Impacts of grazing on vegetation dynamics in a sediment transport complex model

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Abstract.

Arid environments are characterized by the complex interaction between vegetation cover, surface soil properties, and the climate. The dynamic balance between these components makes arid environments highly susceptible to swift changes in vegetation cover and surface morphology in response to climate change. Furthermore, arid environments often support grazing activities, which influence other ecogeomorphic processes and alter the stability of vegetation cover in these environments. Despite the growing knowledge and the parallel modelling advances to simulate the sediment transport, vegetation distribution, and grazing, in arid environments, relatively little progress has been accomplished on the interaction between all these components in combination. Here we present an adaptation of an already established sediment transport-vegetation cellular automata model (Vegetation and Sediment TrAnsport or ViSTA) that represents landscape dynamics, with an agent-based model (GrAM) representing the activity of grazers on the landscape. In this study, our resulting model, ViSTA_GrAM, is subjected to a series of 100-year long tests that aim to highlight the capacity of the model to represent ecogeomorphic processes linked to vegetation composition, rainfall, windspeed, and grazing pressure. While these simulations do not allow to evaluate the performance of the new model to reproduce realistic semi-arid environments, they present the capacity of the model to reproduce and explain major feedback complexities between grazers and the vegetation, in addition to providing insight on the vegetation and wind shear sensitivity of the original model. The simulations reinforce our current knowledge on the resilience of grass-based landscapes to foraging activities and highlight the need to identify growth response rates at the species level to fully understand the complexity of the interactions between individual components within arid environments. Overall, the ViSTA_GrAM model presents the foundation of a better assessment of semi-arid environments response to landscape management measures and a better understanding of the complex interactions shaping semi-arid landscapes.

1 Introduction

Ecosystems in arid and semi-arid environments are defined by complex interactions between anthropogenic land-uses, climatic variability, and in many cases, persistent wind erosion (Nicholson, 1978, 2000; Okin et al., 2006; Peters et al., 2006). Persistent transport of sediment can act to modify a landscape by redistributing resources such as soil nutrients necessary to vegetation growth (Okin and Gillette, 2001), as well as leading to landform adjustments (e.g., dune building or dune reactivation (D'Odorico et al., 2013)) In turn, the increasing presence of vegetation in these environment non-linearly influence the transport of sediment by modifying the wind flow at the surface and providing cover to the sediments (Okin, 2008; Okin et al., 2006). The constant feedback between the sediment transport and the vegetation growth create dynamically stable states for the environments supporting them and can quickly provoke major shifts in the composition or distribution of both the sediments and the vegetation (Bestelmeyer et al., 2015, 2018). In arid regions where grazing is an active use of the land, a failure to adapt the land use strategy to rainfall variability and wind regime can accelerate a shift in the composition and spatial organization of vegetation, leading to a reduction of the grazing capacity of the land and possibly an increase in the wind erosion (Bhattachan et al., 2014; Thomas et al., 2005; Webb and Pierre, 2018). In this context, the onset and severity of wind erosion induced by changes in climatic variables in addition to grazing pressures are an important source of dust emissions and presents important challenges in the context of climate change (Chappell et al., 2018). Although sediment transport by wind can be modelled using empirical approaches, the synergistic impact of grazing pressure on vegetation growth combined with a climatic shift in aridity or wind regime, demands a more integrative assessment. Additionally, the intrinsic generalisation of the ~~spatiality and temporality~~ of empirical wind transport studies contradict the heterogenic nature of the wind transport itself (Ziegler et al., 2020). The wide array of spatial scale, at which these interactions between sediment transport, vegetation and grazing are observable (Ravi et al., 2011), is ~~an other~~ source of complexity in the study of those interactions. It is therefore advantageous to take a complex modelling approach to help elucidate the spatial and temporal connectivity within these interactions to increase the understanding of how a semi-arid landscape may respond to a changing climate. This approach can provide a better understanding of the landscape dynamics in semi-arid environments enabling an improved management of those environments.

Studies looking at the impacts of grazing on vegetation (i.e. species proportions and spatial distribution), within arid environments, have taken various approaches including remote sensing (Ares et al., 2003), empirical modelling (Aubault et al., 2015), and complex modelling (Jeltsch et al., 1997a; Yu et al., 2019). However, few studies have combined a complex modelling approach to analyse the interaction between grazing and wind erosion at the scale of individual grazers or dunes (e.g. Bo et al., 2013; Yan and Baas, 2018). Remote sensing studies on vegetation cover in arid environments (e.g., Patagonia Monte, Colorado Plateau) were developed to track the changes in grazed landscapes and effectively analyse the results of landscape management, but the analysis of the functions and processes that shape the resulting landscape are more difficult to extract (Ares et al., 2003; Yuhas and Goetz, 1994). Aubault et al. (2015) implemented a coupled approach using an empirical model representing pasture growth (GRASP) and a spatio-temporal land erodibilty model (AUSLEM) to evaluate the impact of land management strategies on the erodibility of western Queensland Australia environments. The study highlighted the importance of adapting the grazing strategy and stocking rate to the land type and climate variabilities of an environment, in order to limit the wind erosion and land degradation (Aubault et al., 2015). A combined agent-based model (ABM) approach and real time remotely sensed vegetation leaf area index by Yu et al. (2019), ~~evaluates~~ the consequences of different grazing management strategies on vegetation cover in the region of Zeku, China. Nevertheless, this combined approach ~~is~~ based at a landscape scale and focused on the management strategies rather than the description of the dynamics between the landscape and the grazers (Yu et al., 2019). The cellular automata (CA) model of Jeltsch et al. (1997a) represents the effect on vegetation cover from preferential grazing around a borehole in the Kalahari Desert. The Jeltsch et al. (1997a) model provides a good representation of the preferential grazing gradient around a borehole~~,~~ however, it does not simulate sediment transport and implemented only at a herd level. The approaches summarized here suggest the possible advantages to combine a CA model with an ABM to represent a dynamic and synergistic vegetation-sediment-grazing interaction at appropriate spatial and temporal scales within a semi-arid environment.

The increasing interest in shear stress partitioning approaches developed for sparsely vegetated arid environments (King et al., 2005; Okin, 2008) encouraged the development of CA models to simulate the interaction of vegetation with sediment transport. From this development, those representing the vegetation-wind dynamics and the wind-fluvial dynamics in parabolic and barchans dune fields are the DECAL (Baas and Nield, 2007; Yan and Baas, 2017) and DECAL-CAESAR (Liu and Coulthard, 2017), respectively. Mayaud et al. (2017a) presented a CA model called the Vegetation and Sediment TrAnsport (ViSTA) model (hereafter ViSTA_M17) with a similar methodology to the DECAL model and the Bailey (2011) vegetation model to create a more integrative model to simulate a wind erosion driven landscape. The ViSTA_M17 model includes a stochastic representation of grazing whose approach, which overlooks some important dynamics like the heterogenic distribution of the grazing (important when representing larger regions) limiting field study comparisons. Therefore, the objective of this research is to model the response of a semi-arid landscape to climatic and grazing variabilities with an improved representation of herbivory. To achieve this, we have added an herbivory agent-based model (ABM) to the ViSTA_M17 model and updated several key modules, to improve its representation of the semi-arid environment at larger spatial scales, demonstrated through a series of plausible scenarios. The results from one of these scenarios combined with the herbivory ABM are discussed in the context of southern African environments.

2 Methods

The proposed and implemented model used to represent the arid environment in this research study is named the ViSTA_GrAM model, which integrates the new Grazing Agent Module (GrAM), an ABM representing grazer disturbance, into the ViSTA_M17 CA model. The ViSTA_M17 is a coupled CA model representing the interactions between sediment transport and vegetation in a spatially explicit way to investigate the development of arid and semi-arid environments (Mayaud et al., 2017a). The ViSTA_M17 model use a similar approach to Bailey's (2011) CA model to represent the spatial interaction of the vegetation and the vegetation interaction with sediments. The ViSTA_M17 model considers three types of vegetation (loosely grasses, shrubs and trees) that populate the simulation grid by recording the age and biomass of the vegetation on each cell. The vegetation biomass present on cells is determined by a “growth pathway” relative to the age of that vegetation (Mayaud et al., 2017a). The “growth pathway” is a function defining the optimal gain of plant biomass in relation to its age that can be modified according to the amount of precipitation received by the vegetation. The biomass of the vegetation is then used to determine the strength of the interactions of the vegetation with their neighbors (e.g. competition or facilitation) and with the sediment (e.g. by transforming the biomass to a height value). On the other hand, the survival or death of the vegetation is based on a probability ~~based on~~ the neighborhood competition, the response of the vegetation to precipitation~~s~~, the vegetation biomass, the vegetation age and the sediment balance (i.e., plant response to sediment erosion/deposition) (Mayaud et al., 2017a).

Alongside the representation of the vegetation, the model ViSTA_M17 also simulates the transport of sediment, similarly to the Werner’s (1995) and Nield and Baas (2007) models, by moving sediment~~s~~ slabs of fixed height across cells (Mayaud et al., 2017a). A summary of the ViSTA_M17 treatment of erosion of sediment can be given in two steps. Firstly, a volumetric flux of sediment transport is calculated in relation to the wind speed with deterministic functions. Secondly, a probability of erosion is evaluated for each cell based on the humidity of the surface and the position of the cell in a shadow zone (i.e. zone downwind of a topographic element forming more than a 15° opposite angle between the apex of the element and the surface). The transport of sediment on a cell is the product of the volumetric flux and the probability of erosion on that cell. The sediment deposition is a function of a probability of deposition, based on the position of the cell in a shadow zone, the nature of the surface (e.g., wet or dry sediment, bare rock, etc.) and the presence of vegetation, for each cell downwind of the emission source. The slabs of eroded sediment are then deposited, along a downwind “corridor”, based on the probability of deposition. The ViSTA_M17 sediment model also considers the presence of avalanching processes, in its simulations, based on the angle of repose. In the case of two adjacent cells that present an angle of the surface superior to 30°, sediment is transferred from the higher cell to the lower one until the angle of the sediment surface is lowered bellow 30° as in an avalanche event. By using this methodology, the model ViSTA_M17 can represent the mutual feedbacks between the vegetation and the sediment transport and specifically model the landscape forms produced in arid and semi-arid environments like the skeleton coast (Namibia) and the Kalahari (Botswana) (Mayaud et al., 2017a, 2017b). Changes to the ViSTA_M17 model structure has been made in the ViSTA_GrAM to improve the representation and integration of the new GrAM module. The first modification brought by ViSTA_GrAM concerns the way sediment transport is processed and the second is the way grazing disturbance is incorporated, as explained in the following two sections. The third section outlines the various scenarios simulated for this application.

2.1 Vegetation-sediment~~s~~ interactions

~~The changes concerning~~ the sediment transport function were introduced to improve the oversensitivity of the model to sediment transport in the presence of vegetation (see Appendix A). To enhance the representativeness of sediment transport in the presence of significant vegetation coverage, a new condition was introduced in the erosion processing function of the model. Since the model considers all vegetated cells as being fully covered by closely spaced vegetation, it is reasonable to assume that a skimming flow will be created under vegetation of a significant height (Hesp et al., 2019; Wolfe and Nickling, 1993). This condition states that if there is vegetation of a significant height on a cell, erosion is not possible on that cell, keeping all other interactions possible (Burri et al., 2011; King et al., 2005, 2006; Lancaster and Baas, 1998; Okin, 2008; Raupach et al., 1993). The significant height at which the vegetation suppresses the erosion is that where the sediment deposition will begin. This addition relates the capacity of the vegetation tall enough to trap the sediment, equally with its capacity to suppress the wind flow and consolidate the substrate, keeping sediment under it from moving (Burri et al., 2011; Dupont et al., 2014; Mayaud and Webb, 2017).

