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Earth Surface Dynamics Discussions
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Interactive comment on "Exploring the sensitivity on a soil area-slope-grading relationship to changes in process parameters using a pedogenesis model" *by* W. D. D. P. Welivitiya et al.

Reply for the comments from Anonymous Referee #1 in italic font

General comments

This is a nicely written and well-conducted model study that fits well in ESurf. The au- thors present a sensitivity analysis of the pedogenesis model SSSPAM5D. The results are quite interesting and have important implications for understanding the spatial vari- ability of soil properties in the landscape. I only have two minor concerns. The first is that the setup is relatively simple: straight, planar slope and a relatively limited One- At-a-Time sensitivity analysis, but given the computational demands of the model, this is understandable and hard to work around at this point. Another minor concern is that in this model, there is no feedback between evolving soil properties and runoff rate that controls erosion (Equation 4). Basically r is fixed by the authors. It would be very

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interesting for future work to have some kind of feedback between infiltration rate or saturated hydraulic conductivity or soil water holding capacity and r. For this paper, I would be happy if the authors could include a minor discussion point on this matter. In conclusion, the quality of this paper is excellent and I believe that the point made by the authors, that these results confirm the generality of the area-slope-d50 relation, is important and holds significant implications for geomorphology and soil science. It is definitely a very interesting study to publish in ESurf. Apart from my two minor concerns, I only have some specific comments for the authors to take into account, see below. I also believe the number of figures and tables is quite high and could be reduced. My recommendation is therefore minor revisions in order to streamline the presentation of the results to the reader, by eliminating a few figures and explaining a few statements in the text better.

General Reply

First of all the authors would like to thank the referees for expending their valuable time and energy to review our manuscript. We also greatly appreciate the constructive criticism and the comments of the referees very much. The authors will consider all the comments and suggestions made by the referees and accommodate them in the manuscript wherever it is possible.

In the general comments section the referee has expressed 2 minor concerns regarding the modelling setup. The first concern is the simplicity of the simulation setup where we used a planar slope and the parametric study where we changed a single parameter for each simulation. The second concern is that the model doesn't account for any feedbacks between the discharge rate, erosion and the infiltration. Authors do agree that the simulation setup is relatively simple. The objective of this manuscript is to analyze the robustness of the area-slope-grading relationship under different process parameters. In order to directly compare our parametric study results with previous work by Cohen et al. (2009,2010) we decided to use the same model setup used in those simulations. Using a planar hillslope was also due to the previous model setup and it's a easy way to create

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to understand what is going on. Because the erosion mechanism used is detachment-limited the erosion at one node is not impacted by erosion at upstream nodes, and only by the cumulative area coming from upstream and the local slope. Thus the geometry upstream (i.e. 1D hillslope versus 2D catchment; planar, convex and concave slope) does not impact on the erosion/incision at the node. In this way the model acts upon each node (pedon) individually. In this context the authors believe the simple model setup presented in our manuscript has enough complexity to explore the parameter space of the model.

As the referee suggested the infiltration rate can change with time due to the changing soil grading, particularly in the surface, in the armour layer. Since we are mainly interested in exploring the parameter space of the model and their influence on the soil reorganization, at this initial stage the feedback mechanisms between soil and infiltration has not been modelled. However the authors are in the process of combining the pedogenesis framework presented here with a landform evolution model in the future. The referee's suggestion will be taken in to account when the authors are formulating this coupled soil and landform evolution model.

Specific comments

- I like the S-A-d50 plots and the explanation of how to use them in figure 4. Just as a suggestions to make it more attractive, it would be nice to fill in the contours with colours (using the same scale for all figures makes comparison very fast)

-At the time of the preparation of the original manuscript the authors also discussed regarding using different colors for different contours. This would indeed improve the manuscripts appearance greatly in its online version. However the authors decided against using color contour lines due to 2 main reasons. The first is that if the manuscript is being printed in black and white the colors turned in to gray scale can be very hard to read. The other reason is the large difference in the d50 produced for different parameter simulations. In some simulations the d50 range is larger (eg:10-4mm) and in other cases it is very small (eg:0.5-0.01mm). in such cases assigning colors for contours (even the same scale) for the contour plots will not work because the colors will not change much from plot to plot. If we use different scales (as we have used in this manuscript) and assign

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different plots will have different color contours for the same value according to the scale.

-p.5 line 12-13: The authors can call their model as they will of course, but I am not quite sure if I agree with the 5 dimensions. Because a point-based model simulates 2 (or n) soil properties does not make it a 3D model (or n+3 model)? . Also: “depth down the soil profile”, why not just name it z and talk about the 3 spatial dimensions?

-The authors do agree with the above comment. The model itself is capable of modelling the soil evolution in a large number of points which can be spread in a spatial grid. Also the evolution of the soil profile gives the model a vertical dimension as well. With the other soil properties calculated by the model the authors thought the “5D” is justified. However to alleviate any concern on this matter the authors will change the name of the model to “SSSPAM” instead of “SSSPAM5D”

-p.8 use consistent writing of Shields criterion (if’ve found Shield’s, Shield and Shields in the text)

-*We have changed the wording to be consistent*

-p9 line 12: delete “and”: smaller particles, the cumulative. . .

-*the manuscript updated as per referee’s comment*

-p.9 lines 14-17: repeated from p8 line 15-17. I suggest to eliminate the former.

-the manuscript updated as per referee’s comment

-p. 10 lines 4-7: Is it important how you define the thickness of the armour layer?

-*typically the armour layer depth in the literature is about 2.5 times the diameter of the largest particle in the grading. Since the largest particle diameter of the soil grading we used is 19mm, the armour depth should be 47.5mm or higher. So we used 50mm as the thickness of the armour layer.*

-p.10 Eq4. Define r and x.

-p.13 The authors suddenly talk about chemical weathering here. Yet in paragraph
1.2 no distinction is made. I think it is important to mention this earlier and what the authors mention on p13, line 5 that “we do not explicitly model chemical weathering”.

-*The authors intention was to mention that we only model physical weathering in SSSPAM modelling framework but the dynamic reversed exponential weathering function can be used to define the weathering rate change through the soil profile. The sentence was clarified. See comments to reviewer 2 for more detail.*

-p.14 paragraph 3. Mention here what a and b stands for (see p 16, lines 14-17)

-in this context ‘a’ stands for the Actual measured soil grading and ‘b’ stands for the Synthetic bedrock grading derived from the actual soil grading. The authors do admit the notation is somewhat unclear and clarified in the revised manuscript.

- p14, line 28 gradings

-the manuscript was rectified

-p.18 lines 11-15. I can not see this in the mentioned figure. No mention of 1a and 2b, just 1 vs 2?

-*the authors did not present a separate figure to demonstrate that no matter the surface grading used, the final surface d50 values only depend on the subsurface grading used. This is because the final equilibrium figures are identical to that of the figure 5 with the all other parameters (eg: weathering rate) As the referee has pointed out the figure caption for the figure 5 is unclear it the final sentence should be changed to ;(left column) Ranger1a for surface,Ranger1b for subsurface and (Right column) Ranger2a for surface, Ranger2b for subsurface. The required changes will be done in the revised manuscript*

-p.18 lines 25-26. See one of my main concerns, that grading does not change the discharge/infiltration rate. Can the authors include a short discussion on this? Fine-textured soils will be more prone to crusting, coarse fragments generally promote water infiltration in addition to armouring the surface and reducing erosion. See a good review by Poesen and Lavee (1994, Catena) *is given in the reply to the general comments section. The authors will add a small discussion regarding this in the revised manuscript*

-p18 para- graph 5.2.2. What about changes in the intensity-frequency of events? Authors now only change the absolute amount of discharge. Would these conclusions hold when a time-varying behavior in the event series (with the same annual mean) is applied?

