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

Earth Surface Dynamics

Response to Referee #1 comments:

1. The Introduction oversimplifies the context and justification for the work and undersells the value of an integrated vegetation-grazing-sediment transport model. The first paragraph of the introduction hints at but does not describe the complexity of the interactions among grazing, vegetation and aeolian processes. The treatment of vegetation responses, in particular, is overly simple and I think this weakens the authors' case for what could be important work. The problem description and justification could be strengthened if the authors incorporated discussion of vegetation dynamics and the nature of interactions with/among grazing and aeolian processes. See for example: Okin et al. (2006) in Journal of Arid Environments; Ravi et al. (2011) in Reviews of Geophysics; Bestelmeyer et al. (2018) in BioScience; Webb and Pierre (2018) in Earth's Future. In many areas, the dynamics are likely to be non-linear. Framing the complexity in terms of multi-equilibrial models (e.g., state-and-transition models) and drawing on that literature may help to convey the complexity and need to consider the interactions and feedbacks. See Zhang (2020) in Acta Ecologica Sinica for an example of a coupled ecological-wind erosion model that establishes its roots in the vegetation dynamics.

We thank the referee for their concern on the framing of the research and for the justification of our work on integrated vegetation-grazing-sediment transport model. We recognize the need for a clarification of the context around our work and the justification of the research goal. The non-linearity and capacity to produce emergent pattern of the interactions between the vegetation, sediment transport and grazing are one of the primary reasons we chose to use complex model in our research. Substantial additions to the description of the dynamics and interactions taking place between the vegetation, the sediment transport and the grazing was added in the introduction in order to help the reader understand the need for using a complex model. The context section of the original manuscript was also integrated into the introduction to help link the theory on the dynamics observed in arid environments and the application of those dynamics in models.

2. The model simulations are not sufficiently connected to an established real context such that, while some environments may produce the model responses, the reader will be left wondering "which environment?" and possibly rejecting the results as they are contradictory to many semi-arid systems (e.g., in North America, Australia, Mongolia, Kalahari).

We acknowledge that the lack of connection between the model and a specific semi-arid environment may lead to confusion when interpreting the validity and applicability of the results. We have updated text throughout the manuscript including specifically the methodology and discussion sections to improve the connectivity of the model simulations to particular environments. The evaluation and testing of the model was done by comparing our ViSTA_GrAM results to other model results or data present in the existing literature. We collected studies from different semi-arid environment to maximize the pool of data against which we compared the results of the ViSTA_GrAM model. And while the ViSTA_GrAM results are compared to results coming from various locations, most of the model simulations parametrization were inspired by Kalahari environments and much of the literature used in the discussion to validate these results is also based on Kalahari environments. We consider the Kalahari as the main reference environment for the simulations of the model, but also recognize that not all simulations results are representative of this exact semi-arid system. The response of each simulations to their initial parametrisation is then contained within realistic values for each simulation, but they are not necessarily representative of a particular semi-arid environment. While further testing would be required to define the realism of the model (see response to this reviewer's comment #6), the simulations presented are in context with existing literature using complex models. However, we do think that the representational power of the model could be increased with integrating inputs from meteorological data representative of a specific semi-arid environment. In order to clarify the source of inspiration for each simulation, the introduction and method section was expended to better explain the simulation construction. We also made sure to further discuss the relevance of the simulation results compared to the reference environments of the supporting literature. With the changes made, we disagree with the reviewer that the results from these simulations are in contradiction with those plausible in these environments and added conclusive statements that suggest a higher resilience to changes to climatic and environmental stress than previously observed from linear and empirically-based models.

3. Beyond presenting the model, the purpose of the manuscript and its contribution aren't clear. The authors state that the objective is to identify the response of a semiarid landscape to climate and grazing variabilities, but which landscape? What is the utility of the model? Who is the intended audience and what are the intended applications? What can we learn from the model that we don't already know, perhaps using more accurate methods? What kinds of questions can it be used to addressed? How does the model provide an improvement for managing arid landscapes over previously available tools? These aspects should be addressed in the Introduction and expanded upon in the Discussion and Conclusions.

We want to thank the referee for recognizing the pertinence of the experiment presented and hope to help readers understand the methodology used by clarifying the purpose and the context of the research in the Introduction section of the manuscript. The model ViSTA_GrAM presented in the manuscript has a long-term objective to help identify critical shifts in the stability semi-arid environments and understand the dynamics that produce major changes of the environment's organization. The master (M.Sc.) project on which this manuscript is based aimed more precisely to create a new approach of the grazing representation in the already published ViSTA model. In order to integrate an agent-based model representing grazers in the ViSTA model some modifications had to be made to the original code, particularly regarding the spatial resolution of the model. An upscaling of the grid from cell of 1 m to 5 m cells reduced the pertinence of the sensitivity testing presented in the original publication of the ViSTA model and additional tests were run to evaluate the applicability of the new model configuration. The new series of sensitivity tests highlighted some limitation of the original model that were being exacerbated by its upscaling (described in appendix A). The realism of the simulations presented with the ViSTA_GrAM model in its current state is potentially still limited but does allow for the execution of hypothetical scenarios and a generalization of the dynamics observed in semi-arid environments. The simulations presented in this manuscript are closer to sensitivity tests than case studies, which explain their simplified approach and their use of a wider range of values to represent a specific semi-arid environment. A case can then be made that the current simulations of the model don't present the full potential of the model, but they hint at it. We believe that the ViSTA_GrAM model has the capacity to improve the representation of the spatially implicit and non-linear interaction between the vegetation, the sediment transport, and the grazing. The model can be beneficial to decision makers and land managers based on the provided results, by providing a tool to more precisely evaluate and predict the response of semi-arid environments to adaptation strategies or climatic changes. It is likely that the model alone will not provide an actionable and accessible tool for these types of applications because of the parameterisation of many variables (like many complex model applications), but it can provide the crucial identification of ecological thresholds among plausible scenarios. By resolving the limitation around the effect of the wind angle on the amount of sediment transport observed (see discussion in the manuscript Appendix) and taking more time to create simulations based on concrete meteorological data, we think that the ViSTA_GrAM model will be able to help exploring the threshold values that are responsible for inducing changes of state in semi-arid environments. The study of sensibility of environments to change is important; even more so in environments defined by dynamic stability like arid and semi-arid environments. A better explanation of the project context and a framing of the expectation for the model in its current state has been added to the introduction in the final version of the manuscript. Additional context and clarification on the interpretations that can be made from the results have also be added to the discussion and conclusions. With these changes, we hope to highlight the fact that future work can be envisaged to unlock the full potential of the model.

4. Structure - I think that Section 2 on Context could be integrated with the Introduction to help establish a single foundation for the work. This would reduce repetition between sections and enable the authors to expand on the nature of vegetation changes and feedbacks that make their approach useful.

We thank the referee for their comments on the structure of the article and is help in improving the readability of the manuscript. The Section 2 on context have been integrated in a single section with the introduction to help better frame the research and it questions. As stated in our response to the first comment, the structure and the explanation of the research context of the article have been completely reworked to present a better context for the manuscript.

5. How do we know the model responses are realistic? Relative to which specific environment, location, soils, vegetation communities? The simulations appear to be more hypothetical than grounded in a particular system. How well does the model work the system for which it is parameterized? How well do the authors anticipate the model to work in other systems with other dynamics? Some level of validation is needed for reader to have confidence that the authors' claims of the model working well for its intended purpose are justified.

We thank the referee for their identification of the lack of realism in the simulations presented and their request for a more detailed description of the environments used in our simulations. Changes to the manuscript have been to reflect these comments in the introduction, methods, and discussion to specify the type of vegetation and surface material that are applied in the model simulations presented in the manuscript. Although many of the simulations presented in the manuscript were intentionally created to be hypothetical to identify a plausible range of climatic change applications within semi-arid environments, we did apply the grazing module to the median scenario to best correspond to results from the Kalahari (e.g., Jeltsch et al., 1997). Therefore, we have added the referenced environments when comparing the behaviour of the model with other studies to limit the confusion around the application of the various simulations.

6. I think inadequate information is provided for the reader to understand the sensitivity of the model to grazing and rainfall as only total annual rainfall is described, and inadequate information about the stocking strategy is provided. Arid and semi-arid systems will respond differently to grazing and

rainfall depending on their timing, intensity and duration. Were these aspects considered in the rainfall regimes? How were these aspects represented in the grazing simulations?

We want to thank the referee for their comments on the importance of the rainfall and grazing timing in semi-arid regions. We acknowledge that the effect of the temporal frequency and distribution of the precipitation regime and of the grazing can impact their magnitude on arid or semi-arid environments. We made sure to improve the explanations of the rainfall and the grazing timing in the manuscript to give the reader a better understanding of their implementation in the model. The rainfall and grazing components were integrated as a constant in the simulations presented in the manuscript. The amount of rainfall available to the vegetation during the simulations is always determined as an annual equivalent. The distribution of the annual rainfall amount across each vegetation update iterations is than calculated as a ratio between the annual rainfall available and the number of vegetation updates in a year (potentially allowing a seasonal variability). The simulations are then conceptually distributing the rainfall on the grid in a homogeneous pattern spatially and temporally across all 100 years of simulations. Therefore, although we agree with the reviewer that the seasonal timing could be important in the context of wind erosion and vegetation availability in such an environment, it was decided not to be a focus of the simulations presented in this manuscript. As added to the discussion and conclusions sections, this seasonality component is intended to be tested in a place-specific application within a manuscript in preparation. The grazing temporal distribution on the grid is treated in a similar manner, but its spatial distribution is determined by the decision function of the grazing agents. As stated in the revised method section of the article, the grazers are not limited to a particular section of the grid at any time during the simulation, but the precise location they interact with will be dependant on the vegetation and surface properties. The stocking strategy plan used in the simulation is one of free ranging or continuous season-long ranging over the whole pasture (or grid). We understand the need for clarification of the rainfall distribution in the simulations and additional context was provided in the Method section of the article with the description of the simulations.

Line 33: I think the authors need to define what they mean by vegetation degradation and vegetation health.

The text was revised to be clearer. The vegetation degradation referred to a decrease of the mean vegetation height and a decrease of the vegetation coverage in a general manner. The vegetation health referred specifically to the mean height. This sentence was reformulated in the text to fit in a revised version of the introduction.

Line 39: I don't think that the challenges of understanding these complex interactions can (or should) be reduced to a data collection issue. There are multiple examples of where there are sufficient data to address these interactions (e.g., see those described by Webb et al., 2017; Webb et al., 2020; Sasaki et al., 2018). I also do not think that this is a necessary justification for the authors' approach which also arguably has limited representativeness (to the simulations). The authors might have more reach by expanding on the need for integrative assessments - for which there are multiple approaches - and here present one...

We want to thank the reviewer for his concern about the reach of the research. We agree that the article has more capacity than stated and is more applicable by presenting the methodology as a need to expand the integrative representation of semi-arid environment processes. We reframed the introduction section in order to better represent the need for an integrative model of sediment transport, vegetation and grazing. The correction made to answer this comment are shared with those made to answer the first general comment of the reviewer.

Line 52: I don't know why ViSTA would be englobing, or why it is compelling. I don't think these terms are needed so suggest removing. I also do not think that the paper demonstrates either descriptor.
We want to thank the reviewer for his comment on the vocabulary used to describe the ViSTA model. We agree that the term englobing might be too strong to represent the model. We modified the sentence to instead present the conclusions made by the author of the original ViSTA model on the capacity of their model. This will better represent the initial assumptions that were made at the beginning of this project, since our understanding of the model capacity was directly linked to the original author presentation of the model. We acknowledge that the model might have limitations that would refute its widespread application, but we think those limits could be overcome in future work and are have been added to the discussion section.

