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RESEARCH ARTICLE

Wind erosion response to past and future agro-pastoral trajectories in the Sahel (Niger)

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Abstract
Context Wind erosion plays a major role in land degradation in semi-arid areas, especially in the Sahel. There, wind erosion is as sensitive to land use and land management as to climate factors. Future land use intensification may increase wind erosion and induce regional land degradation.
Objective We aimed to estimate wind erosion responses to changing land management in a Sahelian region.
Methods We defined land use intensification scenarios for a study site in southwestern Niger for two historical situations (1950s and 1990s), and two alternative prospective scenarios (2030s: extensive or intensive). We simulated vegetation growth and horizontal sediment flux of wind erosion for the corresponding landscapes.
Results Annual amounts of horizontal sediment flux increased with land management changes from 1950s (nil flux) to 1990s (176 kg m^{-1} yr^{-1}) and 2030s (452 to 520 kg m^{-1} yr^{-1}), mostly because of differences in land use, declining soil fertility, and practices decreasing the dry vegetation. For 2030s, intensive scenario

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exhibited larger vegetation yields than extensive conditions, but similar large values of horizontal sediment flux, thus questioning the sustainability of both scenarios. Realistic sets of practices had as large an influence as the largest theoretical range of practices on the variability of annual horizontal sediment flux. This variability was as large as that due to meteorological conditions.

Conclusions This study demonstrates that the environmental impact of land use and management practices, of which wind erosion is an aspect, must be assessed at the landscape scale to account for the variability in land cover and associated land management.

Keywords Wind erosion · Agro-pastoral practices · Land management scenarios · Land use · Modelling · Sahel

Introduction

Unprecedented human population and climate change make it increasingly important to understand soil erosion impacts on the sustainability of socio-ecological systems (Webb et al. 2017). The effects of human-driven land cover change—like grazing intensity, grassland conversion to cropland, crop residue management or ecological restoration programs—on wind erosion has been highlighted in China (Zhang et al. 2018; Chi et al. 2019; Du et al. 2019), in the US (Galloza et al. 2018; Duniway et al. 2019; Rakkar et al. 2019), in Southern (Webb et al. 2020) and Eastern Africa (Fenta et al. 2020) and in the Sahel (Abdourhamane Touré et al. 2019). This issue is critical in semi-arid areas, where environmental conditions are marginal for agriculture and where human–environment interactions can have a large impact on the resilience of farming systems to climate stressors (IPCC 2019). Of these semi-arid areas, the Sahel exhibits the largest population growth, leading to a large food demand, whilst being one of the poorest regions worldwide. Sahelian land degradation is a major concern (Fensholt et al. 2013; Mbow et al. 2015) because Sahelian soils are inherently poor in organic matter and nutrients (Breman et al. 2001). In this area, wind erosion plays a major role in land degradation as it can induce annual losses of several millimeters of topsoil (Sterk 2003). The consequent nutrient losses can be of the same order as that needed as uptake for millet growth, the main staple crop in the area (Sterk 2003).

In the Sahel, wind erosion depends on natural factors (wind, rain, vegetation cover) as much as on land management (Pierre et al. 2018). Wind erosion not only depends on land use (e.g. cropland versus rangeland) but also on associated management practices. For a given land use (e.g. cropland), with Sahelian meteorological conditions, wind erosion could vary by as much as a factor of ten (in terms of annual mass of the horizontal sediment flux, see Pierre et al. 2018) depending on management practices. The agro-pastoral practices of local farmers and herders follow risk-avoidance strategies in response to the high variability of Sahelian rainfall, in terms of annual amount as well as event intensity and distribution throughout the rainy season (from June to October approximately). In many agro-pastoral systems, the different practices strongly interact and should thus be considered at the landscape scale. Nutrient transfer to croplands provided by livestock and manure is a good example of such interactions (Turner and Hiernaux 2015). Diversification of resources at the household scale also shapes practices at the landscape scale (Raynaut 2001). As for other dryland cropping systems, cropping practices like choice of crop species and cultivars, sowing date, weeding and management of crop residues can significantly influence wind erosion (Pierre et al. 2018; Thomas et al. 2018). Some of these practices could lead to increased wind erosion and eventually to feedbacks of wind erosion on land health and management through decline in soil fertility or reactivation of dunes (Tidjani et al. 2009).

As stated by *Lavigne-Delville* (1997), cited by Warren et al. (2001): "*soil degradation can only be understood in its social context*." According to these authors (Warren et al. 2001), who relied on a "local political ecology" approach, soil erosion in south-western Niger can be related to socio-economic factors like male migration and access to non-farm incomes. However, observations and quantitative evidence of these interactions are scarce. Wind erosion

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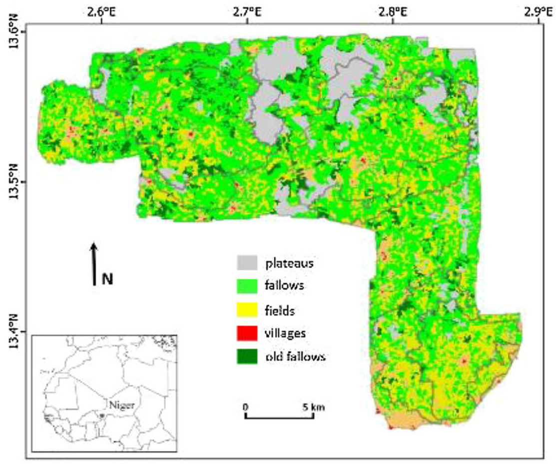

Fig. 1 Location of the study site and main land uses in 1992. (adapted from Hiernaux and Ayantunde (2004))

affects soil fertility over the long-term and thus is not necessarily perceived as an urgent threat by local farmers; this could hinder short-term prevention of wind erosion by local populations, although soil fertility is one of their main concerns (Warren et al. 2003).

Despite the influence of wind erosion on the sustainability of Sahelian agro-pastoral systems, no studies have quantified the interactions among changing land use, agro-pastoral practices and erosion rates in the Sahel. No information on land management has been recorded alongside available classifications of Sahelian land use systems to support such analyses (e.g. Monfreda et al. 2008; Klein Goldewijk et al. 2011; Tappan et al. 2016). Furthermore, little is known about cropland change and land management dynamics at the Sahel-scale (van Vliet et al. 2013). It is therefore challenging to define realistic scenarios of past and future Sahelian land use and agro-pastoral practices, along with associated socio-ecological changes, to evaluate their impacts on wind erosion and its influence on the sustainability of Sahelian agro-pastoral systems. Recent research based on field measurements (Pierre et al. 2014, 2015), model-driven sensitivity analysis (Pierre et al. 2018) and survey of land management and vegetation production (e.g. Hiernaux et al. 2009) provide a basis for developing such scenarios to assess land use and management practices impacts on wind erosion, and to establish a foundation for future systems-level research to address land degradation-climate change interactions.

Here we investigate the impact of past and future trajectories of Sahelian agro-pastoral practices on wind erosion. We develop landscape-level land use strategies and trajectories as scenarios based on expert knowledge and published literature for a case study in southwestern Niger. Using a set of models developed in previous work, we then investigate the impact of the scenarios on wind erosion. The spatial extent of our study site is about 30 km × 30 km, the scale at which land use activities reflect decision-making at the rural community level. This scale also approximates one grid cell for Earth System models (e.g. Pierre et al. 2012), thus investigation at this scale could help address how local-scale heterogeneity in land use and management affecting wind erosion influences regional dust emissions. Section "Materials and methods" introduces the selected study site and defines the scenarios of practices, before describing the modelling approach. Section "Results" presents the results of vegetation and wind erosion simulations and analyzes the impact of practices scenarios on these variables. The results are discussed in Sect. "Discussion"; Sect. "Conclusion" gathers the main conclusions of the study.

Materials and methods

Study site

The study area is a 30 km × 30 km extent in the Fakara district, within the Tillaberi administrative region in southwestern Niger, about 75 km east of the capital, Niamey (Fig. 1). The Fakara district is located between confluent valleys of the Niger River to the West and the fossil valley of Dallol Bosso to the East. The annual rainfall is typical of Sahelian conditions with currently about 500 mm per year (e.g. Marticorena et al. 2017), with a narrow unimodal distribution (June to September) due to the African monsoon. About 20% of the area is covered by shallow loamy sand soils on flat hard pan plateaus, not prone to wind erosion because of soil crusts and tiger bush vegetation cover. Deep sandy soils dominate largely the rest of the landscape, with loamy-clay soils limited to the narrow ephemeral river bed and pond floor, i.e. less than 5% of the landscape area (Turner and Hiernaux 2015). We restrict our analysis to the arable sandy

Table 1 Simulation names and models parameters

Simulation name	Land use	Vegetation model	Parameters	Simulated mass (mean of annual max)
Sav1950s	Savanna	STEP	*Soil fertility: 3.4*	Green: 182 g m^{-2}
			Grazing Pressure: 0 TLU km^{-2}	Tot: 237 g m^{-2}
Fal1990s	Fallows	STEP	*Soil fertility: 2.9*	Green: 142 g m^{-2}
			Grazing Pressure: 8 TLU km^{-2}	Tot: 156 g m^{-2}
FieldBush1990s	Unmanured fields	SarraH	*Manure: none (NF)*	Grains: 104 g m^{-2}
			Sowing density: 6000 plants ha^{-1}	Stalks:152 g m^{-2}
			Residues collecting: 10%	Leaves: 56 g m^{-2}
			Residues laid down: 0%	
			Grazing pressure: 8 TLU km^{-2}	
FieldHome1990s	Manured fields	SarraH	*Manure: slight (mF)*	Grains: 124 g m^{-2}
			Sowing density: 10 000 plants ha^{-1}	Stalks: 241 g m^{-2}
			Residues collecting: 10%	Leaves: 56 g m^{-2}
			Residues laid down: 0%	
			Grazing pressure: 8 TLU km^{-2}	
FieldExt2030s	Unmanured fields	SarraH	*Manure: none (NF)*	Grains: 102 g m^{-2}
			Sowing density: 4 000 plants ha^{-1}	Stalks: 134 g m^{-2}
			Residues collecting: 75%	Leaves: 54 g m^{-2}
			Residues laid down: 0%	
			Grazing pressure: 12 TLU km^{-2}	
FieldInt2030s	Manured fields	SarraH	*Manure: high (F)*	Grains: 128 g m^{-2}
			Sowing density: 12 000 plants ha^{-1}	Stalks: 345 g m^{-2}
			Residues collecting: 75%	Leaves: 61 g m^{-2}
			Residues laid down: 10%	
			Grazing pressure: 20 TLU km^{-2}	

soils ($\sim$ 80% of the area), considering that the remaining 20% are not prone to wind erosion.

