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

Phillipe Gauvin-Bourdon[1], James King[1], Liliana Perez[2]

[1] Laboratoire d'Érosion Éolienne (LÉÉ), Département de Géographie, Université de Montréal, Montréal, H2V 0B3, Canada
[2] Laboratoire de Géosimulation Environnementale (LEDGE), Département de Géographie, Université de Montréal, Montréal, H2V 0B3, Canada

Correspondence to: James King (js.king@umontreal.ca)

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 in 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. The new model provides an improved representation of the 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 highlights 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 represents an important improvement for managing arid landscapes over the previously available tools.

1 Introduction

Ecosystems in arid and semi-arid environments are regions of 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) These

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processes can act to modify a landscape by redistributing resources such as vegetation and soil nutrients (Okin and Gillette, 2001), as well as modifying climatic variables that lead to landform adjustments (e.g., dune building or dune reactivation (D'Odorico et al., 2013)). In regions where grazing is an active use of the land, vegetation degradation resulting from an imbalance between climate and herbivory induces an increase in wind eroded transport of sediment that alters the vegetation health by removing important soil nutrients, and therefore reducing the grazing capacity of the land (Bhattachan et al., 2014; Thomas et al., 2005). In this context, the onset and severity of wind erosion induced by changes in climatic variables or grazing pressure is an important source of dust and presents important challenges in a context of climate change (Chappell et al., 2018). Limitations to our understanding of wind erosion, grazing disturbances, climate change, and ecosystem processes, separately and in combination, are currently a result of inconsistent data collection coverage at appreciable spatial and temporal resolutions. This is a result of arid environments covering large areas that are loosely governed or monitored and have large variabilities in climatic variables; all of which reduce the representativeness of a single monitoring station. Additionally, although sediment transport by wind can be modelled using empirical approaches, the synergistic impact of grazing pressures on vegetation growth combined with a climatic shift in aridity or wind regime, demands a more integrative assessment. 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. In addition, a better understanding of the landscape dynamics in semi-arid environments enables a better management of those environments in the future.

Previous complex models have undertaken the objective of simulating sediment transport by wind modified by the presence of vegetation (e.g., Baas and Nield, 2007; Nishimori and Tanaka, 2001), with one of these having the ability to simulate a disturbance variable, such as fire or grazing (e.g., Mayaud et al., 2017a). The cellular automata (CA) Vegetation and Sediment TrAnsport (ViSTA) model detailed in Mayaud et al. (2017a) hereafter referred to as ViSTA_M17, presents an englobing and compelling approach to the modelling of sediment transport where the grazing representation is implemented stochastically. This stochastic approach overlooks some important dynamics like the heterogenic distribution of the grazing that becomes important when representing larger regions. Therefore, the objective of this research is to identify 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, in the aim to test the resulting model against existing point or spatially limited datasets.

2 Context

Studies looking at the impacts of grazing 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., 1997b; Yu et al., 2019), yet very few have combined a complex modelling approach to analyse the interaction between grazing and wind erosion at the

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individual scale. Remote sensing studies on vegetation cover in arid environments 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) developed a unidimensional empirical model representing pasture growth and soil-water balance based on climatic and land management inputs, evaluating the pasture production based on the land management used at each pasture. However, it does not represent the spatial distribution of the vegetation in these pastures leading to an informative model at the management level but without the processes needed to study the dynamics shaping semi-arid environment. Similarly, the related erosion model by Webb et al. (2009) presents an erodibility index for the landscape between 0 and 1, but does not calculate the actual transport rate of sediment. A combined 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 CA model of Jeltsch et al. (1997b) represents the effect on vegetation cover from preferential grazing around a borehole in the Kalahari Desert. The model provides a good representation of the preferential grazing gradient around a borehole but does not simulate any sediment transport and is only implemented at the herd level. From these past approaches, it is then appropriate to ascertain the possible advantages to combine a CA model for sediment transport within sparsely vegetated landscapes with an ABM for grazing impacts on vegetation at appropriate spatial and temporal scales within an arid environment.

The past development of CA models for sediment transport and those specifically via wind erosion within vegetation, reflected by the then increasing interest in shear stress partitioning approaches developed for sparsely vegetated arid environments (King et al., 2005; Okin, 2008). From this development, currently available CA models representing the vegetation-wind dynamics and the wind-fluvial dynamics in parabolic and barchans dune fields with good precision are the DECAL (Baas and Nield, 2007; Yan and Baas, 2017) and DECAL-CAESAR (Liu and Coulthard, 2017), respectively. While these two models are effective applications of a CA model, they however, do not integrate grazing activity in their simulations. The ViSTA_M17 model reused similar methodology to the DECAL model and the Bailey (2011) vegetation model to create a more integrative model with the goal of simulating a wind erosion driven landscape. Mayaud et al. (2017a) presented the ViSTA_M17 model as a convincing representation of sediment and vegetation dynamics and did include a representation of grazing, but it does not include any spatiality of grazing or any specific attributes that allow for comparisons with field studies.