-*This is a really interesting and important comment. At the time of writing of this manuscript the authors did not consider the changes brought forward by intensity-frequency events. However at the moment the authors are testing a coupled soil and landform evolution model and performed some simulations with constant discharge and some simulations with a lognormal distribution of discharge values with the mean value being the average discharge at different time steps. The results seem to suggest that only dynamics of the soil evolution will change but not the equilibrium final soil grading.*

-p.19 line 8: Ranger 1 or 2?
-*the "Ranger site data set 1" needs to change to "Ranger1a" and "Ranger bedrock grading" needs to change to "Ranger1b". the necessary changes implemented in the revised manuscript*

-p.19, line 17. This is an important conclusion! –paragraph
We agree and this is a primary justification for including all the figures … to see this effect graphically rather than just have the mathematical summary of equation (13). WE will include a mention of this result in the conclusions to the paper (this somehow slipped out attention).

5.2.4 suggest to change to "changing the erodibility and selectivity exponent"
-*Changes were made to the manuscript as per reviewer's comments*

-p.19,line 27: suggest to change to: "the d50-exponent beta"

-p20,line 4: geometry? -Figure

Changes were made to the manuscript as per reviewer's comments

4. Is it not possible to read in the points from Surfer and plot the left figure in mat- plotlib to streamline all figures?
-The figure was redrawn according to reviewer's comments

-Figure 5. The authors need to indicate not only the weathering rate, but also the second variable (Ranger 1 or 2 grading) in the figure.

-*As per reviewer's suggestion the grading used for both surface and subsurface layers added to the figure captions*

-I suggest to eliminate figure 6 in order to reduce the total number of figures -I suggest to eliminate figure 7. The main results are summarized in fig 8 anyways and there are more simulations in fig8 which are also not shown.
-Fig 13 is cut off on the left –Table

-*The authors believe that to be completely thorough we require at least one figure for each change of parameter. The authors believe that all the figures presented in this manuscript are the bare minimum that could present the model results in a comprehensive manner. However the authors will explore any other ways to reduce the number of figures without degrading the quality of the manuscript.*

1. The authors just downgraded their model one dimension here. -Table 2 caption: "to generate" -Table 3 doesn't add much extra over figure 8. Suggest to eliminate.

Table 3 has been eliminated from the manuscript.

Interactive comment on Earth Surf. Dynam. Discuss., doi:10.5194/esurf-2015-54, 2016.

Reviewers comments in italics; Authors response in non-italics

The authors present a model (SSSPAM5D) to investigate the relation between soil grading, surface erosion and weathering. Minor changes to an existing model (mARM3D) are done and a number a 2D simulations have been performed at the soilscape level in the framework of a sensitivity analysis. The main conclusion is that an earlier published area-slope-grading relationship holds when model parameters are altered. Interestingly, the sensitivity analysis shows a dependency of soil grading on the ratio between area and slope exponents, similar to what has been found for other earth surface processes.

The setup of the model runs, the results and the paper in general are very similar to what has been published earlier [Cohen et al., 2010]. A major problem with this choice is that major soil processes such as creep, bioturbation and clay translocation are not considered. Furthermore the model does not reach its full landscape (3D) potential because only 2D soilscape simulations are performed. Moreover, observations are only used for initialisation of model runs and not to calibrate, let alone validate, model results.

Although a numerical soil-hillslope coupled model could indeed serve as an insightful tool to better understand the interdependency between soil grading and earth surface processes, the paper needs significant improvements at several points to be of value for the geo-scientific community. Nevertheless, I think that this paper can be published eventually after addressing some major comments listed below.

We agree that SSSPAM is part of the ongoing development of the approach outlined in the mARM3D papers (we'll address detail differences in response to comments below). The reviewer sees it as a "major problem" that we have not included the full range of processes that are known to be important in soil profile process (though creep is a lateral transfer process rather than one that impacts on the vertical profile directly). The reviewer, however, has missed the intent of this paper which is to examine the generality and robustness of the area-slope-grading dependency of the soil profile arising from a vertical pedogenesis model. Digital soil mappers have discovered similar relationships with terrain attributes (personal communication with GRW) but Cohen's mARM papers was the first to have shown this with a process model. However, Cohen's work was calibrated to one set of climate, geology and process representation (the Ranger field site we have studied since the early 1990s) and before we can compare model results with other field sites we need to know what is the range of behaviours possible from the model. Then we see differences with the field we can, with some degree of certainty, say whether the differences we observe (we are not so naïve that we think we will get a perfect match) are outside what the model can generate, or whether it might simply be that the parameters in the model can be adjusted to match the field. Without an analytic solution for the area-slope-grading relationship (i.e. an equivalent to the slope-area result for topography in Willgoose, Bras, Rodriguez-Iturbe, WRR,

1991) we are limited to doing the general sensitivity study that is in this paper.

Finally we note in one of the comments below that one of the useful features of a sensitivity study like in this paper is that it can highlight what are testable predictions of the model, making it possible to design experiments and field studies that can potentially reject the model if it is wrong.

Major points, not in order of importance

1. In the abstract it is stated that the authors developed a new numerical model (SSSPAM5D) which generalises and extend findings from mARM3D (Cohen 2010). However, only small adaptations to the existing mARM3D model are made and similar synthetic simulations are performed (with altered parameter values). Findings from the previously published mARM3D model are repeated and confirmed. In principle, this should not be a problem but the authors cannot sell this as 'a new model' and more complicated model configurations should be additionally tested (preferably in 3D, see further).

As noted for reviewer 1 more complicated geometries of catchments (e.g. concave or convex 1D profiles or 2D catchment drainage) are not necessary because they generate the same results. The only link from node to node on the hillslope is via the runoff-erosion model, otherwise the soil profiles are independent. The erosion model used in these simulations is a detachment-limited model where the erosion rate is a function only of the upstream area and the local slope. For any given node it is irrelevant what the geometry of the upstream area is (it could a catchment or, as in this paper, a linear hillslope). We believe that the paper is complicated enough as it stands and that adding a 2D catchment as suggested by the reviewer would only add to the figures unnecessarily (particularly as the results are exactly the same). The addition of the sample hillslope profiles in Figure 4b was to highlight how our simulations apply to more complex geometries (commented on favourably by reviewer 1).

2. In comparison to the mARDM3D model, the presented model is not substantially extended in any significant way: nor in numerical methods, nor in the physics behind the model. Therefore, giving it a new name is spurious. Rather, this paper is an application of the existing mARDM3D model and it should be described alike.

