennial species are being substituted by annual species. While the model only focused on a whole plant community (C3 in this study), and did not consider changes in species because of seasonal- and inter-annual variations and functional diversity of the plant community (e.g., Parton et al., 1993; 1995), these results suggest that the DAYCENT model can give reasonable simulations of seasonal and inter-annual changes in soil moisture and AGM in the steppe and desert steppe ecosystems. Generally, the rainfall was higher (soil moisture), and the evapotranspiration was lower, at BU (steppe) than at TsO (desert steppe). The modelled and observed data therefore showed that the conditions were more favorable for higher plant production at BU than at TsO.

Effects of water, temperature, and nitrogen stresses on plant production in the actual and wind-eroded scenarios

Figure 3 shows the monthly precipitation and temperature (a1, a2), and monthly simulated AGP_{act}, W_{stress}, T_{stress} and N_{stress} values for the actual condition and the wind-eroded scenario at TsO (b1, c1) and BU (b2, c2) in the growing season (May–September) for 2002–2011. The monthly average AGP_{act} (gC m^{-2}) for the actual/wind-eroded scenarios were 7.4/6.9 (May), 7.6/7.9 (June–August), and 1.3/1.1 (September) for BU and 0.6/0.3, 0.5/0.45, and 0.5/0.3 for TsO, respectively. At both sites, soil moisture had more effect on AGP_{act} than soil temperature and nitrogen. The W_{stress} was higher at TsO than at BU. At BU, the W_{stress} for the actual/wind-eroded scenarios were 0.673/0.674 (May), 0.918/0.917 (June–August), and 0.918/0.909 (September), respectively. At TsO, W_{stress} was more than 0.9 from May to September for both conditions and ranged from 0.925 to 0.998 (actual condition) and from 0.962 to 0.998 (wind-eroded scenario). The N_{stress} played an important role for AGP_{act} in the onset of the growth (May) and summer periods (June–August) at BU. For the actual/wind-eroded scenarios, the values of N_{stress} at BU were higher from May to August (0.451/0.536), than they were in September (0.430/ 0.522). However, plant production at TsO was not affected by nitrogen. Soil temperature had a negligible effect on AGP_{act} from June to August at both sites. For the actual/wind-eroded scenarios, the values of T_{stress} at BU were 0.732/0.732 for May, 0.083/0.083 for June–August, and 0.677/0.677 for September, respectively. At TsO, the values of T_{stress} were 0.787/0.787 for May, 0.057/0.057 for June–August, and 0.733/0.733 for September, respectively. These results show that water and nitrogen stresses influenced plant production in the critical growing season (June–August) in the Mongolian grasslands, and that temperature stress was only important in the emergence (May) and senescence (September) periods, respectively. Our results are consistent with a previous study on the Mongolian grasslands by Nandintsetseg and Shinoda (2011), who reported that the emergence coincided as the trends in soil moisture changed from decreasing to increasing as temperature increased. To assess how plant production was influenced by textural changes in the wind-eroded topsoil, we compared the simulations of the actual condition and the wind-eroded scenario at both sites from June to August. Figure 4 shows the differences of AGP_{act}, W_{stress} and N_{stress} between the actual condition and the wind-eroded scenario (ΔAGP_{act}, ΔW_{stress} and ΔN_{stress}) in the critical growing season from 2002 to 2011 (total 30 months) at BU and TsO. The ΔAGP_{act} at BU and TsO had mean values of 0.38 (+5.0%) and –0.14 (–20.2%) gC m^{-2}, respectively. Table 2 shows that the ΔAGP_{act} was less than 0 for 10 months at BU and 28 months at TsO while the ΔAGP_{act} was greater than 0 for 20 months at BU and 2 months in 2006 summer at TsO. At TsO (Fig. 4–d1), plant production was mainly controlled by water ($\Delta W_{stress} > 0$ and $\Delta N_{stress} \leq 0$) for 28 months when ΔAGP_{act} was less than 0. Nitrogen ($\Delta W_{stress} < 0$ and $\Delta N_{stress} > 0$) was the main control on plant production for only 2 months during the summer of 2006, which was wetter than normal, when ΔAGP_{act} was greater than 0. This shows that plant production decreased in the wind-eroded scenario at TsO generally, and this decrease was caused by an increase in water stress. At BU (Fig. 4–d2), when ΔAGP_{act} was less than 0, plant production was mainly controlled by water for 7 months, and by nitrogen for 2 months in June 2002 and June 2003 because of the higher precipitation in previous month. When ΔAGP_{act} was greater than 0, plant production was primarily controlled by water for 5 months and by nitrogen for 14 months. The results show that this higher plant production at BU (+5.0%) was mainly because the water stress decreased, and plant growth was thereafter controlled by nitrogen in the critical growing season.

