IMPACT OF AGROPASTORAL MANAGEMENT ON WIND EROSION IN SAHELIAN CROPLANDS

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ABSTRACT

In the Sahel, climate change and demographic growth are raising major concerns about the ability of crop yields to support the local population. Agropastoral management affects wind erosion (e.g., through crop residue management and tillage practices, which modify surface characteristics), which itself substantially affects soil fertility and thus crop yields. There is therefore a need to assess the potential impact of the main Sahelian cropping practices (– like sowing, manuring, and crop residue management) – on wind erosion. Using a modeling approach adapted to an experimental site located in southwestern Niger over the period 2006–2012, and scenarios that describe a set of agropastoral practices, the impacts of these practices on wind erosion are simulated and compared. The results indicate that horizontal fluxes differ by a factor of 10 among scenarios, with annual horizontal fluxes ranging from 121 to 1,317 kg m⁻¹. Modeled wind erosion is most sensitive to the mass of crop residues in the late dry season, but different practices dealing with crop growth or with crop residue management may result in fluxes of the similar magnitude. The collection of the crop residues after grain harvest increases wind erosion, whereas grazing might have mixed effects, probably further mediated by the mobility of livestock as a response to forage availability. The seasonal dynamics of the monthly cumulated horizontal fluxes vary depending on practice; however, the annual cumulated horizontal fluxes are closely correlated with meteorological conditions such as wind speed and rainfall in the previous year. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS: aeolian erosion; agropastoral practices; semiarid; land use management; modeling

INTRODUCTION

Wind erosion is one of the main processes leading to land degradation in arid and semiarid regions (e.g., Lal, 1994). Through transport of the finest particles of the soil surface, wind erosion can induce a loss of nutrients and organic matter and a decrease of the water holding capacity of the soil (Sterk, 2003). This issue is particularly critical in semiarid regions, where the land surface is used for agropastoral activities, which requires maintaining soil fertility over time.

In Algeria, Houyou et al. (2016) have shown that steppe conversion into cropland has led to large wind erosion rates and subsequent soil losses five times larger than a tolerable threshold, indicating an unsustainable land management. Similarly, cultivation has been found to increase wind erosion in drylands of Australia (McTainsh et al., 2011) and the USA (Webb et al., 2014), where agricultural practices dominate over climatic variability in determining wind erosion dynamics (Nordstrom & Hotta, 2004). Conversely, tillage practices might reduce the soil susceptibility to wind erosion: in northwestern USA, Sharratt et al. (2012) estimated soil loss from minimum tillage to be 50% of conventional tillage due to greater residue cover. Numerous studies have investigated the impact of tillage on wind erosion, for example, in Argentina (Mendez & Buschiazzo, 2010), in the Netherlands (Riksen & Visser, 2008), and in Spain (Fister & Ries, 2009). Grazing (Aubault et al., 2015) and trampling (Fister & Ries, 2009; Badcock et al., 2011) may also amplify wind erosion in susceptible drylands, depending on livestock management and land type characteristics.

Among semiarid regions, the Sahel is characterized by a demographic growth among the highest in the world (United Nation, 2015). Climate projections in this region indicate a warming and changes in rain seasonality in the coming century (Sylla et al., 2015), although these estimates are associated with significant uncertainty (Roehrig et al., 2013). The vulnerability of Sahelian societies to climate variability is exacerbated by nutrient-poor soils (Breman et al., 2001) and wind-driven soil erosion (Buerkert et al., 2001).

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Rural populations in this region rely mostly on subsistence agriculture. The capacity of crop yields to feed these populations nowadays and in the coming decades is therefore a major concern. Latest land use maps of West Africa based on photointerpretation (CILSS, 2016) show that Sahelian cropland area has increased during the last decades: for example, cultivated areas in Niger have increased from 12.6% in 1975 to 24.5% in 2013. This trend is also shown in most of the cases reviewed by Van Vliet et al. (2013) over the Sahel and is mainly due to population increase. Expansion of the cultivated area is indeed the most widespread strategy to increase crop production in this region, due to the limited possibilities for intensification (Rasmussen & Reenberg, 2015). In addition to this cropland expansion, changes in agricultural practices further impact wind erosion.

In the Sahel, previous work has shown that wind erosion is enhanced by cropping (Rajot, 2001; Sterk, 2003; Pierre et al., 2015). Net soil loss due to wind erosion in 1 year can reduce the soil nutrient content by approximately the same order of magnitude as the nutrient uptake by millet in 1 year (Drees et al., 1993; Bielders et al., 2002; Sterk, 2003). Moulin & Chiapello (2006) have also suggested that land use change has modified Sahelian dust emission at a regional scale during the 20th century. To date, studies dedicated to the effects of agropastoral practices on Sahelian wind erosion have been mostly provided by experiments at the plot scale, focusing on crop residue management and on deposition of wind-blown particles into fallows (e.g., Michels et al., 1995; Bielders et al., 2002; Sterk, 2003; Abdourhamane Touré et al., 2011). Some studies provided recommendations on the amount of crop residue that should be left on the field after harvest to reduce wind erosion (Michels et al., 1995; Buerkert et al., 1997). Approximately 2,000 kg ha\(^{-1}\) of crop residue clearly inhibited wind erosion, but effects of 500 kg ha\(^{-1}\) were also acknowledged (see also Abdourhamane Touré et al., 2011). However, the application of 2,000 kg ha\(^{-1}\) was considered hardly achievable by farmers due to plant production limitation (Sterk, 2003; Ikazaki et al., 2011). Additionally, crop residues, the management of which depends on socioeconomic factors, are increasingly collected by farmers to be sold or to feed livestock (Akponikpe et al., 2014; Schlecht & Buerkert, 2004; Rasmussen & Reenberg, 2015; Valbuena et al., 2015). Subsequently, there is a decrease in the amount of protective residue on the surface.