The models are different and we have only presented enough detail of the model so that the reader can look at this paper and understand what the various parameters control without having to flip backwards and forwards to the both of the Cohen mARM and mARM3D JGR papers. Just to be clear the differences in the models are:

- mARM is written in Fortran and doesn't fully implement the matrix methods in the Cohen papers (the matrix methodology and mARM were developed in parallel, even though they were presented together in the papers). SSSPAM is written in Python/Cython and fully implements the matrix methodology and is as a result significantly faster (about 10,000X) and more flexible. Accordingly while they solve the same problem there is 0% overlap in the code.

- The fragmentation physics in mARM is hard coded in, whereas in SSSPAM it is quite flexible (the main reason for starting again with the code development).
- There are significant improvement in the numerics in SSSPAM which mean that the mass balance for a given time step size is significantly improved over mARM. The improvements are most noticeable for the sediment particles in the grading fraction encompassing the Shields stress threshold. This is the reason that the results in Figure 4 are slightly different (note that while the contours in both figures have the same slope the d50 for any specific combination of area and slope is slightly higher for SSSPAM). This is also true for the time varying approach to equilibrium (for brevity not shown in the paper) where SSSPAM provides a better to the ARMOUR model (which is a detailed physically based model).

3. The described model does not take into account major processes active at the soil-hillslope scale. Recent advances have shown the importance of creep, eluviation/illuviation, deposition and bioturbation on the depth dependent shape of soil properties such as the particle size distribution [Johnson et al., 2014; West et al., 2014; Campforts et al., 2016]. Moreover, except for creep, those processes are described and implemented in an earlier release of the model [Cohen et al., 2010]. In this earlier publication, the authors state that the impact of these processes on the self-organisation of soil properties was not yet discussed in order to avoid overcomplexity and enhance interpretation. Currently, I do not see the relevance of this work without including those processes, known to be major driving forces of soil development [Braun et al., 2001; Roering et al., 2007; West et al., 2014; Temme and Vanwalleghem, 2015]. Investigating the impact of these processes could be an interesting and probably necessary research question to be answered.

Referring back to our response to point 2 above while Cohen 2010 described, using the matrix methodology, how SOME of these processes could be incorporated into mARM NONE of these have ever been implemented into mARM.

We now address the main point of the comment which is about processes that we have not tested. We are aware of all the work described by the author for natural soils and while many of these processes mentioned are important in different locations we know of other locations where none of these are important (our Ranger field site, and most other rehabilitated mine sites, where there is a predominance of granular material) so we feel its perfectly legitimate to start with the simplest model that has exhibited the slope-area-grading behavior and see if Cohen's results were just good fortune given the process parameters for Ranger or whether we might expect this behavior at other sites. This then provides the confidence that we can look at the sensitivity of the slope-area-grading result to these other processes at some later stage. What the reviewer is asking is that we do further sensitivity studies on the effect of these excluded processes (i.e. another paper) not that this paper is unnecessary.

The selection of the papers [Braun et al., 2001; Roering et al., 2007; West et al., 2014; Temme and Vanwalleghem, 2015] is also rather idiosyncratic and focused on the role of creep. Braun et al., 2001 does not model any soil grading properties and only models creep and soil depth; Roering et al., 2007 also model creep but do not study soil in any form at all, only topography; West et al., 2014 likewise looks at experimental evidence for creep in soils but does not model the implications; Temme and Vanwalleghem, 2015 do not model soil grading but do model a number of other processes though they do NOT show any results using these other capabilities.

In conclusion this comment primarily focuses on the lack of downslope creep in the model. Granted it is missing but you could equally criticize these papers for not including depth variations in the soil properties (which we are simulating) which will no doubt influence the depth dependent movement of soil downslope. You have to start somewhere and we've started on the processes important on our field site at Ranger. If the soil is dominated by granular material then the material grains tend to lock together and not creep downslope.

4. There exists a significant body of literature describing experimental findings where the relation between soil grading and erosion are discussed [Poesen et al., 1998; e.g. Govers et al., 2006]. It would be good to describe these and/or other empirical findings in the introduction of this manuscript.

Good point. We had referred to them in previous papers but neglected to include them here. They have been included.

5. Similar to what have already been done in mARM3D [Cohen et al., 2010], the model is only applied to synthetical landscapes. The simulations performed are almost equal to what has been presented in Cohen 2010 (5 hillslopes profiles). Moreover, the authors only discuss 2D profiles and do not perform landscape simulations. This is in contradiction with what the authors promise in their introduction where they describe a '5D' landscape model. Only performing 'transect' simulations is therefore unfair to the reader. Application of the model to different (3D!) landscapes, similar to what have been proposed by Cohen et al. 2010 seems essential to me. Moreover, the matrix structure of this model is especially of use in the framework of 3D landscape simulations.

This is the first of a series of studies that we are currently writing up using SPPPAM5D so we thought rather have to repeat the model description and adding a discussion of the capability being evaluated in each paper we would write up the general model here and refer back to the single description in subsequent papers. These subsequent papers do the 2D catchments that the reviewer requests but go beyond the sort of analysis in this paper (e.g. looking at the impact of deposition and coupling with a landform evolution model). A minor point; the reviewer describes these landscape wide simulations as 3D but they are strictly speaking scalar fields on a 2D grid.

6. Given the fact that the model and its functionality has already been discussed in literature, this paper would be of much more value to the geo-scientific community if the model is calibrated with field data (directly, not by calibrating it to the mARM3D model that has been calibrated with the results of the mARDM2D model, as described in line 13-17 on page 15).

The reviewer has misunderstood the work done in our Cohen et al papers. The calibration suggested by the reviewer is exactly what was done for the mARM3D papers, which means that the results are specific to that site and material. This paper is about generalizing results from that study. This point is clearly stated at P7 lines 23-2. We have however reworded his section to make this clearer.

7. I am wondering why you use observed soil gradings as an initial condition for your model runs. Shouldn't a good model be able to reproduce these observed gradings by starting from a bedrock?

This is part of the sensitivity study. For constructed waste containment sites it is important to understand how the initial conditions might influence the results (do different initial conditions lead to fundamentally different results or is the effect of initial conditions lost over time … also an important fundamental question for natural soils but crucial for constructed sites). We have also done simulations from bedrock with no significant differences.

Now the observed distribution is used as an initial condition whereas I would think the observed distribution is representing the outcome of natural processes which are in equilibrium. Showing time series on how these grain size distributions are evolving through time could help.

The initial grading is from a mine site which has ben exposed to erosion and weathering for about 20 years and is far from equilibrium (see Sharmeen and Willgoose, 2007, who predicted that it will take about 100 years for the site to reach equilibrium, see their figure 13). The time evolution of the grading down the profile and down the hillslope is the subject of a separate paper which will be submitted shortly. We excluded temporal issues from this paper to keep this paper focused on the equilibrium area-slope-grading relationship.

8. It is unclear how soil production was modelled in this study. I assume the model is based on the soil production function as proposed by Heimsath [1997] but this is not stated clearly.

There is no explicit soil production function. Saprolite is turned into soil by the weathering function at depth. This is also how it was done for mARM3D though in this paper we have explored the impact of using of functions other than the exponential function. We can generate the exponential production function of Heimsath without having to input it (see the Cohen mARM3D 2010 paper for a discussion of this behaviour).

9. The bibliography is poor and not covering current state of the art knowledge on soil formation processes at the landscape scale (see e.g. references above).