2.2 GrAM module description

The second improvement made with the ViSTA_GrAM model is the addition of a new module simulating a spatially explicit impact of grazing. The GrAM module is implemented using an ABM that allows the representation of grazers as agents that can move on the grid and forage on available grasses. Each grazing event is characterized in the model by a frequency, a duration, and the number of agents introduced on the grid. The ViSTA_M17 model already included a frequency of occurrence variable for grazing events (Mayaud et al., 2017a), which is used to define when the GrAM module is called in sequence within the main portion of the ViSTA_M17 model. This frequency variable allows the model to represent different types of grazing strategy (e.g. continuous grazing or rotational grazing) like grazing management specific models (Yu et al., 2019). A new user defined variable was introduced for defining the discrete time scale (*GrAM_event_duration*) for adding grazing agents compared to the stochastic approach used originally in the ViSTA_M17 (Mayaud et al., 2017a). This new *GrAM_event_duration* variable represents the number of days the grazers stay on the grid for each grazing event and is necessary for any model with explicit representation of the grazing activities (Jeltsch et al., 1997a; Marion et al., 2005, 2008). In terms of the model function, the number of iterations executed by GrAM at each grazing event is equal to double the grazing event length (in days). The days are divided into two to represent the tendency of bovine grazers to concentrate their wandering and eating periods at specific morning and afternoon sessions centered around solar noon (Chacon et al., 1976; Hodgson et al., 1991; Orr et al., 2001). The number of agents on the grid, which influences the grazing function, is determined by the combination of the grid size and the stocking rate (in livestock units per hectare; LSU ha^{-1}) implemented in the setup of a model simulation. For example, if there is a grid of 1000 m by 1000 m and a stocking rate of 0.06 LSU ha^{-1}, the GrAM module will place 6 grazing agents on the grid at the beginning of each grazing event.

Once the grazing agents have been introduced on the grid, they all follow the same rules to guide their movement throughout the simulation space; moving to a cell with grass and then subsequently eating the grass on the surrounding cells at each iteration of the grazing event. Figure 1 illustrates each logical step of the grazing agents' cycle when the GrAM module is called. The grazing agents created in the initial step of each grazing event are randomly distributed on the simulation grid. A new set of agents with new random starting positions are created at the beginning of each subsequent grazing event. The simulation grid is not necessarily representing an enclosed pasture in its entirety and each grazing agent does not have any unique attribute except its position. This approach of the grazing agents in the module corresponds to natural environments; whereby domestic grazers roam through a bigger pasture or whereby wildlife range in fully open environments (Burgess, 2006; Ludwig et al., 2017).

Grazing agents have three behaviours that determine how they act on the model grid: 1) Choosing what cell is the best to move to next; 2) the movement to the next cell; and 3) eating the grass that is in those cells. For choosing which cell to move to next, a function operating on a scoring system is established to decide the best next move for the agent (similar to Jeltsch et al. (1997a, 1997b) and Marion et al. (2008)). A score is then attributed for each cell on the grid, and the next destination of the grazer is randomly chosen among the highest scoring cells. This decision function takes into consideration five factors to determine what the best cell is, with each factor having a positive or negative influence on the total score of the cell, and with a total score calculated for each cell on the grid before the grazing agent chooses its next destination. The five factors in order of their importance are: 1) presence of grazers in the cell; 2) the presence of walls (e.g. rock formation) in the cell; 3) the height of the grass in the cell; 4) the slope of sediment surface, and; 5) the previous visit or not of grazers in that cell. The presence of a wall or a grazing agent in a cell has a highly negative impact on the total score of that cell, because it is unrealistic to have a grazer on a wall and because they cannot be physically on top of each other. The height of the grass is second most important factor in the decision-making process; used as an indicator of the amount of forage available for a grazer at this specific location. Cells where no grass is present above the ground are automatically attributed a score of zero since they do not hold any forage for the grazer to eat. While for cells containing above ground grass, the highest score (0.8) is attributed to cell with a medium height (30-75% of the maximum height), since they would strike the perfect balance between forage amount and forage quality (Jeltsch et al., 1997b). While the least desirable grass cells would be the ones which have a very low amount and sub-optimal quality of forage (heights less than 20% of the maximum height) resulting in a minimal score (0.4) and all other heights of grass in a cell would correspond to a score of 0.6. The sediment surface slope of a cell is another factor having a negative influence on the score of a cell. It is recognized that grazers are less mobile in steep slope terrains compared to terrains with small slopes (Kaufmann et al., 2013; Sharpe and Kenny, 2019). A decrease in score of 0.4 is therefore applied to cells having a sediment surface slope superior to 25° to represent the preference of cattle for more horizontal terrains. These exact values were determined through a series of qualitative sensitivity tests and in relation to the height of grass score. The main criteria being that the score attributed to each cell should not lead to a deterministic decision-making process, but create an array of cells with the same high score, from which a destination is chosen randomly. The last factor that can influence the decision of a grazing agent in this model is its memory. To represent the observation that grazers have a slight preference for locations they already visited and where they have found good forage in the past (Jeltsch et al., 1997a, 1997b; Sharpe and Kenny, 2019), the score of a cell is increased by 0.2 when the grazer has already visited the cell. This increase is not enough to make a bare cell more attractive than one with minimal grass but can make a familiar cell with medium forage quality as attractive as an unfamiliar cell with high forage quality. The memory of each grazer is short term and still limited to the present grazing event because at each new grazing event new agents are created. While other factors, like the distance to the nearest waterhole and the presence of faeces, have been identified as potential influences of grazing ranging patterns (Jeltsch et al., 1997b; Marion et al., 2005, 2008; Sharpe and Kenny, 2019; Weber and Jeltsch, 1997), the limited size of the grid and its openness significantly limit the impact of these factors, minimizing their necessity in the present experimental design.

The second behaviour of grazing agents is their movement, based on the result of the above-mentioned decision function. The third behaviour is responsible for the grazing agents eating the grass around them once they have moved to a new position. Once agents have chosen their new position and have moved to it, each grazing agent will then eat the vegetation around that chosen cell in a 625 m^2 Moore neighbourhood centered on the chosen cell. For each grass cell in the 625 m^2 area around the grazer, 0.03 m of the vegetation height is removed to simulate the grazing. The grazed surface and the amount of grass removed at each iteration are determined based on a daily intake of foraging cattle weighing ~450 kg and subsequent sensitivity tests. Depending on their weight and the quality of forage, cattle need between 8 and 18 kg of forage per day to be in good health (Aubault et al., 2015; Burgess, 2006; Chacon et al., 1976; Hodgson et al., 1991; Orr et al., 2001). By eating the equivalent to 0.03 m of grass over an area of 625 m^2 twice a day, the grazing agents of the model eat a maximum of 15 kg per day given simulated grass of a 400 g m^{-3} volumetric mass (Dougill and Thomas, 2004; Hodgson et al., 1991; Jeltsch et al., 1997a; Ludwig et al., 2017; Meyer et al., 2014; Scholes et al., 2002; Wang et al., 2012). Considering that not all cells around the grazing agent will be covered by grass, the amount of grass eaten by the agent in the simulations typically varies between 7 kg and 15 kg, which corresponds to realistic values from semi-arid regions and those specifically identified from southern Africa (Aubault et al., 2015; Burgess, 2006; Chacon et al., 1976; Hodgson, 1985; Orr et al., 2001), allowing the agents to sustain themselves only on the grid. In the case where an agent eats an amount of grass significantly lower than this recommended quantity, it is assumed that the missing balance of food is found outside of the grid (due to its openness) or it is supplemented. In conclusion, the new GrAM module takes an open and relative approach of the grazer's behaviour on the grid, to limit the number of user inputs and calibration necessary to its application.

2.3 Model applications: simulation scenarios

To assess the applicability of the new ViSTA_GrAM model, six groups of scenarios were created to compare the model response to variations in its major components with results published in peer-reviewed literature. The scenarios all take place on a grid of 200 x 200 cells of 5 m resolution each, and therefore representing 100 hectares, over 100 years, to allow the simulated environment to display a recognizable evolution trend. Each simulation ~~is~~ initiated with a 90% ~~of~~ vegetation grid coverage and a sediment bed thickness between 1.0 m and 1.5 m in height depending on the cell. Each vegetated cell ~~begins~~ at a randomly determined height between 0 m and the maximum height for that type of vegetation (1 m for grass, 1.5 m for shrub and 6 m for trees). The first components tested were the sediment balance stress applied on vegetation by sand burial and the vegetation recolonization. The sediment balance stress is a probability of survival, for each vegetation type, determined as a function of the amount of sediment accumulation/erosion occurring on the cell housing the vegetation. The functions of sediment balance stress were parameterized to represent pioneer grasses like *Stipagrostis amabalis* and marram grass (*Ammophila*), woody shrubs like *Rhigozum trichotomum* and trees of the *Acacia* species, taking inspiration from the DECAL model (Mayaud et al., 2017a; Nield and Baas, 2008; Yan and Baas, 2017). The vegetation recolonization process allows vegetation to re-establish itself onto bare cells at the end of each vegetation update. The vegetation type recolonizing a cell is either determined dynamically and influenced by current vegetation proportions or it is non-dynamic and determined by static probabilities; meaning the initial proportion of each vegetation type. The initial distribution of the vegetation's type was 80% of grass, 10% of shrub and 10% of tree for the FD, SDa1, SDb and ND simulations, but 85% of grass, 10% of shrub and 5% of tree for the SDa2 and SDa3 simulations. The combination of sediment balance stress and the vegetation recolonization dynamics c~~reates~~ a matrix of four different types of simulations ranging from fully dynamic to non-dynamic (Table 1). A fully dynamic simulation (FD) ~~represents~~ an environment where a sediment balance stress is applied to the vegetation and the vegetation recolonization is dynamic, while a non-dynamic simulation (ND) ~~represents~~ neither of these processes. The semi-dynamic simulations ~~have~~ either a dynamic vegetation recolonization (SDa) or a sediment balance stress applied to the vegetation (SDb).

Rainfall i~~s~~ the second major factor studied (Table 2). Simulated annual rainfall regimes at 150 mm year^{-1}, 270 mm year^{-1}, and 450 mm year^{-1}, all correspond to natural rainfall regimes in Southern African semi-arid environments (Jeltsch et al., 1996, 1997b; Ludwig et al., 2017; Meyer et al., 2014; Thomas and Twyman, 2004; Weber et al., 1998). The applied rainfall regime of 1000 mm year^{-1} ~~is~~ not characteristic of semi-arid environments but offers good comparison for the three other rainfall regimes. These rainfall regimes where applied as a constant and uniform source of humidity in our representation of theorical environments ranging for semi-arid grasslands and savannas. No windspeed was applied to simulations testing the sediment balance stress, the vegetation recolonization and the rainfall regime, to help isolate the effect of these components. It was later introduced in the simulations testing sediment transport (Table 2) since the transported sediment of an arid environment is linked to the capacity of the wind to initiate transport (Bagnold, 1941; Hsu, 1971; Kawamura, 1951; Lettau and Lettau, 1978; Owen, 1964; Zingg, 1953) and the response of an environment to different sediment balances is a function of windspeed. With all other parameters kept constant (SDa2 simulations with 270 mm yr^{-1}) and a surface windspeed threshold of 5 m s^{-1}, four simulations were made at 5 m s^{-1}, 7.5 m s^{-1}, 10 m s^{-1} and 12.5 m s^{-1}. All simulations testing the four components above were executed with 6-month vegetation update to maximize efficiency and accommodate the growth period of all three vegetation types.

Finally, the last component of the model tested ~~is~~ the response of an environment to different stocking rates of grazers (Table 2). The stocking rates of 0.01, 0.03 and 0.06 LSU ha^{-1}, along with a control simulation where no grazers were introduced, ~~are~~ applied. The grazing pressure was applied continuously throughout the 100 years of simulation in open pastures with evenly distributed boreholes. While this approach to grazing in semi-arid environment is loosely applicable to real case scenarios, it provides a baseline appreciation of the impacts of grazing at an appropriate scale to the chosen scenario scales. To highlight the impact of the stocking rate, the other parameters are kept at their median levels, including a windspeed (7.5 m s^{-1}) and the yearly rainfall (270 mm yr^{-1}) across all SDa3 simulations with sediment stress turned off. A 3-month vegetation update was used in this last series of simulations to minimize the time scale difference between the wind, the grazing, and the vegetation processes. Additionally, a vegetation health index i~~s~~ also calculated at the end of each simulation, representing the relative well-being of each type of vegetation. This index is representative of the ratio between the mean height of given vegetation and the potential maximum height of this type of vegetation, based on the parameterisation of the simulation. Therefore, a vegetation health index near 1 represents an optimal growth of the vegetation when most cells are near their maximum height.

3 Results

In parallel to the development of the new GrAM module, the scenarios outlined above function as tests to assess the capacity of the ViSTA_GrAM model to create simulations supporting the presence of grazers. The resulting tests of pre-grazing (vegetation dynamics, rainfall, windspeed) and grazing are presented in a progressive construction of the final simulations to inform the representation of a grazed semi-arid environment.