The diverse impacts of Sahelian agropastoral practices (e.g., sowing, manuring, grazing, diversity of cropped species, and varieties) on wind erosion have not yet been fully explored. The existing studies do not provide a clear view of the relative effects of such practices and climate variability because of inherent limitations of experimental work (e.g., number of practices that can be tested and duration of the experiment). Such comparison could be documented by using models, but there is currently a lack of studies using coupled modeling for cropping practices and wind erosion in the Sahel. Yet, the ongoing and future changes in Sahelian land use and agropastoral practices call for the use of modeling to estimate the impacts of such changes in terms of wind erosion in the coming decades.

The objective of the present study is to determine, with a modeling framework, how Sahelian agropastoral practices affect wind erosion over a pluriannual period and to identify the practices that most enhance or limit wind erosion. In that purpose, we design simulations according to a set of scenarios representing typical Sahelian practices. We use a crop growth model coupled to a wind erosion model. Both models, as well as their coupling, have been previously tested for Sahelian conditions by comparison with measurements. Pluriannual meteorological data continuously recorded over an agricultural site located in southwestern Niger are used as input data to run the two models. The results are analyzed in terms of sensitivity of wind erosion to Sahelian agropastoral practices.

MATERIAL AND METHODS

Study Site and Data

The Sahel exhibits a short rainy season from June to October, which triggers the seasonal growth of vegetation, followed by a long dry season (Lebel & Ali, 2009). Mean annual precipitation ranges between 100 and 600 mm; most of it is brought by a few mesoscale convective systems that induce strong winds just before the start of the rain. Thus, most wind erosion occurs during the late dry season and beginning of the rainy season, when vegetation cover is low and strong winds are frequent (Abdourhamane Touré et al., 2011; Marticorena et al., 2016).

Only a few species are cropped in the Sahel, the main rainfed staples being millet and sorghum. Agropastoral practices are diverse for these two crops (Sterk, 2003; Marteau et al., 2011; Traoré et al., 2011). Farmers select breeds depending on soil and climate conditions and choose sowing density, sowing date, and manure management depending on environmental, economic, and cultural factors (Roudier et al., 2016; Schlecht & Buerkert, 2004); tillage is rare in the area. Commonly, after harvest, some stalks are collected and/or livestock is given access to the fields to eat the remaining residues and to provide manure. Then, field clearing consists of laying down the remaining standing vegetation before the following rainy season (Abdourhamane Touré et al., 2011). Some of these practices specifically impact crop growth, like the sowing date and the application of manure, whereas crop residue management modifies the surface cover during the dry season.

This modeling study is based on a study site that is a millet field of 100 × 150 m, located on a more than 3 × 4 km Quaternary aeolian sand deposit homogeneously covered by fields and fallows, close to the Banizoumbou village (13.52°N, 2.63°E) in southwestern Niger, approximately 60 km east of Niamey (Abdourhamane Touré et al., 2011; Figure 1). The soil is very sandy (95%), which is typical of Sahelian croplands (Schlecht & Buerkert, 2004). The field
is cultivated by local farmers following their usual practices, and it is thus representative of cultivated fields in the area. Meteorological data (wind velocity, air temperature, relative humidity, and precipitation) were constantly monitored (except when technical problems) from 2006 to 2012 at 6.5-m height with 5-min time resolution (Marticorena et al., 2016). There is considerable interannual variability of wind and rainfall within this period (Table I). Radiation, which is also required as input data for the crop growth model, is provided by the European Center for Medium-Range Weather Forecast (ERA-interim reanalysis).

**Modeling Approach**

Two models are used here to assess the impact of the agropastoral practices on wind erosion: SarraH (Systèmes d’Analyse Régionale des Risques Agroclimatiques version 3.3; Dingkuhn et al., 2003) simulates crop growth, and the DPM (dust production model; Marticorena & Bergametti, 1995) simulates wind erosion. When coupled (Surface Characteristics section), these two models have been shown to produce reasonable estimates of millet growth and wind erosion for the Banizoumbou study site (Pierre et al., 2014, 2015).

SarraH has been widely tested and used for several millet breeds in Senegal, Mali, and Niger (Baron et al., 2005; Kouressy et al., 2008; Marteau et al., 2011; Traoré et al., 2011). This model simulates, at a daily time step, the vegetation mass, grain yield, and leaf area index (LAI), as well as the major phenological stages (germination, vegetative period, reproductive period, and grain maturation and desiccation; see Figure S1 for details). As inputs, it requires daily meteorological data (rainfall, air temperature and relative humidity, radiation, and wind speed), soil characteristics (e.g., water holding capacity), and information about agropastoral practices. The effects of soil fertility (e.g., due to manuring) are taken into account through a coefficient of vegetation production. Recent improvements for dry-season vegetation provide the mass of standing stalks and litter, accounting for the effect of grazing and trampling on crop residue, and for biotic and abiotic factors driving residue decomposition (Pierre et al., 2015).