3 Methods

The proposed and implemented model used to represent the arid environment process in this research study is named the ViSTA_GrAM model (Gauvin-Bourdon, 2020), which integrates the new Grazing Agent Module (GrAM), an ABM representing grazer disturbance, into the ViSTA_M17 CA model. The CA nature of ViSTA_M17 offers a good base structure for an ABM because its representation of the interactions between sediment transport and vegetation are dynamic and can easily interact with another model. It also provided an already tested procedure to represent the sediment transport and vegetation growth (Mayaud et al., 2017b, 2017a). Nevertheless, we have made some changes to the original model structure for better representation and integration of the new GrAM. The first modification brought by ViSTA_GrAM consisted of an update to Python 3.7 standards. On the other hand, two significant changes were made to the original model logic: the first 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.

3.1 Vegetation-sediments interactions

The changes concerning the sediment transport function were introduced to improve an 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 vegetation of significant height, a new condition was introduced in the erosion processing function of the model. This condition states that if there is vegetation of a significant height on a cell, erosion is not be 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).

3.2 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 was revamped by the ViSTA_GrAM model to define when the GrAM module is called in sequence within the main portion of the ViSTA_M17 model. A new 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. 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 in two in order to represent the tendency of bovine grazers to concentrate their wandering and eating periods at specific morning and afternoon sessions (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 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, the GrAM module will place 6 grazing agents on the grid at the beginning of each grazing event.

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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 correspond 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 make the decision of the best next move for the agent (similar to Jeltsch et al. (1997a, 1997b) and Marion et al. (2008)). This decision function takes in 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 makes the choice of 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 have 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 sensitivity tests and in relation to the height of grass score. 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

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make a familiar cell with medium forage quality as attractive as an unfamiliar cell with high forage quality. The memory of each grazer is of 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, which is based on the result of the above-mentioned decision function. The third behavior 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 (Aubault et al., 2015; Burgess, 2006; Chacon et al., 1976; Hodgson, 1985; Orr et al., 2001) and would allow 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, in order to limit the amount of user inputs and calibration necessary to its application.

3.3 Model applications: simulation definitions

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. The scenarios all take place on a grid of 200 x 200 cells of 5 m resolution each, and therefore representing 100 hectares, over a 100-year period, to allow the simulated environment to display a recognizable evolution trend. The first components tested were the sediment balance stress applied on vegetation by sand burial and the vegetation recolonization. The sediment balance stress is an additional factor influencing the vegetation survival chance, based on the response of certain vegetation type to burial or erosion when turned on. The vegetation recolonization is either dynamic and influenced by current vegetation proportions or it is non-dynamic and determined by static probabilities. The combination of these two components allowed us to create four different types of simulations ranging from fully dynamic to non-dynamic

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(Table 1). A fully dynamic simulation (FD) represents an environment where a sediment balance stress is applied on 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 is 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 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 offer a good comparison for the three other rainfall regimes. This range of rainfall regimes is selected to allow for the representation of multiple environments ranging from semi-arid grasslands to tree savannas. No windspeed was applied on 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.

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 Living Stocking Unit (LSU) ha^{-1}, along with a control simulation where no grazers were introduced, is applied. In order 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 is 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 a 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.

4 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 dynamism, rainfall, windspeed) and grazing are presented in a progressive construction of the final simulations to inform the representation of a grazed semi-arid environment.

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4.1 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 own 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 most dynamic simulation type, 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 SDa1 simulations are more responsive to rainfall influence and present a more gradual modification of the final vegetation proportions compared to the simulation FD. 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 SDb and ND simulations, where dynamic vegetation recolonization is disabled, present similar proportions of vegetation type regardless of the rainfall regime applied. 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, while 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 effect of rainfall on vegetation is best observed trough 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 fluctuates 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 a 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

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demonstrates that a higher proportion of a given vegetation type does not directly imply a healthier development. This difference also suggests that the 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 x 10^{-2} g m^{-2} s^{-1}, 2.43 x 10^{-1} g m^{-2} s^{-1} and 3.28 x 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). 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. In particular, 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.