Line 60: The authors should clarify - the impacts of grazing on what? There are many grazing studies of different kinds, most of which have not been connected to aeolian processes.
We clarified the sentence to specify that we are talking about impact of grazing on the proportions and spatial distribution of vegetation species in this sentence.

Line 63: Define what is meant by individual scale. Individual plant?
We referred to the scale of an individual grazer and its impact on the environment. The sentence was revised to clarify the scale at line 56.

Line 66: Developed - should be implemented.
Changed

Line 69: I think the concepts in this sentence are unrelated and the critique should be broken down as the description of the pasture growth model is an oversimplification and not entirely accurate. While the model did not represent spatial patterns, it did represent vegetation dynamics in the sense of effective changes in species composition (state change) associated with increased grazing pressure. (These were represented through feedbacks to soil properties and plant growth parameters.)
We agree with this assessment and have changed the critique to more accurately portray how this model does not meet the objectives designed in the present study.

Line 77-83: These sentences are long and difficult to digest. Can the authors simplify each sentence?
The sentences have been simplified and have been rephrased to increase the readability.

Line 109: It isn't clear to me what this means in real-world terms. Can the authors elaborate with an example? Surely the effect of vegetation height in preventing transport is also dependent on the gap size (spacing) between plants, such that as gap size increases the canopy height at which transport is "controlled" will also increase. e.g., short but closely spaced vegetation can be more effective in controlling transport than tall but widely spaced vegetation.
We thank the reviewer for this comment and concern on the representation of the vegetation impact on sediment transport. Clarification has been added to the text in order to provide more context around the methodology associated with the effect of vegetation on the surface shearing stress in the model. While we recognized that the gap size and therefore the spatial distribution of the vegetation influences the effect of the wind on erosion, those variables are constant within the same cell (5 x 5 m) in the

ViSTA_GrAM model, leaving only the vegetation height to be modified at that scale. However, at the scale between vegetated patches, the gaps between vegetated cells are calculated based on an approach similar to the gap sized corridors of Okin (2008) as described in the original ViSTA_M17 description (Mayaud et al, 2017).

Line 130: The random distribution of grazers is a reasonable first assumption, but not necessarily consistent with grazing behavior, which is likely to be concentrated in landscapes around preferred forage species and water. While the authors start to address the issue a few lines down, this could be a point for more discussion about future work with the model (in the Discussion).
We want to thank the reviewer for their comment on the possibility of improvement of the grazing behavior in the model. We agree that the way grazing behaviors are currently represented in the model can not be applied to all scale and grazing scenarios, but we added a comment on future work possible to remediate to this in the discussion section.

Line 198: In addition to amount, the authors should describe the rainfall characteristics - e.g., was seasonality represented? How were frequency and intensity of rainfall represented? Did these change over time (e.g., were droughts represented in the simulations)? These characteristics will have important effects on vegetation responses to grazing, and subsequent aeolian transport responses.
A temporal description of the rainfall implementation was added to the descriptions of the simulations in the manuscript to answer this question. The seasonality and heterogeneity of the rainfall was not represented in the simulations presented in the manuscript (although the model has this capacity). The current scenarios were aimed at looking at the response of the model to baseline values and the parametrization of the model. Periodic drought was not represented in the simulations, since the rainfall was applied to the simulations as constant input throughout the duration of simulations.

Line 211: Were the stocking rates implemented continuously for the simulation period? The authors should describe the stocking strategy and its implications for the vegetation and aeolian process responses relative to more dynamic (realistic) strategies over 100 years.
A clarification on the grazing strategy taken in the simulation was added to the description of those simulations. The stocking rates were implemented continuously during the simulations and the grazer had access to the entirety of the grid at all time. A comment on the implication of the grazing strategy applied and how we can expect it to affect the simulations results was added at line 253 to help contextualize the result and the discussion.

Line 231: What are the drivers/mechanisms producing the changes is grazing that aren’t included in the simulations? I think these need to be described in more detail for the reader to understand why the model is producing these responses.
We want to thank the reviewer for their comment on the presentation of the mechanisms influencing the simulations in absence of grazing. We recognized that it might be difficult for the reader to identify the mechanisms producing the changes observed in the simulated environments by starting the presentation of results with the FD simulations (the ones with combined effect of multiples processes). The structure of the text was rearranged to inverse the order of presentation of the simulations (ND, SDa, SDb, FD). By doing this we think it will allow for a more progressive presentation of our results and their interpretation in the discussion. The results of the less dynamics simulations will then be able to reinforce and better explain the observations made in the later simulations. In combination, with our reinforced explanation of the models functioning in the methodology section, we believe this change of the text structure should allow the reader to better understand the mechanisms observed in the simulations.

Line 234: Functionally, why would trees decrease in proportion? This suggests the shrubs are outcompeting the trees (which would typically have access to deeper water...).
This behaviour is explained mainly by the definition of the sediment transport stress and is discussed later in the discussion section. In simulations where the sediment balance stress is applied to the vegetation, the trees are less adapted to a high sediment transport regime, as a fast accumulation of sediment on the ground make the establishment and maintenance of a deeper root system more difficult.

Lines 25-255: Again, what are the drivers and mechanisms of the changes in grass/shrub/tree dominance without grazing or other disturbance to trigger these state transitions? Were the simulations started with proportions of vegetation and cover/height/spacing that were conducive to aeolian transport (i.e., near or just beyond a structural threshold that would produce inevitable change)? I think these details need to be addressed more fully in the methods and simulation setup, then explained in the results.
A better description of the initial state of the vegetation grid (spatial distribution and range of initial heights) was added to the methodology section of the manuscript. The main drivers of vegetation proportions changes, in the absence of grazing, is the rainfall regime applied and the sensibility of the vegetation to sediment transport influence. If the rainfall regime or the sediment transport regime does not reinforce the initial dominant type of vegetation, a shift in the vegetation dominance is to be expected in an interval of decades. The complex nature of the model is expected to autoregulate to some extent the vegetation composition of an environment according to the climate forced on that environment. Also see the response to the general comment #3 and response to the comment on Line 90 of the second referee for more detail.

Line 266: What are the mechanisms? i.e., Can the authors explain the response across the simulations relative to how the plant composition and structure were changing?
The sediment surface is being initialised with random heights and therefore the amount of sediment available to transport is greater at the beginning of the simulations. Once the sediment begins to get organized into dunes and the topography of the surface becomes smoother, we observe a decrease in the amount of transported sediment. At the beginning of the simulations, the random distribution of sediment height produces a higher ratio of roughness associated with the sediment surface being erodible compared to the majority of the non-erodible surface once the sediment are organized in dune or dune-like forms.

Line 310: Can the authors define what they mean by state here?
The word “state” was replaced in the text. We meant the organization of the vegetation or sediment landforms.

Line 317: What is meant by poor, and why is sediment transport important for grass survival? Can this be connected to a real-world situation, as usually the opposite in the case in semi-arid systems. Is the result specific to the pioneer grass?
A clarification and example of the type of pioneer grass represented in theses situations and where they can be found is now provided in the text. The word “poor” was replaced in the text by “low”. The survival of grass is linked to the sediment transport through the application of a sediment balance stress in some simulations. This phenomenon can be observed in real-world environments like coastal dune fields and disturbed surfaces.

Section 5.1: The authors need to be more specific about which system the simulations are representative of? Which species (pioneer grass) respond in the ways indicated by the model? Where are these found? How transferrable is the model to other systems where grasses and shrubs may respond in opposite ways to that shown here?

A comment on how the parametrization of the model to represent these types of pioneer grasses are transferable to other semi-arid systems was added to this paragraph. As in the response to the comment on line 317 above, a clarification on the species of pioneer grass and locations where they can be found was added to the text to clarify the interpretations of the results.

Line 343: Can the authors provide actual examples?

The example of cultivated fields was added as an example.

Line 365-370: Observed where - in which systems?

We specified the locations of the reference studies supporting our discussion in the text and made sure to review the manuscript, in order to clarify to which types of environments the results and the conclusion, presented in the article, can be related to.

Line 370: What is meant by low rainfall regime, and why do wetter (650 mm) systems have vegetation composition with less reliance on rainfall?

Low rainfall regimes are considered to be under 650 mm yr^{-1} in this context. The point made in this sentence aimed to describe how vegetation in environments with less humidity available will rely on other sources of nutrients to survive. It is then the vegetation in environments with a rainfall regime of less than 650 mm yr^{-1} that rely less on rainfall and water runoff to provide them in nutrients. The text has been modified to correct the meaning of the sentence.

Line 392: What is meant by measures? More studies?

Measures was changed to studies in the text.

Line 395-397: But this is a model, so surely the response is determined by the model. (i.e., It appears somewhat circular reasoning in comparing the response with Martin and Kok, 2017 and claiming that as a new result).

The Martin and Kok (2017) study is a field work experiment on how the flux of sediment scaled with windspeed in non-vegetated environment. The ViSTA_GrAM model resultz are compared to those of Martin and Kok because they are obtained via a different method. We think the results of the ViSTA_GrAM and of the Martin and Kok study are surprisingly similar despite the sediment transport mechanics in the ViSTA_GrAM being a complex product of the model. This comparison is then to bring interest in the comparison of their result and infer a certain realism of the model from this comparison.

Line 408-409: Why - on what basis should we expect grazing effects to generally be negative for vegetation? I find this statement problematic because it certainly isn’t always true and is much more nuanced depending on management.

The sentence was reworded to eliminate interpretation problem with this statement. We entirely agree that grazing is not necessarily negative for the vegetation and it was not our intention to say that the presence of grazing is always negative for the vegetation in all cases.

Line 421: What do the authors mean by a change in the organization of vegetation?

The sentence was clarified in the manuscript at line 469.

Line 427: It is not clear what the authors mean by compensation in this context. My interpretation of the results in Aubault et al. (2015) is that they showed their systems were highly sensitive to grazing depending on strategy, and that sensitivity varies across soils and plant communities.
The term “compensation” was clarified in the manuscript at line 477. The responses to the comment of line 69 and 431 are also in response to this comment.

Line 431: Again, I think the authors need to specify "for the simulated system", and ideally what that system is. Further, the authors should clarify what they mean by vegetation organization - is that proportions of grass/shrub/trees or spatial arrangement?
The sentence was clarified in the manuscript and is reinforced by our response to the general comment #2 of the referee by providing more information related to the simulated system clarification across the text.

Line 440: The lack of sensitivity of the differentiation due to stocking rates could also indicate insufficient sensitivity to stocking rate, depending on the system the model was parameterized to represent...
We agree with the referee that objectively the lack of sensitivity of the simulation SDa3 to the different stocking rate could suggest a lack of sensitivity of the model itself to the stocking process. Based on additional unpublished preliminary tests that were executed during the development of the model, we observed originally an over sensitivity of the model to the grazing with the first versions of the module GrAM. The simulations were using a similar configuration to the ones presented in the article (dynamic vegetation recolonization process, constant rainfall between 150 and 450 mm yr^{-1} and windspeeds between 7.5 and 12.5 m s^{-1}), but presented a complete degradation of the grasses within 15 to 20 years of simulations. Even at the lowest stocking rates (0.01 LSU ha^{-1}), the simulations would eventually be unable to support grazing activity due to the lack of grass. The rapidity of the degradation in those simulations was surprisingly short considering that no dramatic drought or disturbance of the vegetation cover was represented, in those simulations and the parameterisations were adjusted to the ones presented in the manuscript based on previously published values. This is from the combined analysis of these preliminary tests and other empirical studies that we based our conclusion on the sensitivity of the model. We think that by answering to the referee’s general comments, we have succeeded to better contextualize our conclusions on the model performance.