The DPM has been widely used for regional dust emission modeling (e.g., Laurent et al., 2008; Darmenova et al., 2009; Pierre et al., 2012, 2014) and for wind erosion simulations (Pierre et al., 2014, 2015). DPM estimates horizontal aeolian fluxes by using surface wind friction velocity and surface characteristics (e.g., texture and nonerodible elements). In particular, it has been validated at the field scale against experimental data obtained in semiarid regions of Spain and Niger (Gomes et al., 2003). Wind erosion occurs when the shear stress exerted by the wind on the surface is greater than a threshold. The drag of the wind on the surface is distributed between the obstacles (pebbles and vegetation) and the bare soil according to a drag partitioning scheme, which depends

<table>
<thead>
<tr>
<th>Year</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual rainfall (mm)</td>
<td>533</td>
<td>471</td>
<td>698</td>
<td>307</td>
<td>371</td>
<td>349</td>
<td>807</td>
<td>505</td>
</tr>
<tr>
<td>Proportion of wind $&gt;7$ m s$^{-1}$ (%)</td>
<td>2.2</td>
<td>2.3</td>
<td>2.1</td>
<td>1.4</td>
<td>1.7</td>
<td>1.4</td>
<td>1.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Missing data (%)</td>
<td>0.13</td>
<td>0.30</td>
<td>0.67</td>
<td>7.16</td>
<td>1.38</td>
<td>0.57</td>
<td>5.24</td>
<td>2.21</td>
</tr>
</tbody>
</table>

Missing data affect especially periods of the year at the core or at the end of the rainy season (late August and early October 2009 and mid-November 2012), thus when vegetation has well grown up and protect the soil from wind erosion, and not periods of the year that are the most prone to wind erosion (May–June).
on the surface aerodynamic roughness length $z_0$ (Marticorena & Bergametti, 1995). Wind drag only acts on the fraction of erodible surface that is not covered by vegetation (see Figure S2 for details).

Soil moisture was not monitored at Banizoumbou; thus, the simulated wind erosion is set to zero for rains larger than 1 mm in 1 h, from rain start to 12 h afterward, following Bergametti et al. (2016). Horizontal wind erosion fluxes are provided in kg m$^{-1}$ per time unit (e.g., per year), which refers to the total mass of soil particles crossing a 1-m wide vertical plane perpendicular to wind direction with infinite height, during this time unit. Thus, 1 kg m$^{-1}$ corresponds to 0·1 t ha$^{-1}$·yr$^{-1}$; assuming that the horizontal flux is at equilibrium and exits a 100 × 100 m field oriented along the direction of large wind speeds, with no incoming material from the surrounding plots.

The contribution of wind to the overall interannual variability of simulated horizontal fluxes was characterized by using the dust uplift potential (DUP; Marsham et al., 2011). DUP is an index for potential wind erosion, irrespective of variations in the surface characteristics. For time step $i$, it is calculated as

$$DUP_i = U^2 \left( 1 + \frac{U_i}{U} \right) \left( 1 - \frac{U_i^2}{U^2} \right)$$

Where: $U$ is the wind speed and $U_i$ is the threshold value in the preceding texts, which transport is thought to potentially occur. Because the DUP characterizes the potential contribution of wind speed to wind erosion, we use a constant $U_i$ corresponding to a Sahelian bare soil. The value of 7 m s$^{-1}$ at 6-5 m high has been selected to be consistent with the determination of $U_i$ performed by Abdouramane Touré et al. (2011) on a bare soil in Bainizoumbou. Here, 5-min time steps were used. Annual DUP (hereafter DUP, in m$^3$·s$^{-1}$) is computed by summing instantaneous DUP$_i$ over a full year.

**Surface Characteristics**

SarraH outputs (i.e., LAI and vegetation mass BM) provide input surface characteristics for the DPM (fractional cover $f_{cv}$ and surface aerodynamic roughness $z_0$; Pierre et al., 2015; see also Figure S1). Specifically, SarraH-derived LAI$_{std}$ (for standing vegetation, in m$^2$·m$^{-2}$) is the sum of LAI of green vegetation, computed directly in the model, and LAI of standing residue LAI$_r$ (also in m$^2$·m$^{-2}$). LAI$_r$ is calculated from dry leaf mass BMLeaves$_r$:

$$LAI_r = SLA \cdot BMLeaves_r$$

assuming a specific leaf area (SLA) of 0·018 m$^2$·g$^{-1}$ (a typical value for the end of the millet growth according to SarraH).

The fractional cover of green and dry standing vegetation is computed as

$$f_{cv \ std} = \left( 1 - e^{-K \cdot LAI_{std}} \right)$$

Where: std means standing and $K = 0·45$.

The fractional cover of litter (i.e., flat, soil-covering senescent vegetation) is computed as

$$f_{cv \ lit} = \frac{(0·14 \ BM_{lit} + 0·23)}{100}$$

Where: BM$_{lit}$ is the litter mass (in g m$^{-2}$; Abdouramane Touré et al., 2011). The total fractional cover $f_{cv}$ is the sum of $f_{cv \ std}$ and $f_{cv \ lit}$.

Pierre et al. (2015) used 3 years of measurements (2006–2008) to parameterize $z_0$ from standing millet height. This parameterization only accounted for the variation of plant growth dynamics, but not for the interannual variability in millet mass. Variations in vegetation mass have a significant impact on the aerodynamic roughness (Pierre et al., 2014), and therefore, a new parameterization was developed to take this factor into account.