3.1 Pre-grazing simulations

The sediment balance stress and the vegetation recolonization heavily influence the vegetation composition (Fig. 2). All four simulations (FD, SDa1, SDb and ND) present their unique evolution of vegetation composition, but they also present many similarities. The vegetation composition time series identifies similarities among each type of simulation (Fig. 2), while isolating the respective impacts of sediment balance stress and dynamic vegetation recolonization in the model.

Beginning with the least dynamic simulation type, the ND simulations present virtually no variations of the vegetation proportions, staying near the initial proportions of grass, shrub, and tree of 65%, 17%, and 17%, respectively. The SDb simulations, introducing a stress function relating vegetation growth to the sediment balance, also present similar proportions of vegetation type regardless of the rainfall regime applied, but with a bigger variation in the vegetation proportions in each single simulation. The SDb simulations show a quick decrease in the grass proportion from 80% to 30% in the first 40 years, mirrored by a shrub increase from 10% to 56% over the same period. The SDa1 simulations present a more defined difference and a more gradual modification of the final vegetation proportions, across the rainfall regimes, in comparison. The SDa1 simulations present a general decrease in grass proportion coupled with a general increase in shrub proportion. The tree proportion stays below 20% for all simulations except the 1000 mm yr^{-1} of rainfall. The FD simulations all have a rapid reduction of the grass proportion from 80% to nearly 1% in the first 30 years. In response to this grass proportion decrease, the proportion of shrubs increases toward 100%. With higher annual rainfall, it is possible to observe a decrease in the rate at which the shrubs approach a proportion of 100%. Trees fill the proportion gap between grasses and shrubs, representing under 20% of the total vegetation in all simulations, except in the rainfall regime of 1000 mm yr^{-1}, with a peak proportion at the beginning of the simulation that gradually diminishes towards 30%.

The effect of rainfall on vegetation is best observed through the SDa1 simulations. The SDa1 simulations show a different temporal evolution of the vegetation proportions and a different composition of the final state of the environment with each rainfall level (Fig. 2). Without the important influence of the sediment balance stress on vegetation growth, the impact of each rainfall level on the grid is more easily distinguished. Most SDa1 simulations tend to favour the encroachment of shrubs on the grid. As the rainfall regimes increase from 150 mm yr^{-1} to 450 mm yr^{-1}, the proportion of trees on the final grid becomes more important (going from 0% to 19%), while the grass and shrub composition fluctuate around their initial values. This increase in the tree proportion continues with the highest rainfall regime of 1000 mm yr^{-1} to 97%, with only 2% and 1% coverage by shrubs and grass, respectively. Additionally, an increase in rainfall from 150 mm yr^{-1} to 450 mm yr^{-1} induces prolongation of the period of grass prevalence on the grid. The change between a grass dominated environment to a shrub dominated one occurs after 42, 48 and 82 years of simulations for the 150 mm yr^{-1}, 270 mm yr^{-1} and 450 mm yr^{-1} simulations, respectively. The 1000 mm yr^{-1} simulation is the only simulation not following this trend, with the grass proportion decreasing quickly initially and replaced by trees instead of shrubs.

The health index calculated for each of these simulations is not very sensitive to rainfall. For example, the SDa1 simulations have a grass health index of 0.8 ± 0.01, a shrub health index of 0.54 ± 0.02 and a tree health index of 0.46 ± 0.02 across all rainfall regimes. This contrast in the vegetation health trend with the large trends in observed vegetation proportion demonstrates that a higher proportion of a given vegetation type does not directly imply a healthier development. This difference also suggests that vegetation growth is not limited by rainfall.

Sediment transport is expected to scale with windspeed if no modifications are made to the surface (Martin and Kok, 2017). The SDa2 simulations effectively show a proportional increase in the mean sediment transport with each increase in windspeed level above the 5 m s^{-1} sediment transport threshold (Fig. 3). Compared to the base erosion rate of $5.48 * 10^{-4}$ g m^{-2} s^{-1} in the 5 m s^{-1} simulation, there is a large increase to 8.99×10^{-2} g m^{-2} s^{-1}, 2.43×10^{-1} g m^{-2} s^{-1} and 3.28×10^{-1} g m^{-2} s^{-1} with windspeeds of 7.5 m s^{-1}, 10 m s^{-1} and 12.5 m s^{-1}, respectively. The ratios between the volume of sediment eroded during each iteration and the maximum volume eroded registered over the entire simulation suggests a general decrease in the erosion rate over the length of the simulations. More specifically, the simulations above the erosion threshold observe average eroded volumes representing ≈40% of their maximum eroded volumes (coefficient of variation of 1.01, 0.13, 0.15, 0.18, for 5 m s^{-1}, 7.5 m s^{-1}, 10 m s^{-1} and 12.5 m s^{-1}, respectively). This decrease in transport occurring occurs along a smoothing and an organisation of the sediment surface (which was initialised with random height). While the total amount of sediment eroded is increasing with the windspeed applied on the grid, the ratio to the maximum volume of erosion is decreasing with increasing windspeed. At 7.5 m s^{-1}, the transport represents 60% to 90% of its maximum volume eroded, while at 10 m s^{-1} the ratio is 50% to 75%, and at the 12.5 m s^{-1} windspeed between 40% to 70% of its maximum volume eroded.

3.2 Grazing simulations

The stocking rate is tested with the SDa3 simulations (7.5 m s^{-1} windspeed and 270 mm yr^{-1} rainfall regime), resulting in an environment with a continuous majority of grass during the 100 years of simulation. Without grazing, the grass proportion decreases from ≈85% to ≈68% of the grid through the simulation, mirrored by a proportional increase of shrubs, while the trees disappear after the 55th year of simulation. The grass is also in good health with a final health index of ≈0.72, while the shrubs are significantly well developed with a final health index of ≈0.40. Since the grass is in good health and represents more than 68% of the vegetation on the grid, the environment of reference with no grazing shows it can sustain a good quality of forage for the entirety of the simulation. Therefore, any significant degradation of the grass that would deny the grazers the ability to sustain themselves can then be confidently attributed to the grazers themselves and not to the natural degradation of the environment. With the addition of grazing agents in the SDa3 simulation, no large effect on the vegetation proportions and the vegetation health is observed. The final grass proportion, regardless of the stocking rate applied, is around 68% and with a final shrub proportion around 32%. The health of the vegetation is invariant among each simulation, equal to ≈0.72 for the grass, ≈0.40 for the shrubs, and ≈0.22 for the trees. The final vegetation health index of trees is more variable than the other vegetation types, but they also represent less than 1% of the vegetation on the grid, so their index is appreciably more sensitive. Even if the presence of grazing agents does not translate to a significant modification of the vegetation on the simulation grid, we cannot conclude that the grazers do not affect the landscape in the simulations. One of the outputs of the ViSTA_GrAM model illustrating the impact of stocking rate on the vegetation more accurately is the total amount of forage available to grazers at each iteration (Fig. 4a). The total amount of forage on the grid represents the sum of the volume of grass on each cell multiplied by its volumetric mass. While the forage availability is similar at the seasonal scale (Fig. 4b), there is an increasingly large variation of the amount of forage available between each seasonal vegetation update with an increase in the stocking rate (Fig. 4c). The removal of grass in the short term by the grazers is therefore mitigated by a considerable regrowth of the grass with each new vegetation (seasonal) iteration, which increases with stocking rate and compensates for the action of the grazers (Fig. 4a). The mean natural (no grazing) regrowth rate of 43 mm per season in the simulation increases to 46 mm, 52 mm, and 60 mm for the simulations with 0.01 LSU ha^{-1}, 0.03 LSU ha^{-1} and 0.06 LSU ha^{-1}, respectively. And therefore, the amount of available forage over the long term is similar in all simulations with the final amount of foraging approaching 1.85 x 10^{5} kg, regardless of the stocking rate applied and despite that the mean daily foraging is kept at ≈9.5 kg day^{-1} grazer^{-1}. The grazers are therefore eating enough daily to sustain themselves on the grid without external supplementing (e.g., roaming off-grid or feed) with the grass re-growing the biomass required to conserve sufficient grazing efficiency.

The limited impact of the grazing on the vegetation is also limiting its impact on sediment transport. Temporal removal of vegetation on the grid surface between each vegetation update could be releasing patches of sediments previously trapped by vegetation. The mean saltation rate of the simulations with no grazing is 1.37 x 10^{-4} kg m^{-1} s^{-1} and increases slightly to 1.43 x 10^{-4} kg m^{-1} s^{-1} with the highest stocking rate of 0.06 LSU ha^{-1}. In contrast, both the 0.01 LSU ha^{-1} and the 0.03 LSU ha^{-1} simulations observe slight increases in mean saltation rates of 1.38 x 10^{-4} kg m^{-1} s^{-1} and 1.39 x 10^{-4} kg m^{-1} s^{-1} relative to the no grazing simulation. These differences in sediment transport between the diverse stocking rate simulations are not pronounced enough to be significant but suggest the possible effect of greater vegetation degradation on simulations.

4 Discussion

The components of arid environments (e.g., vegetation, rainfall, sediment transport, and grazing) studied in the simulations of the ViSTA_GrAM model are all fundamental factors ~~defining~~ the organization and composition of their respective environment and any modification to their associated processes should then yield different states of the environment. The outputs obtained from the ViSTA_GrAM simulations demonstrate a general agreement between published results of other studies and the model response to variations in the rainfall, windspeed and stocking rate. The impacts of each component on the final state of the model are not only interesting for its ability to inform about future scenarios but also because they provide the opportunity to compare the level of influence of each change in the environment in conjunction with one another.

4.1 Vegetation dynamics

Low proportions of grass on the FD and SDb simulation grids are observed since there is no transport of sediment in these simulations, significantly hindering the survival of grass. In comparison, the shrubs observe optimal growth with a sediment balance of 0 m. This makes it the favoured vegetation type, even over the trees which have a stress index of zero with a sediment balance of 0 m. In the absence of sediment transport, the vegetation composition of the grids is heavily influenced towards one dominated by shrubs. The original model was parametrized to represent the sediment balance stress effect on pioneer grass (e.g.: *Stipagrostis amabalis or Ammophila* grass) that optimally grows when buried by sediments (Mayaud et al., 2017c). These results are not representative of all types of semi-arid environments but are mainly characteristics of coastal dune fields (e.g.: in Canada). Most of the humid and stabilized sandy environments of Southern Africa, for example, show a greater proportion of trees as opposed to shrubs (Bond et al., 2003; Staver et al., 2011). Even at lower rainfall regimes, the quickly increasing proportion of shrubs in the FD simulations, compared to the results of the SDa1 simulations, is indicative of the model being sensitive to the sediment balance stress. While windborne sediment transport is expected to be an important factor for the vegetation organisation in environments where the moisture availability is low, it is also expected to decrease with increasing moisture availability (Ravi et al., 2010). The effect of sediment transport on the growth curve of vegetation is also difficult to generalize to a wide variety of species considering that each species growth function will have a unique response to sediment burial or erosion (Brown, 1997; Dech and Maun, 2006; Maun, 1998; Maun and Perumal, 1999; Moore, 1996; Van der Putten et al., 1993). For example, the parametrisation of a sediment balance stress for coastal dunes would then not apply to inland stabilized desert dunes. Even if it allows for the observation of an important dynamic in some specific arid environments, the sediment balance stress was not applied to vegetation in subsequent tests. The heavy reliance on the parametrization and subsequent sensitivity of the model to sediment transport would have made it difficult to obtain a balanced coexistence of the multiple vegetation types.

The dynamism of the vegetation recolonization is another important component of the model that significantly influences the simulations through environmental conditions (e.g., rainfall regimes) to significantly influence the vegetation proportions on the grid. This dynamism is normally observed in a natural environment where the water availability and established vegetation will influence the type of vegetation that is the most likely to prosper in that environment (Baudena et al., 2010; Higgins et al., 2000; Scholes et al., 2002; Scholes and Archer, 1997; Van Langevelde et al., 2003). A non-dynamic vegetation recolonization in arid environments, in comparison, represents an actively managed landscape. The ND simulations represent environments where similar proportions of each vegetation type are maintained by an external force each year regardless of the water availability or the established vegetation (e.g.: cultivated fields). While this does not prevent the vegetation ~~to die~~, it ultimately balances the vegetation proportions between the mortality rate and the recolonization rate of each vegetation type. If the effort of keeping the vegetation cover stable in these environments stops, the environment often undergoes a significant modification of its present vegetation cover (Abella et al., 2009; Carpenter et al., 1986). The importance of changes in the vegetation composition, once any external influences stop, can give an appreciation of the amount of energy necessary to keep their composition stable. Since the model does not explicitly calculate the amount of energy necessary to maintain its environment stable, the ND simulations are difficult to use as realistic prevision models for future scenarios. Nevertheless, non-dynamic simulations like the ND and SDb constitute a good example to highlight the dynamic nature of SDa1 and FD simulations.