The study area has been a focal point for research over the last decades, including accounts of meteorological and soil conditions and land use and land management practices (e.g. Goutorbe et al. 1997; Warren et al. 2003; De Rouw and Rajot 2004; Cappelaere et al. 2009; Hiernaux et al. 2009). Several field measurements were dedicated to the dynamics of wind erosion (Rajot 2001; Bielders et al. 2004), some of which included the monitoring of crop residue degradation and land use effects (Abdourhamane Touré et al. 2011). Measurements of meteorological data and dust concentration and deposition fluxes were also collected since 2006 (Marticorena et al. 2010, 2017).

The human population in the study area is mainly composed of Jerma people with a strong minority of Fulani, who are respectively farmers and pastoralists, with a recent conversion of the latter to agro-pastoralism. Some minor groups of Kel Tamacheq and Maouri also live in the area (Hiernaux and Ayantunde 2004). Historical land rights for cropping are recognized to Jerma people in Dantiandou, and to Fulani in Birni Ngaoure. The local land use evolved from very slight human impact in the 1950s to cropping, fallowing and livestock grazing in the 1990s and ongoing cropland expansion today, with the major staple-crop being millet (*Pennisetum glaucum*). Over the same period, land management changed with increasing grazing pressure and collection of crop residues (Schlecht et al. 2001; Akponikpè et al. 2014).

As in most parts of the Sahel, wind erosion in southwestern Niger exhibits a large seasonality related to the monsoonal wind and rainfall regimes. Wind

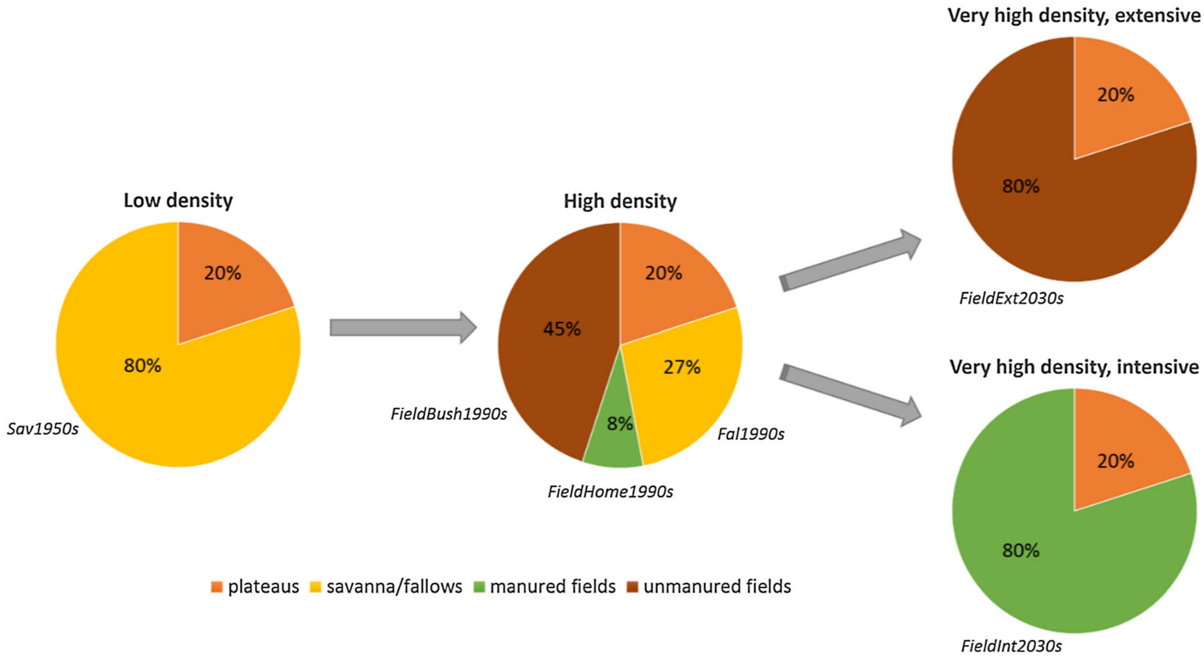

Fig. 2 Land use proportions depending on the scenarios (with simulation names detailed in "Sets of simulations"). Note that for a given land use, land management can differ: e.g. for savanna/fallows, lower soil fertility for fallows in 'High density' than for savanna in 'Low density'; for unmanured fields, lower plants density and larger residues collecting and grazing pressure in 'Very high density, Extensive' compared to 'High density'; for manured fields, larger soil fertility, plants density, residues collecting and grazing pressure in 'Very high density, Intensive' compared to 'High density' (see Table 2)

erosion occurs when wind speed is large and vegetation cover is low. As the high wind speeds are mostly due to convective systems during the first part of the rainy season (May to July, e.g. Bergametti et al. 2017), a large proportion of the annual wind erosion occurs during this period (e.g. Abdourhamane Touré et al. 2011).

Land use and management scenarios

We establish two historical situations and two alternative prospective scenarios that describe evolving land use and land management in the study area, from a *Low density* situation (∼ 1950) to a recent situation (*High density*, ∼ 1990) and to the near future (*Very high density*, ∼ 2030) (Fig. 2). The historical situations are based on published descriptions of land use trends and on expert knowledge. The prospective scenarios develop two different narratives following a *Very high density, Extensive* pathway, in the line of current practices, and a *Very high density, Intensive* one that is probably more sustainable but requires external inputs. The scenarios are defined as follows (see "Wind erosion results from the effect "Models" for modelling details):

(i) « Low density (1950s)» situation
Representative of the mid-20th, this scenario assumes a slight human management of the environment, as noticeable recent human settlement in the area started around 1950 (with about 6 inhabitants.km^{-2}) (Hiernaux and Ayantunde 2004). As no permanent water was accessible, the grazing pressure was slight, limited to the wet season and assumed to have negligible impact on wind erosion (0 TLU km^{-2}). The land cover is herbaceous savanna over all arable land (i.e. 80% of the landscape).

(ii) « High density (1990s)» situation
This scenario is representative of the 1990s with a more densely populated crop-livestock farming system (about 35 inhabitants km^{-2}). It combines several land uses and land management practices. Following population

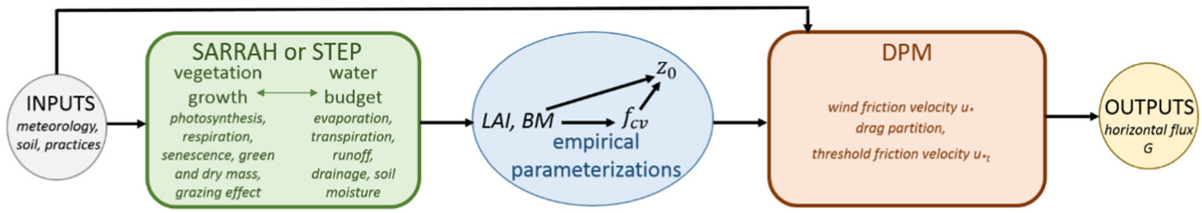

Fig. 3 Scheme of the models combination. Inputs (meteorological data, soil characteristics, land management practices) drive the vegetation models (SarraH for millet fields, STEP for herbaceous savanna/fallows). Vegetation mass and Leaf Area Index (LAI) enable to estimate surface vegetation cover f_{cv} and aerodynamic surface roughness z_0 using empirical parameterizations. f_{cv} and z_0, along with wind data, drive the wind erosion model to compute the horizontal wind erosion flux G (Figure adapted from Pierre et al. (2015)

increase, cropland area increased significantly since the 1950s. Agro-pastoral practices remain extensive and cultivation implies high time-labor and large cropped areas per household, though limited by labor availability (Hiernaux and Turner 2002). The Jerma and Fulani agrarian cultures transformed into sedentary crop-livestock systems (Bonfiglioli 1990). The development of markets in the large village of Dantiandou and in nearby villages favored cash crops in small gardens (cropped by women), small enough to be neglected for wind erosion analysis. Farming is subsistence-oriented and the dominant crop is millet.

10% of the arable land, located near villages or pastoral camps, is under permanent cropping with livestock manure and house wastes providing nutrients, allowing a large sowing density (10 000 plants ha^{-1}). The population pressure is still low enough that the remaining 90% of arable land (bush fields) are under shifting cropping systems with fields cultivated for 5 years and fallowed for 3 years to restore soil fertility (Hiernaux and Turner 2002). Reenberg et al. (2013) observed similar alternate land use of 5 years cropping and 3 years fallowing on sandy dunes in south-eastern Niger after 1984. In these unmanured fields, sowing density is lower (6000 plants ha^{-1}). In all cultivated fields (manured and unmanured), 10% of crop residues were collected at harvest, as an emerging trend of storing and selling part of these residues.

Thus, for a given year, 8% of the total surface is permanently cropped (10% of the 80% that are arable lands), 45% of the land area is under shifting cultivation ((5/8)*90 = 56.25% of the arable land) and 27% is fallow ((3/8)*90 = 33.75% of the arable land). The grazing pressure (8 TLUkm^{-2}) is exerted on the whole landscape and corresponds to an equilibrium between livestock density and forage availability in the landscape (see Supplementary Appendix A).

(iii) « Very high density, Extensive (2030s)» scenario

This scenario intends to be representative of the near future (around 2030), following a narrative in which current agro-pastoral practices are increasingly used. Following the observed recent trends, croplands continue to expand until all arable land is cultivated and no field is fallowed anymore (thus all the landscape but the plateaus). Due to continual nutrient uptake by crops, soil fertility further decreases and farmers adapt planting density to soil fertility (i.e. with lower densities: 4000 plants ha^{-1}). Livestock are more numerous (12 TLU km^{-2}) and can still graze on the plateaus during the wet season and on crop residues during the dry season, but do not necessarily find enough forage on the sandy slopes and valleys of the study area. A large proportion of crop residue (75%) is collected at harvest to feed livestock or to be sold as forage or building material. This estimate aims at representing a large rate of residue harvesting, yet not a total collection, in order to design realistic conditions and not extreme behaviors.