Figure 2 caption could remind the reader what the simulation names were, rather than just referring the reader to Table 1.
Although it is a presentation rule of the journal to keep the caption size of each figure to a minimum, we agree with the reviewer and have expanded the caption for Figure 2 accordingly.

Response to Referee #2 Comments

1. Introduction: it is lacking detailed discussion of how different factors interact with each other modifying landscapes and the processes involved. Some terms used are very generic. For example, authors use 'changes in climatic variables', 'climate change' etc., but it is not clear what they refer to, rainfall, temperature, wind regime? It seems that the authors only modelled the impacts of rainfall and wind strength in this paper. Authors could discuss specifically how rainfall, wind regime, vegetation growth (grass, shrub, tree), and grazing interplay resulting in landscape evolution in arid environments. Authors could then attributes needs of a complex modelling approach to the complex interactions involved and unpredictable landscape responses rather than limited data as stated in the paper. The objectives and aims focus mainly on the point of model improvement and could be made more generic to attract wider audience. The significance and value of this study in terms of scientific understanding and practical use should be clearly stated.

We thank the referee for their concern on the framing of the research and for the justification of our work on integrated vegetation-grazing-sediment transport model. We recognize the need for a clarification of the context around our work and the justification of the research goal. The non-linearity and capacity to produce emergent patterns from the interactions between the vegetation, sediment transport and grazing are one of the primary reasons we chose to use complex models in our research. Additional descriptions of the dynamics and interactions taking place between the vegetation, the sediment transport and the grazing were added in the introduction in order to help the reader understand the need for using a complex model. The context section of the original manuscript has also been integrated in the introduction to help link the theory on the dynamics observed in arid environments and the application of those dynamics in models.

2. Context: authors discuss various models. It would be useful to summarise the pros and cons of these modelling algorithms into a table for easy comparisons.

We thank the referee for their suggestion of a comparison table between the different models discussed in the introduction and context. The complete rewording and merging of the introduction and context sections have allowed for a simpler and more thorough presentation of previously published models to the point where we do not think a table would provide much more clarity than what is now given in the manuscript.

3. Methods: It is not very clear the translation processes and the justification between physical variables in reality and parameters used in the model. For example, significant height of vegetation, iteration number of grazing event length, etc. Also, some important details are missing. For example, authors states that the score to determine the location of grazing agents is determined by a sensitivity test. But the exact process and the criteria used are not clear. The results show that different types of vegetation (grass, shrub, tree) are considered in the model, but it is not clear in the methods how effects of vegetation types are executed in the algorithm. The definition of some terminology used in the model is not clear, for example, sediment balance stress. It would be also useful to review the fundamental algorithms (in particular, interaction between sediment transport and vegetation) before detailing the two updates so that readers are more easily to understand these changes.

We thank the referee for their comment on the clarity of the explanation of the model algorithm. We agree that part of the model might not be completely clear for the reader, since the ViSTA_GrAM model is expanding on the ViSTA_M17 model (Mayaud et al., 2017). A summary of the ViSTA_M17 model algorithm was added to the method section to help the reader understand the workings of the model ViSTA_GrAM as a whole. Some more advanced details of the ViSTA_M17 model might have been overlooked in the submitted manuscript, because it is explained in a previous article on the ViSTA_M17 model. That being the case, we agree with the reviewer that some of the variables coming from the ViSTA_M17 model could benefit from additional explanation in the manuscript. This addition has allowed us to recontextualize the use of each of these variables and explain their relation to the real world. The significant height of the vegetation is one example of these variables originally linked to the ViSTA_M17 model implementation, but that also plays a role in the implementation of ViSTA_GrAM. The short explanation of this variable is that it represents the minimal height of the vegetation for it to influence the capacity of the wind to erode sediment under that vegetation. This variable is then directly tied with the way the ViSTA_M17 model is related to vegetation growth. The iteration number of grazing event lengths, on the other hand, is a new variable introduced within the ViSTA_GrAM model to help represent the time scale of the grazing event. It is an equivalent in "real world" time to the number of model iterations executed each time the GrAM function is called. We have added more emphasize on the definition of the terminology used and gave further direction for the reader to relevant original publications in the method section to eliminate confusion about the working of the introduced model.

4. Discussion: although authors compared impacts of individual components with literature, it is still not entirely clear how realistic the modelled scenarios and responses of each component are as a whole system.

We thank the referee for this concern about the realism of the model ViSTA_GrAM and its performance as a whole system. We think this can be answered in a similar fashion to the first referee concern about the lack of real-world environment to comparison with the model comparison. A better contextualization of the simulations in the manuscript and a better formulation of what those simulations are representing have been added and will give the reader a better context around the conclusions that are drawn from these simulations. The research presented in the manuscript is a first step toward a more integrative approach to the study of arid environment shift. The simulations presented in the manuscript are considered of both exploratory simulations as well as realistic case studies. However, we must recognize in that context that the model response as a system will overlook some systemic dynamics of the arid environment, since some of the environmental variables are parameterised (like many complex model applications). In summary, we have expanded the method section to better contextualize the simulations and expanded the discussion on the response of the whole system.

L31: Please expand to clarify how 'these processes' modify landscapes and climatic variables, how these processes interact with each other.

"These processes" have been changed to specifically define the persistent transport of sediment in arid environments. The section about the modification of climatic variables was removed from this sentence to allow be defined in more depth at line 39.

L34: Not clear what ‘imbalance between climate and herbivory’ means. ‘Climate’ is too vague term, please clarify.
The word “climate” was changed to specify the rainfall and the wind speed as the two main “climatic” parameters evaluated in this study.

L36: Authors only talked about wind erosion, and missed the associated sand deposition processes which could be important to vegetation growth as well.
The line was reframed to present a more inclusive approach to the sediment transport influence on the vegetation growth.

L42: wind transport using empirical approaches itself has intrinsic limitations. Please discuss the relevant literature.
We agree that the wind transport studies using empirical approaches have intrinsic limitations that might justify the use of complex modeling to complement them. We added additional explanations of the spatial and temporal limitations of wind transport representation using empirical approach (with relevant literature) at line 45.

L85: The integration of grazing activity into a CA model has been employed in Yan N. and Baas A.C.W. (2018) Transformation of parabolic dunes into mobile barchans triggered by environmental change and anthropogenic disturbance. Please revise the text accordingly.
The text was revised to consider the proper capacity of the DECAL model in our revision of the work similar in approach to the current study. We apologize for the overlook of the 2018 version of the DECAL model and its capacity to represent grazing in dunes fields.

L90: An overview of modelling algorithms should be included.
A short description of the original ViSTA model was added at the beginning of the method section (line 89-119). The reader can access the original publications on the model ViSTA_M17 itself for a deeper understanding of algorithm since it would not be appropriate to duplicate the entirety of the explanations of the original ViSTA model in this manuscript.

L120: how the time scale is defined? How the iteration numbers of each grazing event are determined?
We specified the nature of the time scale parameters in the method section to eliminate doubt from the reader around their provenance. The time scale of the grazing events can be defined by a user through the SETUP file.

L125: how the stocking rate was defined? What the number means in reality?
The stocking rate is also defined by the user in the SETUP file of the model. The stocking rate is defined as a ratio between the number of grazers present on a pasture and the surface of the pasture as discussed in the methods section.

L136: how the cell was chosen for grazing agents?
The explanation of the grazing agent movement was expanded in the text to add clarity. The movement of grazing agents is determined mainly through a decision function. Once a score has been attributed to each cell via the decision function, a single cell is randomly chosen among the array of cells with the highest score.

L156: Authors states that the score to determine the location of grazing agents is determined by a sensitivity test. But the exact process and the criteria used are missing.

The sensitivity test around the score to determine the grazers' location were qualitative tests looking at the impact of each factor of decision guided by existing literature. We wanted to make sure that the decision factor for a grazer's direction was not unbalanced to the point of creating a deterministic decision-making process. We added explanation about the tests and the criteria used in the text at line 185.

L191: Explain what exactly processes involved when sediment balance stress or vegetation dynamic is used in the model? It is not clear to me how they are executed in the model.
We expanded the description of the sediment balance stress and the vegetation recolonization to improve its explanation. The sediment balance stress is a modifier to the probability of survival of the vegetation. The value of the modifier applied to the vegetation survival probability is determined as a function of the annual sediment balance. This function is inspired by the DECAL model vegetation growth process and was already explained in the original publication of the ViSTA_M17 model. The vegetation recolonization dynamic refers to the process of decision around the type of vegetation (grass/shrub/tree) that will colonize a bare cell.

L203: I don't understand how sediment balance stress is executed in the model without considerations of windspeed. Please clarify the definition of sediment balance stress, is it independent of sediment transport?
See answer to comment on L191 above.

L209: please justify 6 month updating time. It seems quite long considering the growth of grasses.
The 6-month update was originally chosen to optimize the simulation time of the model, considering that the time scale chosen for the vegetation must accommodate the grass, the shrubs and the tree growth period. We further justified the updating time of the vegetation in the manuscript at line 250.

L231: how growth of grass, shrub, and trees are controlled by the model? Do the different types of vegetation interact with each other?
We answered this comment in combination with the general comment #3 and the comment of line 90 above, please see corresponding responses to those comment for more information.

L236: what do you mean 'more responsive to rainfall'?
We mean by that phrasing that the difference of the responses of the model to rainfall regime is more apparent with SDa simulations compared to FD simulations.

L274: why stocking rate is only tested with SDa3 simulation?
The stocking rate was only presented in the SDa3 simulations because these simulations were the most appropriate to the observation of grazing activities and to available previous literature environments (e.g., Kalahari). The other types of simulations were mainly designed to inform the extent to which the ViSTA_GrAM model could be applied to semi-arid environment supporting grazers. A general reframing of the manuscript and the modifications given through our responses to the other general comments of the referee allow to better contextualize why the grazing only appear in the SDa3 simulations. We think the clearer statement of the study goals and context of application given in the revised manuscript will help the reader understand the choice of the SDa3 simulations as being the only one with grazing applied.

L312: 'good sensitivity', please specify the criteria?
We thank the referee for this comment regarding the validity of the terms "good sensitivity" in this context. The term was used in reference to the comparison, between the ViSTA_GrAM results and the

results of other studies, that is made in the discussion section. To better present the section, this sentence was modified at line 357.

L391: please expand in more detail.
We have rephrased this sentence to allow for a better development of this statement. See line 438-443.

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 ~~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~~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 ~~highlights~~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 ~~represents an important improvement for managing arid landscapes over the previously available tools.~~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 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 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 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.

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.

~~3~~2 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 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 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 beThe 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 precipitations, 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 sediments 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-sediments 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).

~~3.2~~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 ~~was revamped by the ViSTA_GrAM model~~is used to define when the GrAM module is called in sequence within the main portion of the ViSTA_M17 model. ~~A new~~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.~~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 ~~in~~into two~~ in order~~ 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 ~~make the decision of~~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 ~~in~~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 ~~makes the choice of~~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 ~~have~~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 ~~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~~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) ~~and would allow~~, 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, ~~in order~~ to limit the ~~amount~~number of user inputs and calibration necessary to its application.

~~3.3~~2.3 Model applications: simulation ~~definitions~~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. 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 (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).~~ 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 creates 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 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 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 ~~offer a~~offers good comparison for the three other rainfall regimes. ~~This range of~~ These rainfall regimes ~~is selected to allow for the~~where applied as a constant and uniform source of humidity in our representation of ~~multiple~~theorical environments ranging ~~from~~for semi-arid grasslands ~~to tree~~and savannas. No windspeed was applied ~~on~~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 ~~Living Stocking Unit (~~LSU~~)~~ ha^{-1}, along with a control simulation where no grazers were introduced, ~~is~~are applied. ~~In order~~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 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~~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 ~~dynamism~~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.