The vegetation mass, $M_{tot}$, simulated in SarraH at the beginning of plant growth is much lower than values that might be consistent with the observed changes in roughness $z_0$ at the study site during this period. Thus, a modified vegetation mass, $M_{tot \ cor}$ is computed from a linear interpolation of the simulated $M_{tot}$ from germination to the beginning of the reproductive stage (and $M_{tot \ cor} = M_{tot}$ during the rest of the time). The new parameterization of $z_0$ is then based on a regression between this modified vegetation mass $M_{tot \ cor}$ of a reference SarraH simulation (from Pierre et al., 2015) and $z_0$ at Banizoumbou over 2006–2008:

$$z_0 = 0·00036 \cdot M_{tot \ cor}$$

Where: $M_{tot \ cor}$ is in g m$^{-2}$ and $z_0$ is in m.

When only litter is present (from field clearing to the following germination):

$$z_0 = 0·0012 \ln(f_{cv}) + 0·0013$$

following Abdouramane Touré et al. (2011). At the beginning of plant growth, the new vegetation is still very small and would result in a low surface roughness, whereas litter may remain from the previous growing year, possibly inducing a larger surface roughness. Therefore, $z_0$ is calculated as the maximum of Equations 5 and 6 during this period, which is to say that $z_0$ is controlled by old litter until new vegetation induces a greater roughness. The lowest possible roughness lengths is the aerodynamic roughness length of the bare soil $z_{0s}$, which has been determined from field measurements ($z_{0s} = 9·7 \cdot 10^{-5}$ m; Pierre et al., 2015). Using this new approach (the maximum of results from Equations 5 and 6), the correlation between modeled and measure-based $z_0$ is $R = 0·76$ ($n = 555$), with RMSE = 0·63. This is a significant improvement over the previous parameterization used in Pierre et al. (2015) ($R = 0·46$ with RMSE = 1·05).

**Scenarios**

Scenarios were designed to focus on Sahelian agropastoral practices that might have noticeable impacts on wind erosion, by changing one parameter (corresponding to one practice) at a time among the parameters that define a reference scenario.
AGROPASTORAL MANAGEMENT IMPACT ON WIND EROSION IN SAHELIAN CROPLANDS

(Ref). This reference scenario is based on local observations in the millet field at Banizoumbou by Abdourhamane Touré et al. (2011) and was simulated in Pierre et al. (2015). Then, each scenario assesses the impact of one practice individually with the parameters ranging within realistic values for Sahelian conditions (Table II). In doing so, we aim to isolate the effect of specific agropastoral practices that have not yet been examined in terms of their impacts on wind erosion in the Sahel: crop choice, sowing date, sowing density, use of manure, residue management, and grazing.

Crop choice: Following observations in southwestern Niger by Saidou et al. (2010) and Marteau et al. (2011), one sorghum and three millet varieties (reference Hainy Kirey, long cycle Somno, both photoperiod-sensitive; and short cycle Souna) are included in the simulations. Although rainfall in Banizoumbou is rather low for sorghum, other studies have observed this crop in southern and southwestern Niger (Schlentch & Buerkert, 2004; Valbuena et al., 2015) and even in eastern Niger (Bezançon et al., 2009).

Sowing date: Sowing is mostly done at the beginning of the rainy season, but it can also be done before the rainy season starts or even during the early part of the rainy season (Saidou et al., 2010; Marteau et al., 2011). In our modeling, we used three sowing scenarios representing these three approaches. The Early Sow scenario depicts the “dry-seeding” strategy: From 1 April, seed germination can occur if the soil water content is large enough.

Sowing density: In practice, seeds are sown in holes spread across a field and plants are thinned after germination during the first weeks of growth (Marteau et al., 2011). In the simulations, it is assumed that fields are also weeded at the beginning of crop growth and that each hole has three plants after thinning. Under these conditions, simulated plant densities are set to 10,000 plants ha\(^{-1}\) at the lowest and reach up to 50,000 plants ha\(^{-1}\), in agreement with previous studies in southwestern Niger (Buerkert et al., 1997; Saidou et al., 2010; Marteau et al., 2011), although these values are relatively high for the study site strictly speaking (Hiernaux & Turner, 2002).

Use of manure: Manuring is a common practice in the study area (de Ridder et al., 2004; Andrieu et al., 2015; Valbuena et al., 2015); its effects on soil fertility in the model are expressed by modifying the coefficient of vegetation production in SarraH.

Crop residue management: Three crop residue management practices are simulated based on observations in southwestern Niger (e.g., Akponikpe et al., 2014); collection (to be used as forage) or flattening of (i) none, (ii) half, or (iii) all of the residues after harvest. Fields are cleared (i.e., remaining standing vegetation is laid down as litter) at different dates during the dry season, until the latest possible (in June) just before the start of the following rainy season.

Grazing: In the simulations, grazing pressure ranges between no grazing and 50 TLU km\(^{-2}\) (tropical livestock units). The high value is observed in heavily grazed Sahelian areas, but it would likely not apply during several months as simulated here because livestock are typically moved to places with more forage.

Permutations of these various agropastoral choices result in a series of 18 scenarios, with names related to the parameter that is changed compared with the reference scenario. For example, in the No Graze scenario, all parameters are the same as in the Ref scenario except that there is no simulated grazing pressure.