Discussion

When we compared the simulations of the AGP_{act} between the actual condition and the wind-eroded scenario, we found that plant production in the wind-eroded topsoil decreased by 20.2% in the desert steppe area (TsO) and slightly increased by 5.0% in the wetter steppe (BU) during the critical growing season from 2002 to 2011. These results indicate that the effects of the coarse-textured topsoil on the plant production may change with variations in the environmental conditions in the Mongolian grasslands. In the desert steppe area, the annual precipitation was lower (Fig. 5–a1) (between 38.2 and 164.5 mm from 2002 to 2011) than at BU. In both scenarios, this precipitation did not penetrate into the deeper soil but was stored in the topsoil layer (Figs. 5–a2 and 5–a3). The coarse topsoil meant that the water holding capacity in the wind-eroded scenario was low, and the evapotranspiration was greater than in the actual condition (Fig. 5–a4). Therefore, there was less soil moisture in the root-zone (0.1–0.3 m depth) in the wind-eroded scenario than in the actual condition (Fig. 5–a5). Previous studies have stated that biological processes in arid ecosystems with extremely low precipitation were mainly controlled by water (Noy-Meir, 1973). Field studies have also shown that, when the available precipitation was less than 200 mm, the productivity of natural grass was low and did not differ significantly under different N fertilizer application rates (Smike et al., 1965). Also, Nandintsetseg and Shinoda (2011) showed that the soil moisture was below the Mongolian mean and close to the wilting point throughout the year in the desert steppe. The soil available water, therefore, is the main influence on plant production in arid ecosystems (Le Houerou et al., 1984; Lauenroth and Sala., 1992). At TsO, plant production decreased in the wind-eroded scenario because of increased water stress, caused by an increase in evapotranspiration and a decrease in the soil water in the root zone. In contrast, in the wetter steppe (BU), the main reason for the slight increase in plant production was a decrease in water stress. As shown in Fig. 5–b1, when the annual precipitation ranged from 89.2 to 250.4 mm (from 2002 to 2011), more precipitation penetrated into the deeper soil in the wind-eroded scenario, because of the lower water holding capacity and higher hydraulic conductivity in the wind-eroded topsoil (Figs. 5–b2 and 5–b3). The evapotranspiration from the coarse topsoil in the wind-eroded scenario was therefore lower than that from the loamy topsoil in the actual condition (Fig. 5–b4). Together, these factors mean that there was more water in the root-zone to facilitate plant growth (Fig. 5–b5) in the wind-eroded scenario. Previous researchers have called this the inverse texture hypothesis (e.g., Noy-Meir, 1973, Sala et al., 1988), and it has been observed in sandy regions with relatively high precipitation (< 300 mm). After adding equal amounts of water in experiments in a warm greenhouse, Alizai and Hulbert (1970) showed that evaporation was often greater from a loam bare soil than from sand. Field studies (Sala et al., 1988; Yang et al., 2009) have shown that the plant production was higher in sandy soils with lower water holding capacity in wetter grasslands than in loamy soils with higher water holding capacity on the Tibetan Plateau and the Central Grassland region of the US. Although the plant growth is limited by the soil available water in semi-arid regions where inverse texture effects are obvious, it is more sensitive to nitrogen stress when there is enough soil water during the summer, as also reported elsewhere. From their field study, Hooper and Johnson (1999) reported that plant production was limited by both water availability and nitrogen in a semi-arid region, but that production responded positively to N additions as the water availability increased. Also, Kinugasa et al. (2012) reported that, when N was added to the wetter steppe soils at BU, had more effect on plant production in wetter years (when the water stress was lower) than in drier years (when the water stress was higher).