(iv) « Very high density, Intensive (2030s)» scenario

This last scenario is an alternative to what could occur around 2030, assuming funds are available (e.g. from a national policy) to purchase fertilizers and additional animal feed. The association of cropping and livestock is assumed to be maximized and soil fertility is supported with fertilizers. In this case, all arable land is cultivated using manure and inorganic N and P fertilizers and plant densities are large (12,000 plants ha^{-1}). The fertilizers enhance both grain and stalks/leaf yields and thus fodder resources for livestock, in turn producing more manure. Yet, as in the *Extensive* scenario, livestock (20 TLU km^{-2}) do not necessarily find enough forage on the sandy slopes and valleys of the study area. A large proportion of crop residue (75%) is collected at harvest and 10% is laid down for surface mulching on crop fields.

Models

Wind erosion results from the effect of wind on an unprotected soil surface (i.e. with low or no vegetation cover). It is a threshold phenomenon: the wind has to reach a minimum speed, depending on the surface characteristics, to initiate the movement of soil particles (Greeley and Iversen 1985). Vegetation acts as an obstacle to the wind effect on the surface. Thus, it is essential to characterize the vegetation cover in order to estimate wind erosion. Therefore, we use one model for wind erosion and two models for vegetation cover—one to simulate the herbaceous cover of savanna/fallows and one to simulate millet growth in fields (Fig. 3).

Each scenario depicts a landscape composed of several land units corresponding each to a given land use. For each land unit, simulations of vegetation and horizontal sediment flux were run for the corresponding set of practices (see Table 1 for the detailed parameters of each simulation). Thus, the spatial scale of the simulations was the scale of a land unit (e.g. a field or a savanna grassland, typically of about 1 ha). The resulting horizontal sediment fluxes were aggregated at the scale of the study area, as the weighed mean of horizontal sediment flux from several land uses i.e. from several model simulations. Transport and spatial redistribution of the horizontal wind erosion flux is not considered here. We briefly describe the models below; more detailed information on equations and parameters of the models can be found in Pierre et al. (2015, 2018) and in Supplementary Appendix B and C.

Wind erosion model

We use here the Dust Production Model (DPM, Marticorena and Bergametti 1995) to estimate wind erosion. This model has provided reliable estimates of the horizontal sediment mass flux at the local scale (Gomes et al. 2003; Pierre et al. 2014) as well as for dust emissions at regional scale (Laurent et al. 2008; Pierre et al. 2012). The DPM estimates horizontal sediment flux *G* as a function of the total wind friction velocity u_* over the vegetated surface and the threshold wind friction velocity u_{*t}, which depends on surface characteristics:

$$G = E\frac{\rho_a}{g}u_*^3\left(1+\frac{u_{*t}}{u_*}\right)\left(1-\frac{u_{*t}^2}{u_*^2}\right) if u_* > u_{*t}, G = 0 \text{ otherwise} \tag{1}$$

with:

E: proportion of erodible surface ($E = 1 - f_{cv}$ where f_{cv} is the cover ratio of the surface by vegetation).

ρ_a: air density (= 0.001227 g cm^{-3}).

g: gravity (= 981 cm s^{-2}).

The horizontal sediment flux G is expressed in kg m^{-1} per time unit, i.e. the total mass of particles crossing a 1-m wide vertical plane perpendicular to wind direction with infinite height during the time unit. The drag of the wind on the ground surface is distributed between the soil surface and the vegetation according to a drag partition scheme. In the DPM, the drag partition scheme depends on the surface aerodynamic roughness length z_0, of prime importance for wind erosion modelling, and is estimated here from vegetation characteristics. We use the parameterizations of ground surface characteristics established by Pierre et al. (2015; Eq. 8) to estimate z_0 for spontaneous herbaceous, and by Pierre et al. (2018; Eqs. (2 to 6) to estimate E and z_0 for millet. These parametrizations account for the distinct geometry of millet and herbaceous as they have been empirically defined for

Table 2 Interannual variability of meteorological conditions over the 12-year period

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	mean	std	std/mean
Rainfall (mm)	533	471	698	307	371	349	807	504	432	584	548	450	**505**	**144**	**0.28**
Prop wind > 7 m s^{-1} (%)	*2.24*	*2.29*	*2.08*	*1.41*	*1.68*	*1.35*	*1.52*	*0.84*	*0.68*	*0.98*	*0.54*	*0.59*	**1.35**	**0.63**	**0.47**

each of these two cover types. They depend on vegetation mass or vegetation cover, and they distinguish between standing and prostrate (i.e. litter) vegetation (see Supplementary Appendix C).

Vegetation models

The STEP model (Mougin et al. 1995) was developed to simulate the growth of seasonal Sahelian herbaceous vegetation, while the SarraH model (Baron et al. 2005) simulates crop growth for millet. Both vegetation models have been extensively tested for several Sahelian study sites (e.g. Tracol et al. 2006; Pierre et al. 2011 for STEP; and Kouressy et al. 2008; Marteau et al. 2011 for SarraH). They run on a daily time step, using meteorological data and soil texture information as inputs, and providing vegetation mass and Leaf Area Index (LAI) as main outputs. The SarraH model further provides grain yields as well as separate stalk and leaf mass. Among dry vegetation, standing straws inhibit more wind erosion than prostrate litter due to their larger effectiveness at reducing wind momentum near the surface (e.g. Pi et al. 2020). Thus we need information on both dry vegetation types. STEP already had a dry season submodel to simulate dry vegetation during the dry season. SarraH has been added a dry season submodel to simulate crop residue dynamics after harvest (Pierre et al. 2015; see also Supplementary Appendix B). According to these dry season submodels, livestock ingests part of dry leaves, and tramples dry stems and leaves, while abiotic factors also induce vegetation degradation. Grazing pressure was assumed to be spatially homogenous over all land uses.

STEP and SarraH models require parameters related to agro-pastoral practices. Namely, these parameters are:

(i) for STEP: soil fertility and grazing pressure,
(ii) for SarraH: cultivar, intensity of the use of manure, sowing date, sowing density, proportion of collected residues at harvest, proportion of residues laid down at harvest, grazing pressure (after harvest) and date of field clearing (date at which all remaining standing residues are laid down on the soil).

In SarraH, grazing pressure is only applied to dry vegetation, in line with the exclusion of livestock from Sahelian cropped fields during the rainy season. In STEP, a light grazing effect on green vegetation is implicitly accounted for in the growth parameters, while grazing pressure is applied in the dry season. Soil fertility is taken into account through a productivity coefficient. Here, we adjusted the productivity coefficient to attain target herbaceous and millet production levels for each set of practices under the scenarios (see “Sets of simulations”).

Meteorological data

In order to separate effects of climate change from land management practices, the simulations were run for each land use and associated set of management practices using the same meteorological 12-year series. As in Pierre et al. (2018), we used meteorological data (wind speed, air temperature, relative humidity, and precipitation) monitored in Banizoumbou since 2006 at 6.5 m height with 5-min resolution (Marticorena et al. 2017), but over a longer period (2006–2017). Temporal coverage of meteorological measurements was very good with less than 3% of missing wind and rainfall data. Solar radiation data were re-analyses of the European Center for Medium-Range Weather Forecast (ERA-Interim; Dee et al. 2011). Meteorological data were converted to daily

Table 3 Pluriannual mean and standard deviation of annual maximum and minimum vegetation mass (in g m^{-2}) for the 6 simulations

Simulation	Green max	Straws max	Litter max	Total min
Sav1950s	182 ± 32	138 ± 16	25 ± 3	77 ± 10
Fal1990s	142 ± 25	83 ± 14	30 ± 4	20 ± 6
FieldHome1990s	409 ± 108	243 ± 81	120 ± 49	12 ± 5
FieldBush1990s	307 ± 113	173 ± 76	81 ± 43	7 ± 4
FieldExt2030s	286 ± 110	43 ± 20	15 ± 8	1 ± 0.7
FieldInt2030s	519 ± 123	55 ± 16	37 ± 11	0.6 ± 0.2

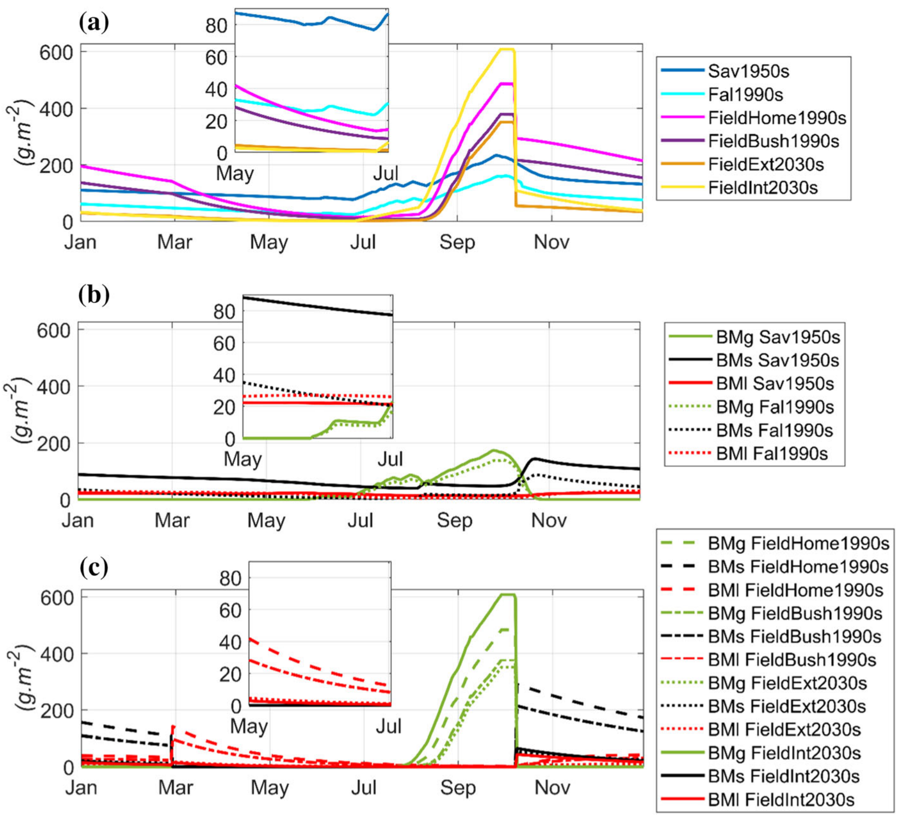

Fig. 4 Vegetation amounts in 2010 for (**a**) total vegetation for the 6 simulations, (**b**) green vegetation (BMg), standing straws (BMs) and litter (BMl) for the 2 herbaceous simulations, and (**c**) the 4 millet simulations

values for vegetation modelling, whereas 5-min wind and rainfall data were used for wind erosion modelling. Horizontal aeolian flux was then summed to get daily, seasonal and annual values for the analysis. Following Bergametti et al. (2016; pers. comm.), simulated wind erosion was assumed to be nil for rains larger than 0.4 mm in 4 h, from rain start to 12 h after