4.2 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 represent 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 a natural degradation of the environment. With the addition of grazing agents in the SDa3 simulation no large effects 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 have no effect on 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

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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 1.85×10^5 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 a sufficient grazing efficiency.

The limited impact of the grazing on the vegetation is also limiting its impact on the sediment transport. Temporal removal of vegetation on the grid surface between each vegetation update could be releasing patch of sediments previously trapped by vegetation. The mean saltation rate of the simulations with no grazing is 1.37×10^{-4} kg m^{-1} s^{-1} and increases slightly to 1.43×10^{-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 1.38×10^{-4} kg m^{-1} s^{-1} and 1.39×10^{-4} kg m^{-1} s^{-1} relative to the no grazing simulation. These differences in sediment transport between the diverse stocking rate simulations is not pronounced enough to be significant but suggests the possible effect of greater vegetation degradation on simulations.

5 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 state and composition of their respective environment and any modification to their associated processes should then yield different states of environment. The outputs obtained from the ViSTA_GrAM simulations demonstrate a good sensitivity of the model to variation in rainfall, windspeed and stocking rate. The impacts of each component on the final state of the model is 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.

5.1 Vegetation dynamics

A poor proportion 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 an 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 0 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 that optimally grows when buried by sediments (Mayaud et al., 2017b). These results are not representative of all types of semi-arid environments. Most of the humid and stabilized sandy environments of Southern Africa, for example, show a greater proportion of trees as opposite 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 be applicable 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 on 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. 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 model 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 of 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, make it more realistic for observing the impact of rainfall, windspeed, or grazing regimes on the model.

5.2 Rainfall

The rainfall regime of an environment is one of the most influential components of the vegetation state of a 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 reality, 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, if there is no secondary factor encouraging the growth of grass, a significant proportion of shrubs emerges along side 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 optimal 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.

5.3 Sediment transport

The effect of climate change on windspeed is regionally variable and uncertain (McInnes et al., 2011), encouraging studies of wind-driven environments response to multiple wind regimes. Arid environments benefit from such measures, since an increase in wind speed could result in an increase in the erosion rate even if there is no modification of the surface. Furthermore, with an increase in windspeed coupled to the remobilization of sediment due to a decrease in vegetation, the resulting transport could 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, are 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.

5.4 Grazing

Grazing is a type of disturbance and is generally approached as having a negative impact on the environment; expected to present a degradation of the vegetation cover over time. 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 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 of 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 organisation of the vegetation (Aubault et al., 2015; Hickman and Hartnett, 2002; Jeltsch et al., 1997a). The maximum stocking rate an environment is able to 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 compensation 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 is influenced more by the vegetation organisation than the stocking rates applied. Knowing that 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 that there is a potential of increased sediment transport, but it is not translated in actual 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 highlight 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 environment.

6 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. The sensitivity of the vegetation to

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sediment stress balance is currently high for its use in a semi-arid rangeland simulation but could realistically be implemented in a representation of coastal dunes. The recolonization dynamics of vegetation allowed for the self-organization of the vegetation composition and returned a diverse array of environments. In comparison, the non-dynamic simulations were not able to present the same diversity in the resulting environments, highlighting the advantage provided by using a cellular automaton as the base grid for ViSTA_GrAM. It is currently difficult to compare the sediments transport rates estimated in the model with empirical data because the horizontal saltation flux of the simulations is not specifically calculated. Nonetheless, the internal scaling of the transport rate with windspeed and the underlying transport dynamics are concordant to our theoretical knowledge of transport dynamics. The sensitivity of vegetation to rainfall variation represents a range of environments from grasslands to savannahs to closed woodlands. Finally, the implementation of grazing as an agent-based module permitted to observe the biological response process of grasses following the removal of biomass by foraging grazers. The results returned by simulations using the GrAM module within the ViSTA_GrAM model highlights the complex nature of vegetation interactions with grazers and validates the use of complex modelling to represent those interactions.

The introduced ViSTA_GrAM model presents a realistic representation of the environmental dynamics taking place in arid environments and demonstrates favourable opportunities to improve the studies of landscape vulnerabilities to climate change. Future work would include the horizontal saltation flux as an output, introduce several grass species growth response curves, and calibrate the model against more empirical data. By further developing the model, we think it can offer an invaluable tool to help extend available field data and plan for future data collection strategies.

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 a 5-year period, while similar landforms are normally formed over 100-year to 1000-year period in a natural environment (Hugenholtz et al., 2012; Lima et al., 2002; Yan and Baas,

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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 a 5-year period 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 surfaces 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 in 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.