Relatively few studies have discussed changes in vegetation because of changes in soil texture driven by wind erosion as they occur slowly (Lyles, 1975, 1977; Larney et al., 1998), and may only become noticeable after several years or decades. Previous studies found that the sand content in surface soil increased by 6.5% and silt decreased by 7.2% over a 36-year period because of wind erosion (Kansas Lyles and Tatarko, 1986). Li et al. (2009) showed that fine particles (< 125 μm) declined and sand particles (> 250 μm) increased significantly after two years in an area that was affected by serious wind-erosion. There may be a significant decrease in the proportion of fine particles in surface soil that are enriched by higher amounts of soil organic carbon and nutrients, as wind erosion progresses (Li et al., 2007; Li et al., 2009; Yan et al., 2018), which may then cause decreases in plant production in wind-eroded regions. However, our results show that the decreases in plant production were mainly caused by increases in water stress in wind-eroded topsoil at both sites on the Mongolian grasslands (28 months at TsO and 6 months at BU). A field experiment in farmland in arid and semi-arid regions in Inner Mongolia showed that soil that was subject to wind erosion since the 1980s was significantly coarser, less fertile and drier than non-eroded land. Moreover, when high amounts of sand accumulate (72.6% sand), the average soil moisture content decreased significantly (Zhao et al., 2006). These results imply that the soil water status may be affected more than the soil nutrient pool in the wind-eroded coarse-textured topsoil in arid and semi-arid regions.

Conclusions

In this study, we compared how the vegetation at two sites in steppe and desert steppe Mongolian grassland landscapes differed between an extremely wind-eroded topsoil, represented by the top 0.1 m comprising clay and sand contents of 1% and 99% (wind-eroded scenario), and the actual grassland condition using an ecosystem model. The results from our study highlight the importance of identifying how temperature, soil moisture and nutrient (nitrogen) stresses influence plant production in topsoil that might be eroded by wind in dust source areas in the Mongolian grasslands. Moreover, this study provided new insights into how plant production in arid and semi-arid regions is affected by wind-eroded soil and that the soil water status may be affected more than the soil nutrient pool for decreases in plant production as the topsoil becomes coarser as the wind erosion progresses.

Although natural wind-driven soil erosion processes occur slowly over several years or decades, dust events, a major driver of land degradation worldwide, have increased in severity over recent decades, because of climate change and human disturbances. Hence, realistic changes in soil physical properties need to be considered when assessing how wind-driven soil erosion affects the ecosystem carbon budget (Van Oost et al., 2007). This study will contribute to current understanding of the potential effects of wind erosion on plant production in dust source areas, and specifically about the particular stresses that vegetation in wind-eroded arid and semi-arid grasslands are subjected to.

Abbreviations

AGM: Above-ground mass; AGP_{act}: Actual above-ground plant production; AGP_{max}: Maximum potential above-ground plant production; AGP_{pot}: Potential above-ground plant production; *b*: The slope coefficient in the formal regression equation of the observed and simulated data; BU: Bayan-Unjuul; D_{abs}: Mean absolute deviation; MGs: Mongolian Grasslands; N_{stress}: Nitrogen stress; RMSE: Root mean square error; TsO: Tsogt-Ovoo; T_{stress}: Temperature stress; W_{stress}: Water stress; ΔAGP_{act}: The difference in the actual above-ground plant production between the actual condition and the wind-eroded scenario; ΔN_{stress}: The difference in the nitrogen stress between the actual condition and the wind-eroded scenario; ΔW_{stress}: The difference in the water stress between the actual condition and the wind-eroded scenario

Declarations

Availability of data and material

Data sharing not applicable to this article as no datasets were generated or analysed during the current study. Please contact author for data requests.

Competing interests

The authors declare that they have no competing interest

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Authors' contributions

KK, BN, and MS proposed the topic and conceived and designed the study. KK and BN analyzed the data. All authors contributed to writing the manuscript. All authors read and approved the final manuscript.

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Figures legends

Figure 1. The steppe (Bayan-Unjuul, BU) and the desert steppe (Tsogt-Ovoo, TsO) grassland sites in Mongolia and the different vegetation zones.

Figure 2. (a1 and a2) Time series of daily precipitation, and comparison of the daily observed (depth 0.1 m) and simulated (depth 0.075 m) soil moisture, and (b1 and b2) the daily observed and simulated above-ground mass (AGM, live plus standing dead grasses) at BU from 2002 to 2011 at TsO and from 2002 to 2016 at BU. Asterisks following the correlation coefficient (*) indicate significance at the 95% level.

Figure 3. Monthly precipitation and air temperature (a1 and a2) and the monthly simulated W_{stress}, T_{stress}, N_{stress} and AGP_{act} for the actual condition and the wind-eroded scenario during the growing season (May–September) from 2002 to 2011 at TsO (b1 and c1) and BU (b2 and c2), respectively.