RESULTS AND DISCUSSION

Total Wind Erosion
For the period 2006–2012, mean annual simulated horizontal flux is 794 kg m\(^{-1}\) for the reference scenario (Ref). The scenario with the highest annual mean (1,317 kg m\(^{-1}\)) was the one in which all crop residue is collected (Tot HarvRes). The result for the maximum grazing pressure (Max Graze) was very similar (1,298 kg m\(^{-1}\)) to the Tot HarvRes scenario. The No Graze scenario produces the lowest mean annual flux (121 kg m\(^{-1}\)), an order of magnitude lower than Tot HarvRes. The other scenarios yield fluxes between 475 (Late FClear) and 1,015 kg m\(^{-1}\) (Tot LayRes; Figure 2).

<table>
<thead>
<tr>
<th>Practices</th>
<th>Reference parameters</th>
<th>Scenario 1</th>
<th>Parameter 1</th>
<th>Scenario 2</th>
<th>Parameter 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant species</td>
<td>Millet</td>
<td>Sorghum</td>
<td>Sorghum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millet variety</td>
<td>Hainy Kirey</td>
<td>ShortC Mil</td>
<td>Souna</td>
<td>LongC Mil</td>
<td>Somno</td>
</tr>
<tr>
<td>Sowing date</td>
<td>7 June</td>
<td>Early Sow</td>
<td>1 April</td>
<td>Late Sow</td>
<td>1 July</td>
</tr>
<tr>
<td>Sowing density (plants ha(^{-1}))</td>
<td>10,000</td>
<td>Mean Dens</td>
<td>30,000</td>
<td>Max Dens</td>
<td>50,000</td>
</tr>
<tr>
<td>Manure effect (g MJ(^{-1}))</td>
<td>4</td>
<td>No Man</td>
<td>3-6</td>
<td>Max Man</td>
<td>4-4</td>
</tr>
<tr>
<td>Harvested residues (%)</td>
<td>0</td>
<td>Mean HarvRes</td>
<td>0.5</td>
<td>Tot HarvRes</td>
<td>1</td>
</tr>
<tr>
<td>Laid down residues (%)</td>
<td>0</td>
<td>Mean LayRes</td>
<td>0.5</td>
<td>Tot LayRes</td>
<td>1</td>
</tr>
<tr>
<td>Grazing pressure (TLU km(^{-2}))</td>
<td>5</td>
<td>No Graze</td>
<td>0</td>
<td>Max Graze</td>
<td>50</td>
</tr>
<tr>
<td>Date of field clearing</td>
<td>1 Jan</td>
<td>Mean FClear</td>
<td>1 Mar</td>
<td>Late FClear</td>
<td>1 Jun</td>
</tr>
</tbody>
</table>

Values for the “reference” scenario (second column) are taken from Pierre et al. (2015). For each scenario, all parameters but one (fourth and sixth columns) are the same as in the reference scenario. SarraH, Systèmes d’Analyse Régionale des Risques Agroclimatiques; TLU, tropical livestock units.
For comparison, the traditionally managed millet field at Banizoumbou was observed by Abdourhamane Touré et al. (2011) to have a total horizontal flux of 900 kg m\(^{-1}\) over 2006–2008, corresponding to an annual mean flux of 300 kg m\(^{-1}\). A nearby bare plot experienced 1,300 kg m\(^{-1}\) average annual horizontal flux. Bielders et al. (2004) reported average annual horizontal flux of approximately 300 kg m\(^{-1}\) for a millet field from 1996 to 1998. The mean annual simulated fluxes in Pierre et al. (2015), which used a slightly different wind speed dataset, were about 500 kg m\(^{-1}\) for 2006–2008.

Simulations suggest that different practices can lead to similar final values of mean annual horizontal flux. For instance, maximum sowing density (Max Dens) and use of manure (Max Man) – both of which involve an increase in vegetation mass compared with Ref – yield similar values (Figure 2). In addition, the scenarios with mean harvest of residues (Mean HarvRes) and no manure (No Man) yield similar values, as do the sorghum scenario (Sorghum), the short-cycle millet scenario (ShortC Mil), and the laying down all the residues after harvest scenario (Tot LayRes). Early sowing (Early Sow) yields similar mean annual flux estimates as Ref because it induces a slightly earlier germination (and thus harvest) only when the rainy season starts earlier than usual (1 year out of 7, in 2006). Assuming that each time series of seven annual values (i.e., for each scenario, over 2006–2012) follows a normal distribution, Fisher’s tests and \(t\)-tests show that these annual fluxes are significantly different from the reference value for almost all scenarios. Only LongC Mil, Early Sow, and Late Sow simulations are too close to the reference scenario to exhibit significantly different horizontal fluxes.

Figure 3 illustrates the impact of specific agropastoral practices by showing the differences between related scenarios at the end of the parameter space. For instance, grazing and trampling (difference between No Graze and Max Graze: 1,177 kg m\(^{-1}\)) and residue collection (difference between Tot HarvRes and Ref: 524 kg m\(^{-1}\)) have the greatest impact on fluxes, whereas sowing date (18 kg m\(^{-1}\) between Early Sow and Late Sow) and sowing density (117 kg m\(^{-1}\) between Max Dens and Ref) have the smallest impact on fluxes. In between, the date of field clearing, millet variety, manuring, flattening residue at harvest, and crop type have decreasing impacts on horizontal flux. There is greater impact on simulated flux between millet varieties than between reference millet and sorghum because the sorghum variety selected here exhibits similar crop growth and dynamics as the reference millet. Overall, practices that affect crop residue exert the greatest control on horizontal aeolian fluxes, whereas practices related to green vegetation exert less control on fluxes.