~~4.1~~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~~ 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 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. ~~most dynamic simulation type, the~~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~~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 ~~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 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). 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. ~~In particular, at~~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~~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 55^{th} 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~~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 ~~a~~the natural degradation of the environment. With the addition of grazing agents in the SDa3 simulation, no large ~~effects~~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 ~~have no effect on~~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 1.85×10^5 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 patches 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~~are not pronounced enough to be significant but ~~suggests~~suggest the possible effect of greater vegetation degradation on simulations.

~~5~~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 ~~state~~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 ~~good sensitivity~~general agreement between published results of other studies and the model response to ~~variation~~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.

~~5.1~~4.1 Vegetation dynamics

~~A poor proportion~~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 ~~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 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., 2017b). These results are not representative of all types of semi-arid environments.~~(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 ~~opposite~~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 ~~be applicable~~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 ~~on~~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 ~~model~~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 ~~of~~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.

~~5.2~~4.2 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).~~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 an 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.

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~~5.3~~4.3 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.~~, 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 ~~could exponentially increase (Bhattachan et al., 2014).~~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).~~(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~~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.

~~5.4~~4.4 Grazing

Grazing is a type of disturbance ~~and is generally approached as having a negative impact on the environment; expected to present~~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 ~~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 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 ~~is able to~~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 ~~compensation~~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 ~~is~~are 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~~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 ~~highlight~~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 ~~environment. ~~environments.

~~6~~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. ~~The sensitivity of the vegetation to 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 interactionsSeries 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 introduced ViSTA_GrAM model presents a realisticin its current state still has some limitations, notably concerning his representation of the environmental dynamics taking place in 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 and demonstrates favourable opportunities to improve the studies of landscape vulnerabilities to climate change. Future, future work wouldshould include the horizontal saltation flux as an output, introduce several grass species growth response curves, and calibrate the model against more empirical data. ByWith further developingdevelopment 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 available field data and plan for future data collection strategiesour 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 a 5-year period5 years, while similar landforms are normally formed over 100-year years to 1000-year period 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 ~~a~~ 5~~-year period~~ 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 ~~surfaces~~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 ~~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.

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.

Acknowledgements

This research was fully funded through the Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery Grants awarded to second and third authors. We would like to thank Jerome Mayaud for his permission to access the original model and Calcul Québec for access to their computing resources. We would like to thank comments made by two anonymous reviewers and the editor that greatly improved the manuscript.

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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-DynamicNondynamic **(ND)**	Sediment balance stress **off** Recolonization dynamic **off**

Table 1: Description of the parametrization of simulations testing the impact of vegetation dynamicdynamics 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.

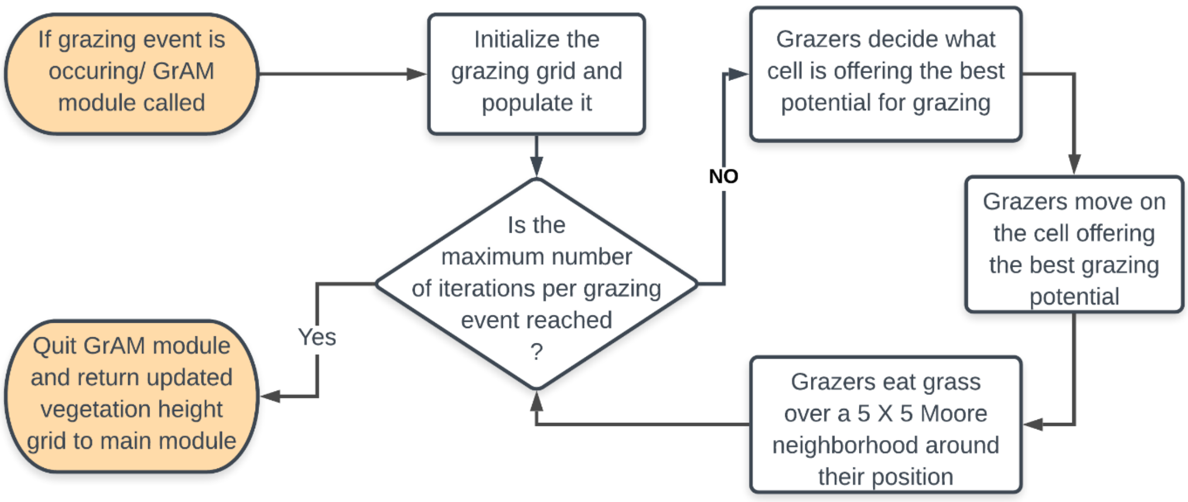


Figure 1: ~~**GrAM Flowchart**~~**Flow diagram summarizing the main behaviours of the grazers agent in the GrAM module.**

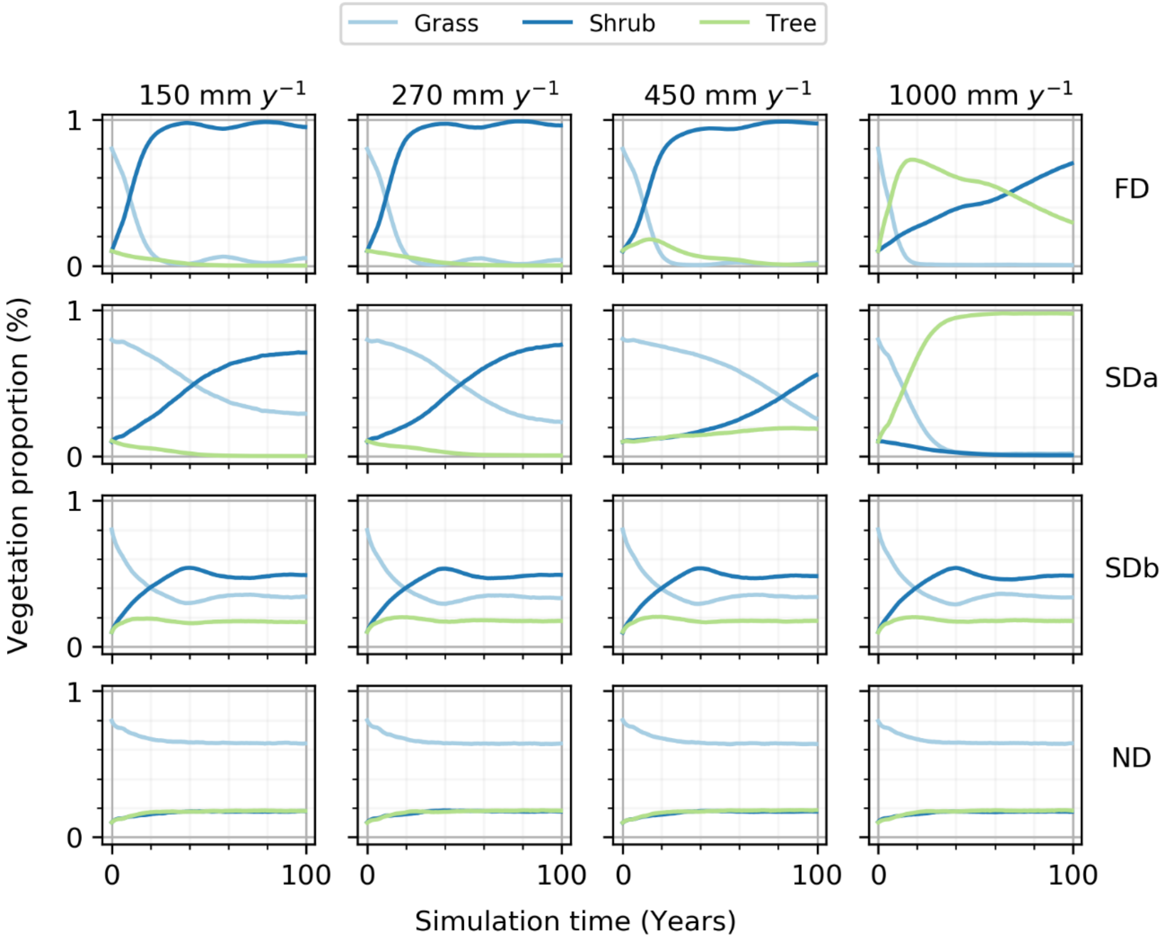


Figure 2: Time series of the proportion of the simulation grid occupied by each vegetation type during simulations. ~~**See Table 1 for more information about the simulation configuration.**~~**The fully dynamic simulations (FD) represent environments where the vegetation is sensitive to a sediment balance 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.**

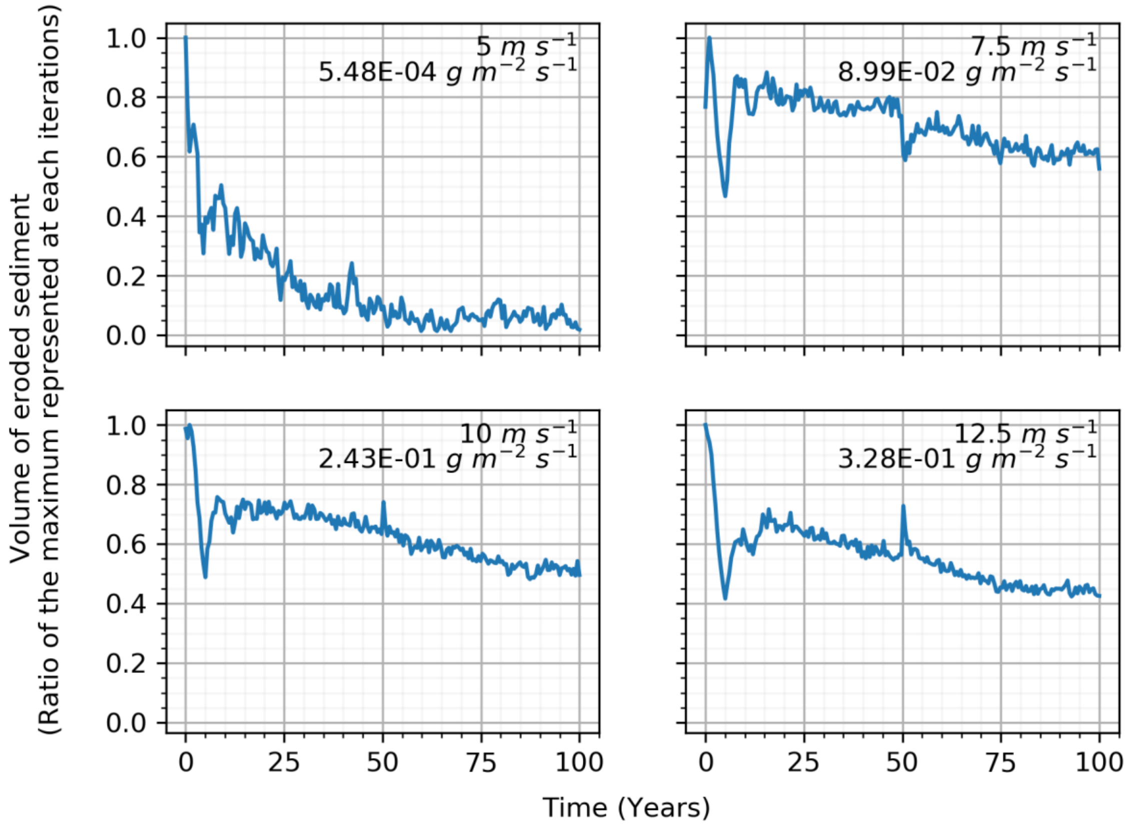


Figure 3: Time series of eroded sediment volume and the mean erosion rate of 5-year simulations with different windspeeds.