As previously mentioned we're not sure that we'd consider creep a soil formation process, rather it's a soil transport process. Nevertheless, we have included some of these papers in the introduction.

10. Presentation of the results could be much better; The first three figures are more or less copy pasted from Cohen 2010. The others are mainly log-log plots. A few of these plots should be enough to *illustrate the presented results.*

Figures 1, 2, 3 are from our previous papers (as indicated in the figure captions) but in terms of understanding the model they are a very concise summary of the 3 key aspects of the model (the profile, the fragmentation model, and the depth dependent weathering function) so we think they are required (based on feedback from AGU and EGU presentations).

Figure 4 shows that SSSPAM can replicate mARM3D. Since it is an entirely new code base with improved numerics this provides confidence that SSSPAM is working correctly. Also Figure 4b shows how to interpret these contour plots for a more realistic hillslope profile.

Figure 5 is very similar to a figure in Cohen 2010 but with the new model, and is the nominal case against which all the subsequent figures are compared.

With respect to the other figures we have include one contour plot for every parameter changed if there has been a significant change. In several cases a parameter change did not change the contours so we just noted that in the text. Yes there a lot of contour plots but we have only included those that are needed to substantiate the conclusions of the paper.

Comments by line

p1

Line 1: The title is difficult to understand. I would suggest something more explicit and would consider mentioning the name of the applied model in the title (mARM3D).

The model is not mARM3D. We have changed the paper title to something simpler but feel strongly that it should not include the name of the model since the results are likely to be independent of the details of the model

p2

Line 5: Here and throughout the paper, I do not see the need to introduce this model as a 'new' model because it is almost similar to the previous mARM3D model.

As previously indicated this is a completely new code from the ground up so deserves a new name, but we have quite explicit in the paper that is based on the pioneering work of mARM.

Line 16-18: The influence off different depth dependent weathering functions has already been discussed in previous work [Cohen et al., 2010]. It is unclear to what extend findings reported here are different from this earlier publication.

This paper examines the depth dependent properties of the soil than Cohen and a new one (an analytic solution to chemical weathering that is presented in Willgoose (2016) “Models of Soilscape and Landform Evolution”, Cambridge Press, currently in the editorial process). Cohen modeled them but did not examine the slope-area-grading relationship below the surface so was not able to conclude what the spatial organization of soil was below the surface.

p3

line 2-6: First paragraph is a bit difficult to follow. I agree that soils play an important role in environmental processes but try to give some hints to the reader on how to frame this.

-The paragraph is changed to make it clearer

Line 8: Add references.

-new references added

Line 9: What do you mean with ‘optimum performance’. Model efficiency?

-In this context the authors meant “provide accurate predictions” The manuscript is edited accordingly

Line 10: What are ‘high quality spatially distributed soil attributes’? This is very unclear for readers who are not familiar with this matter. Try to be more specific, maybe give some examples.

-the authors meant soil attributes such as Hydraulic conductivity, soil moisture content etc.

Line 12. Grading: I suggest you explain this term the first time it is used. Line 14 .. it are the soil...Line 29: “However useful these PTFs are”. Rewrite

- The manuscript is edited according to referees comment

Line 22-14 on page 4: This paper isn’t about soil mapping, right? These paragraphs seem to be redundant given the nature of the paper. Rather, the authors could elaborate a bit more on soil-pedogenesis processes which are of real matter in soil genesis models.

The digital soil mapping community is very interested in pedogenesis models as a way of providing a better physical basis to their empirical regression methods for digital soil mapping (i.e. the GlobalSoilMap initiative). The World Soil Society in 2015 instituted a focus group on this subject for this very reason. Thus these paragraphs are not redundant but link to major initiatives outside the geology/geomorph community, which many readers may not be aware of.

Page 4:

Line 9: Please ad references to original work other than McBratney et al.

-references added

Line 17: I do not see how GIS products would have revolutionised the society through modelling. They can trigger each other but are not necessarily linked.

Poor wording on our part. The ease of use of GIS has revolutionized modelling by making distributed modelling easier to do and interpret.

Line 24: Define armouring, example is given in Cohen et al. [2009]. First line of the introduction.

-The structure of the introduction section changed and the definition has been moved up

Page 5

Line 2: soil profilesLine 3: remove 'using pedogenic processes'

Line 6 I do not see how the need can be clear. In Cohen et al [2010] it is written: "The paper aims to confirm the robustness of the logâĂŘlog linear relationship be- tween area, slope and d50". And further: "This suggests that the logâĂŘlog linear relationship between area, slope and d50 is a robust result." So, it has already been shown that there is a robust relationship between topographical properties and particle diameter. In my opinion, adding initial model configurations and plotting different par- ticle sizes (d10,d90) is only of marginal additional value. What would be of real value is the integration of processes like creep, bioturbation and illuviation as suggested in Cohen et al. [2010]: Additional processes (e.g., chemical weathering, translocation) will be integrated in the future. This will allow for more complex studies of soil evolution processes and relationships. Our vision is that with additional development and valida- tion mARM3D will provide insight into the quantitative processes leading to soil spatial organization and a detailed description of functional soil properties for environment models.

The sentence has been removed and the rest of the paragraph reworded.

Cohen et al (2010) showed the robustness of the relationship with changes in in-profile weathering relationship but did not investigate the full range of parameter values because it was calibrated to field data. We agree about the importance of other processes but have prioritized developing a model that can be coupled to a landform evolution model (so we can do some of the lateral transport processes like creep). This coupling work is in the process of being finalized and will be published in due course.

Line 8: shortly summarize what is meant with 'generalize' and 'extends it numerics'. The reader should be triggered to continue reading which he isn't. In the contrary, in its current form, the paper is not attractive to read and it is very vague up to this point what you are going to do exactly and why.

We have sharpened the introduction section to make it clearer earlier what the objective of the paper is.

Line 12-13: SSSPAM5D: showing off with 5 dimensions does not really make sense here. Each LEM or soil evolution model has a temporal dimension. Soil grading is a property, not a dimension. I would suggest to just call it 3D. Moreover, I would avoid the use of another word for basically the same model and suggest the use of mARM3D rather than SSSPAM5D throughout the paper (see also comments before). If the authors insist on using a new name I would propose mARM3D.v2.0.

Since both reviewers are (unnecessarily) uncomfortable with the 5D terminology we will remove any reference to it and refer o the model as SSSPAM. However, as a matter of principle we disagree with the reviewers. The model is 5D. As the reviewer states the x,y,t coordinates are 3D, the soil depth is another dimension and the cumulative distribution function of the soil is a 5th dimension (technically the soil grading is a 5 dimensional scalar field). Again as mentioned above SSSPAM is a completely new code base. We thought long and hard about whether to continue to use mARM name for this version but decided not to, to avoid confusion with the original codebase for mARM (which the 4th co-author has extended with aeolian processes separately to this project … see, for example, JGR 2015, and another paper currently on ESDD). In passing we note that to be technically correct mARM3D is also 5D but at the time of that publication we were swayed by review comments along the lines of those here.

Line 14: It is recommended to restructure the introduction. First describe the processes you are going to deal with (Armouring, Weathering), then explain why there is a need for your study.

-Introduction restructured

Line 15-16: there is still not a good definition of what armouring exactly is up to this place.