The FD and SDa1 simulations have demonstrated their capacity to realistically representing fundamental processes within arid environments. While the FD simulations explicitly consider more interactions between its components, the hypersensitivity of the vegetation to sediment stress limits the viability of this type of simulation to evaluate the impact of other landscape dynamics. The more reasonable sensitivity to environmental changes in the SDa1 simulations makes it more realistic for observing the impact of rainfall, windspeed, or grazing regimes on the model.

4.2 Rainfall

The rainfall regime of an environment is one of the most influential components of the vegetation state of simulation when the vegetation recolonization is dynamic. Since climate classification systems are based on rainfall amounts to classify the types of environment around the globe (Lehmann et al., 2011; Middleton and Thomas, 1997), it is expected that this component of the model will have a significant impact on the evolution of the environments simulated. The reduction of rainfall in some arid environments could lead to dune remobilization to completely change the dynamic states of these environments (Bhattachan et al., 2014). In the context of climate change, the study of rainfall regime impacts on arid environment composition is of key interest.

The model ViSTA_M17 calibration tests already demonstrated that the response of the vegetation to multiple rainfall regimes with similar conditions to the SDa1 simulations corresponded to real vegetation patterns and temporal evolution (Mayaud et al., 2017a). The dominance of the shrubs over the grass in all SDa1 simulations with 450 mm yr-1 or less, does not correspond to what was initially expected, but it is also not outside of what is realistically observed in African semi-arid and savannas environments (Bond et al., 2003; Hassler et al., 2010; Lehmann et al., 2011; Ludwig et al., 2017; Sankaran et al., 2005). In reality, African semi-arid environments with less than 650 mm yr^{-1} of rainfall tend to present higher proportions of grass (Hassler et al., 2010; Ludwig et al., 2017; Sankaran et al., 2005), but will also have a lesser vegetation composition reliance on rainfall regime (Bond et al., 2003; Lehmann et al., 2011). Under low rainfall regimes (<650 mm yr^{-1}), if there is no secondary factor encouraging the growth of grass, a significant proportion of shrubs emerges alongside grasses (Burgess, 2006; Kraaij and Milton, 2006; Oñatibia and Aguiar, 2016). The simulation where grass persists the longest (rainfall regime of 450 mm yr-1), is also where rainfall has the most influence on the vegetation proportions and therefore encouraging a grass-dominated vegetal cover. Tree populations thrive at rainfall amounts of over 650 mm yr-1 and in the absence of recurring fires, this influence of the rainfall is expected to ultimately lead to a closed woodland (Bond et al., 2003; Burgess, 2006; Lehmann et al., 2011; Sankaran et al., 2005; Scanlon et al., 2007; Staver et al., 2011). The resulting landscape observed with the SDa1 simulation at 1000 mm yr-1 is a prime example of this situation (Fig. 2). The ViSTA_GrAM model demonstrates the major impact a rainfall regime can have on the vegetation composition of an environment but also highlights the need to consider other factors to represent the entirety of the possible arid environment vegetation diversity.

The relatively high and constant health index of the grasses observed in the SDa1 simulations regardless of the rainfall regime and grass proportion is another indicator of the complexity involved in the growth of vegetation in arid environments. Even if the final proportion of grass is often lower than the proportion of shrubs and trees, the grasses have a more rapid growth than the two other types of vegetation. This optimization also explains why an increased grass proportion is observed in simulations with a vegetation update every 3 months compared to update every 6 months. This change in vegetation composition represents the importance of the seasonality of disturbances in environments with limited moisture availability (Lehmann et al., 2011; Staver et al., 2011). The resulting landscape of the SDa3 simulations with an update in vegetation every seasonal change (3 months) is very similar to what is observed in the ranging land of Namibia (Hassler et al., 2010; Ludwig et al., 2017) and why the SDa3 simulation (with the 3 months vegetation update) is used in the simulations testing stocking rate effects in the ViSTA_GrAM model.

4.3 Sediment transport

The effect of climate change on windspeed is regionally variable and uncertain, with some regions demonstrating increases in the magnitude and frequency of the wind resulting in an overall increase in the mean wind regime (McInnes et al., 2011). Therefore, ~~arid and semi-arid environments can greatly benefit from~~ regional studies of the response of wind-driven environments to wind climatology changes, since sediment transport by wind is a principal challenge under future climate scenarios. For example, an increase in wind speed would increase the erosion rate even if there is no modification of the other surface variables. Furthermore, with an increase in windspeed coupled to the remobilization of sediment due to a decrease in vegetation, the resulting transport would exponentially increase (Bhattachan et al., 2014). The SDa2 simulations present similar surfaces to interact with varying windspeeds, resulting in a linear increase in saltation rate with windspeed (Fig. 5), corresponding to the findings of Martin and Kok (2017). To allow a better comparison of the results between the two studies, the windspeeds of 5.0 m s-1, 7.5 m s-1, 10 m s-1 and 12.5 m s-1 were transformed to an equivalent shear stress of 0.09 N m-2, 0.14 N m-2, 0.18N m-2 and 0.23 N m-2, respectively. From Fig. 5, it is possible to identify significant similarities between the results of the SDa2 simulations in the ViSTA_GrAM and the Martin and Kok (2017) Jericoacoara and Rancho Guadalupe sites (their Fig. 2). The increase in sediment transport, between each shear stress level, is nearly identical between the model and the field studies, despite the different values of sediment transport since the landscapes of the SDa2 simulations are highly vegetated and the sites of Jericoacoara and Rancho Guadalupe sites are bare. The rate of eroded sediment emissions in the ViSTA_GrAM model is difficult to compare to empirical data directly because the model is presently not able to return a horizontal saltation flux. The sediment interactions are not less realistic in the model because of this, but the addition of the saltation flux as a module-level output would certainly help the model to study future landscape management scenarios.

4.4 Grazing

Grazing is a type of disturbance that can harm the vegetation leading to a degradation of the vegetation cover over time under unsuitable grazing strategies. The SDa3 simulations, testing the impact of the grazers with the model ViSTA_GrAM (Table 2), show little influence of grazing on vegetation final states. Even if these results are not very different from those obtained by the original model ViSTA_M17 (Mayaud et al., 2017a), the ViSTA_GrAM model simulations present additional insights on the interaction between grazers and vegetation in Southern African semi-arid environments. While the vegetation is not altered by the grazing enough to produce a change in its spatial organisation or coverage, the impact of the grazing is noticeable when looking at the evolution of the total biomass of grasses between the update of vegetation and the response in the mean growth of the grasses. The combination of a decrease of the available grass biomass and an increase of the mean growth of the grass under an increasing stocking rate applied in the simulations suggest that the environment can compensate for the action of the grazer. The grasses observe an increasing growth rate under grazing, allowing for the environment to recuperate the foraged biomass. This compensation mechanism is already recognized in multiple previous studies (Hickman and Hartnett, 2002; Leriche et al., 2001; McNaughton, 1983) as able to highly limit the degradation of vegetation under low to moderate stocking regime. Under an intensive stocking regime, the regrowth rate of the vegetation does not equate to the grazing degradation and results in a change in the vegetation spatial reorganization and a decrease of the grass proportion (Aubault et al., 2015; Hickman and Hartnett, 2002; Jeltsch et al., 1997a). The maximum stocking rate an environment can sustainably carry is highly variable based on the vegetation species, the nutrient availability, and the water availability (Hickman and Hartnett, 2002; McNaughton, 1983; Rietkerk et al., 1997, 2002). Therefore, the environmental conditions of a landscape influence the impact of the grazers and concurrently influence the vegetation repartition, making their impacts in shaping landscapes less apparent than other variables (e.g., rainfall) because the impact is muted by other environmental dynamics. Multiple studies in arid and semi-arid grasslands, with environmental conditions similar to the ones represented in the SDa3 simulations, show the same increase of the vegetation biomass production in response to the presence of grazers (Aubault et al., 2015; Ludwig et al., 2017; Yu et al., 2019). The lack of sensitivity to varying stocking rates in the results presented in this study are therefore attributed to the sensitivity of the environment to grazing and not to the sensitivity of the model itself.

The results from this study demonstrate that the changes in the amount of sediment eroded are influenced more by the vegetation organisation than the stocking rates applied. Knowing no significant changes in the transport rate will be observed without significant changes in the long-term vegetation cover, the small intermittent increases in sediment erosion in the SDa3 simulations can be associated with the degradation in vegetation cover by foraging even though it is not reflected in the mean amount of sediment eroded. The increase in stocking rate suggests there is a potential of increased sediment transport, but it is not translated in long-term increased transport because of the lack of change in the vegetation cover. Again, while the present simulation configuration does not result in a significant difference in sediment transport amounts, it demonstrates the capability to exhibit a variation of the transport under different environmental conditions.

The ViSTA_GrAM model demonstrates its capacity to represent the multiple processes defining arid environments and that a deeper representation of the dynamics of grazing is possible with the help of an agent-based model. The lack of differentiation possible between the simulations with different stocking rates highlights the need for a good definition of the influence of each process on the resulting landscape returned by the model. While the presentation order of each process in this paper informs of the general hierarchy between the processes, the sensitivity tests presented are not complete enough to compare the effect of each of these processes on a normalized scale. Further work on a normalized sensitivity classification of each process would allow for a quantifiable comparison of their importance and help guide impact studies of environmental change in arid environments.

5 Conclusion

This study proposes and implements a model to represent realistic dynamics in a semi-arid environment. This ViSTA_GrAM model extends the modelling capacities of the ViSTA_M17 model by representing the grazing interaction via an ABM module. The rescaling of the simulations grid to 200 by 200 cells of 5 m resolution allowed for the representation of a larger landscape without diminishing the pertinence of the interactions between the model components. Series of simulations, representing hypothetical semi-arid environments, were compared to published results in peer-reviewed literature and have demonstrated the capacity of the ViSTA_GrAM model to effectively represent the interaction between the vegetation, the rainfall regime, the sediment transport and the grazing in a theoric context. The integration of the GrAM module within the ViSTA_GrAM model showed the results of the vegetation interactions with grazers at a finer scale than the original ViSTA_M17 model, highlighting the complex nature of those interactions and reaffirming the need of integrative approach to study these processes. The model in its current state still has some limitations, notably concerning ~~his~~ representation of ~~the resulting~~ sediment transport and the sensitivity of the model vegetation growth to this transport. To address these limitations and offer a better evaluation of the model application to real semi-arid environments, future work should include the horizontal saltation flux as an output, introduce several grass species growth response curves, and calibrate the model against more empirical data. With further development of the model and with an application of the model made in direct comparison to empirical data, we think it can offer an invaluable tool to help extend our understanding of arid environments and help improve landscape management in such environments.

Appendices

Appendix A: Sensibility testing supporting modifications made to the model ViSTA_M17

This appendix describes some inconsistencies between the ViSTA_M17 representation of sediment transport and the ViSTA_GrAM aims that led to the modification of some processes within the former model. Two aspects of the sediment transport processes posing a problem with the implementation of the new GrAM module were the time scale at which recognizable dunes were formed and the impact of wind angles on the resulting landforms. The identification of these processes, during the development of the ViSTA_GrAM model, led to the modification of the ViSTA_M17 to address these issues, but due to some limitations in the resources available, could not be entirely addressed and resolved. Future users of the model should be aware of these limitations (detailed below) and use the model accordingly.

The time scale at which recognizable dunes were formed in ViSTA_M17 simulations was found to be abnormally quick for vegetated environments following a review of the original documentation (Mayaud et al., 2017a) and subsequent testing of the ViSTA_M17 model. Even with vegetation coverage on 90% of the grid and low windspeeds of 5.625 m s^{-1} (considering a threshold of 5.0 m s^{-1}), the model was observing increases in sediment heights of 1.5 m in 5 years (Fig. A1). With windspeed of 10 m s^{-1} and more, dune ridges of ≈10 m in height were formed in 5 years, while similar landforms are normally formed over 100 years to 1000 years in a natural environment (Hugenholtz et al., 2012; Lima et al., 2002; Yan and Baas, 2018). This level of mobility of the sediments, despite the generalized vegetation coverage, highlighted a clear underestimation of the vegetation influence on sediment mobilisation. Therefore, an updated module, limiting the erosion of sediment under vegetation cover, was introduced in the ViSTA_GrAM model. By inhibiting erosion on cells with vegetation high enough to favour deposition, the accumulation of sediment was limited (e.g., to a maximum of 1 m in 5 years at a high windspeed of 12.5 m s^{-1}). The resulting landforms of these simulations with the new module that inhibited erosion became more aligned with those observed in a semi-arid environment to other model results and where grazing occurs (Lima et al., 2002; Yan and Baas, 2018).