Table 4 Pluriannual mean and standard deviation of monthly horizontal sediment flux (in kg m^{-1}) for the 6 simulations, and a bare soil

Simulation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sav1950s	0	0	0	0	0	0	0	0	0	0	0	0
Fal1990s	0	0	0	0	0	12 ± 17	8 ± 16	0	0	0	0	0
FieldHome1990s	0	0	0	0	46 ± 102	111 ± 107	59 ± 87	1 ± 2	0	0	0	0
FieldBush1990s	1 ± 5	0	0	7 ± 14	89 ± 161	159 ± 136	82 ± 101	3 ± 5	0	0	0	0
FieldExt2030s	19 ± 55	12 ± 28	21 ± 39	72 ± 93	178 ± 171	238 ± 144	104 ± 88	6 ± 9	0	0	0	1 ± 2
FieldInt2030s	3 ± 9	1 ± 3	6 ± 10	64 ± 68	196 ± 162	237 ± 147	59 ± 78	1 ± 2	0	0	0	0
Bare soil	*64 ± 91*	*64 ± 59*	*111 ± 68*	*129 ± 93*	*234 ± 152*	*246 ± 132*	*108 ± 77*	*22 ± 10*	*22 ± 12*	*11 ± 12*	*9 ± 11*	*18 ± 16*

the end of the rain event (the end of the event being defined as soon as there is no rain during 4 h).

Meteorological conditions at the study site exhibit a large interannual variability (Table 2). The mean annual rainfall over the used time-series is 505 mm with a standard deviation of 144 mm. The proportion of high wind speeds (greater than 7 m s^{-1}, at 5-min resolution, 6.5 m height, corresponding to wind erosion threshold for the bare soil at the study site, see Abdourhamane Touré et al. 2011) was also highly variable through years with a mean of 1.35% and a standard deviation of 0.63%.

Sets of simulations

Detailed information about simulation names and parameters are reported in Table 1. Note that given land uses (e.g. manured fields) exhibit different associated land management practices among scenarios.

In the *Low Density* scenario, the soil fertility of savanna—in the grassland vegetation model (STEP), used in the 'Sav1950s' simulation—was set to produce an annual maximum mass of green vegetation of about 180 g m^{-2} (237 g m^{-2} for the sum of standing green and dry vegetation) on average for the 12-year meteorological data used, to be in agreement with observations (see Table 28 in Hiernaux and Ayantunde 2004).

In the *High Density* scenario, the soil fertility in fallows (simulation 'Fal1990s' with STEP model) was lower than in savannas of the *Low Density* scenario, due to nutrient depletion induced by shifting cultivation (Turner and Hiernaux 2015). It was adjusted to produce an annual maximum mass of green vegetation of about 140 g m^{-2} (150 g m^{-2} for the sum of standing green and dry vegetation) on average over the 12-year period, to be in agreement with observations (Table 28 in Hiernaux and Ayantunde 2004). Similarly, the soil fertility in millet fields was set (in the crop model SarraH) to simulate a total aboveground mass of about 312 g m^{-2} for unmanured fields (simulation 'FieldBush1990s') and 421 g m^{-2} for manured fields (simulation 'FieldHome1990s'), close to the values observed by Hiernaux and Ayantunde (2004; Table 28). The simulated vegetation amounts for stalks (152 g m^{-2} and 241 g m^{-2}) and for leaves (56 g m^{-2} in both cases) were also in fair agreement with observations. Simulated grain amounts (104 g

m^{-2} and 124 g m^{-2}) were large and likely overestimated. However, grains are filled during the late rainy season, when vegetation cover already prevents wind erosion, and they are collected at harvest, and so do not play a role for soil protection during the dry season. Therefore, the uncertainty in simulated grain amounts was not problematic for our study. For the *High density* scenario, livestock density was assumed to be balanced with forage availability over the study site (see Supplementary Appendix A for the estimate of the grazing pressure).

Both *Very high density* scenarios are prospective and thus do not compare with observations. They assume cropland expansion over all the arable land in the simulation area. There was no manure effect for the croplands of the *Extensive* scenario (simulation 'FieldExt2030s' with SarraH model) and a full manure and fertilizer effect for the croplands of the *Intensive* scenario (simulation 'FieldInt2030s' with SarraH model). Accordingly, millet sowing density was high for *Intensive* and low for *Extensive*, while grazing pressure increased slightly in *Extensive* and significantly in *Intensive*, compared to the *High density* scenario.

For all scenarios including croplands (*High density*, *Very high density, Extensive* and *Very high density, Intensive*), the cultivar was millet Haini Kirey, sown on June 7th and fields were cleared on March 1st. These practices were set up in agreement with previous work (Pierre et al. 2018) as they were not prone to change under the socio-environmental conditions defining the scenarios.

Results

Per land use

Wind erosion depends on the occurrence of strong winds combined with a low soil protection by vegetation. Thus, we must scrutinize *(i)* the seasonality of vegetation to understand *(ii)* the seasonality of horizontal sediment flux and ultimately *(iii)* its annual amounts. Vegetation mass is of particular interest, as it is a relevant variable to estimate the drag partition of the wind due to vegetation (see "Wind erosion model").

Vegetation mass seasonality

For the same meteorological conditions, differences were large between millet and herbaceous mass (see Table 3 for pluriannual amounts, and Fig. 4 where 2010 illustrates the seasonality of vegetation growth). At the beginning of the rainy season, herbaceous growth was faster than millet growth, while the maximum standing mass was much larger for millet than for herbaceous (Fig. 4a). As described below, differences are also noticeable between simulations for each vegetation type.

Herbaceous

'Sav1950s' and 'Fal1990s' simulations exhibited the same dynamics (e.g. onset of vegetation growth in early June and maximum in late September, see Fig. 4b) but lower green vegetation maximum amounts for 'Fal1990s' (140 g m^{-2} in 2010, 142 ± 25 g m^{-2} pluriannual mean) than for 'Sav1950s' (174 g m^{-2} in 2010, 182 ± 32 g m^{-2} pluriannual mean) due to a lower soil fertility. Similarly, standing straws reached larger maximum amounts for 'Sav1950s' (144 g m^{-2} end of October in 2010; 138 ± 16 g m^{-2} pluriannual mean) than for 'Fal1990s' (87 g m^{-2} in 2010; 83 ± 14 g m^{-2} pluriannual mean) because of the difference in green vegetation amounts and because the grazing pressure increased from 0 for 'Sav1950s' to 8 TLU km^{-2} for 'Fal1990s'. This grazing pressure also induced a faster decrease of standing straws amounts for 'Fal1990s' than for 'Sav1950s'. As trampling transforms straws into litter, litter amounts became slightly larger for 'Fal1990s' during the dry season (from December to April; maximum of 31 g m^{-2} in 2010; 30 ± 4 g m^{-2} as pluriannual mean), before reaching lower values than for 'Sav1950s' (maximum of 24 g m^{-2} in 2010; 25 ± 3 g m^{-2} as pluriannual mean) at the end of the dry season. Altogether, annual minimum amounts of total vegetation were thus lower for 'Fal1990s' (24 g m^{-2} in 2010 -, 20 ± 6 g m^{-2} pluriannual mean) than for 'Sav1950s' (77 g m^{-2} in 2010, 77 ± 10 g m^{-2} pluriannual mean). This minimum value was usually reached by the end of June (e.g. June 26th in 2010).

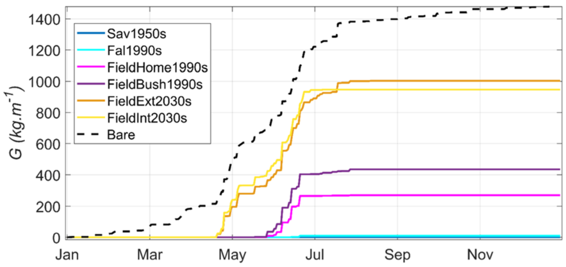

Fig. 5 Cumulated daily horizontal sediment flux G for the 6 simulations and a bare soil in 2010

Millet

A larger soil fertility and larger plant density yielded a larger green vegetation amount for 'FieldHome1990s' compared to 'FieldBush1990s' over the whole rainy season, along with a faster increase in green vegetation mass at growth onset (Fig. 4c). Maximum green vegetation in 2010 was 483 g m^{-2} for 'FieldHome1990s' (409 ± 108 g m^{-2} pluriannual mean) and 377 g m^{-2} for 'FieldBush1990s' (307 ± 113 g m^{-2} pluriannual mean). The same observation applied between 'FieldHome1990s' and 'FieldInt2030s', with a larger soil fertility and plant density for the latter, yielding the largest maximum green vegetation amount (608 g m^{-2} in 2010; 519 ± 123 g m^{-2} pluriannual mean). Maximum green vegetation amounts were similar between 'FieldBush1990s' and 'FieldExt2030s' (351 g m^{-2}; 286 ± 110 g m^{-2} pluriannual mean), the only difference stemming from green vegetation having a slightly larger plant density for 'FieldBush1990s' (6000 plants ha^{-1}) than for 'FieldExt2030s' (4000 plants ha^{-1}). These observations held true for every year and for each part of the plant (grains, stems, leaves; not shown).

Differences in crop residue management induced contrasting behaviors for dry vegetation (standing straws, that include standing dry stems and leaves; and litter, that include flattened dry stems and leaves) compared to green vegetation. 'FieldHome1990s' yielded the largest standing straw mass (maximum of 291 g m^{-2} in 2010; 243 ± 81 g m^{-2} pluriannual mean), followed by 'FieldBush1990s' (215 g m^{-2} in 2010; 173 ± 76 g m^{-2} pluriannual mean). Although the difference in green vegetation amounts was slight between 'FieldBush1990s' and 'FieldExt2030s', it became larger for standing straws because of the larger proportion of crop residues collected at harvest for 'FieldExt2030s' (54 g m^{-2} in 2010; 43 ± 20 g m^{-2} pluriannual mean) compared to 'FieldBush1990s'. Similarly, the large proportion of crop residues collected at harvest for 'FieldInt2030s' (that occurred usually at the beginning of October, e.g. October 9th in 2010) yielded a low maximum amount of standing straws after harvest (65 g m^{-2} in 2010; 55 ± 16 g m^{-2} pluriannual mean), although this simulation produced the largest green vegetation amounts. It was also similar to 'FieldExt2030s', which produced the lowest green vegetation amounts.