Figure 4. The monthly differences in AGP_{act} (a1 and a2), W_{stress} (b1 and b2), and N_{stress} (c1 and c2) between the actual condition and the wind-eroded scenario (ΔAGP_{act}, ΔW_{stress}, and ΔN_{stress}) (a1–c1, a2–c2) and the number of months when plant growth experienced water and nitrogen stresses (d1, d2), during the critical growing season (June–August) from 2002 to 2011 at TsO and BU, respectively.

Figure 5. Schematic representation of the different mechanisms that drove the changes in plant production in wind-eroded coarse-textured topsoil on the desert steppe (TsO, from a1 to

a5) and the steppe (BU, from b1 to b5) because of the inverse texture effect. The different-sized (thick and thin) arrows indicate the magnitude (high and low) of the variables (precipitation, ET: evapotranspiration, and infiltration).

Tables

Table 1. Model parameterizations of the vegetation, soil, and meteorological characteristics

Parameter	**BU**	**TsO**
Potential above-ground monthly production (gC m^{-2})	300*	100*
Optimum temperature for steppe (°C)	20.0*	22.0*
Maximum temperature for steppe (°C)	35.0*	37.0*
Physiological shoutdown temperature for root death and change in shoot/root ratio of grass (°C)	2.0*	
Maximum shoot death rate at very dry soil conditions for steppe (0–1)	0.2*	
Shoots which die during senescence month (0–1)	0.95*	
The maximum root death rate at very dry conditions for steppe	0.05*	
The thickness of soil layers (m)	0.3(a)	0.4(a)
Soil pH (topsoil)	6.5(a)	8.17(a)
Root depth (m)	0.4(a)	0.4 (a)

Soil field capacity (topsoil) (0–1)	0.21(a)	0.23(a)
Soil wilting point (topsoil) (0–1)	0.07(a)	0.10(a)
Soil bulk density (topsoil) (g cm^{-3})	1.44(a)	1.49(a)
Clay content (topsoil) (0–1)	0.09(a)	0.17(a)
Sandy content (topsoil) (0–1)	0.65(a)	0.64(a)
Silt content (topsoil) (0–1)	0.24(a)	0.19(a)
Initial belowground biomass (g m^{-2})	200*	
Initial relative soil moisture content (0–1)	0.16*	
Annual precipitation (mm)	(b)	
Daily minimum air temperature (°C)		
Daily maximum air temperature (°C)		
Standing dead removed by a grazing event	0.01(a)	0.05 (c)
Content of feces	0.25*	
Live shoots removed by a grazing event	0.1(a)	0.5(a)

* From DAYCENT data-setting (around the world);

(a) Observation data at BU (Nandintsetseg and Shinoda, 2015) and at TsO, mean parameters were related to the vegetation and soil types

(b) Meteorological data from IRIMHE;