The wind angle is another parameter of the model having an unexpected impact on the resulting landscape development in the ViSTA_M17 model. While it is known that certain landforms can only be reproduced in models by multidirectional winds (e.g., star dunes (Courrech du Pont, 2015)), the wind direction should have little influence on the sediment transport rate with all other things equal. However, the wind direction was observed in the ViSTA_GrAM model to influence the sediment transport rate, where winds from east or west (0°-60°/180°-240° in the model) produced less sediment transport than winds from north or south (90°-150°/270°-330°) as indicated in the elevation models shown in Fig. A2. Both of these wind orientations return widely different distribution of sediment after only a 5-year simulation (Fig. A2). East-west winds produce isolated dunes of 5 m in width and have an accumulation of sediments along the borders where the wind enters the grid, while north-south winds produce evenly distributed ridges across the grid. Since all simulations all had the same windspeed and starting surface characteristics (7.5 m s^{-1} windspeed and a 5 m s^{-1} threshold with an initially random sediment height), it is surprising to observe the difference in sediment transport and sediment distribution. A solution to this resulting problem in the model has yet to be found, but we speculate that the problem comes from the wind partitioning and subsequent calculation of the sediment deposition pathway. To permit a comparison of the tested simulations in this study, the wind angle was kept constant at 120° to limit the border effects on the sediment distribution.

Code and Data availability

The GrAM module code and the modifications to the original ViSTA_M17 model code (https://github.com/jeromemayaud/ViSTA) were written by Phillipe Gauvin-Bourdon in the Python® programming language (Python 3.7.7 64bits) with the permission of Jerome Mayaud. A full version of the ViSTA_GrAM model code is freely available on Github (https://github.com/Phillgb/ViSTA_GrAM) along with the simulations files used in the present manuscript.

Author contribution

PGB conceived and developed the GrAM module and integrated it in the ViSTA model, carried out the simulations and analyses of the model and wrote the manuscript with the support of JK and LP. JK helped design the study and helped write the manuscript. LP helped design the study. All authors discussed the results and contributed to the final manuscript.

Competing interests

The authors declare that they have no conflicts of interest.

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References

Abella, S. R., Engel, E. C., Lund, C. L. and Spencer, J. E.: Early Post-Fire Plant Establishment on a Mojave Desert Burn, Madroño, 56(3), 137–148, doi:10.3120/0024-9637-56.3.137, 2009.

Ares, J., Bertiller, M. and Bisigato, A.: Modeling and Measurement of Structural Changes at a Landscape Scale in Dryland Areas, Environ. Model. Assess., 13, 2003.

Aubault, H., Webb, N. P., Strong, C. L., McTainsh, G. H., Leys, J. F. and Scanlan, J. C.: Grazing impacts on the susceptibility of rangelands to wind erosion: The effects of stocking rate, stocking strategy and land condition, Aeolian Res., 17, 89–99, doi:10.1016/j.aeolia.2014.12.005, 2015.

Baas, A. C. W. and Nield, J. M.: Modelling vegetated dune landscapes, Geophys. Res. Lett., 34(6), 1–5, doi:10.1029/2006GL029152, 2007.

Bagnold, R. A.: The physics of blown sand and desert dunes, Dover Publications inc., Mineola., 1941.

Bailey, R. M.: Spatial and temporal signatures of fragility and threshold proximity in modelled semi-arid vegetation, Proc. R. Soc. B Biol. Sci., 278(1708), 1064–1071, doi:10.1098/rspb.2010.1750, 2011.

Baudena, M., D'Andrea, F. and Provenzale, A.: An idealized model for tree–grass coexistence in savannas: the role of life stage structure and fire disturbances: A model for tree–grass coexistence, J. Ecol., 98(1), 74–80, doi:10.1111/j.1365-2745.2009.01588.x, 2010.

Bestelmeyer, B. T., Okin, G. S., Duniway, M. C., Archer, S. R., Sayre, N. F., Williamson, J. C. and Herrick, J. E.: Desertification, land use, and the transformation of global drylands, Front. Ecol. Environ., 13(1), 28–36, doi:10.1890/140162, 2015.

Bestelmeyer, B. T., Peters, D. P. C., Archer, S. R., Browning, D. M., Okin, G. S., Schooley, R. L. and Webb, N. P.: The Grassland–Shrubland Regime Shift in the Southwestern United States: Misconceptions and Their Implications for Management, BioScience, 68(9), 678–690, doi:10.1093/biosci/biy065, 2018.

Bhattachan, A., D'odorico, P., Dintwe, K., Okin, G. S. and Collins, S. L.: Resilience and recovery potential of duneland vegetation in the southern Kalahari, Ecosphere, 5(1), 1–14, doi:10.1890/ES13-00268.1, 2014.

Bo, T. L., Fu, L. T. and Zheng, X. J.: Modeling the impact of overgrazing on evolution process of grassland desertification, Aeolian Res., 9, 183–189, doi:10.1016/j.aeolia.2013.01.001, 2013.

Bond, W. J., Midgley, G. F. and Woodward, F. I.: What controls South African vegetation — climate or fire?, South Afr. J. Bot., 69(1), 79–91, doi:10.1016/S0254-6299(15)30362-8, 2003.

Brown, J. F.: Effects of Experimental Burial on Survival, Growth, and Resource Allocation of Three Species of Dune Plants, J. Ecol., 85(2), 151, doi:10.2307/2960647, 1997.

Burgess, J.: Country pasture / forage resource profiles: Botswana, Food and Agriculture Organization of the United Nations (FAO)., 2006.

Burri, K., Gromke, C., Lehning, M. and Graf, F.: Aeolian sediment transport over vegetation canopies: A wind tunnel study with live plants, Aeolian Res., 3(2), 205–213, doi:10.1016/j.aeolia.2011.01.003, 2011.

Carpenter, D. E., Barbour, M. G. and Bahre, C. J.: Old Field Succession in Mojave Dessert Scrub, Madroño, 33(2), 13, 1986.

Chacon, E., Stobbs, T. H. and Sandland, R. L.: Estimation of herbage consumption by grazing cattle using measurements of eating behaviour, Grass Forage Sci., 31(2), 81–87, doi:10.1111/j.1365-2494.1976.tb01122.x, 1976.

Chappell, A., Lee, J. A., Baddock, M., Gill, T. E., Herrick, J. E., Leys, J. F., Marticorena, B., Petherick, L., Schepanski, K., Tatarko, J., Telfer, M. and Webb, N. P.: A clarion call for aeolian research to engage with global land degradation and climate change, Aeolian Res., 32, A1–A3, doi:10.1016/j.aeolia.2018.02.007, 2018.

Courrech du Pont, S.: Dune morphodynamics, Comptes Rendus Phys., 16(1), 118–138, doi:10.1016/j.crhy.2015.02.002, 2015.

Dech, J. P. and Maun, M. A.: Adventitious Root Production and Plastic Resource Allocation to Biomass Determine Burial Tolerance in Woody Plants from Central Canadian Coastal Dunes, Ann. Bot., 98(5), 1095–1105, doi:10.1093/aob/mcl196, 2006.

D'Odorico, P., Bhattachan, A., Davis, K. F., Ravi, S. and Runyan, C. W.: Global desertification: Drivers and feedbacks, Adv. Water Resour., 51, 326–344, doi:10.1016/j.advwatres.2012.01.013, 2013.

Dougill, A. J. and Thomas, A. D.: Kalahari sand soils: spatial heterogeneity, biological soil crusts and land degradation, Land Degrad. Dev., 15(3), 233–242, doi:10.1002/ldr.611, 2004.

Dupont, S., Bergametti, G. and Simoëns, S.: Modeling aeolian erosion in presence of vegetation, J. Geophys. Res. Earth Surf., 119(2), 168–187, doi:10.1002/2013JF002875, 2014.

Hassler, S. K., Kreyling, J., Beierkuhnlein, C., Eisold, J., Samimi, C., Wagenseil, H. and Jentsch, A.: Vegetation pattern divergence between dry and wet season in a semiarid savanna – Spatio-temporal dynamics of plant diversity in northwest Namibia, J. Arid Environ., 74(11), 1516–1524, doi:10.1016/j.jaridenv.2010.05.021, 2010.

Hesp, P. A., Dong, Y., Cheng, H. and Booth, J. L.: Wind flow and sedimentation in artificial vegetation: Field and wind tunnel experiments, Geomorphology, 337, 165–182, doi:10.1016/j.geomorph.2019.03.020, 2019.

Hickman, K. R. and Hartnett, D. C.: Effects of grazing intensity on growth, reproduction, and abundance of three palatable forbs in Kansas tallgrass prairie, Plant Ecol., 159, 11, 2002.

Higgins, S. I., Bond, W. J. and Trollope, W. S. W.: Fire, resprouting and variability: a recipe for grass-tree coexistence in savanna, J. Ecol., 88(2), 213–229, doi:10.1046/j.1365-2745.2000.00435.x, 2000.

Hodgson, J.: The control of herbage intake in the grazing ruminant, Proc. Nutr. Soc., 44(2), 339–346, doi:10.1079/PNS19850054, 1985.

Hodgson, J., Forbes, T. D. A., Armstrong, R. H., Beatie, M. M. and Hunter, E. A.: Comparative Studies of the Ingestive Behaviour and Herbage Intake of Sheep and Cattle Grazing Indigenous Hill Plant Communities, Br. Ecol. Soc., 28(1), 205–227, doi:10.2307/2404126, 1991.

Hsu, S.-A.: Wind stress criteria in eolian sand transport, J. Geophys. Res., 76(36), 8684–8686, doi:10.1029/JC076i036p08684, 1971.

Hugenholtz, C. H., Levin, N., Barchyn, T. E. and Baddock, M. C.: Remote sensing and spatial analysis of aeolian sand dunes: A review and outlook, Earth-Sci. Rev., 111(3–4), 319–334, doi:10.1016/j.earscirev.2011.11.006, 2012.

Jeltsch, F., Milton, S. J., Dean, W. R. J. and van Rooyen, N.: Tree Spacing and Coexistence in Semiarid Savannas, J. Ecol., 84(4), 583, doi:10.2307/2261480, 1996.

Jeltsch, F., Milton, S. J., Dean, W. R. J. and van Rooyen, N.: Analysing Shrub Encroachment in the Southern Kalahari: A Grid-Based Modelling Approach, J. Appl. Ecol., 34(6), 1497–1508, doi:10.2307/2405265, 1997a.

Jeltsch, F., Milton, S. J., Dean, W. R. J. and van Rooyen, N.: Simulated pattern formation around artificial waterholes in the semi-arid Kalahari, J. Veg. Sci., 8(2), 177–188, doi:10.2307/3237346, 1997b.

Kaufmann, J., Bork, E. W., Blenis, P. V. and Alexander, M. J.: Cattle habitat selection and associated habitat characteristics under free-range grazing within heterogeneous Montane rangelands of Alberta, Appl. Anim. Behav. Sci., 146(1–4), 1–10, doi:10.1016/j.applanim.2013.03.014, 2013.

Kawamura, R.: Study on Sand Movement by Wind, Rep. Phys. Sci. Res. Inst. Tokyo Univ., 5(3–4), 95–112, 1951.

King, J., Nickling, W. G. and Gillies, J. A.: Representation of vegetation and other nonerodible elements in aeolian shear stress partitioning models for predicting transport threshold, J. Geophys. Res. Earth Surf., 110(4), 1–15, doi:10.1029/2004JF000281, 2005.

King, J., Nickling, W. G. and Gillies, J. A.: Aeolian shear stress ratio measurements within mesquite-dominated landscapes of the Chihuahuan Desert, New Mexico, USA, Geomorphology, 82(3–4), 229–244, doi:10.1016/j.geomorph.2006.05.004, 2006.

Lancaster, N. and Baas, A.: Influence of vegetation cover on sand transport by wind: field studies at Owens Lake, California, EARTH Surf. Process. Landf., 23, 14, 1998.