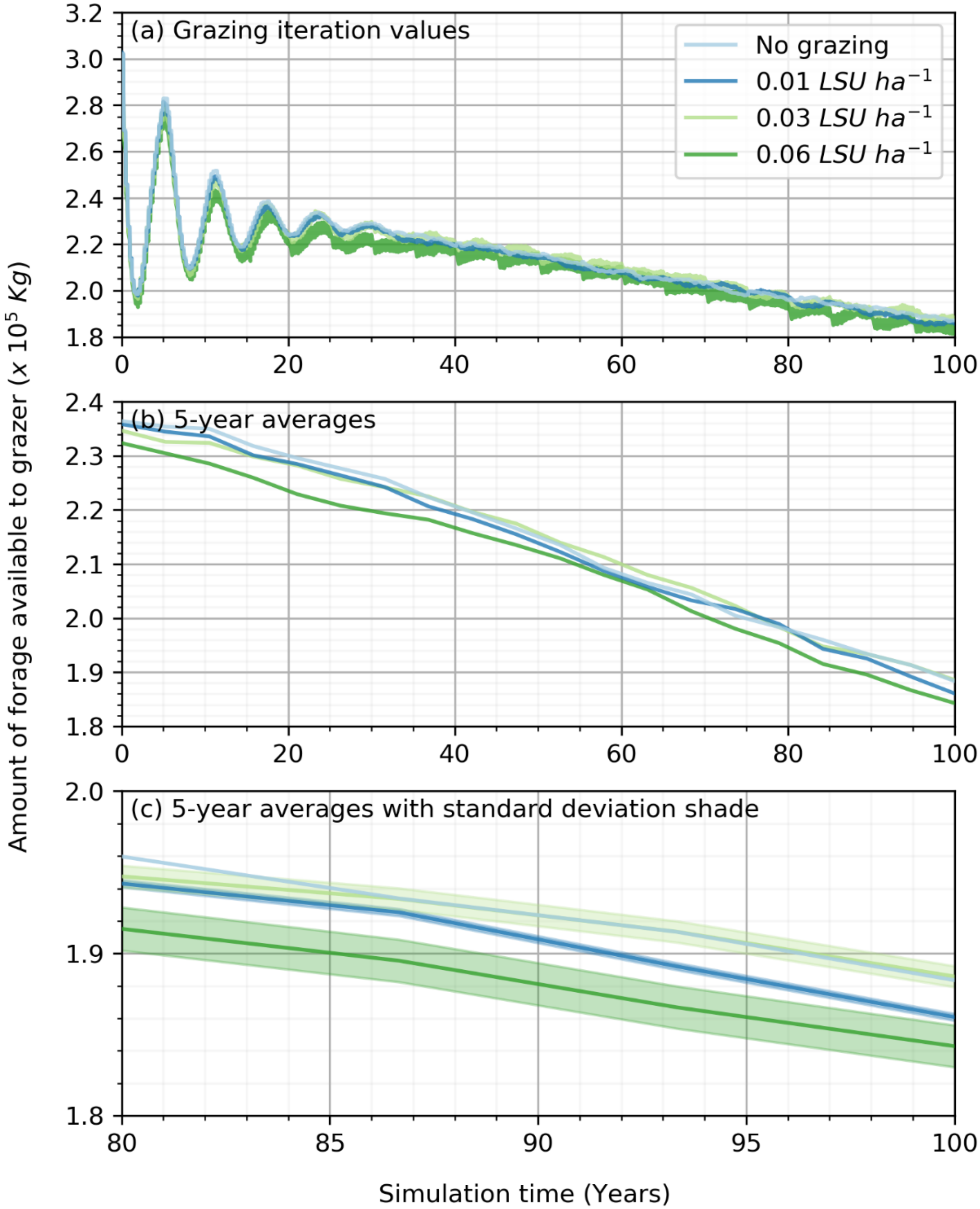
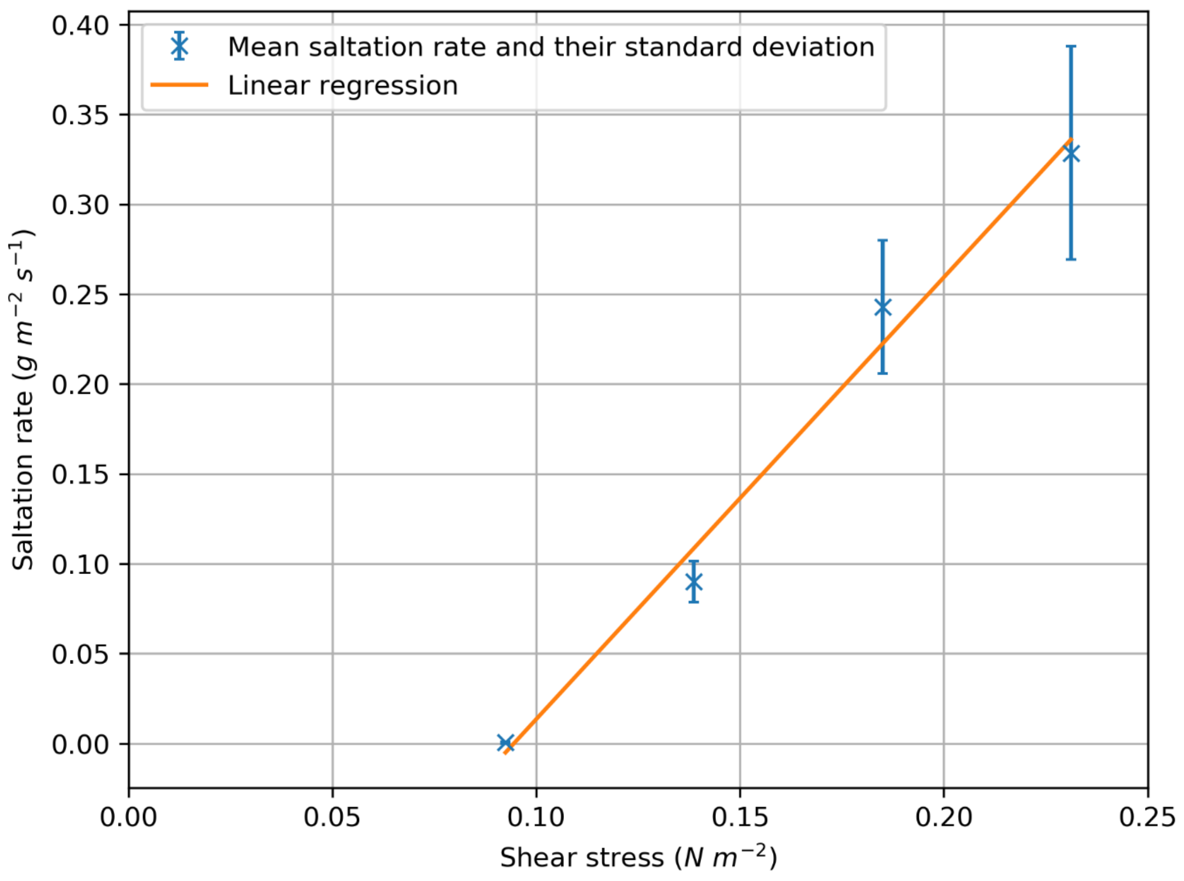


Figure 4: Time series of the available amount of forage available to grazers on the simulation grid.


Mean saltation rate and their standard deviation
Linear regression
Saltation rate ($g\ m^{-2}\ s^{-1}$)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.05
0.10
0.15
0.20
0.25
Shear stress ($N\ m^{-2}$)

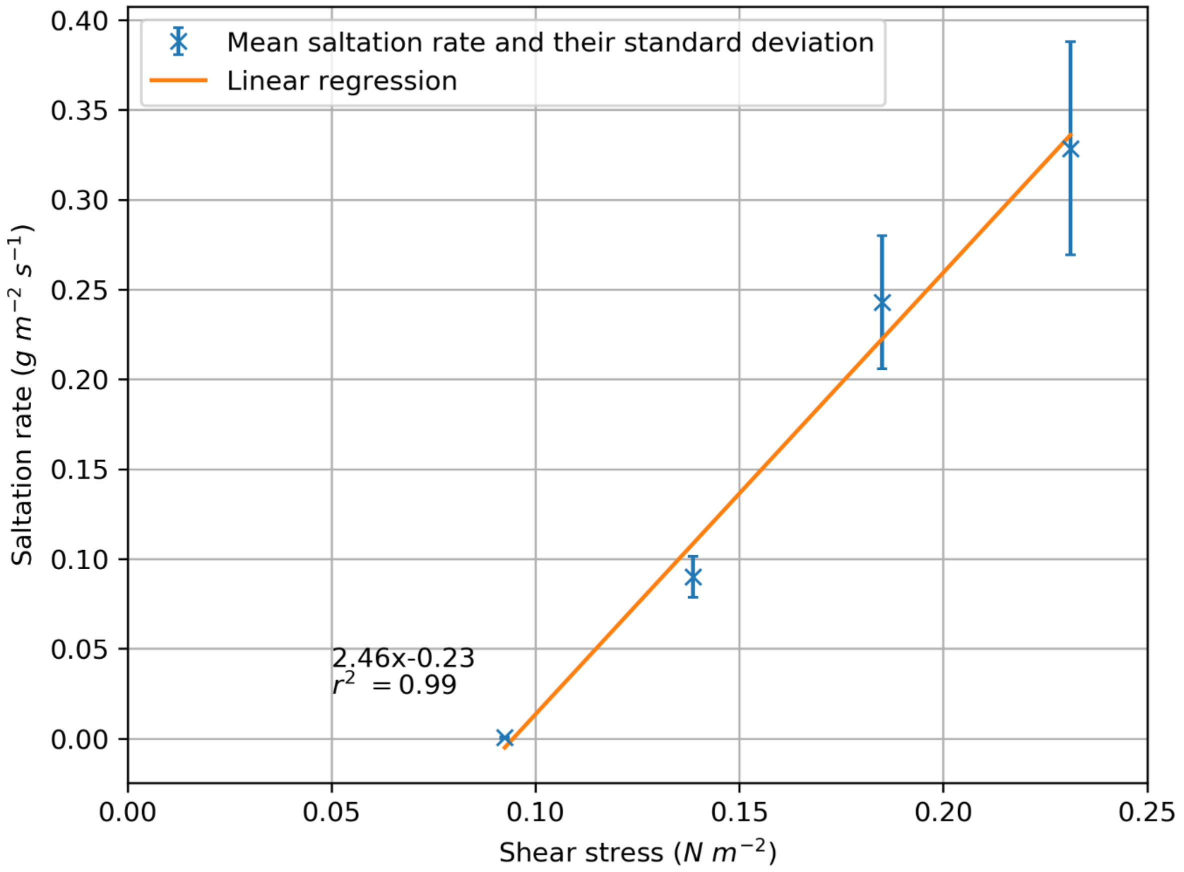


Figure 5: Relation of the mean saltation rate and their standard deviations with shear stress. (p-value = $6.59*10^{-3}$).