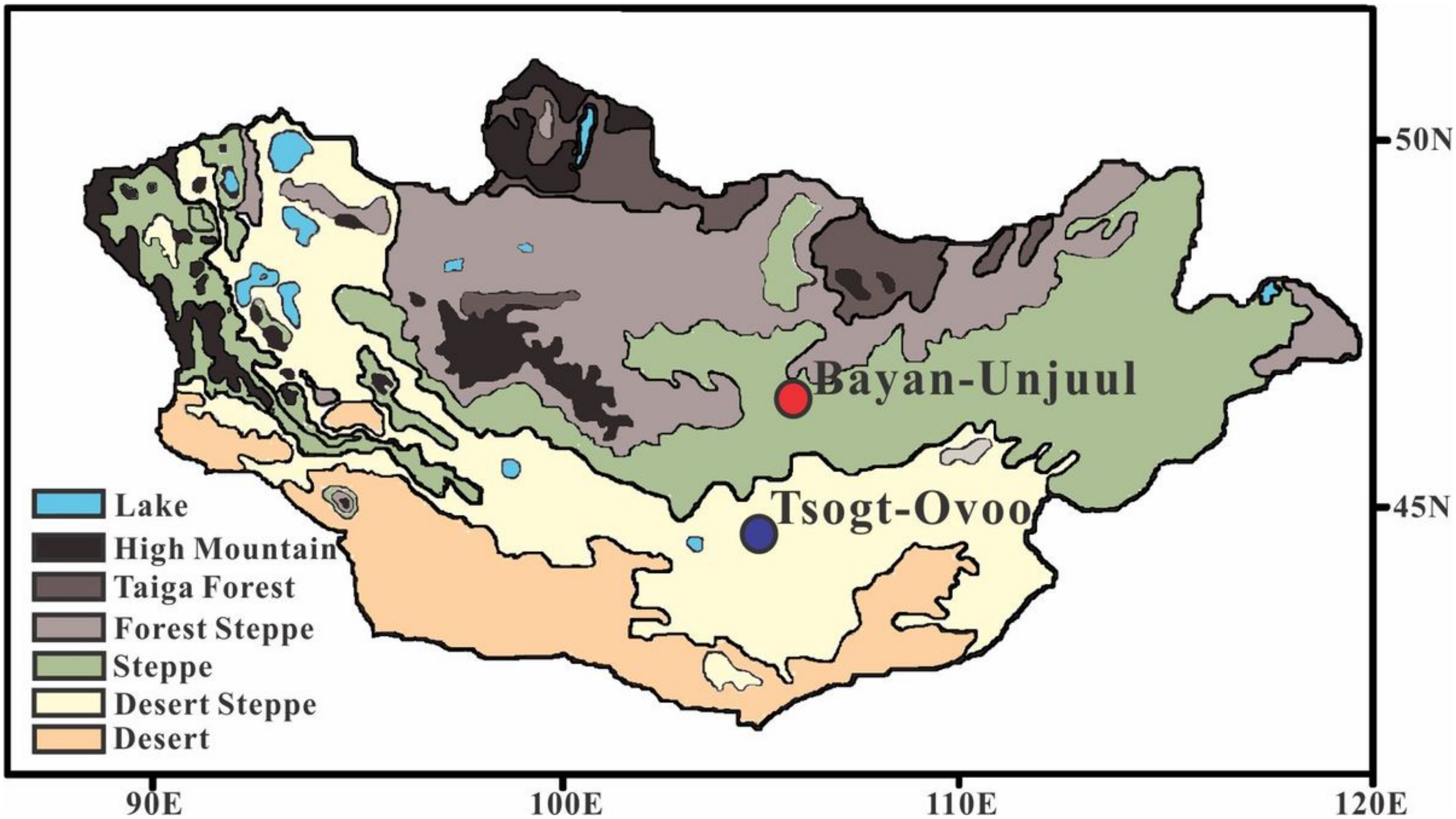
(c) Analogizing with live shoots removed by a grazing event at BU and TsO.

Table 2. The number of months when different controls affected plant production during the growing season from 2002 to 2011

		$\Delta AGP_{act} < 0$				**$\Delta AGP_{act} > 0$**			
	location	$\Delta W>0$ $\Delta N>0$	$\Delta W>0$ $\Delta N=0$	$\Delta W>0$ $\Delta N<0$	$\Delta W<0$ $\Delta N>0$	$\Delta W>0$ $\Delta N<0$	$\Delta W<0$ $\Delta N>0$	$\Delta W<0$ $\Delta N=0$	$\Delta W<0$ $\Delta N<0$
Months	BU	1	0	7	2	5	14	0	1
	TsO	0	28	0	0	0	0	2	0

ΔAGP_{act}, ΔW, and ΔN: The differences in the actual plant production, water stress, and nitrogen stress between the actual condition and the wind-eroded scenario.