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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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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**
Non-Dynamic **(ND)**	Sediment balance stress **off** Recolonization dynamic **off**

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

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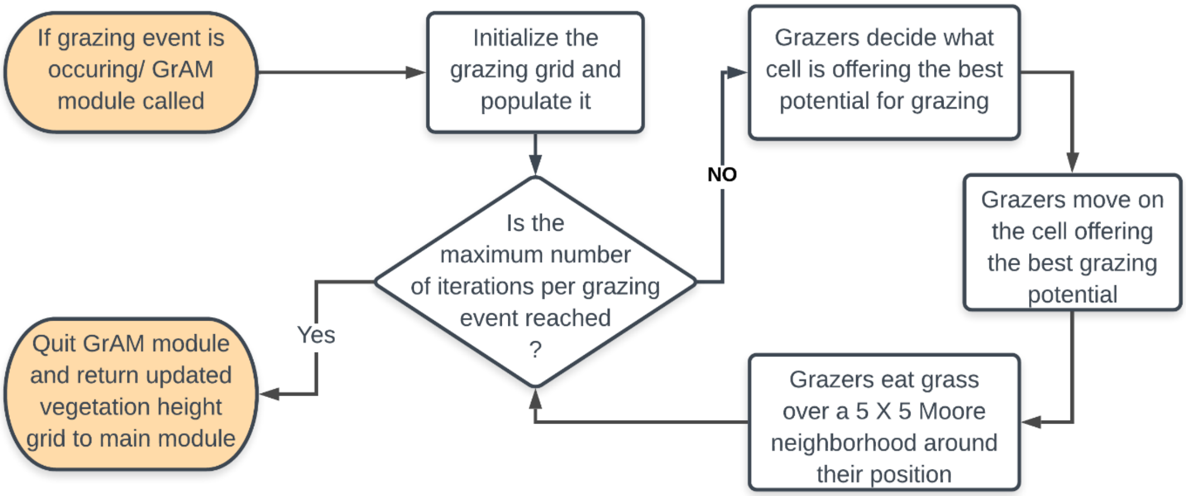
Simulation	Rainfall (mm yr^{-1}) *			
FD	150	270	450	1000
SDa1	150	270	450	1000
SDb	150	270	450	1000
ND	150	270	450	1000
	Windspeed (m s^{-1}) **			
SDa2	5	7.5	10	12.5
	Stocking rate (LSU ha^{-1}) ***			
SDa3	0.00	0.01	0.03	0.06
*All simulations executed with windspeeds of 0.0 m s^{-1}. **All simulations 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.



720 **Figure 1: GrAM Flowchart**

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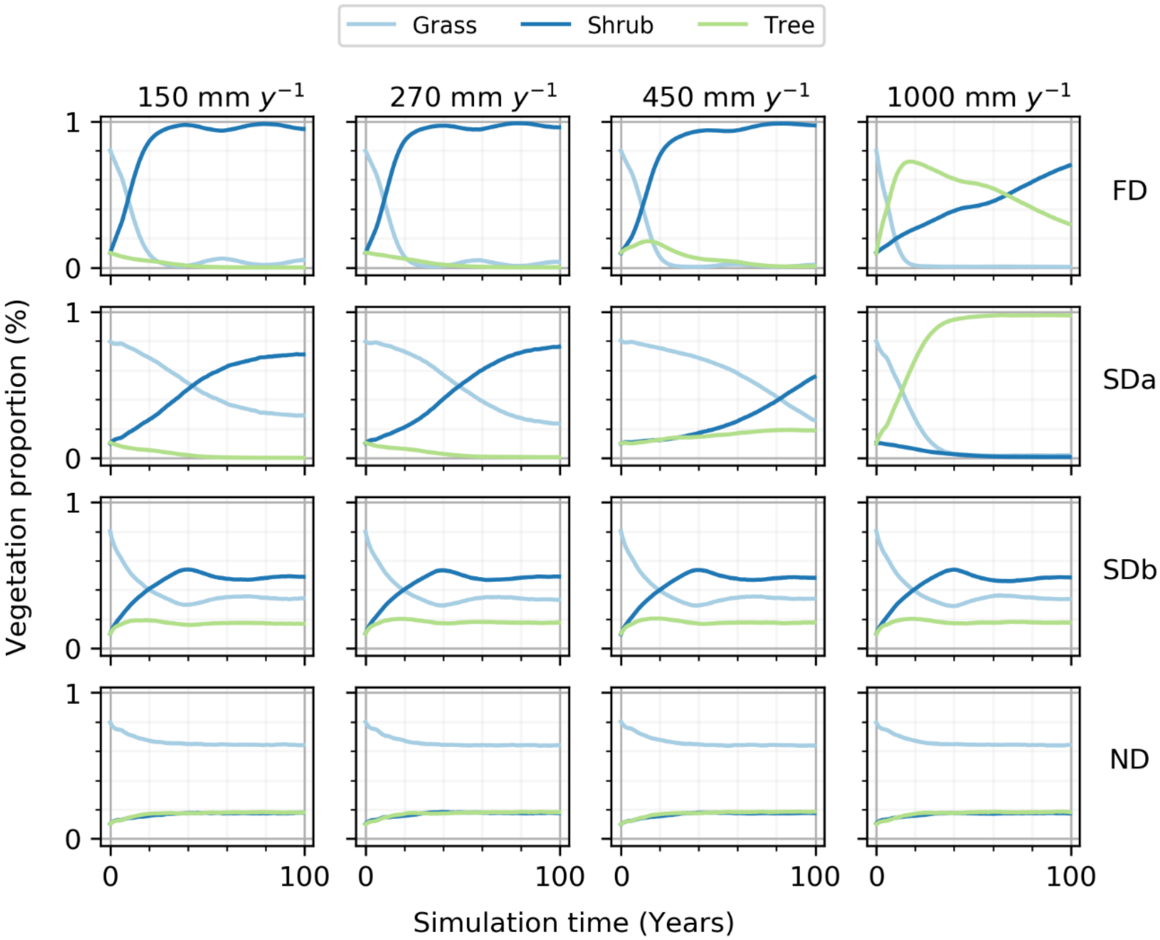