-Introduction restructured the definition is given earlier

Line 21: In line 15 armouring is a result of fluvial erosion . Here it is fluvial or wind erosion. Please clarify.

-manuscript updated to clarity this issue

Line 21-31 Finally, the definition of armouring pops up. I would recommend moving it up. Refer to existing literature throughout the text rather referring to citations at one line (e.g. line 17). Try to avoid repeatedly citing the Sharmeen and Willgoose paper of 2006 and diversify the references .

-Introduction restructured

Page 6

Line 14-15: Again, refer to the literature throughout the text.

-references added

Line 26-27: This is already mentioned before. What is exactly the influence of weathering to armouring, sediment fluxes and erosion rates. Have they observed positive feedbacks, negative feedbacks,. . . ?

-The weathering process breakdown the coarse particles in the amour layer. This would increase erosion and the increased erosion draws coarse particles from subsurface layers depending on the rate of erosion. In the end it becomes a balance between erosion and weathering rather than negative or positive feedback. The introduction section restructured

Line 27-2: Mostly redundant or already mentioned before. Rather give the reader insights on what exactly were the findings of the ARMOUR model runs.

-sentences removed and consolidated

Page 7

Line 4. According to the reference list, mARM1D seems not to be the right terminology. It is mARM [Cohen et al., 2009] OR mARM3D [Cohen et al., 2010].

Typo on our part.

Line 4-5: "complex nonlinear physical processes" Which processes are complex? Which process is nonlinear?

-the entrainment of sediments by the flow is a complex non-linear process. Manuscript is updated to clarify this matter

Line 10-17: this is interesting and well explained, it would be good to summarize the results of ARMOUR in a similar way on page 6 instead of line 22-23.

-summary of ARMOUR was added to the manuscript

Line 26: The authors should also explain in more detail what has been done with the mARM3D model as this is the model they use throughout the study.

-a small discussion on mARM3D was added to the manuscript.

Line 28: "and allows more general assessments and predictions of pedogenesis" very vague. Clarify.

-re worded the sentence to clarify the aim of the manuscript

Line 29: 'the extensions in': the updates to the existing modelling framework mARM3D

-As explained earlier the SSSPAM is a newly coded model based on physics of mARM3D. hence we believe what we have presented here is actually extensions that carry SSSPAM beyond mARM3D

Line 29: comparing your model with the mARM3D model is not a calibration, let alone a validation.

Yes it is a calibration (it is also a validation because it showed that the model can mostly replicate the older mARM3D model). The model is calibrated against another model so we are comfortable that SSSPAM will reproduce the output of mARM for the similar parameters (this is part of the reason for Figure 4 to provide some assurance that this is the case). We are not claiming it is calibrated against a field site. For instance, mARM was calibrated to a much more sophisticated model (ARMOUR). ARMOUR, however, WAS calibrated against field data. We know this is very indirect but it is not possible to calibrate mARM or SSSPAM directly to the field data because of the approximations required in their conceptualisations. This conceptualisation is the key to the high speed of the model. If it weren't for this high speed we would have continued using the ARMOUR model, which has a strong physical basis, but which is so slow that's its infeasible to couple it with a landform evolution model (we'd some serious supercomputer time to even generate a single slope-area-grading contour figure using ARMOUR).

Line 31: Here you clarify that you are only going to investigate the soilscape. As already mentioned before, I find this of little additional value to existing literature [Cohen et al., 2010] where 'more complex' systems are already studied (using a DEM from a real landscape).

Well actually the landscape used in Cohen 2010 was not a real landscape either but a design proposal for a waste encapsulation structure. We used it because it shows many features common to waste encapsulation structures so gave us some insight to what soils might look like on such structures. And as noted previously our previous work has confirmed that the results form a 1D hillslope are the same as for a 2D catchment given the formulation we have used for erosion (i.e. detachment limited), and the 1D hillslope is significantly easier to understand.

Page 8 Line 5-14: any differences with this model in comparison to mARM3D? It would be interesting to add or at least discuss the effect of a depth dependent creep function where in depth grading can be influenced by differences between incoming and outgoing grading properties of soil fluxes [see e.g. Roering et al., 2007; West et al., 2014; Campforts et al., 2016].

The reviewer seems to be rather fixated on creep. Not all sites have creep as a significant process, particularly ones with a high proportion of granular material (the grains tend to lock together and not move).

Line 6: builds on rather than extends

-How the SSSPAM model is differentiated from mARM3D has been addressed earlier

p 8-11: The methodology section is mainly a copy from Cohen et al. 2010. I suggest the authors refer to *this publication for full details of the methodology and clearly indicate what exactly has been changed. I see two minor points of adaptation in comparison to the mARM3D model:*

1. The introduction of an asymmetric distribution of weathered soil particles to smaller classes (a concept already used in other pedogenesis models [Vanwalleghem et al., 2013; Temme and Vanwalleghem, 2015]).

2. The use of a third depth dependent weathering function with the highest erosion rate at the bedrock-soil interface.

See our comments at the beginning of the review response. We disagree with the reference to the papers by Temme and Vanwallaghem as we are currently collaborating with T&V to do the exact work the reviewer claims is in those papers.

p14

Line 13-14: what do you mean with 'input'. Are these used to constrain the initial particle size distributions of the uppermost layers? What about the other layers, are they set to bedrock?

-Yes for most of the simulations the authors used the Ranger1a grading for the initial surface layer and Ranger1b grading as the initial grading for all other subsurface layers. Ranger1b is the corresponding synthetic bedrock layer for the Ranger1a actual grading. Ranger2a actual grading and the Ranger2b synthetic bedrock grading was used to assess the influence of different initial conditions on the area-slope-d50 relationship. The last paragraph of this section was changed to clarify this point

Line 16-17: what do you mean with third and fourth gradings? From Table 1, I guess the 'third and fourth' layer are representing the bedrock of the first and the second gradings? Please rephrase. Very unclear what exactly Ranger 1b and 2b refer to.

-See the previous response

p16

Line 10-14: Finally, the authors clearly explain what they are going to investigate and how it differs from earlier literature. To me, these tests are not of sufficient additional value. Verifying the impact of other soil processes mentioned before and evaluating these at the catchment scale would strongly improve this contribution.

I guess we have to agree to disagree about strategy of what should be done first. It only makes sense to do creep in the context of the coupled landform-soilscape modeling rather than on the standalone soilscape model because creep forces the landform to evolve as well as the soilscape. Nothing in this paper caused the landscape to significantly evolve (e.g. the amount of erosion is really quite nominal relative to the scale of the landform) so using it as is as a standalone soilscape model is OK.

Line 17-20: time series of particle size distributions would help to understand this.

Added

Page 17

Line 20: Here, the authors admit they are reluctant to study the interesting soilscape- landscape coupling at its full potential. As mentioned earlier, there is already a good understanding of the 'simple' relationships both in terms of modelling [Cohen et al., 2010] and field data [Govers et al., 2006]. This paper would therefore be an excellent opportunity to indeed focus on these coupled models which can easily be tested with the efficient structure of mARM3D.

As the reviewer has indicated we have already done this in Cohen 2010 and there is no value repeating the 2D simulations done by Cohen (it gives the same results as the 1D hillslopes). The coupling of the soilscape model and landscape evolution model has been largely completed and we are shaking the bugs out and analyzing the rather complex results as we speak. This work will deserve a paper in its own right building upon the insights of this paper.