Figures



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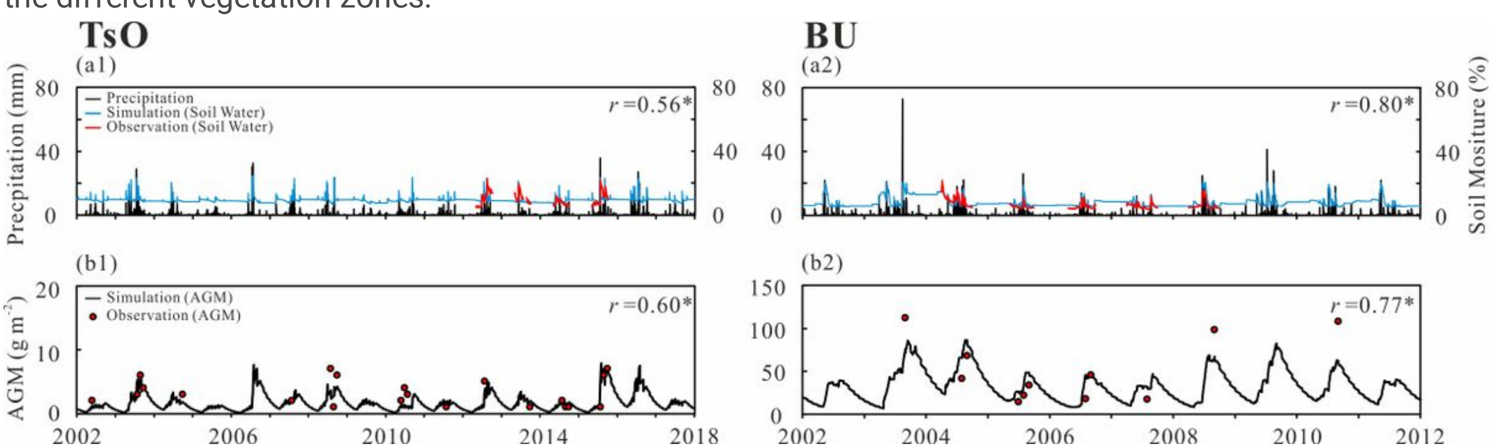
The steppe (Bayan Unjuul, BU) and the desert steppe (Tsogt Ovoo, TsO) grassland sites in Mongolia and the different vegetation zones.



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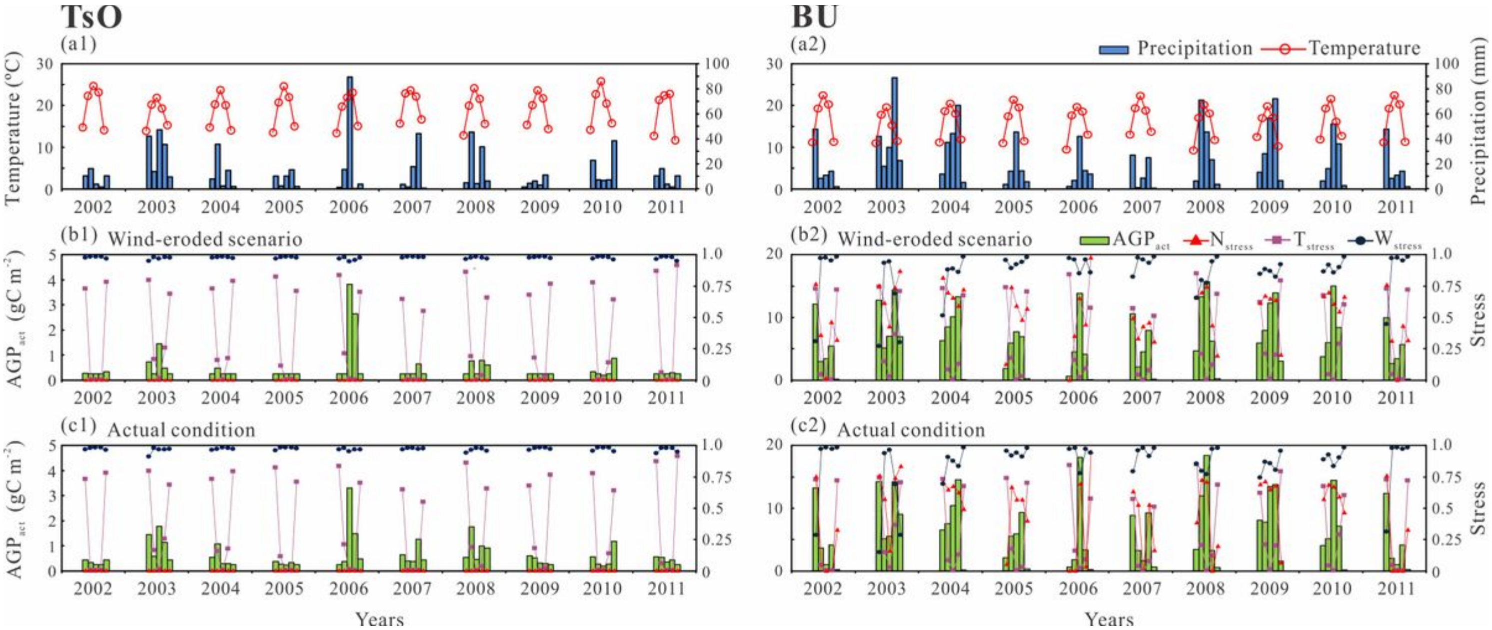