Lehmann, C. E. R., Archibald, S. A., Hoffmann, W. A. and Bond, W. J.: Deciphering the distribution of the savanna biome, New Phytol., 191(1), 197–209, doi:10.1111/j.1469-8137.2011.03689.x, 2011.

Leriche, H., LeRoux, X., Gignoux, J., Tuzet, A., Fritz, H., Abbadie, L. and Loreau, M.: Which functional processes control the short-term effect of grazing on net primary production in grasslands?, Oecologia, 129(1), 114–124, doi:10.1007/s004420100697, 2001.

Lettau, K. and Lettau, H. H.: Experimental and Micrometeorological field studies of dune migration, in Exploring the world's driest climate, pp. 110–147, Madison., 1978.

Lima, A. R., Sauermann, G., Herrmann, H. J. and Kroy, K.: Modelling a dune field, Phys. Stat. Mech. Its Appl., 310(3–4), 487–500, doi:10.1016/S0378-4371(02)00546-0, 2002.

Liu, B. and Coulthard, T. J.: Modelling the interaction of aeolian and fluvial processes with a combined cellular model of sand dunes and river systems, Comput. Geosci., 106, 1–9, doi:10.1016/j.cageo.2017.05.003, 2017.

Ludwig, L., Isele, J., Rahmann, G., Idel, A. and Hülsebush, C.: Rangeland forage biomass production and composition under different grazing regimes on a Namibian oraganic livestock farm, in Innovative Research for Organic 3.0, vol. 2, pp. 558–563, Thünen Report 54, New Delhi, India., 2017.

Marion, G., Swain, D. L. and Hutchings, M. R.: Understanding foraging behaviour in spatially heterogeneous environments, J. Theor. Biol., 232(1), 127–142, doi:10.1016/j.jtbi.2004.08.005, 2005.

Marion, G., Smith, L. A., Swain, D. L., Davidson, R. S. and Hutchings, M. R.: Agent-based modelling of foraging behaviour: the impact of spatial heterogeneity on disease risks from faeces in grazing systems, J. Agric. Sci., 146(5), 507–520, doi:10.1017/S0021859608008022, 2008.

Martin, R. L. and Kok, J. F.: Wind-invariant saltation heights imply linear scaling of aeolian saltation flux with shear stress, Sci. Adv., 3(6), e1602569, doi:10.1126/sciadv.1602569, 2017.

Maun, M. A.: Adaptations of plants to burial in coastal sand dunes, Can. J. Bot., 76, 29, 1998.

Maun, M. A. and Perumal, J.: Zonation of vegetation on lacustrine coastal dunes: effects of burial by sand, Ecol. Lett., 2(1), 14–18, doi:10.1046/j.1461-0248.1999.21048.x, 1999.

Mayaud, J. R. and Webb, N.: Vegetation in Drylands: Effects on Wind Flow and Aeolian Sediment Transport, Land, 6(3), 64, doi:10.3390/land6030064, 2017.

Mayaud, J. R., Bailey, R. M. and Wiggs, G. F. S.: A coupled vegetation/sediment transport model for dryland environments, J. Geophys. Res. Earth Surf., 122(4), 875–900, doi:10.1002/2016JF004096, 2017a.

Mayaud, J. R., Bailey, R. M. and Wiggs, G. F. S.: Modelled responses of the Kalahari Desert to 21st century climate and land use change, Sci. Rep., 7(1), 3887, doi:10.1038/s41598-017-04341-0, 2017b.

Mayaud, J. R., Bailey, R. M. and Wiggs, G. F. S.: Supporting information for : A new coupled vegetation / sediment-transport model for dryland environments, J. Geophys. Res. Earth Surf., 51, 2017c.

McInnes, K. L., Erwin, T. A. and Bathols, J. M.: Global Climate Model projected changes in 10 m wind speed and direction due to anthropogenic climate change, Atmospheric Sci. Lett., 12(4), 325–333, doi:10.1002/asl.341, 2011.

McNaughton, S. J.: Compensatory Plant Growth as a Response to Herbivory, Oikos, 40(3), 329, doi:10.2307/3544305, 1983.

Meyer, T., D'Odorico, P., Okin, G. S., Shugart, H. H., Caylor, K. K., O'Donnell, F. C., Bhattachan, A. and Dintwe, K.: An analysis of structure: biomass structure relationships for characteristic species of the western Kalahari, Botswana, Afr. J. Ecol., 52(1), 20–29, doi:10.1111/aje.12086, 2014.

Moore, P. D.: Mystery of moribund marram, Nature, 380(6572), 285–286, doi:10.1038/380285a0, 1996.

Nicholson, S. E.: Climatic variations in the Sahel and other African regions during the past five centuries, J. Arid Environ., 1(1), 3–24, doi:10.1016/S0140-1963(18)31750-6, 1978.

Nicholson, S. E.: Land surface processes and Sahel climate, Rev. Geophys., 38(1), 117–139, doi:10.1029/1999RG900014, 2000.

Nield, J. M. and Baas, A. C. W.: Investigating parabolic and nebkha dune formation using a cellular automaton modelling approach, Earth Surf. Process. Landf., 33(5), 724–740, doi:10.1002/esp.1571, 2008.

Okin, G. S.: A new model of wind erosion in the presence of vegetation, J. Geophys. Res. Earth Surf., 113(2), 1–11, doi:10.1029/2007JF000758, 2008.

Okin, G. S. and Gillette, D. A.: Distribution of vegetation in wind-dominated landscapes: Implications for wind erosion modeling and landscape processes, J. Geophys. Res. Atmospheres, 106(D9), 9673–9683, doi:10.1029/2001JD900052, 2001.

Okin, G. S., Gillette, D. A. and Herrick, J. E.: Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments, J. Arid Environ., 65(2), 253–275, doi:10.1016/j.jaridenv.2005.06.029, 2006.

Orr, R. J., Rutter, S. M., Penning, P. D. and Rook, A. J.: Matching grass supply to grazing patterns for dairy cows, Grass Forage Sci., 56(4), 352–361, doi:10.1046/j.1365-2494.2001.00284.x, 2001.

Owen, P. R.: Saltation of uniform grains in air, J. Fluid Mech., 20(2), 225–242, doi:10.1017/S0022112064001173, 1964.

Peters, D. P. C., Bestelmeyer, B. T., Herrick, J. E., Fredrickson, Ed. L., Monger, H. C. and Havstad, K. M.: Disentangling Complex Landscapes: New Insights into Arid and Semiarid System Dynamics, BioScience, 56(6), 491, doi:10.1641/0006-3568(2006)56[491:DCLNII]2.0.CO;2, 2006.

Raupach, M. R., Gillette, D. A. and Leys, J. F.: The effect of roughness elements on wind erosion threshold, J. Geophys. Res., 98(92), 3023, doi:10.1029/92JD01922, 1993.

Ravi, S., Breshears, D. D., Huxman, T. E. and D'Odorico, P.: Land degradation in drylands: Interactions among hydrologic–aeolian erosion and vegetation dynamics, Geomorphology, 116(3–4), 236–245, doi:10.1016/j.geomorph.2009.11.023, 2010.

Ravi, S., D'Odorico, P., Breshears, D. D., Field, J. P., Goudie, A. S., Huxman, T. E., Li, J., Okin, G. S., Swap, R. J., Thomas, A. D., Van Pelt, S., Whicker, J. J. and Zobeck, T. M.: Aeolian processes and the biosphere, Rev. Geophys., 49(3), RG3001, doi:10.1029/2010RG000328, 2011.

Rietkerk, M., van den Bosch, F. and van de Koppel, J.: Site-Specific Properties and Irreversible Vegetation Changes in Semi-Arid Grazing Systems, Oikos, 80(2), 241, doi:10.2307/3546592, 1997.

Rietkerk, M., Boerlijst, M. C., van Langevelde, F., HilleRisLambers, R., van de Koppel, J., Kumar, L., Prins, H. H. T. and de Roos, A. M.: Self-Organization of Vegetation in Arid Ecosystems., Am. Nat., 160(4), 7, 2002.

Sankaran, M., Hanan, N. P., Scholes, R. J., Ratnam, J., Augustine, D. J., Cade, B. S., Gignoux, J., Higgins, S. I., Le Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K. K., Coughenour, M. B., Diouf, A., Ekaya, W., Feral, C. J., February, E. C., Frost, P. G. H., Hiernaux, P., Hrabar, H., Metzger, K. L., Prins, H. H. T., Ringrose, S., Sea, W., Tews, J., Worden, J. and Zambatis, N.: Determinants of woody cover in African savannas, Nature, 438(7069), 846–849, doi:10.1038/nature04070, 2005.

Scholes, R. J. and Archer, S. R.: Tree-Grass Interactions in Savannas, , 30, 1997.

Scholes, R. J., Dowty, P. R., Caylor, K., Parsons, D. a. B., Frost, P. G. H. and Shugart, H. H.: Trends in savanna structure and composition along an aridity gradient in the Kalahari, J. Veg. Sci., 13(3), 419–428, doi:10.1111/j.1654-1103.2002.tb02066.x, 2002.

Sharpe, P. and Kenny, L. B.: Grazing Behavior, Feed Intake, and Feed Choices, Horse Pasture Manag., 121–139, doi:10.1016/B978-0-12-812919-7.00008-1, 2019.

Staver, A. C., Archibald, S. and Levin, S. A.: The Global Extent and Determinants of Savanna and Forest as Alternative Biome States, Science, 334(6053), 230–232, doi:10.1126/science.1210465, 2011.

Thomas, D. S. G. and Twyman, C.: Good or bad rangeland? Hybrid knowledge, science, and local understandings of vegetation dynamics in the Kalahari, Land Degrad. Dev., 15(3), 215–231, doi:10.1002/ldr.610, 2004.

Thomas, D. S. G., Knight, M. and Wiggs, G. F. S.: Remobilization of southern African desert dune systems by twenty-first century global warming, Nature, 435(7046), 1218–1221, doi:10.1038/nature03717, 2005.

Van der Putten, W. H., Van Dijk, C. and Peters, B. A. M.: Plant-specific soil-borne diseases contribute to succession in foredune vegetation, Nature, 362(6415), 53–56, doi:10.1038/362053a0, 1993.

Van Langevelde, F., Van De Vijver, C. A. D. M., Kumar, L., Van De Koppel, J., De Ridder, N., Van Andel, J., Skidmore, A. K., Hearne, J. W., Stroosnijder, L., Bond, W. J., Prins, H. H. T. and Rietkerk, M.: Effects of Fire and Herbivory on the Stability of Savanna Ecosystems, Ecology, 84(2), 337–350, doi:10.1890/0012-9658(2003)084[0337:EOFAHO]2.0.CO;2, 2003.

Wang, L., Katjiua, M., D'Odorico, P. and Okin, G. S.: The interactive nutrient and water effects on vegetation biomass at two African savannah sites with different mean annual precipitation, Afr. J. Ecol., 50(4), 446–454, doi:10.1111/j.1365-2028.2012.01339.x, 2012.

Webb, N. P. and Pierre, C.: Quantifying Anthropogenic Dust Emissions, Earths Future, 6(2), 286–295, doi:10.1002/2017EF000766, 2018.

Weber, G. E. and Jeltsch, F.: Spatial aspects of grazing in savanna rangelands: a modelling study of vegetation dynamics, Ecosyst. Sustain. Dev., 16, 427–436, 1997.

Weber, G. E., Jeltsch, F., van Rooyen, N. and Milton, S. J.: Simulated long-term vegetation response to grazing heterogeneity in semi-arid rangelands, J. Appl. Ecol., 35, 687–699, 1998.

Werner, B. T.: Eolian dunes: computer simulations and attractor interpretations, Geology, 23(12), 1107–1110, doi:10.1130/0091-7613(1995)023<1107:edcsaa>2.3.co;2, 1995.

Wolfe, S. A. and Nickling, W. G.: The protective role of sparse vegetation in wind erosion, Prog. Phys. Geogr. Earth Environ., 17(1), 50–68, doi:10.1177/030913339301700104, 1993.

Yan, N. and Baas, A. C. W.: Environmental controls, morphodynamic processes, and ecogeomorphic interactions of barchan to parabolic dune transformations, Geomorphology, 278, 209–237, doi:10.1016/j.geomorph.2016.10.033, 2017.

Yan, N. and Baas, A. C. W.: Transformation of parabolic dunes into mobile barchans triggered by environmental change and anthropogenic disturbance: Transformation of parabolic dunes into mobile barchans, Earth Surf. Process. Landf., 43(5), 1001–1018, doi:10.1002/esp.4299, 2018.