Rather this paper is to look at the sensitivity of the results to changes in process rates and functional dependencies, which was not done in Cohen 2010. Sharmeen and Willgoose (2007) (where the behavior of the more complex physically based model ARMOUR model was examined) compared ARMOUR with results from Govers et al 2006. The comparison is quite good so since SSSPAM has been indirectly calibrated to ARMOUR we expect that the SSSPAM comparison will also be quite good. Some words to that effect have been added.

Page 18:Line 21-22: Can this be confirmed by field data?

We're not sure how you might collect the required field data. Clearly this would be a useful test of the model performance. We note here that one of things that the sensitivity study potentially highlights for us is what types of experiments and/or field studies might be able to test the model predictions.

p19

Line 1: Cohen 2013, missing in the reference list

Fixed

Line 6: I am wondering why d50 values are so low in figure 7.a2 in comparison to figure 7.a1. If all the parameters remain constant except for $\alpha 1$ and $\alpha 2$, I would expect higher erosion rates (equation 3) for figure (a2) where $\alpha 1$ increases from 0.639 to 1.359. Consequently, I would expect larger particle sizes *for simulation a2 instead of smaller particle sizes. Can the authors clarify or explain this?*

-Here $\alpha 1$is the exponent value for discharge and $\alpha 2$ is the exponent value for slope. For comparison the discharge rate is in the order of 10^{-6} $m^3/s/m$ while slope is in the order of 10^{-2}. So changing the exponent of discharge reduces the erosion at all the nodes with slope-area combinations as a whole, while changing the exponent on slope only change the slope dependence. Because of this low erosion rate in this figure weathering dominates all the nodes and the d50 of all the nodes reduce significantly.

Line 8: which Ranger number for the bedrock? 1a/1b?

Typo. Wrong naming convention was used. Edited the sentence and clarified the manuscript

P 20

Line 18-20: as to no surprise because symmetric redistribution attributes the largest amount of material to the second daughter.

Agreed but its worth explicitly noting that the model gives the result expected.

Line 23: Rephrase.

-There were some words missing from the sentence. Rectified and the manuscript updated

Line 32: Can the model also evolve to this equilibrium if one starts from bedrock as initial condition?

Yes

p21

Line 16-20: Although logical and model simulations are not essential to get this, this is indeed interesting.

A nice backhanded complement. Some results are obvious in retrospect, but it's the simulations that highlighted the behaviour in the first place.

p22

Line 25: It would be good to illustrate how that can be done.

We are currently in discussions with members of the digital soil mapping community about this. Briefly they see the methods here as a physically based supplement to the empirical statistical regression methods they currently use to generate soil properties on grids. Their regressions are derived from regression of observed soil properties against terrain properties. We may be able to highlight terrain attributes that will provide more rational terrain covariates in their regressions.

Line 26- p 23 line 9: Making the coupling to land evolution models is indeed interesting. Scaling up this finding form the soilscape to the landscape would be a very interesting contribution to this study. Given the architecture of the model I assume such upscaling can be done relatively easy. Also, it would be interesting to elaborate more on the physical implications of this finding. Are there datasets available confirming this trend?

The results of this coupling is quite challenging to understand (the effect of localized deposition; timescales of landform evolution versus soils evolution; spatial organisation of the topography … slope-area … when the soil is spatial organised as well; 1D hillslope versus 2D landscape) and will be in a future paper. The challenge of the coupled model, plus the field observation that soils at some of our field sites evolved faster than the landform (so soils equilibrate to the slowly evolving landform), is the reason why we think a focused study on understanding the soils model on a fixed landform is needed prior to looking at the coupled evolution.

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Exploring the sensitivity on a soil area-slope-grading relationship to changes in process parameters using a pedogenesis model

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Submitted to: Earth System Dynamics (ESD)

Abstract

This paper generalises the physical dependence of the relationship between contributing area, local slope, and the surface soil grading using a pedogenesis model and allows an exploration of soilscape self-organisation. A parametric study was carried out using different parent materials, erosion, and weathering mechanisms. These simulations confirmed the generality of the area-slope-d_{50} relationship. The relationship is also true for other statistics of soil grading (e.g. d_{10}, d_{90}) and robust for different depths within the profile. For small area-slope regimes (i.e. hillslopes with small areas and/or slopes) only the smallest particles can be mobilised by erosion and the area-slope-d_{50} relationship appears to reflect the erosion model and its Shield's Stress threshold. For higher area-slope regimes, total mobilization of the entire soil grading occurs and self-organisation reflects the relative entrainment of different size fractions. Occasionally the interaction between the in-profile weathering and surface erosion draws the bedrock to the surface and forms a bedrock outcrop. The study also shows the influence on different depth dependent in-profile weathering functions in the formation of the equilibrium soil profile and the grading characteristics of the soil within the profile. We outline the potential of this new model and its ability to numerically explore soil and landscape properties.

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1. Introduction

Soil is a product of various physical processes acting on earth's crust. Weathering is a major contributor to soil production, along with transport processes that transport new material away and bring new material into a point. Weathering is a general term used to describe all the processes which cause rocks or rock fragments to disintegrate or alter through physical [*Ollier*, 1984; *Wells et al.*, 2006; *Wells et al.*, 2008; *Yokoyama and Matsukura*, 2006], chemical [*Green et al.*, 2006; *Ollier*, 1984] or biological means [*Strahler and Strahler*, 2006]. Disintegration of rock material through physical weathering can occur by (1) unloading, (2) expansion and contraction of rock through heating and cooling cycles, (3) stress developing in rock fractures due to freezing water, (4) salt crystal growth or tree root intrusions, and (5) abrasion of rock by harder materials transported by flowing water or glaciers [*Thornbury*, 1969]. Physical weathering where larger soil particles are broken down into smaller particles is dominant in the surface layer of material where it is more exposed. Weathering also occurs underneath the surface and the weathering rate at these subsurface layers can be modelled with depth dependent weathering functions.

Spatial redistribution of soil can occur due to different processes such as soil creep and erosion. Soil creep is the process of downslope movement of soil over a low grade slope with a substantial soil mantle under the force of gravity and friction [*Ollier and Pain*, 1996]. Although soil creep can have significant influence on some soil properties on some land forms [*Braun et al.*, 2001; *Roering et al.*, 2007; *West et al.*, 2014] on landforms with interlocking rock fragments, its influence is not significant. On the other hand erosion can occur in all landforms in one form or another. Erosion is term used for removal of material from an existing soil profile. Erosion can occur due to a number of processes such as (1) surface water flow (Fluvial erosion), (2) wind (Aeolian erosion), (3) flow of glaciers (Glacial erosion) and (4) animal or plant activity (Biological erosion) and others. Fluvial and Aeolian erosion tend to create an "Armour" on the soil surface. Depending on the energy of the erosion medium (water or air), transportable fine particles are preferentially entrained and transported from the surface soil layer. This process coarsens the remaining surface soil layer enriching it with coarser, less mobile, material. With time, if the energy of the transport medium remains constant, an armoured layer is formed with all the transportable material removed. At this time the sediment transport reaches zero. This armour, where all the materials are larger than the largest grains which the transport medium can entrain, prevents

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erosion of material from the subsurface. If the energy of the transport medium increases, the existing armour can be disrupted, and a newer stable armour with coarser material can be formed [*Sharmeen and Willgoose*, 2006]. Armouring in river beds has been widely understood and studied extensively for mostly streams and rivers [*Gessler*, 1970; *Gomez*, 1983; *Lisle and Madej*, 1992; *Little and Mayer*, 1976; *Parker and Klingeman*, 1982].