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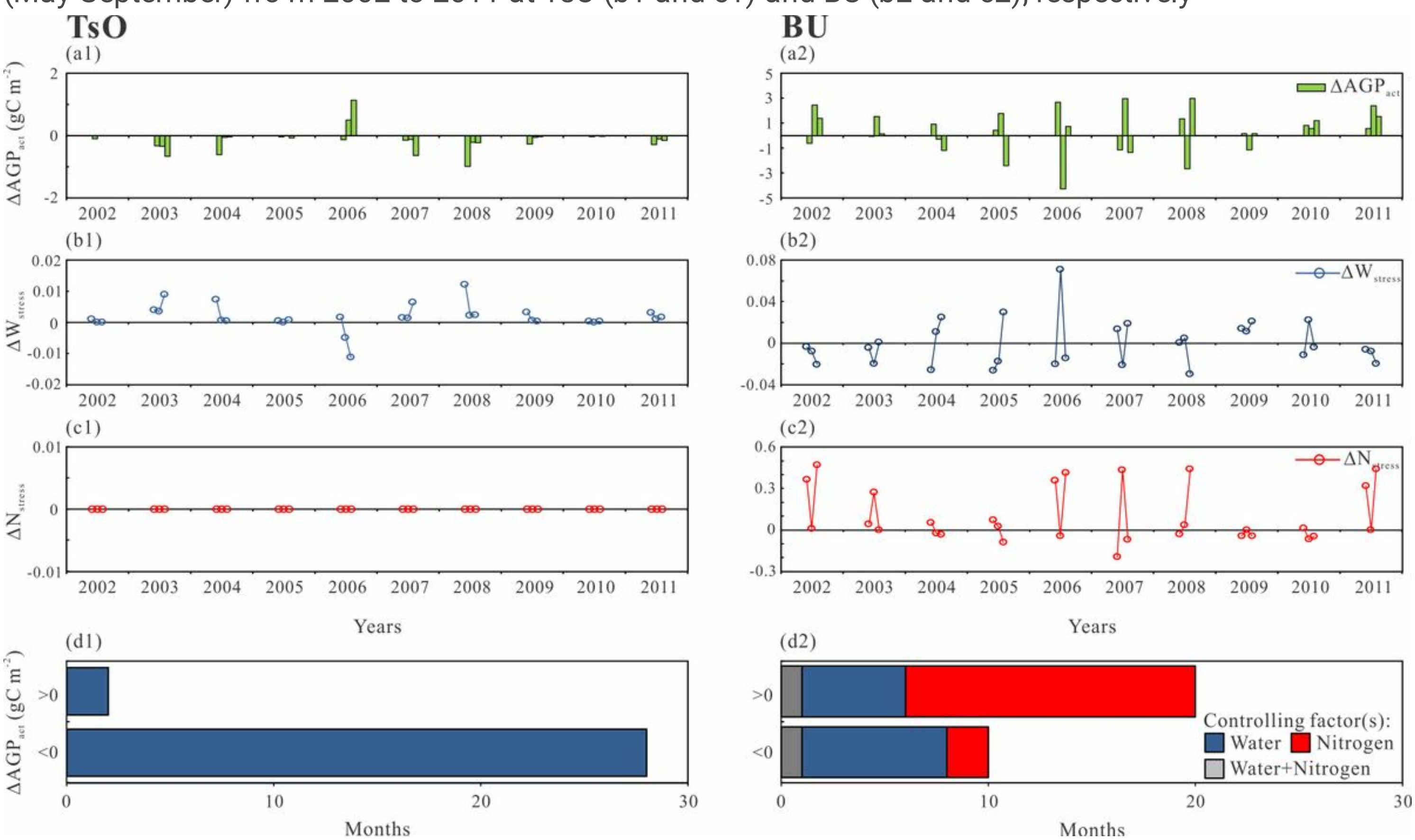
Monthly precipitation and air temperature (a1 and a2) and the monthly simulated W stress , T stress , N stress and AGP act for the actual condition and the wind eroded scenario during the growing season (May September) fro m 2002 to 2011 at TsO (b1 and c1) and BU (b2 and c2), respectively



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The monthly differences in AGP act (a1 and W stress (b1 and b2), and N stress (c1 and c2) between the actual condition and the wind eroded scenario ((Δ AGP act , Δ W stress , and Δ N stress) (a1 c1, a 2 c2) and the number of months when plant growth experienced water and nitrogen stresses (d1, d2), during the critical growing season (June August) from 2002 to 2011 at TsO and BU, respectively.