725 **Figure 2: Time series of the proportion of the simulation grid occupied by each vegetation type during simulations. See Table 1 for more information about the simulation configuration.**

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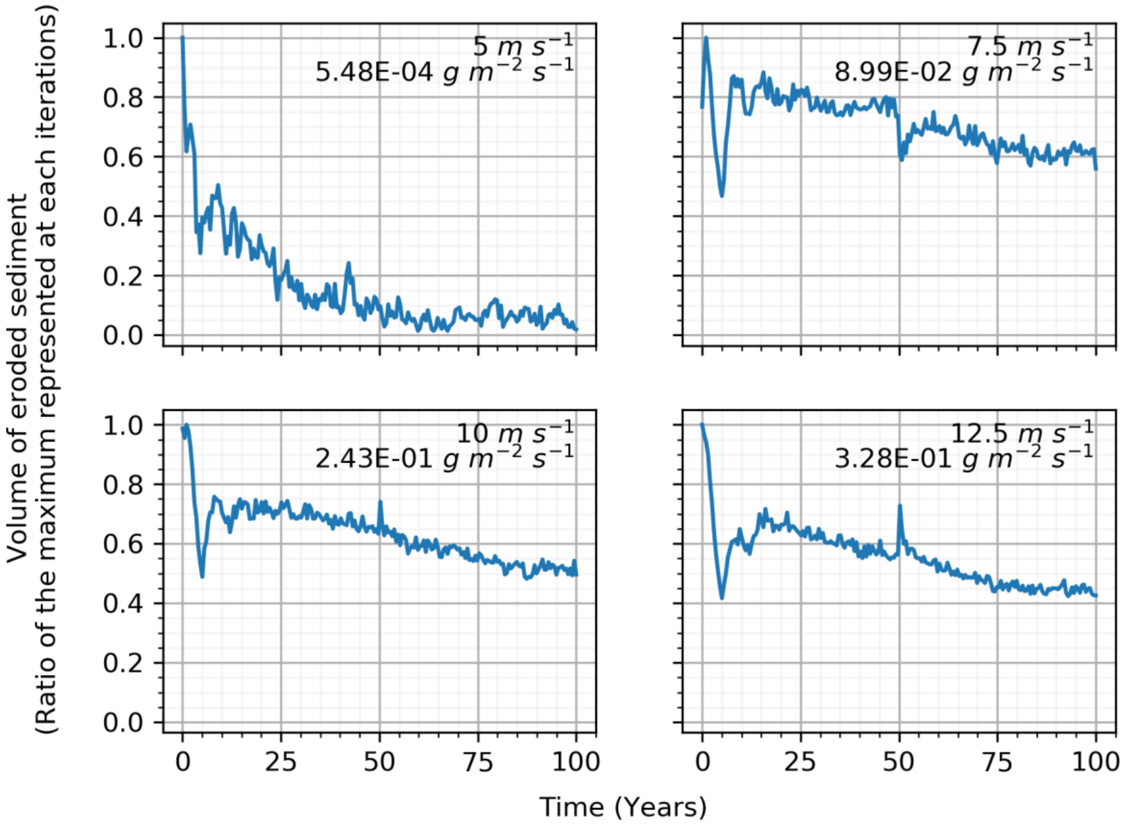

Figure 3: Time series of eroded sediment volume and the mean erosion rate of 5-year simulations with different windspeeds.