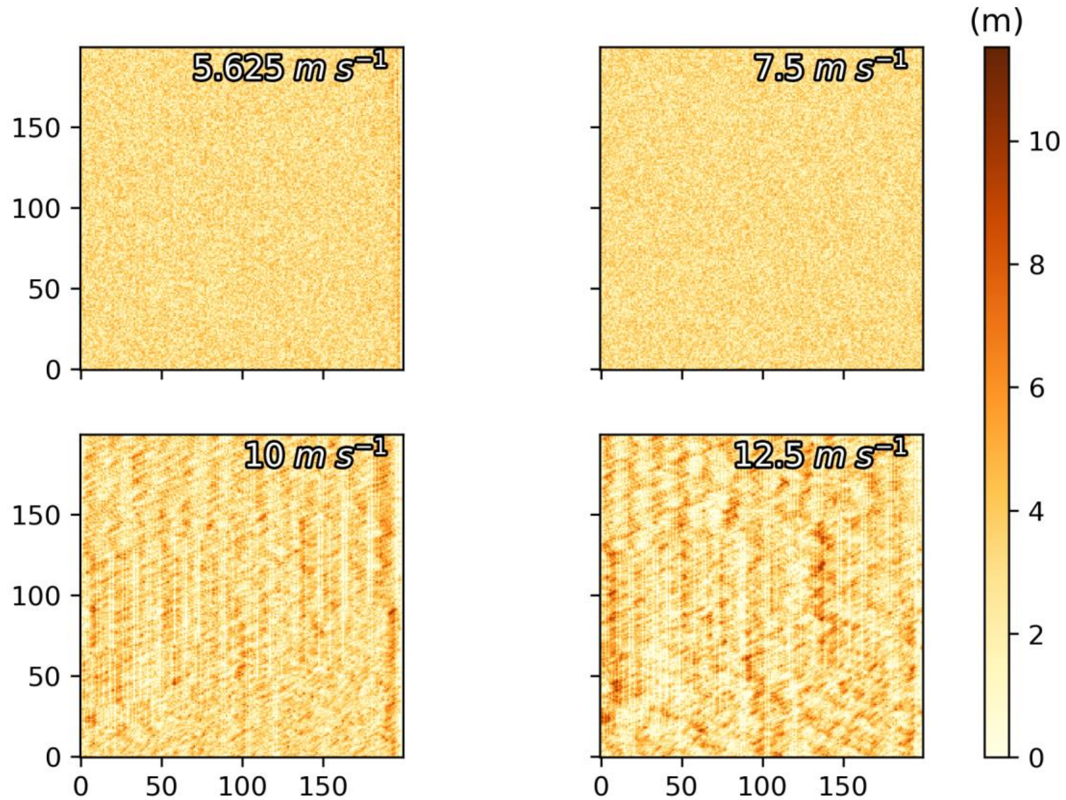


Figure A1: Final sediment height representation of 5-years simulations with different windspeeds

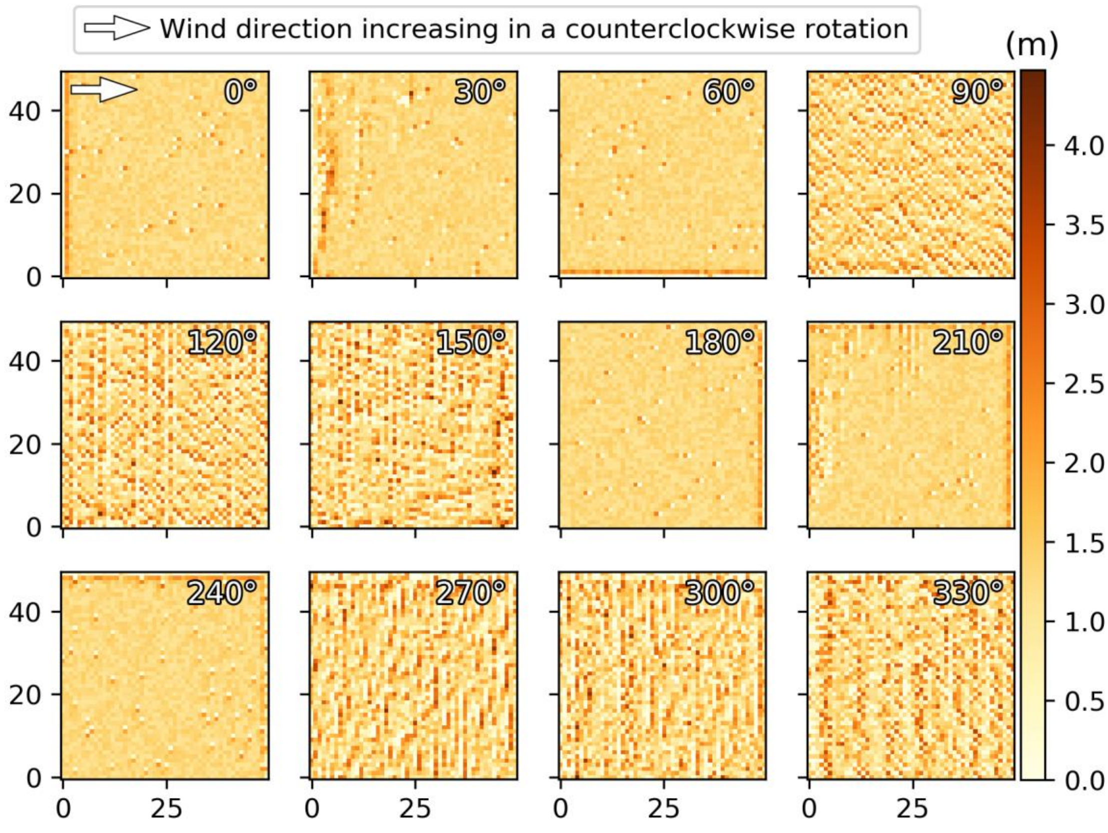


Figure A2: Final sediment height representation of 5-years simulations with different wind angles.

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 ~~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~~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 ~~highlights~~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 ~~represents an important improvement for managing arid landscapes over the previously available tools.~~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 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 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 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.

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.

~~3~~2 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 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 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 beThe 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 precipitations, 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 sediments 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-sediments 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).

~~3.2~~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 ~~was revamped by the ViSTA_GrAM model~~is used to define when the GrAM module is called in sequence within the main portion of the ViSTA_M17 model. ~~A new~~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.~~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 ~~in~~into two~~ in order~~ 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 ~~make the decision of~~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 ~~in~~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 ~~makes the choice of~~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 ~~have~~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 ~~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~~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) ~~and would allow~~, 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, ~~in order~~ to limit the ~~amount~~number of user inputs and calibration necessary to its application.

~~3.3~~2.3 Model applications: simulation ~~definitions~~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. 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 (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).~~ 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 creates 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 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 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 ~~offer a~~offers good comparison for the three other rainfall regimes. ~~This range of~~ These rainfall regimes ~~is selected to allow for the~~where applied as a constant and uniform source of humidity in our representation of ~~multiple~~theorical environments ranging ~~from~~for semi-arid grasslands ~~to tree~~and savannas. No windspeed was applied ~~on~~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 ~~Living Stocking Unit (~~LSU~~)~~ ha^{-1}, along with a control simulation where no grazers were introduced, ~~is~~are applied. ~~In order~~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 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.

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

4.13.1 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 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. most dynamic simulation type, theThe 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~~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 ~~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 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 8.99×10^{-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. ~~In particular, at~~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~~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 ~~represent~~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 ~~a~~the natural degradation of the environment. With the addition of grazing agents in the SDa3 simulation, no large ~~effects~~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 ~~have no effect on~~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~~ 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 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 ~~is~~are not pronounced enough to be significant but ~~suggests~~suggest the possible effect of greater vegetation degradation on simulations.

~~5~~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 ~~state~~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 ~~good sensitivity~~general agreement between published results of other studies and the model response to ~~variation~~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.

~~5.1~~4.1 Vegetation dynamics

~~A poor proportion~~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 ~~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 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., 2017b). These results are not representative of all types of semi-arid environments.~~(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 ~~opposite~~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 ~~be applicable~~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 ~~on~~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 ~~model~~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 ~~of~~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.

~~5.2~~4.2 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).~~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 an 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.

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5.34.3 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., 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 could exponentially increase (Bhattachan et al., 2014).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).(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~~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.

~~5.4~~4.4 Grazing

Grazing is a type of disturbance ~~and is generally approached as having a negative impact on the environment; expected to present~~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 ~~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 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 ~~is able to~~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 ~~compensation~~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 ~~is~~are 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~~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 ~~highlight~~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 ~~environment. ~~environments.

~~6~~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. ~~The sensitivity of the vegetation to 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~~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 ~~introduced ViSTA_GrAM~~ model ~~presents a realistic~~in its current state still has some limitations, notably concerning his representation of the ~~environmental dynamics taking place in~~ 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~~ and demonstrates favourable opportunities to improve the studies of landscape vulnerabilities to climate change. Future~~, future work ~~would~~should include the horizontal saltation flux as an output, introduce several grass species growth response curves, and calibrate the model against more empirical data. ~~By~~With further ~~developing~~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 ~~available field data and plan for future data collection strategies~~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 ~~a 5-year period~~5 years, while similar landforms are normally formed over 100~~-year~~ years to 1000~~-year period~~ 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 ~~a~~ 5~~-year period~~ 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 ~~surfaces~~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 ~~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.

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.

Acknowledgements

This research was fully funded through the Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery Grants awarded to second and third authors. We would like to thank Jerome Mayaud for his permission to access the original model and Calcul Québec for access to their computing resources. We would like to thank comments made by two anonymous reviewers and the editor that greatly improved the manuscript.

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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-DynamicNondynamic **(ND)**	Sediment balance stress **off** Recolonization dynamic **off**

Table 1: Description of the parametrization of simulations testing the impact of vegetation dynamicdynamics 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.

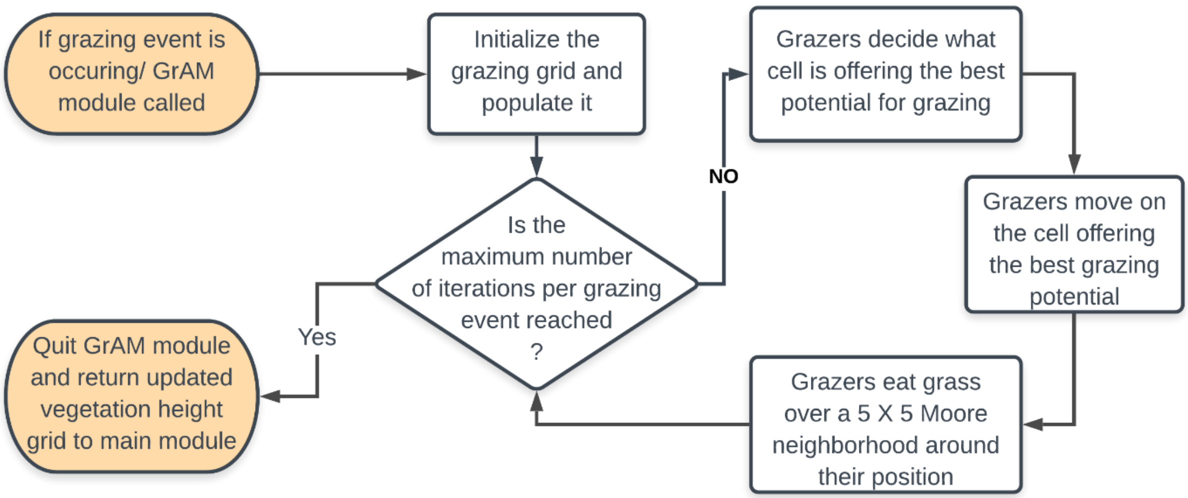


Figure 1: ~~GrAM Flowchart~~Flow diagram summarizing the main behaviours of the grazers agent in the GrAM module.