Figure 2. Mean annual simulated horizontal fluxes over 2006–2012 for all scenarios and their difference (in %) from the reference flux. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 3. Difference in mean annual simulated horizontal fluxes between scenarios over 2006–2012. [Colour figure can be viewed at wileyonlinelibrary.com]
**Seasonal Dynamics**

Simulated horizontal fluxes cumulated monthly are shown in Figure 4 for the *Max Graze*, *No Graze*, and *Ref* scenarios. Years 2008 and 2009 are shown due to the differing frequency of large winds (Table I) in these years. Wind erosion mostly occurs during the first half of the year, with May to July exhibiting the highest fluxes (Figure 4a). Flux begins earlier in the year for *Max Graze* (January–February) compared with *Ref* (April). In *No Graze*, flux begins even later (May). This temporal behavior is driven by the difference in residue cover (Figure 4b).

New vegetation growth starts in July, and millet mass reaches a maximum – similar for the three scenarios – at the end of September. Simulated vegetation mass reaches a maximum of about 400 g m⁻² in all the three scenarios, in agreement with observations in millet fields from Niamey area of 300 to 500 g m⁻¹ in 2004–2009 (Marteau et al., 2011), although this is larger than millet mass of 200 to 300 g m⁻² reported by Rockström & de Rouw (1997) for fields in Banizoumbou in 1994–1996.

![Figure 4. Monthly horizontal flux (a) and total vegetation mass (b, in logarithmic scale) for Max Graze, No Graze, and Ref scenarios in 2008 and 2009. [Colour figure can be viewed at wileyonlinelibrary.com]](image-url)

In the *No Graze* scenario, some residue remains at the end of the dry season, reducing wind erosion during spring. In the *Ref* scenario, the surface is also protected by a small amount of residue in the middle of the dry season (e.g., about 7 g m⁻² in April 2009). In the *Max Graze* scenario, residue disappears in about 2 months, leaving the soil without protection for the remainder of the dry season. Although the maximum effect of grazing is likely overestimated in our simulations, these results underscore the importance of crop residues during the spring to mitigate horizontal transport.

Different millet varieties result in considerable differences in simulated horizontal fluxes (Figure 2). The difference between millet varieties in monthly horizontal flux is clearly visible during the main erosive period (April to July), when only litter remains before next germination (Figure 5a). During this period, fluxes are greater for *ShortC Mil* than for *Ref* and are, in turn, greater than in the *LongC Mil* scenario.

In the *ShortC Mil* scenario, the growth cycle (~2.5 months) is shorter than in the *Ref* (~3.5 months) and
LongC Mil (~4 months) scenarios. Thus, crop residue starts decreasing earlier in ShortC Mil than in the other scenarios, resulting in greater flux. Furthermore, the short cycle variety allocates proportionally more matter to grains than Ref and LongC Mil, resulting in a lower difference in the mass of crop residue after harvest than in total vegetation mass before harvest (Figure 5b). Thus, although the ShortC Mil scenario’s maximum vegetation mass is greater than Ref for some years (not shown), the earlier decrease leads to lower residue cover during the spring at the beginning of the following growing season resulting in greater overall fluxes.

The vegetation mass in the LongC Mil scenario can be lower or higher than the vegetation mass in the Ref scenario depending on the year, that is, depending on when millet undergoes water stress. But the decrease in residue cover starts later in the LongC Mil scenario due to longer growing period compared with ShortC Mil and Ref. Thus, depending on the details of the year’s precipitation, when LongC Mil produces greater maximum vegetation mass than Ref, the corresponding flux in the following dry season is lower than that of Ref (years 2006 to 2009 and 2012). Conversely, when LongC Mil produces less vegetation mass than Ref, the simulated horizontal flux in the following dry season is higher than that of Ref (in 2010 and 2011).

Different practices can lead to varying seasonal fluxes that nonetheless result in similar total fluxes. For example, for the No Man and Mean HarvRes scenarios (corresponding to crop growth and crop residue management, respectively), the monthly horizontal fluxes are greater for Mean HarvRes than No Man at the beginning of the rainy season (May and June), but they are greater for No Man than Mean HarvRes during the middle of the rainy season (July–August) (Figure 6a). Partial collection of crop residues yields lower litter mass for Mean HarvRes compared with No Man during the dry season (Figure 6b), resulting in greater horizontal flux. Conversely, No Man results in a later increase in vegetation mass at the beginning of crop growth; thus, the horizontal flux is larger during this period for No Man compared with Ref and Mean HarvRes. This pattern is consistent across all years of the study period (not shown).

**Interannual Variability of Wind Erosion**

Annual flux tends to increase when DUP becomes larger, as illustrated in Figure 7 where annual horizontal fluxes for all scenarios are drawn versus the annual DUP in a boxplot. However, this trend does not strictly apply for all years, partly due to the temporal distribution of the strongest winds. Specifically, strong winds in June (when most scenarios have the lowest cover) significantly contribute to total horizontal fluxes (Figures 4–6). For instance, 2008 exhibits the greatest DUP, but the frequency of winds higher than 7 m s⁻¹ in June 2008 is only 3.9%, compared with 5.7% and 6.9% for 2006 and 2007, respectively. As a result, 2006 and 2007 experience higher fluxes than 2008.