The importance of soil as an agricultural and commercial resource, and as an influencing factor on environmental processes such as climate regulation, is well established [*Jenny*, 1941; *Bryan*, 2000; *Strahler and Strahler*, 2006; *Lin*, 2011]. However spatially distributed quantification of soil properties is difficult because of the complexity and dynamic nature of the soil system itself [*Hillel*, 1982]. The necessity for quantified and spatially distributed soil functional properties is clear [*Behrens and Scholten,* 2006; *McBratney et al.,* 2003]. Moreover, explicit soil representation in models of environmental processes and systems (e.g. landform evolution, and hydrology models) has increased rapidly in the last few decades. For accurate prediction these physically-based and spatially-explicit models demand high quality spatially distributed soil attributes such as hydraulic conductivity [*McBratney et al.*, 2003].

The need for improved soil data arises in two main areas: (1) better mapping of the description of the soil (e.g. particle size distribution, soils classification), and (2) improved representation of soil functional properties (e.g. hydraulic conductivity, water holding capacity). For most environmental models the soil functional properties are of greatest interest since they determine the pathways and rates of environmental process. Accordingly this paper is focussed on a soil representation that can underpin the derivation of functional properties. Pedotransfer functions exist (albeit with large uncertainty bounds) to then relate these soil descriptions to functional properties. The existence of these pedotransfer functions intellectually underpins the rationale of the work in this paper. While these techniques are not the focus of this paper, some discussion of them is pertinent so that the importance of the scaling relationship discussed in this paper can be fully appreciated.

Traditional soil mapping typically uses field sampling and classifies soils into different categories based on a mixture of quantitative (e.g. pH) and qualitative features (e.g. colour). It does not directly provide the functional soil properties required by environmental models. Several techniques have been introduced to tackle this lack of functional description such as pedotransfer functions, geostatistical approaches, and state-factor (Clorpt) approaches

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[*Behrens and Scholten*, 2006]. Pedotransfer functions (PTFs) have been developed to predict functional soil properties using easily measurable soil properties such as particle size grading, organic content, and clay content. Although PTF's are very useful, they are limited because they need spatially distributed soil descriptions and, in many cases, site specific calibration [*Benites et al.*, 2007]. Geostatistical approaches interpolate field data to create soil-attribute maps. Clorpt or Scorpan approaches [*McBratney et al.*, 2003] use regression or fuzzy-set theory to create soil-attribute or soil-class maps [*Behrens and Scholten*, 2006].

Geostatistical digital soil mapping using field sampling of soil is possible for a specific site where the area is small [*Scull et al.*, 2003]. However, it can be prohibitively expensive and time consuming for larger sites. Soil mapping techniques, such as Clorpt or Scorpan, use digitization of existing soil maps. They generate soil classes through decision tree methods and artificial neural networks using easily measurable soil attributes (similar to PTFs) to generate the digital soil maps [*McBratney et al.*, 2003]. Although much work has been carried out they also suffer the need for site-specific calibration.

Remote sensing technologies such as gamma ray spectroscopy have introduced novel methods of characterizing soil properties and developing digital soil maps [*Triantafilis et al.*, 2013; *Wilford*, 2012]. The digital soil maps produced by gamma ray spectroscopy are relatively coarse and their spatial coverage is limited while their links with functional properties remain uncertain [*McBratney et al.*, 2003]. Developments in geographic information systems (GIS) have enabled fast and efficient characterization and analysis of large amounts of spatial and non-spatial data [*Scull et al.*, 2003]. The ease of use of GIS has revolutionized modelling by making distributed modelling easier to do and interpret [*Singh and Woolhiser*, 2002]. This is the rationale for the GlobalSoilMap initiative, which aims to provide a global 90m map of soil properties for the world [*Sanchez et al.*, 2009].

Many researches have reported strong relationships between terrain attributes and soil. For example, using field measurements *Moore et al.* [1993] found significant correlations between terrain attributes and soil properties such as soil wetness index and soil organic carbon content. *Poesen et al.* [1998] reported a strong relationship between the slope gradient and the rock fragment size on the soil surface. Statistical [*Gessler et al.*, 2000; *Gessler et al.*, 1995] and process based models [*Govers et al.*, 2006] have been proposed to predict these relationships. They have been implemented to predict the soil attributes data using terrain attributes as a proxy. ARMOUR [*Sharmeen and Willgoose* 2006] is a physically

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based model that simulates (1) rainfall-runoff event overland flow, (2) erosion and the selective entrainment of fine sediments that creates armouring of the soil surface, and (3) weathering of the particles on the surface that breaks down the armour. ARMOUR simulates the evolution of the soil surface on a hillslope. However, the very high computing resources and long run times (1000s of years at minute time resolution) of the physically based modelling prevented the coupling of ARMOUR with a hillslope evolution model.

Cohen et al. [2009] developed a state-space matrix soils model, mARM, and calibrated it to output from ARMOUR. mARM was significantly more computationally efficient than ARMOUR, and was able to simulate more complex hillslope geometries. It was sufficiently fast that it could be used to simulate the spatial distribution of the soil profile as well the surface properties. By incorporating the weathering characteristics of soil profile into mARM, *Cohen et al.* [2010] developed mARM3D which was able to explore the evolution of soil profiles for small catchments. *Cohen et al.* [2009] was the first to identify using pedogenic processes the relationship between the hillslope soil grading, and the hillslope gradient that this paper further investigates. However, it was only tested for a small number of cases, and for one set of climate and pedogenic data.

Cohen et al. [2010] showed the robustness of the relationship with changes in in-profile weathering relationship but did not investigate the full range of parameter values. This paper generalises the mARM3D formulation and extends its numerics to allow us to test the relationship for more general conditions. We present the results and insights obtaining by the new modelling framework, State Space Soilscape Production and Assessment Model (SSSPAM). The state-space based model we developed using the SSSPAM framework simulates soil evolution in 2 horizontal dimensions (i.e. x and y), depth down the soil profile, time, and the soil particle size distribution with depth.

1.1 Modelling approaches

The combined effect of armouring and weathering on the soil evolution on hillslopes was first explored by *Sharmeen and Willgoose* [2006]. They investigated interactions between particle weathering and surface armouring and its effect on erosion using a physically-based one-dimensional hillslope soil erosion model called ARMOUR. To carry out their simulations they used surface soil grading data from two mine sites (1) Ranger Uranium Mine (Northern Territory, Australia), and (2) Northparkes Gold Mine (New South Wales, Australia). They demonstrated that the influence of weathering was significant in the

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armouring process, sediment flux, and erosion rate. ARMOUR could also modify the armour properties, and even prevent the development of armour, by rapidly disintigrating the coarse material. If the amount of sediment generated by weathering is large it can be stored on the surface during times when the transport capacity is not large enough to entrain all the material. They called this a "transport-limited" regime. On the other hand for low weathering rates the armour will build up and prevent the subsurface material from eroding which was called "weathering-limited" regime. In between these two extremes they identified a equilibrium region where the erosion and weathering balance each other and where only the fine fraction generated by weathering is removed form the surface leading to a stable armour layer. The grading of the armour layer was found to be different to the underlying soil grading [*Sharmeen and Willgoose*, 2006]. Using ARMOUR they demonstrated the feasibility of using a physically-based model to represent soil evolution to study geomorphological evolution and as a simple model for pedogenesis. The main drawback of the numerical approximation used in ARMOUR model was its high computational complexity and very long run times which prevented it from being used for more complex geometries such as 2D catchments [*Cohen et al.*, 2009], or its coupling with a landform evolution model.