'FieldInt2030s' was the only simulation in which some of the residues were laid down as litter at harvest. For all millet simulations, field clearing on March 1st induced a sharp increase in litter mass. From then on, as for the mass of standing straws, litter mass was the largest for 'FieldHome1990s' (maximum of 142 g m^{-2} in 2010; 120 ± 49 g m^{-2} pluriannual mean), intermediate for 'FieldBush1990s' (98 g m^{-2} in 2010; 81 ± 43 g m^{-2} pluriannual mean), and the lowest for 'FieldInt2030s' (44 g m^{-2} in 2010; 37 ± 11 g m^{-2} pluriannual mean) and 'FieldExt2030s' (18 g m^{-2} in 2010; 15 ± 8 g m^{-2} pluriannual mean). As they considered the same grazing pressure, 'FieldHome1990s' and 'FieldBush1990s' exhibited the same rate of decrease of dry vegetation amounts. 'FieldInt2030s' decreased faster than 'FieldExt2030s' because of a larger grazing pressure; their litter masses were very small (e.g. about 2 g m^{-2} at the beginning of June 2010, versus 15 g m^{-2} for 'FieldBush1990s' and 23 g m^{-2} for 'FieldHome1990s').

Although maximum mass of standing straws was of similar magnitude between some herbaceous and millet simulations ('FieldBush1990s' and 'Sav1950s'; 'FieldInt2030s' and 'Fal1990s'), this did not hold true during the dry season due to contrasting rates of decrease of dry vegetation. Altogether, annual minimum mass of total vegetation reached much lower values for millet than for grass, ranging between 0.6 ± 0.2 g m^{-2} for 'FieldInt2030s' (0.6 g m^{-2} in 2010) to 12 ± 5 g m^{-2} for 'FieldHome2030s' (13.5 g m^{-2} in 2010), also usually reached at the end of June (June 27th in 2010, July 24th for 'FieldBush1990s').

Horizontal sediment flux seasonality

Table 4 presents the pluriannual means of monthly horizontal sediment flux and Fig. 5 illustrates its seasonality for year 2010, with an additional case of

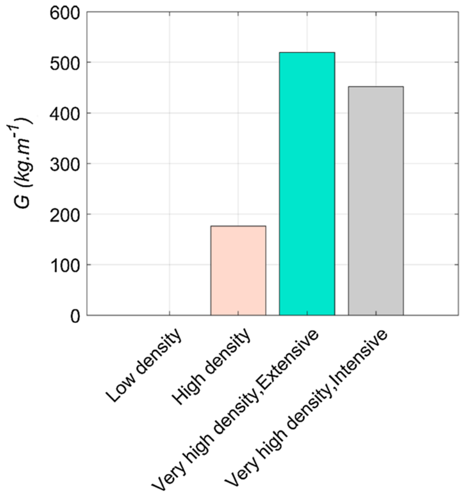

Fig. 6 Annual mean horizontal sediment flux over the 12-year period for all scenarios

bare soil for comparison, enabling to assess the impact of meteorological conditions only, although this latter case is not realistic in terms of land management. In all cases, horizontal sediment flux was nil to negligible from August to January, suggesting that meteorological conditions yielded no wind erosion during that period. Both prospective simulations led to non-negligible amounts from January to March, yet lower than for bare soil, indicating that the dry vegetation cover reduced wind erosion during that time, even for low amounts of vegetation mass. In spring (April to July), monthly amounts of horizontal sediment flux were nil to negligible for herbaceous cover, intermediate for the 1990s croplands and large for 'future' croplands. During (late) spring, horizontal sediment flux for bare soil was similar to that for 'FieldExt2030s' and 'FieldInt2030s' ('FieldBush1990s'), as vegetation cover had almost disappeared at that time in these simulations. Altogether, the horizontal sediment flux was thus the largest for croplands, especially in May (46 ± 102 kg.m^{-1} for 'FieldHome1990s' to 196 ± 162 kg m^{-1} for 'FieldInt2030s' kg m^{-1}), June (111 ± 107 kg m^{-1} for 'FieldHome1990s' to 238 ± 144 kg m^{-1} for 'FieldExt2030s' kg m^{-1}) and July (59 ± 87 and 59 ± 78 kg m^{-1} for 'FieldHome1990s' and 'FieldInt2030s' to 104 ± 88 kg m^{-1} for 'FieldExt2030s' kg m^{-1}).

Monthly horizontal sediment fluxes were constantly larger for 'FieldBush1990s' than for 'FieldHome1990s', mostly from May to July, as threshold friction velocity (u_{*t}) was always larger for 'FieldHome1990s' than for 'FieldBush1990s' due to larger vegetation amounts. In 2010, this threshold reached a minimum value of 47.9 cm s^{-1} for 'FieldBush1990s' on July 24th and 58.0 cm s^{-1} for 'FieldHome1990s' on June 27th (not shown).

The difference in horizontal sediment flux between 'FieldExt2030s' and 'FieldInt2030s' was slight and resulted from seasonal differences in vegetation cover. Crop residue management yielded close amounts of litter for both simulations, yet with slightly larger amounts for 'FieldExt2030s' than for 'FieldInt2030s' at the end of the dry season due to a larger grazing pressure for 'FieldInt2030s'. Thus, the threshold friction velocity was larger for 'FieldExt2030s' than for 'FieldInt2030s' at the end of the dry season and became lower at the beginning of the rainy season (not shown). For example, in 2010 u_{*t} reaches a minimum value of 25.2 cm s^{-1} for 'FieldInt2030s' and 29.0 cm s^{-1} for 'FieldExt2030s' on June 27th, before increasing to 38.6 cm s^{-1} for 'FieldInt2030s' but only to 29.7 cm s^{-1} for 'FieldExt2030s' on July 1st because of the larger soil fertility and sowing density in 'FieldInt2030s'. This fast increase for 'FieldInt2030s' after vegetation germination prevented wind erosion earlier in the year than for 'FieldExt2030s'. Altogether, the horizontal sediment flux was thus larger for 'FieldInt2030s' at the end of the dry season (May–June) and larger for 'FieldExt2030s' during the beginning of the rainy season (end of June to beginning of August).

Mean annual horizontal sediment flux

The mass of total horizontal sediment fluxes and its annual mean were computed for each simulation (i.e. for each land unit) and for a bare soil over the 12-year period. As observed in the previous subsections, the vegetation cover of 'Sav1950s' was always large enough to prevent wind erosion, notably because of a large soil fertility and no grazing pressure. The decrease in soil fertility and the intermediate grazing pressure in 'Fal1990s' compared to 'Sav1950s' yielded a low horizontal sediment flux of 20 ± 28 kg m^{-1} per year on average.

In agreement with the seasonality discussed above, 'FieldHome1990s' yielded the lowest annual horizontal sediment flux among the four cultivated cases (217 ± 263 kg m^{-1} yr^{-1}) due to a large soil fertility

Table 5 Frequency of days with wind erosion larger than 0, 20 or 50 kg m^{-1} for each scenario and the bare soil over the 12-year period

Scenario	Freq. of days with wind erosion > 0 kg m^{-1} (%)	Freq. of days with wind erosion > 20 kg m^{-1} (%)	Freq. of days with wind erosion > 50 kg m^{-1} (%)
Low density (1950s)	0	0	0
High density (1990s)	5.9	0.8	0.2
Very high density, Extensive (2030s)	15.5	2.2	0.4
Very high density, Intensive (2030s)	11.9	2.2	0.4
Bare soil	44.1	4	0.6

and a low rate of residue collection and thus large vegetation amounts protecting the soil from wind during the rainy season and the dry season. Conversely, 'FieldExt2030s' yielded the largest horizontal sediment flux (649 ± 515 kg m^{-1} yr^{-1}), in response to residue collection, yet about 1.6 times lower than a bare soil (1037 ± 533 kg m^{-1} yr^{-1}). It was closely followed by 'FieldInt2030s' (565 ± 396 kg m^{-1} yr^{-1}), which produced larger green vegetation amounts than 'FieldExt2030s' thanks to manure and fertilizers, but had some residues laid down at harvest (in addition to residue collection) and a larger grazing pressure on dry vegetation from then on. 'FieldBush1990s' yielded intermediate values of horizontal sediment flux (341 ± 363 kg m^{-1} yr^{-1}), with a low soil fertility but also a very low proportion of residue being collected. Standard deviations over the 12-year series were large, yet the relative order of annual sediment fluxes remains every year, from 'FieldExt2030s' yielding the largest values to 'Sav1950s' yielding the lowest ones

Landscape scale responses

Mean annual horizontal sediment flux

Mean annual horizontal sediment flux for scenarios are reported in Fig 6, as weighted combinations of the simulations over the whole landscape according to the corresponding land use proportions, including the plateaus (see Fig 2). Under the *Low density* scenario, annual horizontal sediment flux remained zero across the landscape. For the *High density* (1990s) scenario, the combination of fallows, unmanured and manured

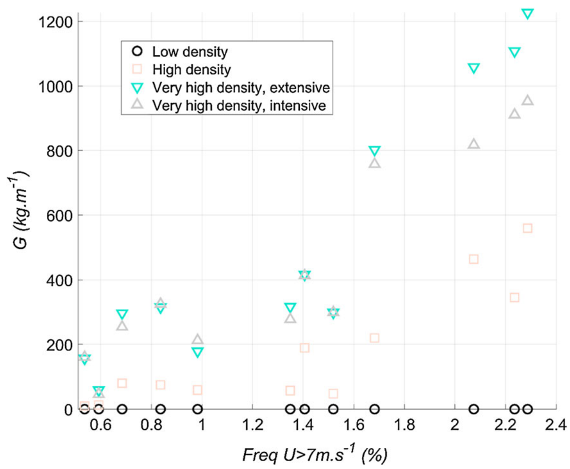

Fig. 7 Annual horizontal sediment flux versus frequency of large winds over the 12-year period for all scenarios

fields, and plateaus, yielded an average horizontal sediment flux of 176 kg m^{-1} yr^{-1}. The weighing slightly reduced the values for both future scenarios (*Very high density, Extensive:* 520 kg m^{-1}.yr^{-1} and *Very high density, Intensive*: 452 kg m^{-1} yr^{-1}) compared to single land uses, as their estimates included 20% of the landscape covered by plateaus that are not prone to wind erosion. Similarly, bare soil would induced a horizontal sediment flux of 830 kg m^{-1} yr^{-1} over the landscape, with no wind erosion over the plateaus.