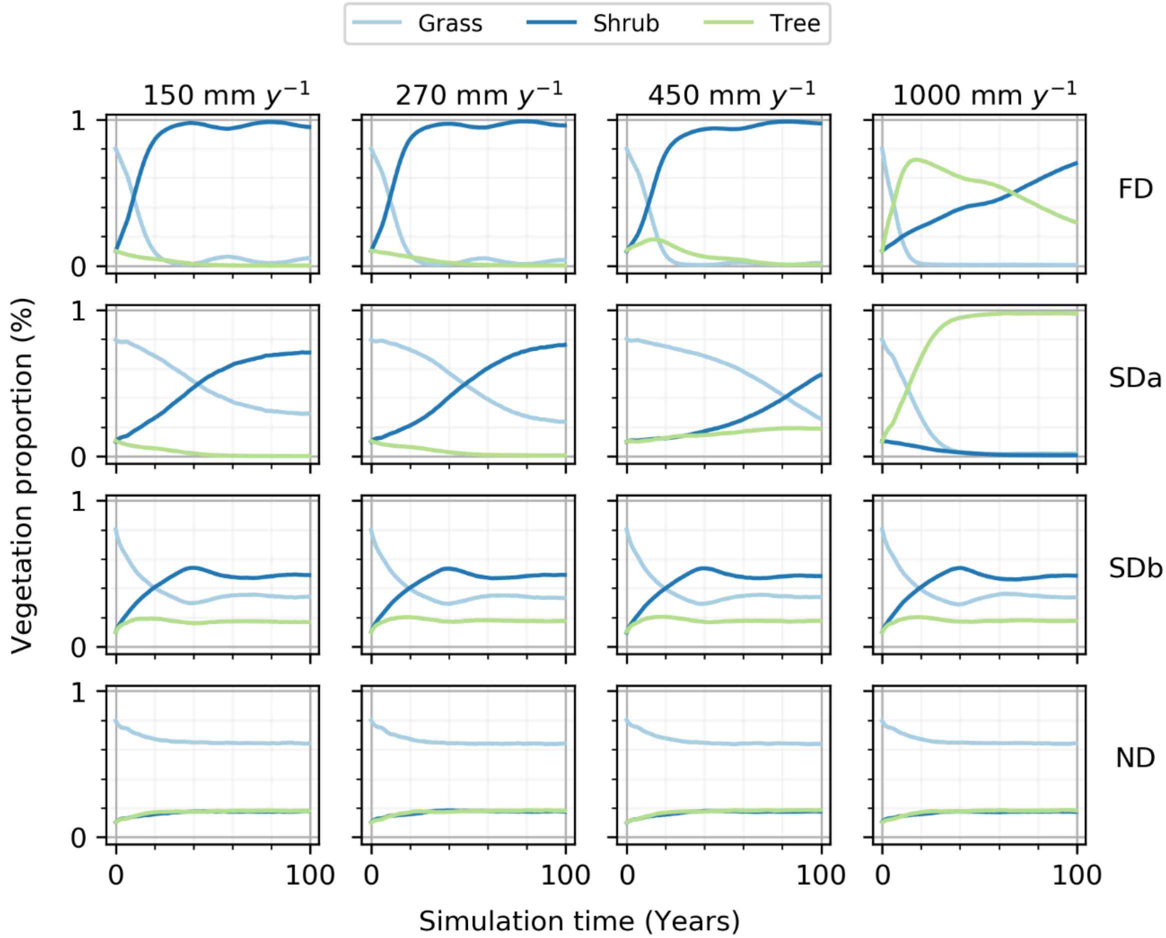


Figure 2: Time series of the proportion of the simulation grid occupied by each vegetation type during simulations. ~~**See Table 1 for more information about the simulation configuration.**~~**The fully dynamic simulations (FD) represent environments where the vegetation is sensitive to a sediment balance 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.**

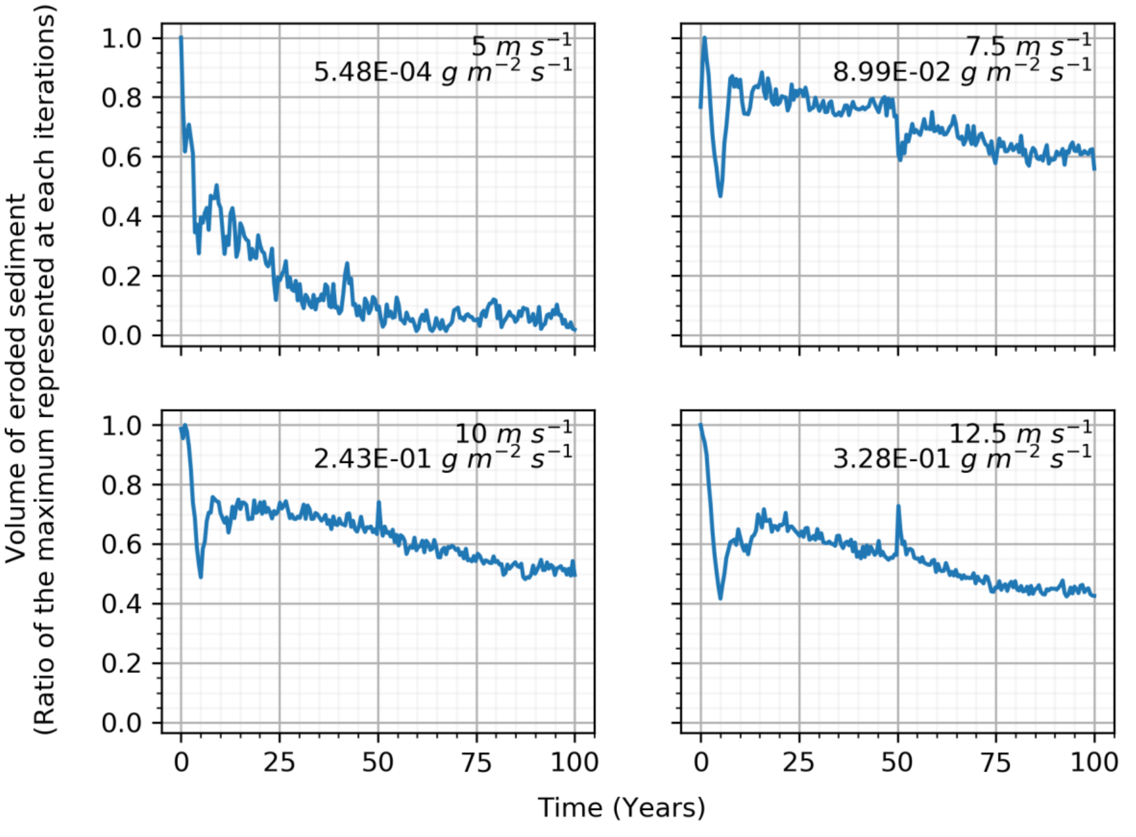
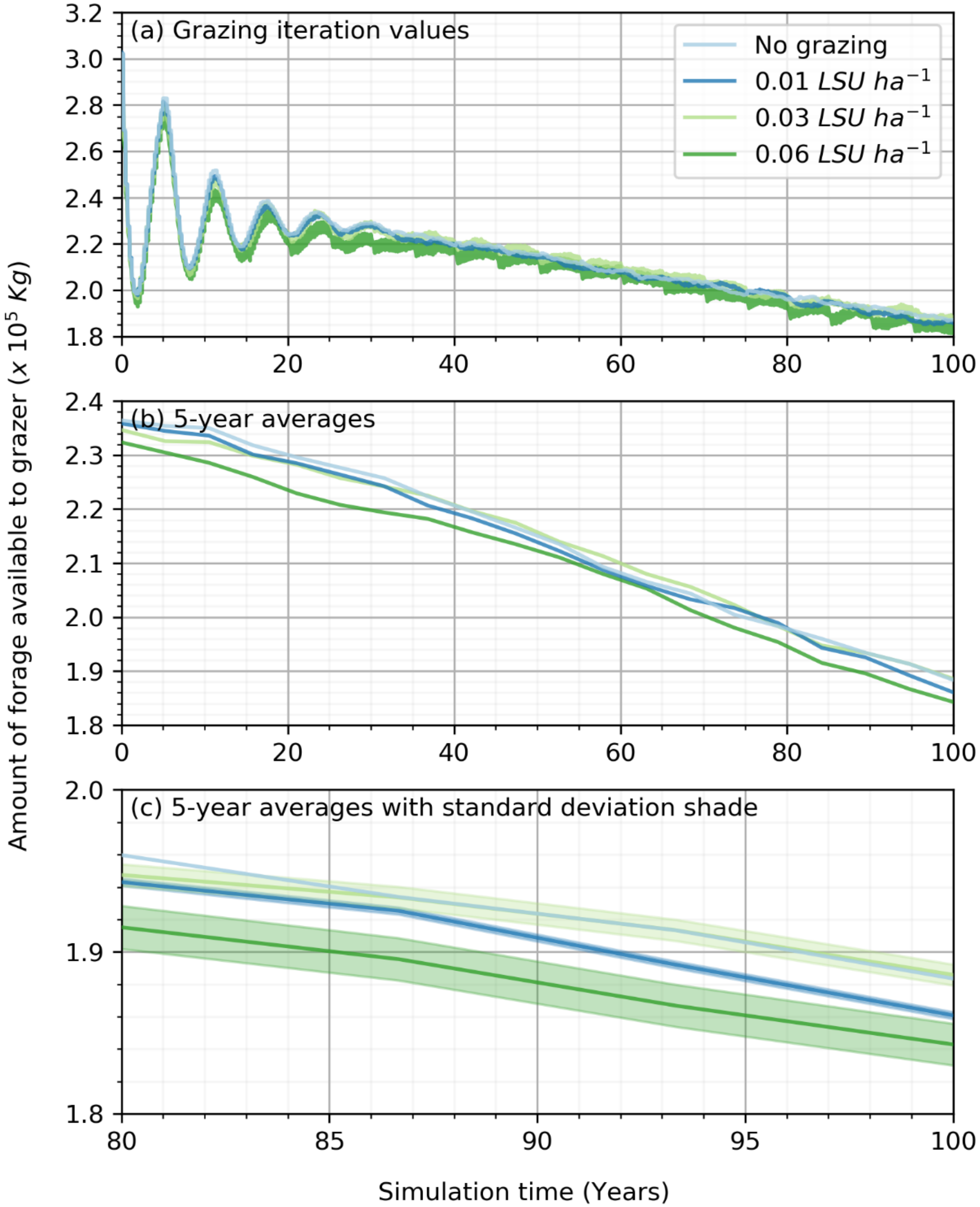
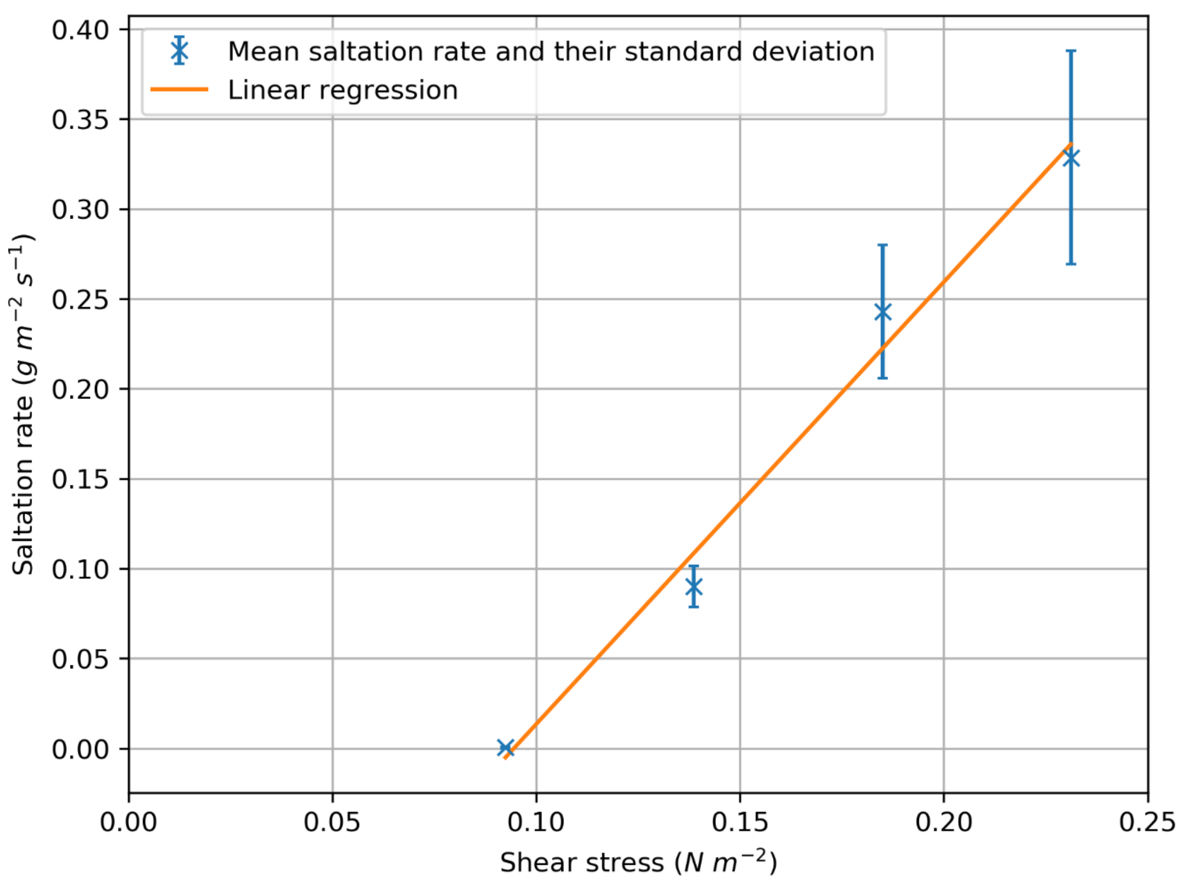