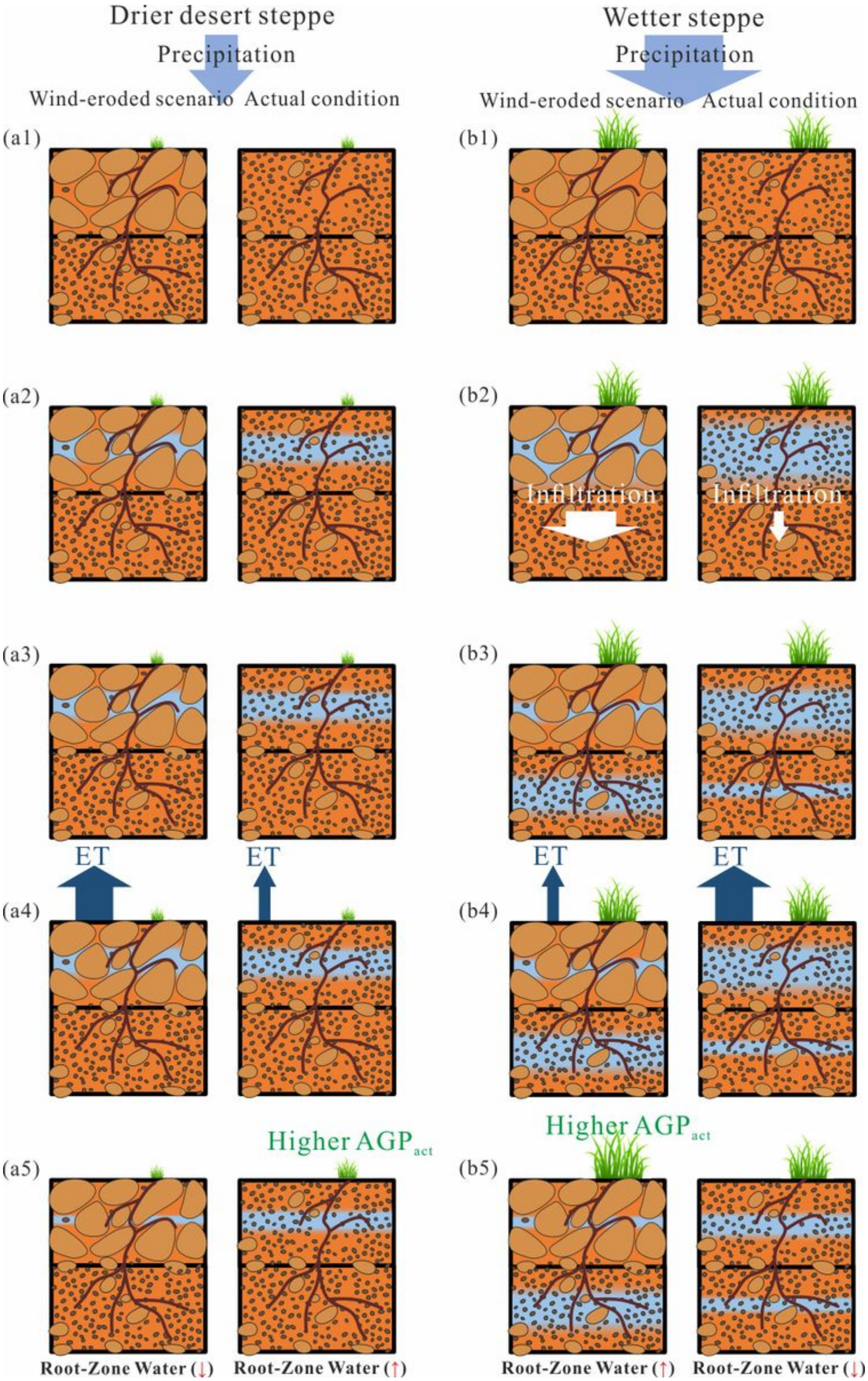

Figure 5

Schematic representation of the different mechanisms that drove the changes in plant production in wind eroded coarse textured topsoil on the desert steppe (TsO, from a1 to a5) and the steppe(BU, from b1 to b5) because of the inverse texture effect. The different sized (thick and thin) arrows indicate the magnitude (high and low) of the variables (precipitation, ET: evapotranspiration, and infiltration).

Supplementary Files

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