Thus, the fact that landscapes are composed of several land uses had a noticeable influence on the final results among scenarios. As an example, the unmanured fields of the *High density* scenario ('FieldBush1990s') produced a mean annual horizontal sediment flux of 341 kg m^{-1}.yr^{-1}. Yet, under the

Table 6 Observations of vegetation mass and horizontal sediment flux, from literature mostly dedicated to southwestern Niger

	Millet	Herbaceous
Annual maximum mass of total vegetation (g m^{-2})	300–500	40–160
	Marteau et al. (2011)	Hiernaux et al. (2009)
	(Niamey area, 2004–2009)	(Fakara area, Niger, 1994–2006)
	200–300	150–230
	Rockström & de Rouw (1997)	Mougin et al. (2009)
	(Banizoumbou, 1994–1996)	(Gourma, Mali, 2005–2007)
Mass of residues (g m^{-2})	100–300 standing in October	
	Schlecht et al. (2001)	
	(Western Niger, 1997–1998)	
	20–40 litter in May	
	Schlecht et al. (2001)	
	(Western Niger, 1997–1998)	
Grain yield (g m^{-2})	40–100	
	Marteau et al. (2011)	
	(Niamey area, 2004–2009)	
	40–50	
	Rockström & de Rouw (1997)	
	(Banizoumbou, 1994–1996)	
Annual horizontal sediment flux (kg m^{-1})	300–400 millet field	2–20
	Abdourhamane Touré et al. (2011)	Rajot (2001)
	(Banizoumbou, 2007–2008)	(Banizoumbou, 1996–1998)
	1100–1800 bare soil	
	Abdourhamane Touré et al. (2011)	
	(Banizoumbou, 2007–2008)	

High density scenario, unmanured fields constitute only 45% of the landscape (and fallows, manured fields, and plateaus respectively 20%, 8%, and 20% of the landscape), yielding a landscape scale horizontal sediment flux (per unit area) much lower than for unmanured fields only.

As for the land use estimates, the landscape scale values exhibited large standard deviations over the 12-year time series (not shown), yet the relative order of annual sediment fluxes remained consistent every year, from *Very high density, Extensive* yielding the largest amounts to *Low density* yielding the lowest.

Altogether, these mean annual horizontal sediment fluxes differed by approximately a factor 2.5 to 3 between *High density* and *Very high density*, while *Low density* yields no wind erosion. Thus, both future scenarios suggest a significant increase of wind erosion compared to historical and recent situations (under current meteorological conditions). However, both yielded a lower horizontal sediment flux than bare soil (1.6 times lower for *Extensive* and 1.8 times lower for *Intensive*). The *Extensive* scenario yielded slightly larger values of horizontal sediment flux than the *Intensive* one, related to lower green vegetation amounts in *Extensive*, which is not totally counterbalanced by the lower use of crop residues in *Extensive* compared to *Intensive*.

Wind erosion frequencies and large events

For present-day meteorological conditions, the frequency of days with wind erosion ranged from 0 for

Low Density to 15.5% for *Very High Density, Extensive* (and 44.1% for bare soil), with lower values of 11.9% for *Very High Density, Intensive* and 5.9% for *High Density* (Table 5). Thus, land use and land management had an impact on both total amount and frequency of horizontal sediment flux. In addition, any land use and land management simulated here largely reduced the occurrence of wind erosion compared to a bare soil, especially for small events.

Most of the erosive days occurred in May, June and July, with 70% (*Very high density, Extensive*) to 77% (*Very high density, Intensive*) and 88% (*High density*) of events occurring over this period (not shown). Large events, with horizontal sediment flux larger than 50 kg m^{-1} per day, also concentrate between mid-May and early July. They sum up to 19%, 19%, and 21% of the total sediment flux of the 12-year period for *High density, Very high density, Extensive* and *Very high density, Intensive*, respectively, although they represented only about 3% of the erosive days. These figures emphasize the large seasonality of wind erosion, which persisted with a mosaic of land uses over the simulated landscape.

In addition, the differences in total amounts of horizontal sediment flux between the *High Density* and the *Very High Density* scenarios were related to significant differences in the frequencies at which the landscape was prone to wind erosion, for all kind of events. Between *Extensive* and *Intensive*, the differences were mostly due to days with horizontal sediment flux lower than 20 kg m^{-1}, as the frequencies of days with larger events were similar.

Large aeolian sediment transport events can abrade plants, especially if they occur during the beginning of plant growth (Sterk 2003). Here, maximum daily horizontal sediment flux was about 100 kg m^{-1} (102 kg m^{-1} on May 13th 2008 and 108 kg m^{-1} on June 29th 2008 for *Very high density, Intensive*; 100 kg m^{-1} on June 9th 2010 for *Very high density, Extensive*; versus 111 kg m^{-1} on May 13th 2008 for a bare soil), occurring in croplands at the end of the dry season Maximum daily horizontal sediment flux for *High density* was 71 kg m^{-1} (on July 4th 2008). Given that most wind erosion events lasted less than 1 h (not shown), these figures compare with the ones from Michels et al. (1995), who noticed a significant abrasion effect on millet seedlings after horizontal sediment flux of about 37 kg m^{-1} over 15 min.

Interannual variability of horizontal sediment flux

The large interannual variability of meteorological conditions raises the question of the extent to which cropping practices may prevent wind erosion, compared to the variability of wind erosion due to meteorological conditions. For each scenario, annual horizontal sediment flux exhibited large interannual variability, about the same order as its pluriannual mean (see Table D1 in Supplementary Appendix D). Thus, for the same practices, meteorological conditions induced large variability in the annual horizontal sediment flux (of about 70% to 105%, depending on the scenario).

Similarly, each year, the variability of the horizontal sediment flux among scenarios was about the same order as its mean over the four scenarios (Table D2; this does not include the bare soil case). Thus, for the same meteorological conditions, land management induced large variability in the horizontal sediment flux (of about 80% to 110%). Altogether, the variability of annual horizontal sediment flux due to land management was of the same order as that due to meteorological conditions. While such observations were made on benchmark simulations (Pierre et al. 2018), these results show that realistic sets of practices have as large an influence as the largest theoretical range of practices on the variability of annual horizontal sediment flux.

More specifically, the results show that:

(1) Management promoting wind erosion tended to reduce annual wind erosion relative variability related to meteorological conditions (see e.g. the low values of the coefficients of variation over years of 0.70 and 0.79 for *Very high density, Extensive* and *Intensive* in Table D1, with both scenarios associated with the largest horizontal sediment fluxes; the latter decreased to 51% for the case of a bare soil).

(2) Conversely, the relative variability of annual horizontal sediment fluxes between scenarios (i.e. due to management) tended to be the lowest when high winds were the most frequent. There was a significant ($p < 0.05$) anticorrelation (R = −0.65) between the annual frequencies of high wind events and the relative variability of annual horizontal sediment fluxes in Table D2 (n = 12).

Additionally, there was a correlation of about 0.9 (n = 12, p-value < 0.0005) between the annual horizontal sediment flux and the frequency of winds higher than 7 ms^{-1} for all landscapes (Fig. 7). This correlation was larger for both *Very high density* scenarios (R = 0.92 for Extensive, 0.93 for Intensive) than for the *High density* situation (R = 0.87). This trend is driven by cropped land uses, while fallows in the *High density* landscape yielded a correlation lower than 0.3 (not shown). Indeed, for cropped surfaces, the low vegetation cover during the erosive period of the year allowed wind erosion to mainly depend on wind conditions.

Discussion

The steady increase in rural population density since the 1950s induced a widespread cropland expansion throughout the Sahel (van Vliet et al. 2013; Tappan et al. 2016). As lands are becoming increasingly cultivated, fields are less often fallowed and generally with no chemical fertilizer applied (though manure can be applied in fields located close to villages or pastoralist camps) and soil fertility tends to decline (Turner and Hiernaux 2015). Meanwhile, crop residues are increasingly collected (although not necessarily exported from the village territory), which has a large impact on wind erosion as the surface becomes less protected from wind. Both phenomena, decrease in soil fertility and increase in crop residues collection, have been observed and reported in the literature, including in southwestern Niger (Schlecht et al. 2001; Akponikpè et al. 2014).

Our simulations show that a consequence of these changes is an increasing horizontal airborne sediment flux, from nil flux with 1950s land management (*Low density*) to intermediate values with 1990s land management (*High density*) and large values with potential land management in 2030s (*Very high density*). Also, as weighted mean of land uses composing each landscape, available forage (maximum annual amounts of grass and millet leaves) decreases from 189 g m^{-2} (*Low density*) to 72 g m^{-2} (*High density*) and to 49 g m^{-2} (*Very high density, Intensive*) or 43 g m^{-2} (*Very high density, Extensive*). Thus, the disappearing of fallows and rangelands in the prospective scenarios led to a decrease in forage availability and an increase in horizontal sediment flux compared to historical and recent situations.

The horizontal sediment flux was only slightly lower for the *Intensive* prospective scenario (based on a tight combination of cropping and livestock farming) than for the *Extensive* one (with increased use of current practices and soil depletion), although intensification could enable larger amounts of grain and forage production. This difference in vegetation amounts was due to practices enhancing green vegetation growth in *Intensive* (manuring and sowing density), allowing a higher collection of crop residues while keeping horizontal sediment flux of the same magnitude as in the *Extensive* scenario. Compared to the *Extensive* scenario, *Intensive* provides sensibly higher grain yields, slightly higher mass of millet leaves, and much larger stalks mass. The latter constitutes a resource as they can be sold, e.g. as building material (yet they are not palatable for livestock). Their annual maximum amounts ranged from 0 for *Low density* (no millet fields) to 88 g m^{-2} for *High density*, 107 g m^{-2} for *Very high density, Extensive* and 276 g m^{-2} for *Very high density, Intensive*.