Yu, R., Evans, A. J. and Malleson, N.: An agent-based model for assessing grazing strategies and institutional arrangements in Zeku, China, Agric. Syst., 171, 135–142, doi:10.1016/j.agsy.2019.02.004, 2019.

Yuhas, R. H. and Goetz, A. F. H.: Monitoring and modeling semi-arid landscape response to climate change, in Proceedings of IGARSS '94 - 1994 IEEE International Geoscience and Remote Sensing Symposium, vol. 2, pp. 1036–1038, IEEE, Pasadena, CA, USA., 1994.

Ziegler, N. P., Webb, N. P., Chappell, A. and LeGrand, S. L.: Scale Invariance of Albedo-Based Wind Friction Velocity, J. Geophys. Res. Atmospheres, 125(16), doi:10.1029/2019JD031978, 2020.

Zingg, A. W.: Wind tunnel studies of the movement of sedimentary material, in Proceedings of the 5th Hydraulic Conference, vol. 34, pp. 111–135, State university of Iowa, Iowa city. [online] Available from: http://ir.uiowa.edu/uisie/34, 1953.

Simulations	Vegetation dynamics
Fully Dynamic **(FD)**	Sediment balance stress **on** Recolonization dynamic **on**
Semi-Dynamic A **(SDa)**	Sediment balance stress **off** Recolonization dynamic **on**
Semi-Dynamic B **(SDb)**	Sediment balance stress **on** Recolonization dynamic **off**
Nondynamic **(ND)**	Sediment balance stress **off** Recolonization dynamic **off**

Table 1: Description of the parametrization of simulations testing the impact of vegetation dynamics and rainfall influence on resulting arid environments.

Simulation	Rainfall (mm yr^{-1}) *			
FD	150	270	450	1000
SDa1	150	270	450	1000
SDb	150	270	450	1000
ND	150	270	450	1000
	Windspeed (m s^{-1}) **			
SDa2	5	7.5	10	12.5
	Stocking rate (LSU ha^{-1}) ***			
SDa3	0.00	0.01	0.03	0.06

*All simulations executed with windspeeds of 0.0 m s^{-1}.

**All simulations were executed with 270 mm yr^{-1} of rainfall.

***All simulations executed with windspeeds of 7.5 m s^{-1} and rainfall of 270 mm yr^{-1}

Table 2: Summary of the parametrization of simulations made with ViSTA_GrAM model.

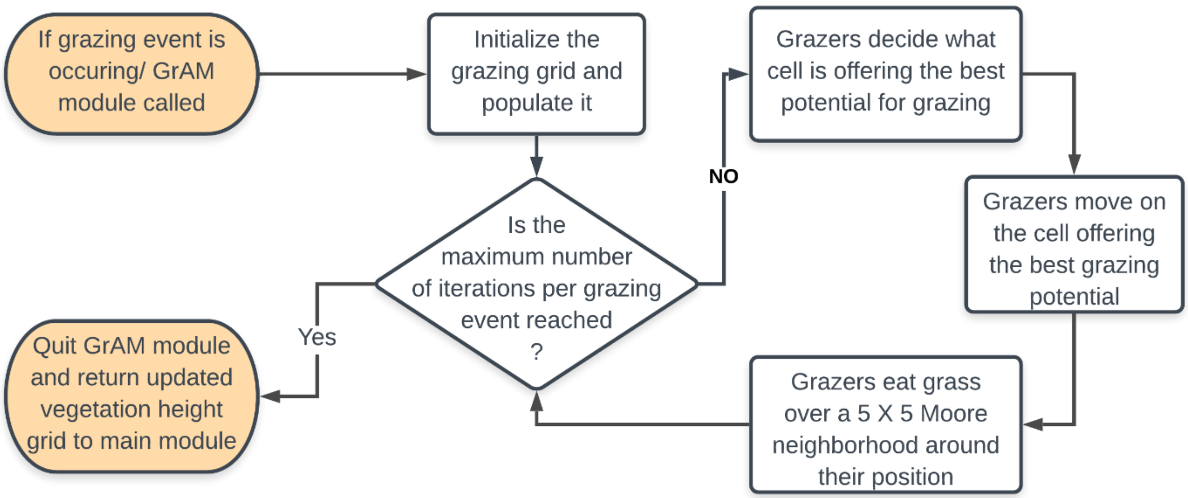


Figure 1: Flow diagram summarizing the main behaviours of the grazers agent in the GrAM module.

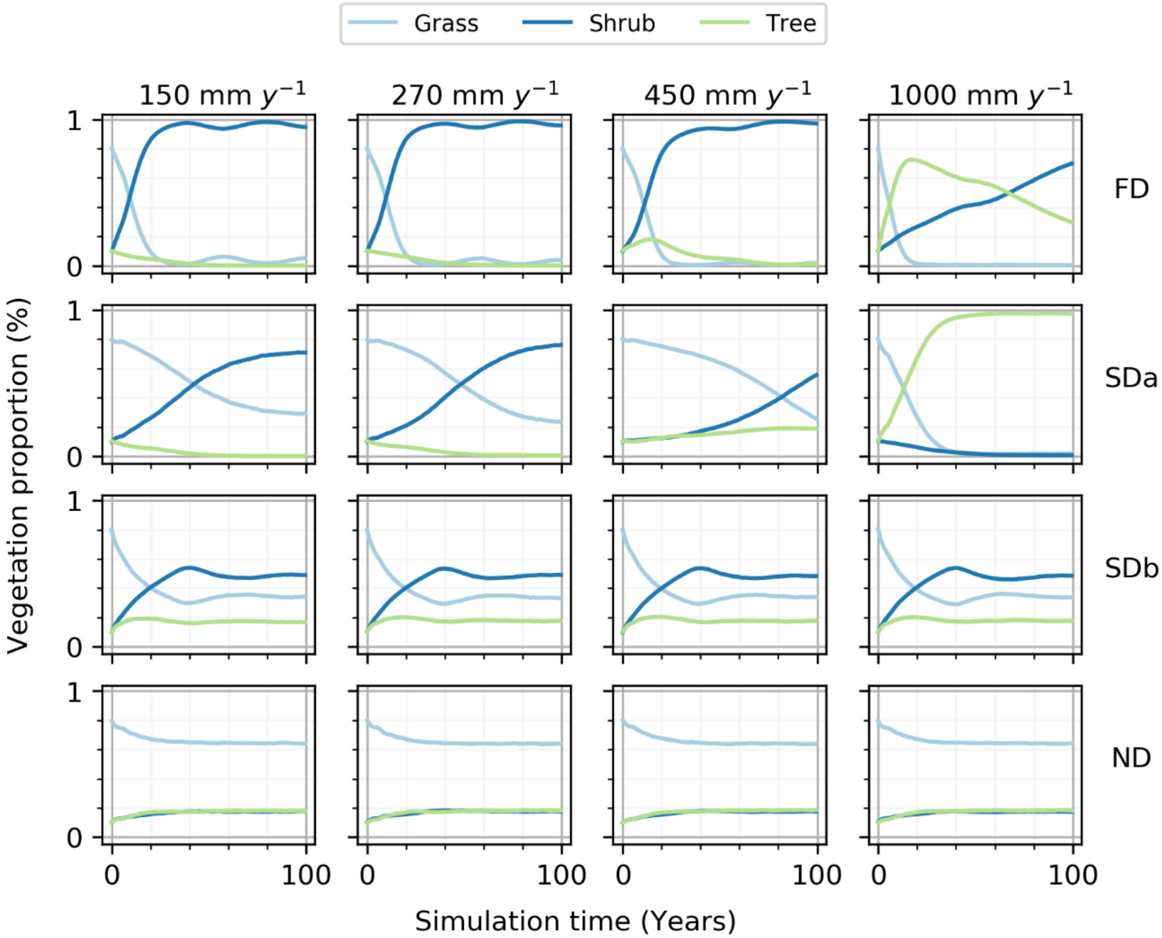
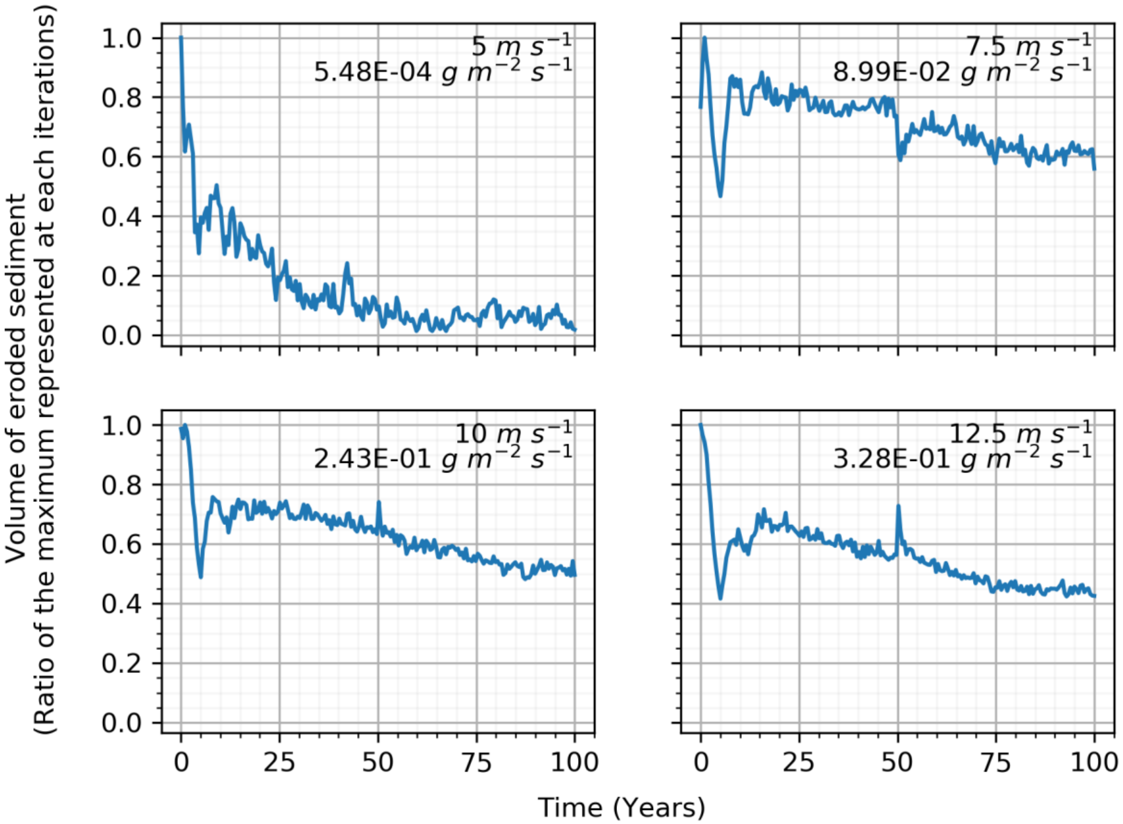


Figure 2: Time series of the proportion of the simulation grid occupied by each vegetation type during simulations. The fully dynamic simulations (FD) represent environments where the vegetation is sensitive to a sediment balance stress and have a dynamic recolonization process. The first semi-dynamic simulations (SDa) represent environments where the vegetation recolonization is dynamic, but no sediment balance stress is applied. The second semi-dynamic simulations (SDb) represent environments where the vegetation is sensitive to a sediment balance stress, but the vegetation recolonization is static. The nondynamic simulations (ND) represent environments where the vegetation is not sensitive to a sediment balance stress and the vegetation recolonization is static.