Figure 3: Time series of eroded sediment volume and the mean erosion rate of 5-year simulations with different windspeeds.



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


Mean saltation rate and their standard deviation
Linear regression
Saltation rate ($g\ m^{-2}\ s^{-1}$)
Shear stress ($N\ m^{-2}$)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40

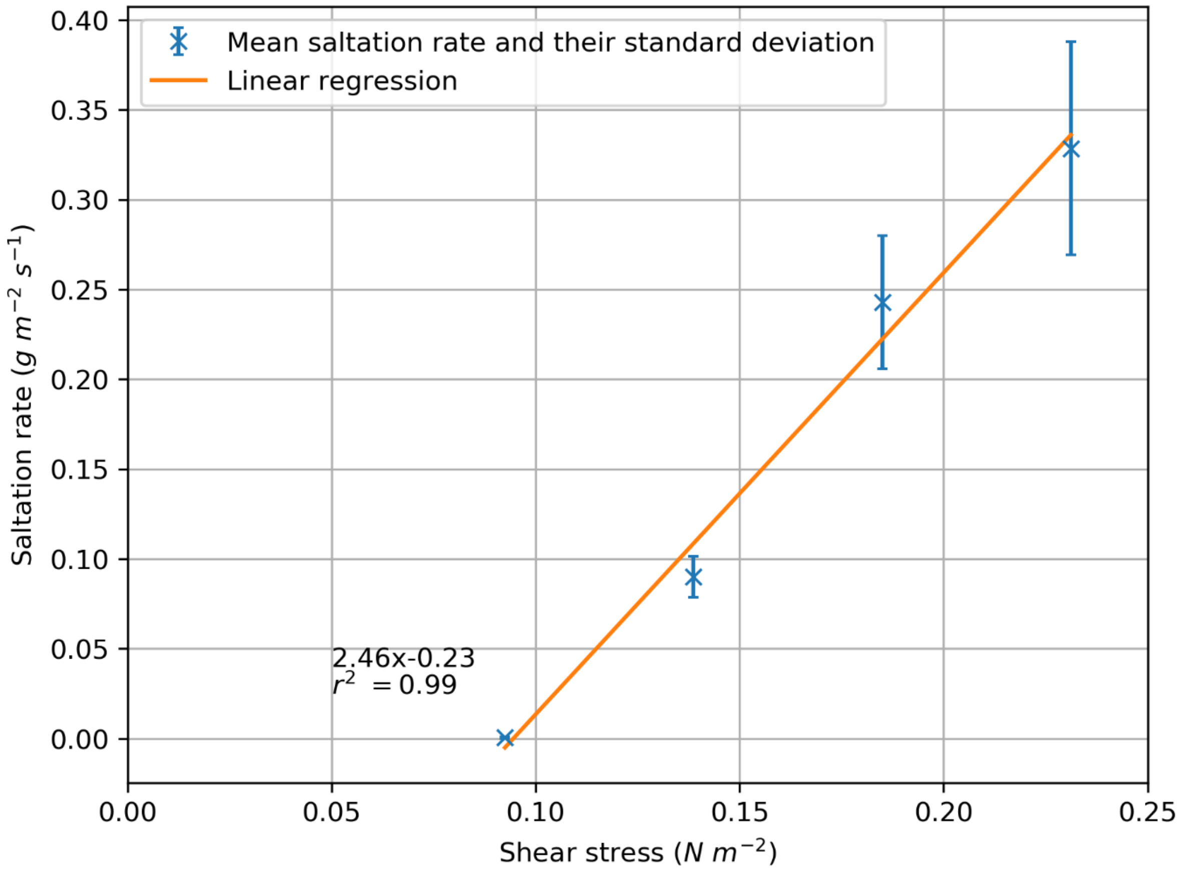


Figure 5: Relation of the mean saltation rate and their standard deviations with shear stress. (p-value = 6.59*10^{-3}).

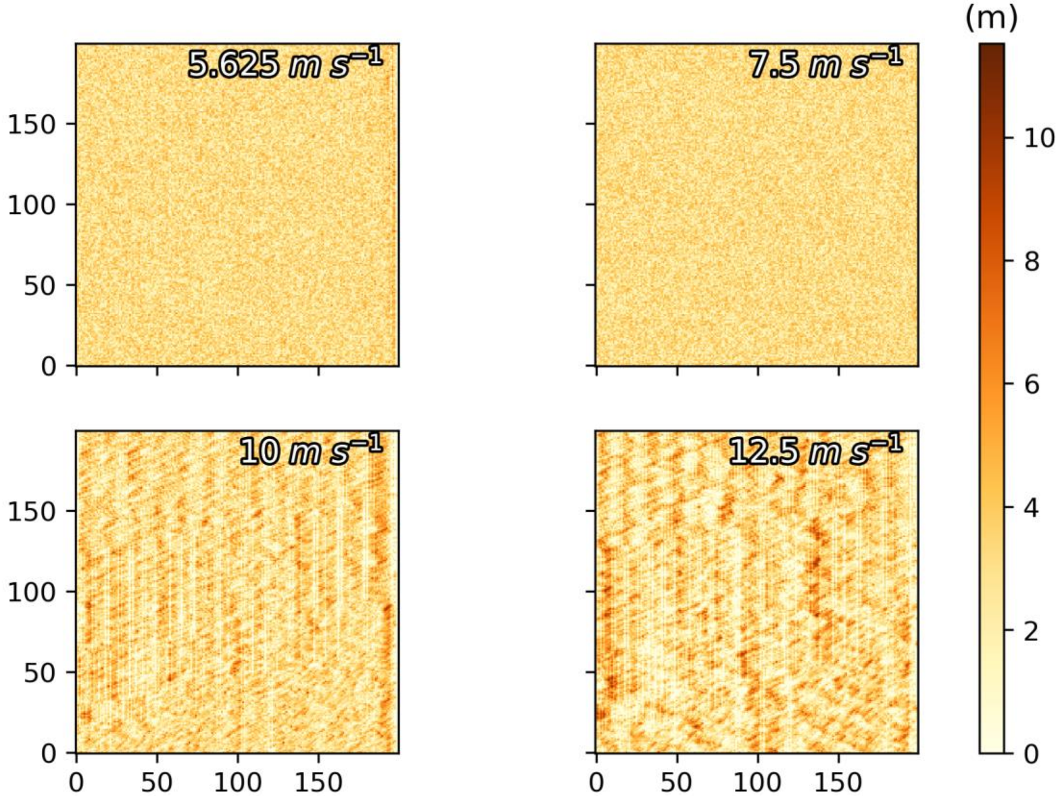


Figure A1: Final sediment height representation of 5-years simulations with different windspeeds

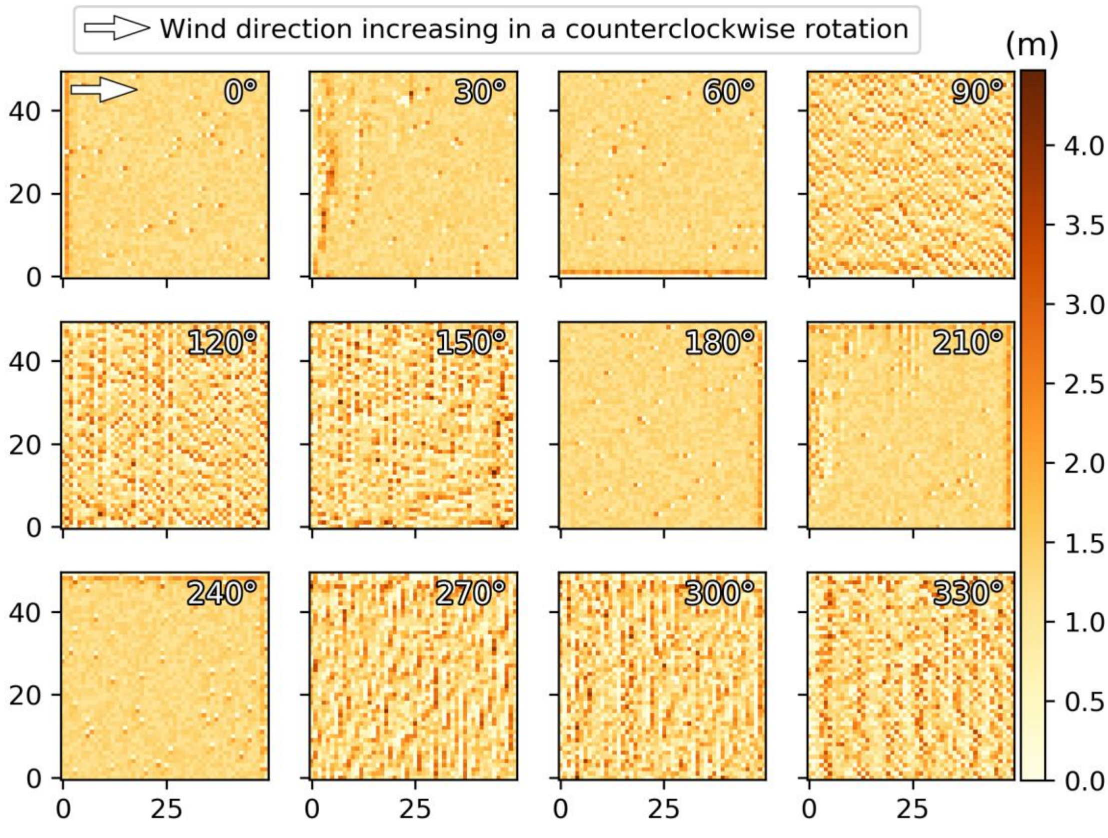


Figure A2: Final sediment height representation of 5-years simulations with different wind angles.