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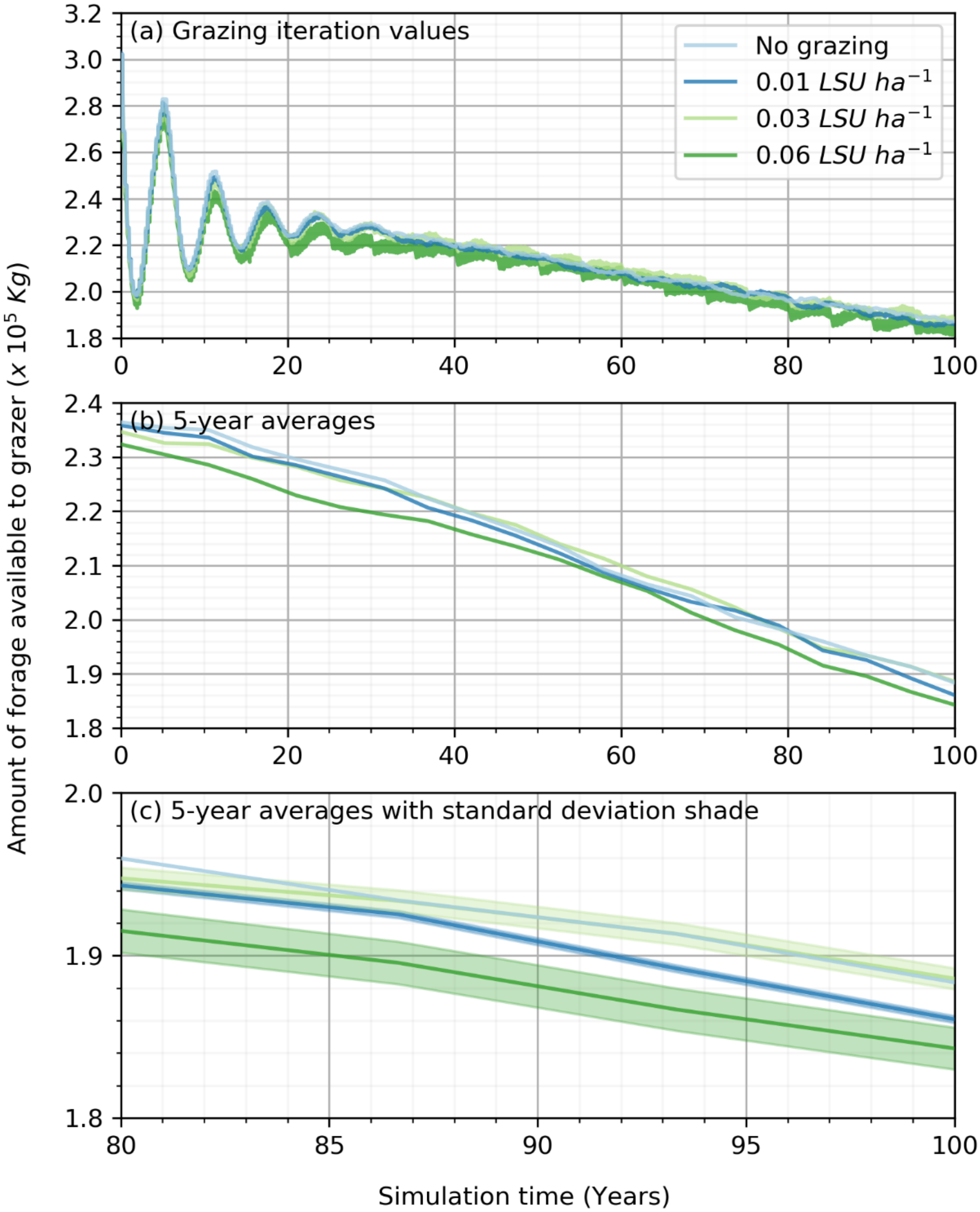

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Figure 4: Time series of the available amount of forage available to grazers on the simulation grid.