815 **Figure 3: Time series of eroded sediment volume and the mean erosion rate of 5-year simulations with different windspeeds.**

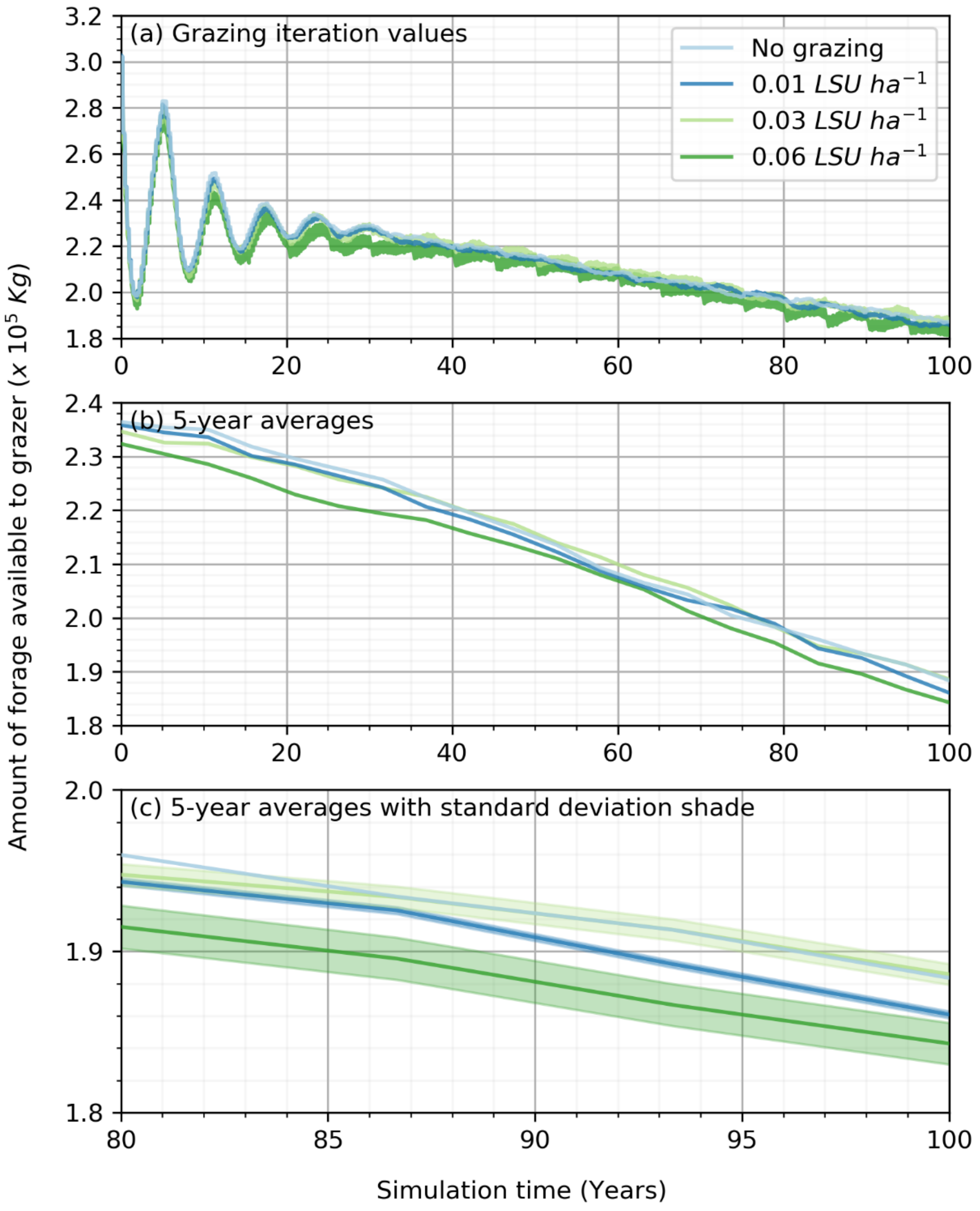
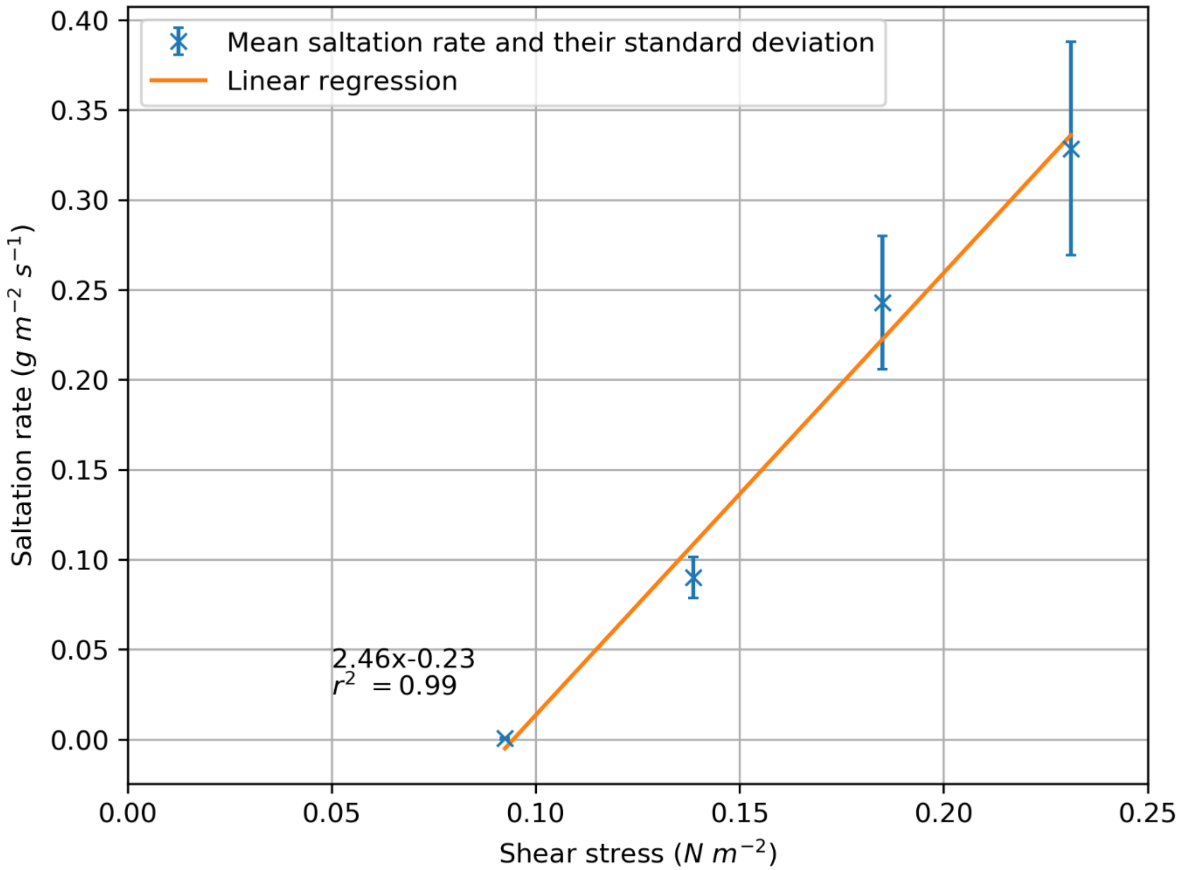


Figure 4: Time series of the available amount of forage available to grazers on the simulation grid.



820

Figure 5: Relation of the mean saltation rate and their standard deviations with shear stress (p-value = 6.59*10^{-3}).

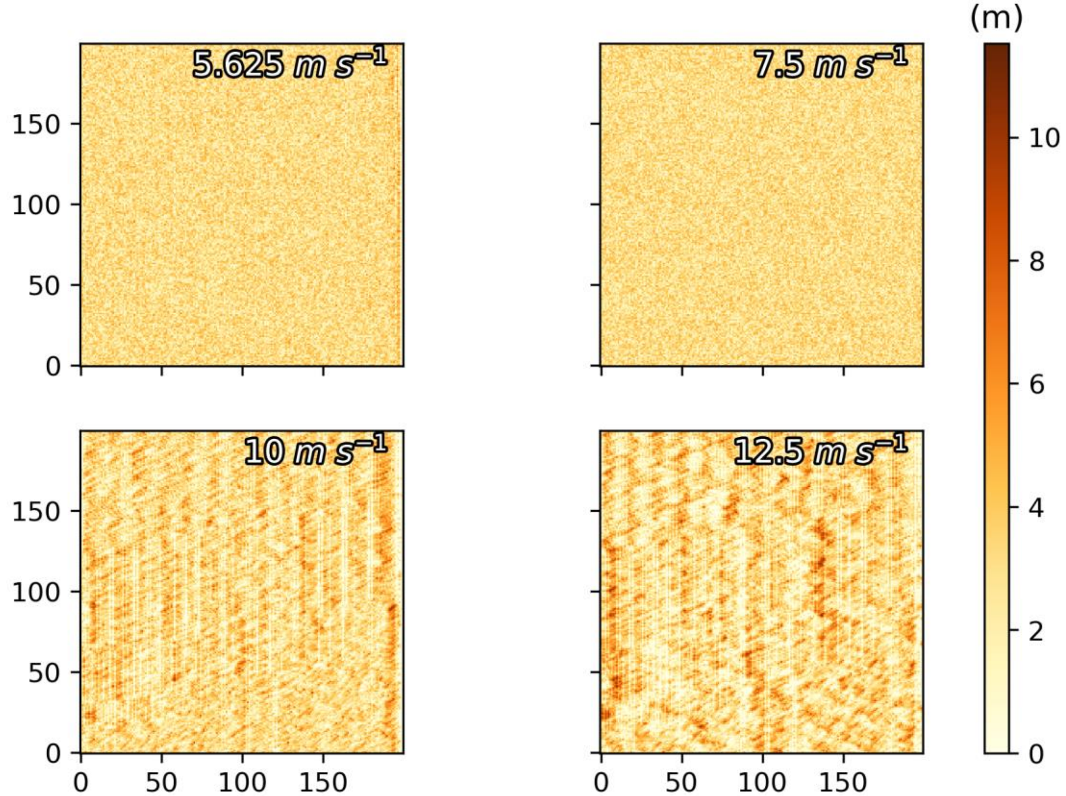
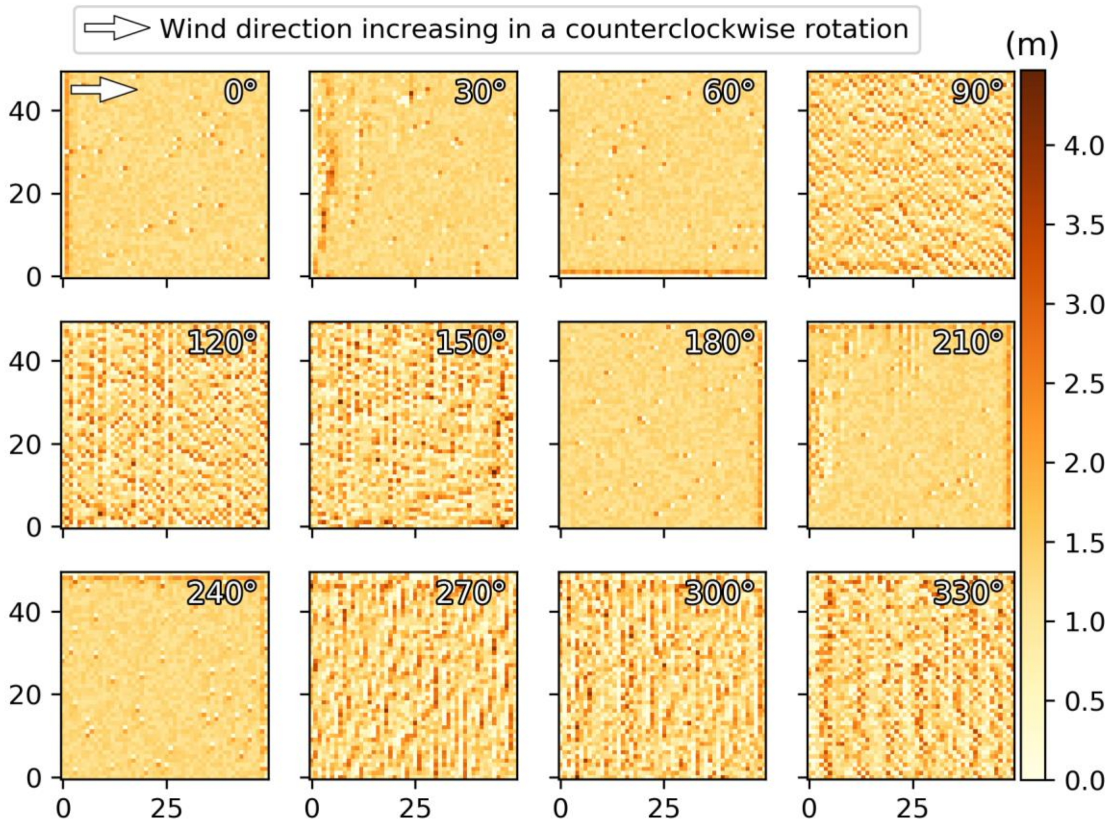


Figure A1: Final sediment height representation of 5-years simulations with different windspeeds



825 **Figure A2: Final sediment height representation of 5-years simulations with different wind angles.**