The variability among scenarios of annual horizontal fluxes is high for all years. The differences between the 25th and 75th percentiles (edges of the boxes in Figure 7) vary between ~200 and ~400 kg m⁻² yr⁻¹ and tend to increase with DUP. But this value represents a decreasing proportion (from about 50% – 75% in 2012 – to 30%) of the median annual flux (middle line in the boxes), suggesting that the more wind conditions favor erosion, the less agropastoral practices exert an influence on annual flux. The low outliers in Figure 7 (for which the difference from the median is larger than an interquartile) correspond to the No Graze (no wind erosion occurs for that scenario from 2010 onward, due to crop residues that remain from

![Figure 6: Monthly horizontal flux (a) and total vegetation mass (b, in logarithmic scale) for No Man, Mean HarvRes, and Ref scenarios in 2011 and 2012.](wileyonlinelibrary.com)
previous years) and Late FClear scenarios. TotHarvRes and MaxGraze scenarios account for the high outliers in Figure 7. Between these extreme values, simulated horizontal fluxes for all other scenarios range each year in similar relative order (not shown).

The annual simulated horizontal fluxes for each scenario correlate well with DUP ($R = 0.75$ to $0.97$; Table III), with the highest correlation occurring when the soil becomes bare soon after harvest (Tot HarvRes and Max Graze) and the lowest correlation occurring when scenarios result in the most protected surfaces (No Graze and LongC Mil).

The main impact of rainfall on wind erosion operates through dry vegetation during the late dry season and beginning of the next rainy season (i.e., dry stalks and litter from the previous vegetation cycle, while the new green vegetation mass is still very low) because most wind erosion

Table III. Correlation coefficient of the annual horizontal fluxes with the annual dust uplift potentials (R DUP) – a proxy for potential wind erosion – with vegetation maximum mass of the previous year (R veg max $y^{-1}$) and associated $p$-values and standard deviation (in kg m$^{-1}$) of the annual horizontal fluxes due to climate factors (among years) and their coefficient of variation (CV = SD/mean) over 2006–2012, for all scenarios

<table>
<thead>
<tr>
<th>Scenario name</th>
<th>No Graze</th>
<th>Late FClear</th>
<th>Mean FClear</th>
<th>LongC Mil</th>
<th>Max Dens</th>
<th>Max Man</th>
<th>Mean Dens</th>
<th>Ref Early Sow</th>
<th>R DUP</th>
<th>$p$-value</th>
<th>R veg max $y^{-1}$</th>
<th>$p$-value</th>
<th>std over years</th>
<th>CV over years</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Graze</td>
<td>0.75</td>
<td>0.95</td>
<td>0.97</td>
<td>0.82</td>
<td>0.89</td>
<td>0.93</td>
<td>0.92</td>
<td>0.94</td>
<td>0.94</td>
<td>0.0518</td>
<td>0.0009</td>
<td>0.0002</td>
<td>0.0242</td>
<td>0.0072</td>
</tr>
<tr>
<td>Late FClear</td>
<td>0.0518</td>
<td>0.0009</td>
<td>0.0002</td>
<td>0.0242</td>
<td>0.0072</td>
<td>0.0028</td>
<td>0.0033</td>
<td>0.0015</td>
<td>0.0014</td>
<td>0.0058</td>
<td>0.0068</td>
<td>0.1201</td>
<td>0.8459</td>
<td>0.2339</td>
</tr>
<tr>
<td>Mean FClear</td>
<td>178</td>
<td>348</td>
<td>376</td>
<td>292</td>
<td>381</td>
<td>392</td>
<td>399</td>
<td>427</td>
<td>434</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LongC Mil</td>
<td>0.47</td>
<td>0.73</td>
<td>0.59</td>
<td>0.43</td>
<td>0.56</td>
<td>0.57</td>
<td>0.56</td>
<td>0.54</td>
<td>0.54</td>
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</tbody>
</table>

Figure 7. Boxplot of annual wind erosion (in kg m$^{-1}$) versus the annually cumulated dust uplift potential (in m$^3$ s$^{-3}$) and the corresponding year for all scenarios.
occurs during this period of the year when total vegetation amounts are low and large wind speeds are frequent. Thus, wind erosion depends on the previous vegetation maximum, which depends on the rainfall amount and distribution during the previous rainy season (e.g., Kergoat et al., 2017). Annual horizontal fluxes are anticorrelated (although correlation coefficients are often not significant at the 0·10 level) with the vegetation maximum mass of the previous year for most scenarios ($R = -0.39$ to $-0.94$, except for LongC Mil). This analysis does not include scenarios in which crop residues are collected or removed (Tot HarvRes, Mean HarvRes, and Max Graze) because the interannual linkage operating through crop residue is broken in these scenarios. The strongest interannual anticorrelation is obtained for the No Graze scenario, which exhibits the greatest amounts of crop residue during the dry season.

The coefficient of variation (CV) of annual horizontal flux due to climate factors (i.e., computed among all years, successively for each scenario) ranges between 0·31 (Tot HarvRes) and 1·47 (No Graze; Table III), which correspond, respectively, to the highest and lowest mean annual horizontal fluxes (Figure 2). Besides No Graze, standard deviations are relatively constant across scenarios ($\pm 300$ to $450$ kg m$^{-1}$), and therefore, decreasing CV is the result of increasing total horizontal fluxes. Thus, the more agropastoral practices favor horizontal flux, the lower the relative variability induced by climate factors. Additionally, the variability due to climate factors for the Ref scenario induces annual horizontal fluxes ranging from 270 kg m$^{-1}$ in 2012 to 1,280 kg m$^{-1}$ in 2006. This compares to the difference between mean annual fluxes among scenarios, that is, due to practices, which range from 120 kg m$^{-1}$ for No Graze to 1,300 kg m$^{-1}$ for Tot HarvRes.