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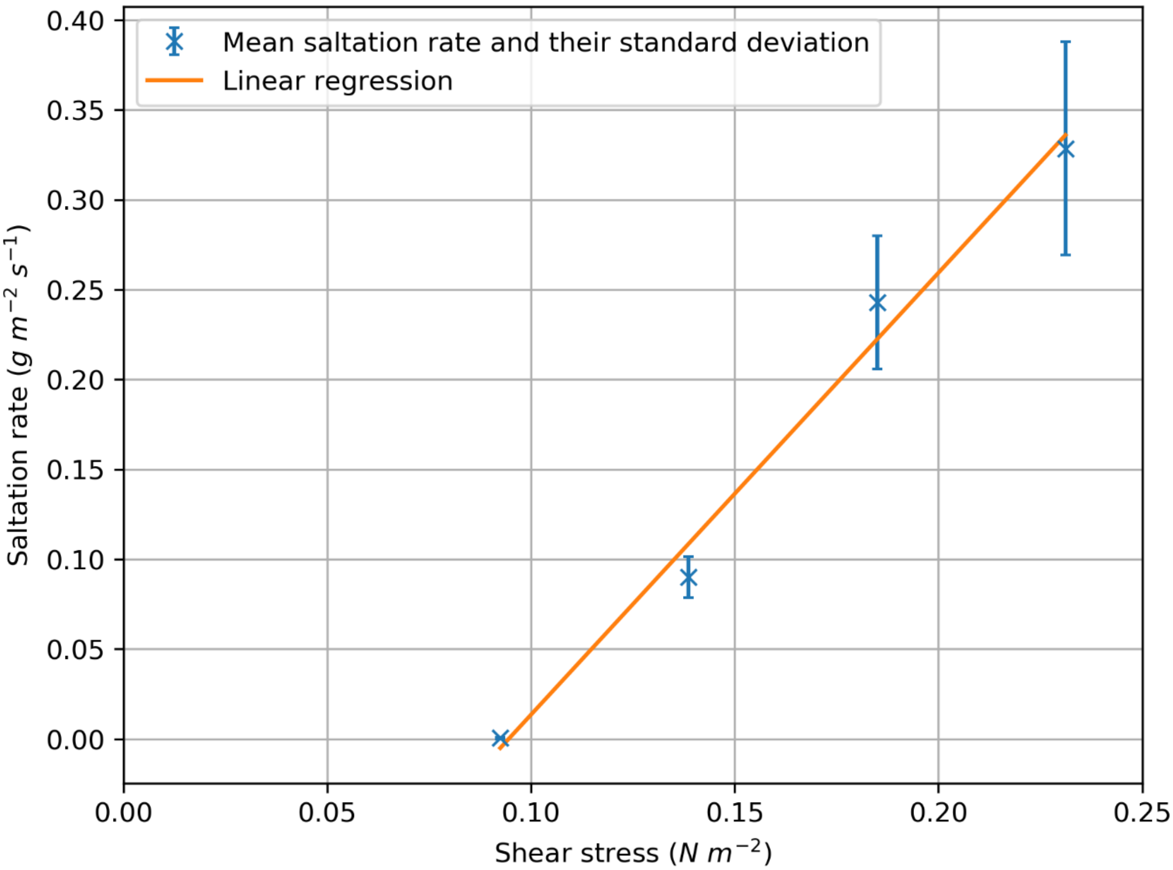

Figure 5: Relation of the mean saltation rate and their standard deviations with shear stress.