Thus, although the *Intensive* prospective scenario yielded larger vegetation production, it resulted in horizontal sediment fluxes of similar magnitude to the *Extensive* scenario. Such large horizontal sediment fluxes could deplete soil fertility and thus increasingly require the use of fertilizers, reducing the long-term sustainability of such a scenario. This result could help designing future land management policies to assess wind erosion risk along with other ecological issues like forage production and soil nutrients depletion.

Altogether, the simulated values were in good agreement with the few existing observations (Table 6), in terms of vegetation amounts as well as horizontal sediment flux, for both vegetation types.

Our results show that realistic sets of practices have as large an influence as the largest theoretical range of practices on the variability of annual horizontal sediment flux. They induced a variability of annual horizontal sediment flux as large as that due to meteorological conditions. This study goes one step further than the benchmark study of Pierre et al. (2018) that addressed one land management practice at a time, considering the largest range of variation for each practice. Here, we considered scenarios representing a combination of land uses over the landscape with realistic proportional areas and associated land management practices. The practices associated with each land use within a scenario ensured internal consistency (e.g. sowing density related to soil fertility, livestock pressure related to forage availability) as land management operates in agro-pastoral systems. Off-farm activities were implicitly taken into account as they might provide income for producers to purchase fertilizers (like in '*Very high density, Intensive*').

In future research, improvements could be brought to the simulations. For example, to explicitly account for wind erosion feedbacks on soil nutrients, dust emissions (spatially exported from the landscape) should be estimated, and spatial interactions of aeolian fluxes between land units should be taken into account, like fallows trapping part of the horizontal sediment flux from neighboring plots (Bielders et al. 2004). Such estimates of sediment redistribution (i.e. budget between loss and deposition among surface types) due to wind erosion at the landscape scale would be highly valuable for assessing the dynamics of soil fertility. Similarly, trees and shrubs could be taken into account for their effect on wind erosion. As shown by Leenders et al. (2016), for a well-instrumented study site in Burkina Faso, shrubs usually decrease wind erosion in their lee and increase it on their sides, with a net decreasing effect, while trees increase wind speed and thus wind erosion around their trunk.

Some uncertainties in our simulations may derive from the depiction of crop residue management in the prospective scenarios (e.g. rates of crop residues collection, constant grazing pressure throughout the dry season). Simulated practices inside a given village could exhibit a range of values instead of a unique one (e.g. rate of residues collection, dates of sowing and clearing, …; see e.g. Raynaut 2001). Spatial and seasonal variability of grazing (Turner et al. 2005) could also be accounted for in spatially explicit simulations, although such information is especially challenging to assess. Accordingly, the submodels for dry vegetation carry uncertainties in dry vegetation amounts, as observations used to calibrate them are very rarely available. Their improvements would require extensive measurements of both dry vegetation amounts and livestock grazing and trampling, with a good spatial and temporal coverage.

Finally, a step forward will be to run new simulations with climate conditions from past measurements and from climate projections to combine land management dynamics with regional climate change and local meteorological conditions over the long term. Climate projections to 2100 for the Sahel suggest a broad increase in temperature (Roehrig et al. 2013), opposite trends in annual rainfall between western (decrease) and central and eastern (increase) Sahel, a later monsoon onset (Monerie et al. 2020), and more intense rain events. These trends are associated with changes in the regional circulation, e.g. a stronger Saharan heat low (a near-surface thermal low pressure system) which affects the strength of the monsoon flow (Parker et al. 2005) and could further favor the occurrence of intense mesoscale convective systems which produce wind gusts (Fitzpatrick et al. 2020). As suggested by our results, these changes in meteorological conditions will affect vegetation cover and wind erosion, thus the impacts of wind erosion on the productive potential of Sahelian landscapes will be strongly influenced by future land management. The strong correlation that we noticed between horizontal sediment flux and the occurrence of strong winds recalls the fact that climate models must reproduce the occurrence and the intensity of the strongest winds in order to assess the impacts of climate change on future wind erosion.

Conclusion

Wind erosion has been simulated for a study site in southwestern Niger for four scenarios describing typical agro-pastoral practices of the past and future decades (1950s, 1990s, and 2030s). These scenarios focus on the dynamics of practices that are related to population increase, cropland expansion and possible future intensification. Our results clearly illustrate how evolving land use and associated management practices can affect horizontal airborne sediment flux. They underline the larger horizontal sediment flux for croplands compared to rangelands and fallows, and the importance of crop residue management for controlling soil and nutrient losses from Sahelian agro-pastoral systems. Other factors like manuring and related crop density also produced noticeable differences in horizontal sediment fluxes among scenarios.

Our results show that land use and management changes in the study area from the 1950s to the 1990s increased aeolian sediment transport rates and are likely to continue to increase wind erosion in the coming decades. The two prospective scenarios for the 2030s exhibited similar horizontal sediment fluxes, but much larger vegetation yields under intensification (relying on external inputs and a tight crop-livestock integration) than for extensive conditions. Such a large increase of wind erosion in the coming decades would induce noticeable soil loss and associated nutrient loss, and thus ultimately a decrease in soil fertility. This land degradation would become increasingly difficult to counterbalance using fertilizers, the use of which, in addition, requires financial resources. Thus, these results bring to question the sustainability of both prospective scenarios for the 2030s.

These conclusions are particularly valuable as they have been developed for a set of consistent land use trajectories, from scenarios based on extensive knowledge of land use and land management practices of the study site. This study goes further than benchmark studies which considered one practice at a time and its sole range of variability, isolated from other practices. Thus, it recalls the fact that the environmental impact of land use and management practices, of which wind erosion is an aspect, must be assessed at the landscape scale in order to account for the contrasted surface types and associated land management.

Agro-pastoral practices are motivated by environmental and socioeconomic conditions under which smallholders must balance wind erosion trade-offs against millet yield and fodder production. While this study focused on the impacts of evolving practices, future research will combine both varying practices and climate conditions. Such results must be analyzed in relation to social changes to interpret the effect of land use changes and to better assess the impact of possible evolutions of agro-pastoral practices for the coming decades. Ultimately, future work will assess the feedbacks of wind erosion on land management and socioeconomic conditions. The scenarios and methodology we developed here are generalizable beyond this wind erosion study to systems-level investigations of human–environment interactions in the Sahelian area.

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Declarations

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References

Abdourhamane Touré A, Rajot JL, Garba Z, Marticorena B, Petit C, Sebag D (2011) Impact of very low crop residues cover on wind erosion in the Sahel. CATENA 85:205–214

Abdourhamane Touré A, Tidjani AD, Rajot JL, Marticorena B, Bergametti G, Bouet C, Ambouta KJM, Garba Z (2019) Dynamics of wind erosion and impact of vegetation cover and land use in the Sahel: a case study on sandy dunes in southeastern Niger. CATENA 177:272–285

Akponikpè PBI, Gérard B, Bielders CL (2014) Soil water crop modeling for decision support in millet-based systems in the Sahel: a challenge. Afr J Agr Res 9:1700–1713

Baron C, Sultan B, Balme M, Sarr B, Traore S, Lebel T, Janicot S, Dingkuhn M (2005) From GCM grid cell to agricultural plot: scale issues affecting modelling of climate impact. Phil Trans r Soc B 360:2095–2108

Bergametti G, Rajot JL, Pierre C, Bouet C, Marticorena B (2016) How long does precipitation inhibit wind erosion in the Sahel? Geophys Res Lett. https://doi.org/10.1002/2016GL069324

Bergametti G, Marticorena B, Rajot JL, Chatenet B, Féron A, Gaimoz C, Siour G, Coulibaly M, Koné I, Maman A,

Zakou A (2017) Dust Uplift Potential in the Central Sahel: an analysis based on 10 years of meteorological measurements at high temporal resolution. J Geophys Res Atmos 122:12433–12448
Bielders CL, Rajot J-L, Michels K (2004) L'érosion éolienne dans le Sahel nigérien: influence des pratiques culturales actuelles et méthodes de lutte. Sécheresse 15:19–32
Bonfiglioli AM (1990) Pastoralisme, agro-pastoralisme et retour: itinéraires sahéliens. Cahiers des Sciences Humaines, 3. La Théorie En Question 26:255–266
Breman H, Groot JJR, van Keulen H (2001) Resource limitations in Sahelian agriculture. Global Environ Chang 11:59–68
Cappelaere B, Descroix L, Lebel T, Boulain N, Ramier D, Laurent J-P, Favreau G, Boubkraoui S, Boucher M, Bouzou Moussa I, Chaffard V, Hiernaux P, Issoufou HBA, Le Breton E, Mamadou I, Nazoumou Y, Oi M, Ottlé C, Quantin G (2009) The AMMA-CATCH experiment in the cultivated Sahelian area of south-west Niger – Investigating water cycle response to a fluctuating climate and changing environment. J Hydrol 375:34–51
Chi W, Zhao Y, Kuang W, He H (2019) Impacts of anthropogenic land use/cover changes on soil wind erosion in China. Sci Total Environ 668:204–215
de Rouw A, Rajot J-L (2004) Soil organic matter, surface crusting and erosion in Sahelian farming systems based on manuring or fallowing. Agr Ecosyst Environ 104:263–276
Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Hólm EV, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally AP, Monge-Sanz BM, Morcrette J-J, Park B-K, Peubey C, de Rosnay P, Tavolato C, Thépaut J-N, Vitart F (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q.J.R. Meteorol Soc 137:553–597
Du H, Zuo X, Li S, Wang T, Xue X (2019) Wind erosion changes induced by different grazing intensities in the desert steppe, Northern China. Agric Ecosys Environ 274:1–13
Duniway MC, Pfenningwerth AA, Fick SE, Nauman TW, Belnap J, Barger NN (2019) Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world. Ecosphere 10:e02650
Fensholt R, Rasmussen K, Kaspersen P, Huber S, Horion S, Swinnen E (2013) Assessing land degradation/recovery in the African Sahel from long-term Earth observation based primary productivity and precipitation relationships. Remote Sens 5:664–686
Fenta AA, Tsunekawa A, Haregeweyn N, Poesen J, Tsubo M, Borrelli P, Anagos P, Vanmaercke M, Broeckx J, Yasuda H, Kawai T, Kurosaki Y (2020) Land susceptibility to water and wind erosion risks in the East Africa region. Sci Total Environ 703:135016
Fitzpatrick RGJ, Parker DJ, Marsham JH, Rowell DP, Guichard FM, Taylor CM, Cook KH, Vizy EK, Jackson LS, Finney D, Crook J, Stratton R, Tucker S (2020) What drives the intensification of Mesoscale Convective Systems over the West African Sahel under climate change? J Climate 33:3151–3172
Galloza MS, Webb NP, Bleiweiss MP, Winters C, Herrick JE, Ayers E (2018) Exploring dust emission responses to land cover change using an ecological land classification. Aeolian Res 32:141–153
Gomes L, Rajot JL, Alfaro SC, Gaudichet A (2003) Validation of a dust production model from measurements performed in semi-arid agricultural areas of Spain and Niger. CATENA 52:257–271
Goutorbe JP, Lebel T, Dolman AJ, Gash JHC, Kabat P, Kerr YH, Monteny B, Prince SD, Stricker JNM, Tinga A, Wallace JS (1997) An overview of HAPEX-Sahel: a study in climate and desertification. J Hydrol 188–189:4–17
Greeley R, Iversen JD (1985) Wind as a geological process on Earth, Mars, Venus and Titan, Cambridge University Press. ed, Cambridge Planetary Science Series. Cambridge/London/New York/New Rochelle/Melbourne/Sydney.
Hiernaux P, Ayantunde A, Kalilou A, Mougin E, Gérard B, Baup F, Grippa M, Djaby B (2009) Trends in productivity of crops, fallow and rangelands in Southwest Niger: impact of land use, management and variable rainfall. J Hydrol 375:65–77
Hiernaux P, Ayantunde A (2004) The Fakara: a semi-arid agro-ecosystem under stress (Report of research activities), First phase (July 2002-June 2004) of the DMP-GEF Program (GEF/2711–02–4516). International Livestock Research Institute (ILRI), Niamey, Niger.
Hiernaux P, Turner MD (2002) The influence of farmer and pastoralist management practices on desertification processes in the Sahel. In Reynolds JF, Stafford Smith MD (Eds), Global Desertification: Do Humans Cause Deserts?, Dalhem Workshop Reports. Berlin, Germany, 135–148.
IPCC (2019) Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.
Klein Goldewijk K, Beusen A, van Drecht G, de Vos M (2011) The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. Global Ecol Biogeogr 20:73–86
Kouressy M, Dingkuhn M, Vaksmann M, Heinemann AB (2008) Adaptation to diverse semi-arid environments of sorghum genotypes having different plant type and sensitivity to photoperiod. Agr Forest Meteorol 148:357–371
Laurent B, Marticorena B, Bergametti G, Léon JF, Mahowald NM (2008) Modeling mineral dust emissions from the Sahara desert using new surface properties and soil database. J Geophys Res. https://doi.org/10.1029/2007JD009484
Lavigne Delville P (1997) Sahelians agrarian systems: Principal rationales. In Raynaut C, Grégoire E, Janin P, Koechlin J, Lavigne Delville P (Eds), Societies and Nature in the Sahel. London, UK, 138–158.