Yields and Crop Residue Amounts

In actual fields, Sahelian farmers make decisions on cropping practices by considering, among other things, potential crop yields and livestock production, which utilizes crop residue. In the simulations, most scenarios provide similar grain yields of about 1,000 kg ha$^{-1}$ (not shown), in reasonable agreement with observations from Rockström et al. (2002) for sorghum in Burkina Faso for similar rainfall conditions in 1998–2000 ($300$ to $1,500$ kg ha$^{-1}$) and from Marteau et al. (2011) for millet fields around Niamey in 2004–2009 ($400$ to $1,000$ kg ha$^{-1}$). Some field surveys, however, suggest lower plant productivity and crop yields, including Rockström & de Rouw (1997) who observed millet yields of about 500 kg ha$^{-1}$ for traditional fields in Banizoumbou in 1994–1996. This implies that the present simulations are closer to well-maintained crops in fertile soils. Furthermore, simulated yields may be overestimated because the model does not take into account factors like pests, diseases, granivory, and competition with weeds.

Short cycle millet (ShortC Mil) results in the greatest crop yields, although with the highest interannual variability. The ShortC Mil scenario also has lower residue present on the following 1 November compared with the other millet varieties, thus favoring wind erosion. Overall, most scenarios yield crop residue on 1 November greater than the 800 kg ha$^{-1}$ suggested by Abdourhamane Touré et al. (2011) as sufficient to prevent wind erosion. The large values for residue on 1 November are in agreement with the values of 1,000 to 2,500 kg ha$^{-1}$ observed by Schlecht et al. (2001) in western Niger in October. Thus, given the meteorological conditions of the study site, there are several scenarios that could be chosen by farmers to produce yields and significant crop residue after harvest.

Scenarios Limitations

This study addresses the impact of different managements individually, meaning that all factors have been considered independently. Although this is useful in identifying the most important variables and the most critical periods for wind erosion, it ignores the complexity of management practices at the landscape scale. Actual land management decisions in Sahelian croplands may combine several of the practices tested here. For example, high grazing pressure would be associated with considerable amounts of manure, increasing soil fertility and potentially large sowing density (Schlecht et al., 2004). Moreover, grazing pressure is likely to decrease as vegetation mass decreases because livestock will move to places with more forage. Farmers choose the sowing date and the plant variety depending on the beginning of the rainy season, and they further adjust the sowing density to soil fertility (Marteau et al., 2011). For the study site, short cycle and long cycle millet are probably not the best adapted cultivars, although they could be selected for specific situations (Roudier et al., 2016). In addition, two different plants can be intercropped in the same field (e.g., millet and cowpeas; Schlecht & Buerkert, 2004). However, cowpeas usually start growing later than reference millet (Saidou et al., 2010), so neglecting intercropping in the simulations is not likely to influence the conclusions presented here. Beyond the practices examined here, Sahelian farmers also work under other constrains, like the availability of labor during the year, the proximity of fields, and demands related to both cropping and livestock farming.

CONCLUSION

The impact of Sahelian agropastoral practices on wind-driven soil erosion has been explored combining a model simulating crop growth and one computing wind erosion. In that purpose, we have tested the coupling of these models in 18 scenarios applied to a site in western Niger where measures had been carried out allowing an evaluation of the simulations.

The simulated horizontal fluxes vary by a factor of 10 among the scenarios, with values that are generally consistent with the literature. Previous studies focused on the effects of crop residues on wind erosion; the present work confirms that crop residue management exerts a greater control on aeolian fluxes than cropping practices during the growing season. Grazing might have mixed impacts,
probably mediated by livestock mobility. Importantly, our simulations show that agropastoral practices do influence the seasonality of wind erosion and that annual horizontal fluxes are closely correlated to meteorological conditions such as wind speed and previous year rainfall.

At this stage, combined modeling of crop growth (including residues during the dry season) and wind erosion is in its infancy, and the results presented here are from simple scenarios. Studies on the impacts of agropastoral practices on wind erosion in the Sahel are few, and our results need to be tested, for example, with dedicated field experiments to monitor grazing pressure and the subsequent horizontal fluxes. Thus, rather than being intended to provide recommendations to famers, this study aims at filling a gap in the existing literature on the effects of agropastoral practices on Sahelian wind erosion, particularly through a methodological progress in coupled modeling.

However, in the case of southwestern Niger, the amount of crop residues in late dry season appears to be an important control on wind erosion: scenarios that affected this, such as field clearing at the end the dry season, residue collection, and grazing contribute to wind erosion risks according to the model simulations. This suggests that a widespread and increasing collection of crop residues in the Sahel during the coming decades might significantly increase wind erosion in this region.

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REFERENCES


SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Figure S1: Scheme of the coupling between the two models: SarRaH for crop growth and DPM for wind erosion (LAI, leaf area index; BM, vegetation mass; fcv, fractional cover; z0, surface aerodynamic roughness).

S1: Crop growth modelling.

S2: Wind erosion modelling.