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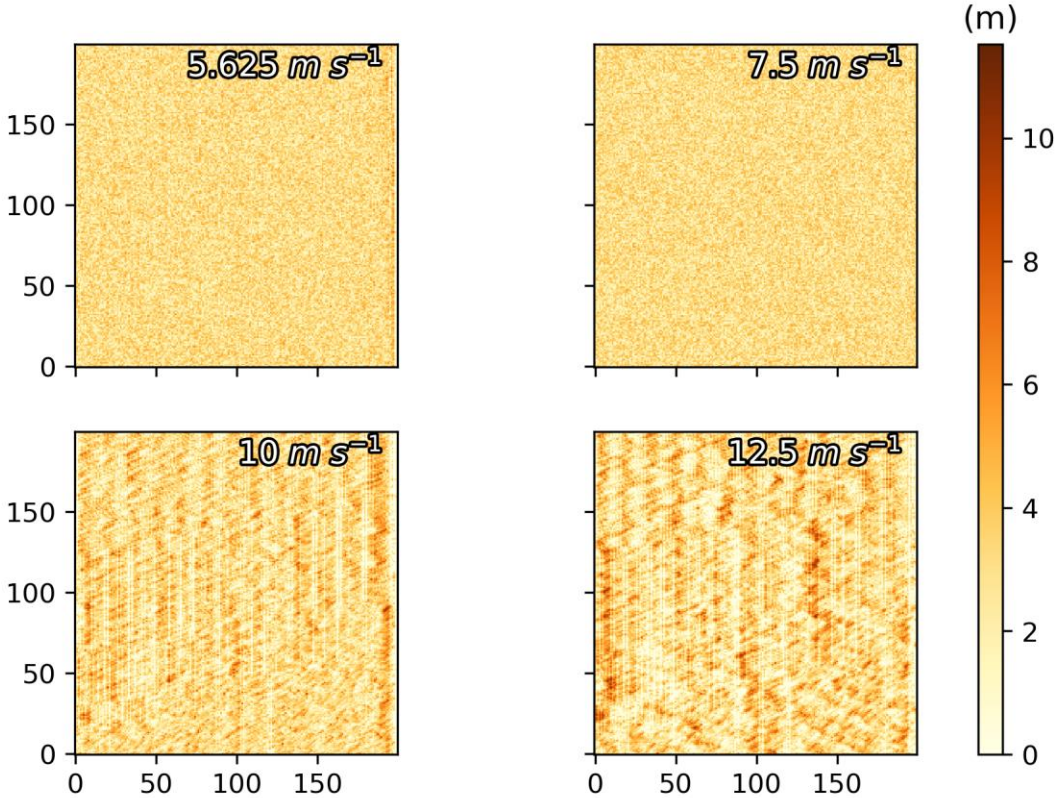

Figure A1: Final sediment height representation of 5-years simulations with different windspeeds

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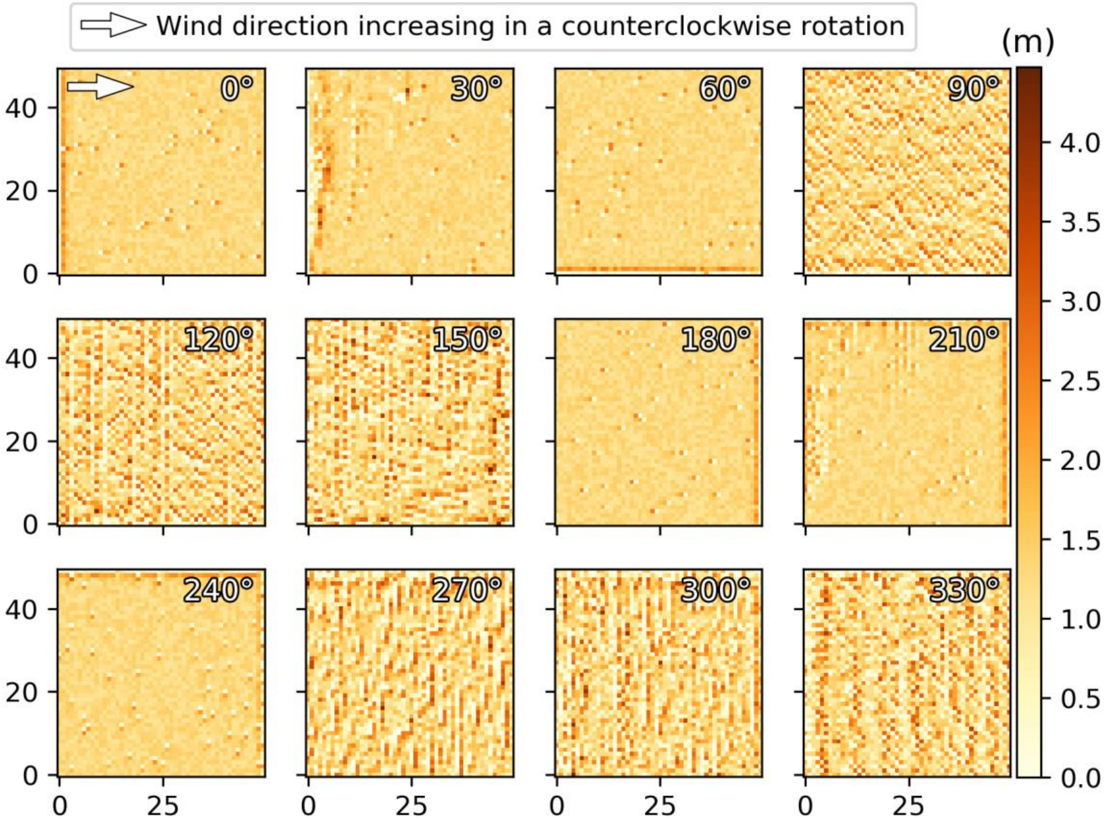

Figure A2: Final sediment height representation of 5-years simulations with different wind angles.