Leenders JK, Sterk G, Boxel JH (2016) Wind erosion reduction by scattered woody vegetation in farmers' fields in northern Burkina Faso. Land Degrad Develop 27:1863–1872

Marteau R, Sultan B, Moron V, Alhassane A, Baron C, Traoré SB (2011) The onset of the rainy season and farmers' sowing strategy for pearl millet cultivation in Southwest Niger. Agr Forest Meteorol 151:1356–1369

Marticorena B, Bergametti G (1995) Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme. J Geophys Res 100:16415–16430

Marticorena B, Chatenet B, Rajot JL, Traoré S, Coulibaly M, Diallo A, Koné I, NDiayeZako TA (2010) Temporal variability of mineral dust concentrations over West Africa: analyses of a pluriannual monitoring from the AMMA Sahelian Dust Transect. Atmos Chem Phys 10:8899–8915

Marticorena B, Chatenet B, Rajot JL, Bergametti G, Deroubaix A, Vincent J, Kouoi A, Schmechtig C, Coulibaly M, Diallo A, Koné I, Maman A, NDiayeZako TA (2017) Mineral dust over west and central Sahel: seasonal patterns of dry and wet deposition fluxes from a pluriannual sampling (2006–2012). J Geophys Res Atmos 122:1338–1364

Mbow C, Brandt M, Ouedraogo I, De Leeuw J, Marshall M (2015) What four decades of Earth observation tell us about land degradation in the Sahel? Remote Sens 7:4048–4067

Michels K, Armbrust DV, Allison BE, Sivakumar MVK (1995) Wind and windblown sand damage to pearl millet. Agron J 87:620–626

Monerie P-A, Sanchez-Gomez E, Gaetani M, Mohino E, Dong B (2020) Future evolution of the Sahel precipitation zonal contrast in CESM1. Clim Dynam 55:2801–2821

Monfreda C, Ramankutty N, Foley JA (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cy. 22, GB1022. https://doi.org/10.1029/2007GB002947

Mougin E, Lo Seen D, Rambal S, Gaston A, Hiernaux P (1995) A regional Sahelian grassland model to be coupled with multispectral satellite data. I: model description and validation. Remote Sens Environ 52:181–193

Parker DJ, Burton RR, Diongue-Niang A, Ellis RJ, Felton M, Taylor CM, Thorncroft CD, Bessemoulin P, Tompkins AM (2005) The diurnal cycle of the West African monsoon circulation. Q J R Meteorol Soc 131:2839–2860

Pi H, Webb NP, Huggins DR, Sharratt B (2020) Critical standing crop residue amounts for wind erosion control in the inland Pacific Northwest, USA. CATENA 195:104742

Pierre C, Bergametti G, Marticorena B, Mougin E, Lebel T, Ali A (2011) Pluriannual comparisons of satellite-based rainfall products over the Sahelian belt for seasonal vegetation modeling. J Geophys Res 116:D18201

Pierre C, Bergametti G, Marticorena B, Mougin E, Bouet C, Schmechtig C (2012) Impact of vegetation and soil moisture seasonal dynamics on dust emissions over the Sahel. J Geophys Res Atmos. https://doi.org/10.1029/2011JD016950

Pierre C, Bergametti G, Marticorena B, AbdourhamaneTouré A, Rajot J-L, Kergoat L (2014) Modeling wind erosion flux and its seasonality from a cultivated sahelian surface: a case study in Niger. CATENA 122:61–71

Pierre C, Kergoat L, Bergametti G, Mougin É, Baron C, Abdourhamane Touré A, Rajot J-L, Hiernaux P, Marticorena B, Delon C (2015) Modeling vegetation and wind erosion from a millet field and from a rangeland: two Sahelian case studies. Aeolian Res 19:97–111

Pierre C, Kergoat L, Hiernaux P, Baron C, Bergametti G, Rajot J-L, Abdourhamane Touré A, Okin GS, Marticorena B (2018) Impact of agropastoral management on wind erosion in Sahelian croplands. Land Degrad Develop 29:800–811

Rajot JL (2001) Wind blown sediment mass budget of Sahelian village land units in Niger. Bulletin De La Société Géologique De France 172:523–531

Rakkar MK, Blanco-Canqui H, Tatarko J (2019) Predicting soil wind erosion potential under different corn residue management scenarios in the central Great Plains. Geoderma 353:25

Raynaut C (2001) Societies and nature in the Sahel: ecological diversity and social dynamics. Global Environ Chang 11:9–18

Reenberg A, Maman I, Oksen P (2013) Twenty years of land use and livelihood changes in SE-Niger: obsolete and short-sighted adaptation to climatic and demographic pressures? J Arid Environ 94:47–58

Roehrig R, Bouniol D, Guichard F, Hourdin F, Redelsperger J-L (2013) The present and future of the West African Monsoon: a process-oriented assessment of CMIP5 simulations along the AMMA transect. J Climate 26:6471–6505

Schlecht E, Kadaouré I, Graef I, Hülsebusch C, Mahler F, Becker K (2001) Land-use and agricultural practices in the agro-pastoral farming systems of western Niger — a case study. Erde 132:399–418

Sterk G (2003) Causes, consequences and control of wind erosion in Sahelian Africa: a review. Land Degrad Develop 14:95–108

Tappan GG, Cushing WM, Cotillon SE, Mathis ML, Hutchinson JA, Herrmann SM, Dalsted KJ (2016) West Africa Land Use Land Cover Time Series: U.S. Geological Survey data release, https://doi.org/10.5066/F73N21JF.

Thomas DT, Moore AD, Bell LW, Webb NP (2018) Ground cover, erosion risk and production implications of targeted management practices in Australian mixed farming systems: lessons from the Grain and Graze program. Agr Syst 162:123–135

Tidjani AD, Bielders CL, Ambouta KJ-M (2009) Seasonal dynamics of the parameters determining wind erosion on rangeland in Eastern Niger. Geo-Eco-Trop 33:39–56

Tracol Y, Mougin E, Hiernaux P, Jarlan L (2006) Testing a sahelian grassland functioning model against herbage mass measurements. Ecol Model 193:437–446

Turner MD, Hiernaux P (2015) The effects of management history and landscape position on inter-field variation in soil fertility and millet yields in southwestern Niger. Agr Ecosyst Environ 211:73–83

Turner MD, Hiernaux P, Schlecht E (2005) The distribution of grazing pressure in relation to vegetation resources in semi-arid West Africa: the role of herding. Ecosystems 8:668–681

van Vliet N, Reenberg A, Rasmussen LV (2013) Scientific documentation of crop land changes in the Sahel: a half

empty box of knowledge to support policy? J Arid Environ 95:1–13
Warren A, Batterbury S, Osbahr H (2001) Soil erosion in the West African Sahel: a review and an application of a "local political ecology" approach in South West Niger. Global Environ Chang 11:79–95
Warren A, Osbahr H, Batterbury S, Chappell A (2003) Indigenous views of soil erosion at Fandou Béri, southwestern Niger. Geoderma 111:439–456
Webb NP, Marshall NA, Stringer LC, Reed MS, Chappell A, Herrick JE (2017) Land degradation and climate change: building climate resilience in agriculture. Front Ecol Environ 15:450–459
Webb NP, Okin GS, Bhattachan A, D'Odorico P, Dintwe K, Tatlhego M (2020) Ecosystem dynamics and aeolian sediment transport in the southern Kalahari. Afr J Ecol 58:337–344
Zhang H, Fan J, Cao W, Harris W, Li Y, Chi W, Wang S (2018) Response of wind erosion dynamics to climate change and human activity in Inner Mongolia, China during 1990 to 2015. Sci Total Environ 639:1038–1050