Cohen et al. [2009] simplified ARMOUR by reformulating it as a state-space matrix model, mARM, where the complex nonlinear physical processes of particle entrainment in ARMOUR were modelled using transition matrices. By doing so *Cohen et al* was able to reduce the numerical complexity of ARMOUR and significantly reduce runtimes. The computational efficiency of mARM allowed *Cohen et al* to explore (1) time-and space-varying relationships between erosion and physical weathering rates at the hillslope scale, (2) more complex planar drainage geometries, and (3) interactions between the soil profile and the soil surface properties. They found that for erosion-dominated slopes the surface coarsens over time, while for weathering-dominated slopes the surface fines over time. When both processes operate simultaneously a slope can be weathering-dominated upslope (where runoff and therefore erosion is low) and armouring-dominated downslope. In all cases, for a constant gradient slope the armour coarsens downslope (i.e. as drainage area increases) as a result of a balance between erosion and weathering. Thus even for weathering-dominated slopes the surface grading catena is dependent on armouring through the balance between weathering and armouring [*Cohen et al.*, 2009]. They also observed that for many slopes the surface initially armours but, after some period of time (space and rate dependent), weathering begins to dominate and the grading of the soil surface subsequently fines. Depending on the relative rates of armouring and weathering the final equilibrium grading of

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the slope may be finer or coarser than the initial conditions but in all cases the surface coarsened with increasing area and slope. Subsequently mARM3D was developed by *Cohen et al.* [2010] to incorporate soil profile evolution by using several soil profile layers and a semi-infinite bedrock layer into the mARM framework. They used exponential and humped exponential depth dependent weathering functions (soil production functions) to quantify the weathering characteristics of the soil profile and the bedrock. They concluded that although the soil depth and the subsurface soil profiles are dependent on the depth dependent weathering function, their effect on the spatial organisation of the grading of the soil surface was minimal. Their simulations showed that the area-slope-d_{50} relationship was still present at the soil surface even with different depth dependent weathering functions.

These results were in good agreement with the results of the ARMOUR model used by *Sharmeen and Willgoose* [2006]. The work of both Sharmeen and Cohen used process parameters calibrated to observed field erosion [*Willgoose and Riley*, 1998] and laboratory weathering data [*Wells et al.*, 2006; *Wells et al.*, 2008] for a site at Ranger Uranium Mine. Thus their conclusions only apply to the site at Ranger.

The aim of this paper is to present a new model (SSSPAM) that extends this previous work and generalises the conclusions using a sensitivity analysis of its process parameters. In this way we test the robustness of the Cohen's area-slope-d50 relationship under different conditions (e.g. different climates and soil production functions). Here we present (1) the extensions in SSSPAM, (2) calibration and validation of SSSPAM, and (3) exploration of the spatial and temporal patterns of soil grading and weathering and armouring processes. The model discussed here is the soilscape component of a coupled soil-landscape evolution model and this paper aims to better understand the behaviour of this soilscape model before examining the more complex coupled soil-landform system.

2. The SSSPAM model

SSSPAM is a state-space matrix model simulating temporal and spatial variation of the grading of the soil profile through depth over a landscape and extends the approach of the mARM model [*Cohen et al.*, 2009] and mARM3D [*Cohen et al.*, 2010]. It uses matrix equations to represent physical processes acting upon the soil grading through the soil profile. SSSPAM uses the interaction between a number of layers to simulate soil grading evolution

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(Figure 1). These layers are: (1) A water layer flowing over the ground which moves soil particles laterally, (2) a surface soil layer from which the water entrains soil particles and which produces an armour over the soil below, (3) several soil layers representing the soil profile, and (4) a semi-infinite non-weathering bedrock/saprolite layer underlying the soil. In SSSPAM two processes are modelled: erosion due to overland flow, and weathering within the profile. The armouring module consists of 3 components.

The grading of the surface (armour) layer changes over time because of three competing processes, (1) selective entrainment of finer fractions by erosion, (2) the resupply of material from the subsurface (that balances the erosion to ensure mass conservation in the armour layer) and (3) the breakdown of the particles within the armour due to physical weathering. The erosion rate of the armour layer is calculated from the flow shear stress. The entrainment of particles into surface flow at each time step from the armour layer is determined by the erosion transition matrix, which is constructed using Shield's shear stress threshold. The Shield's shear stress threshold determines the maximum particle size that can be entrained in the surface water flow. For particles smaller than the Shield's shear stress threshold a selective entrainment mechanism is used which was found to be a good fit to field data [*Willgoose and Sharmeen*, 2006]. Resupply of particles to the armour layer from underneath is mass conservative. The rate of resupply equals the rate of erosion, so the armour's mass is constant.

The weathering module simulates the disintegration of particles in the armour and underlying soil profile layers. Weathering is also modelled with a transition matrix. It defines the change in the armour grading as a result of the fracturing of particles through the weathering mechanism. The "Body Fracture" mechanism (Figure 2) splits the parent particle into a number of daughter particles. *Wells et al.* [2008] found that a body fracture model with 2 equal-volume daughter fragments best fitted his laboratory salt weathering experiments. This does not guarantee that this fragmentation mechanism is appropriate for other rock types not tested by Wells, and one of the cases studied in this paper is a generalisation of this equal volume fragmentation geometry. Weathering in this paper is mass conservative so that when larger particles break into smaller particles the cumulative mass of the soil grading remains constant. Thus we do not model dissolution.

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The state vector $\underline{g}$ defines the soil grading at any specific time and in every layer. Entries g_i in the state vector $\underline{g}$ are the proportion of the material in the grading size range i. The evolution (of the state vector) from one state to another state during a single time step is defined using a matrix equation. This matrix (called the transition matrix) describes the relationship between the states at two times and defines the change in the state during a time step

$$\underline{g}_{t_2} = (\mathbf{I} + \mathbf{R}\Delta t)\underline{g}_{t_1} \qquad (1)$$

where $\underline{g}_{t_1}$ and $\underline{g}_{t_2}$ are state vectors defining the soil grading at time t_1 and t_2, $\mathbf{R}$ is the marginal transition matrix, $\mathbf{I}$ is the identity matrix, and Δt is the timestep [*Cohen et al.*, 2009].

For multiple processes Equation (1) can be applied sequentially for each process, using the **R** matrix appropriate for each of the processes.

Within each layer the equation for weathering follows equation (1)

$$\underline{g}_{t_2} = \left[\mathbf{I} + (W\Delta t)\mathbf{B}\right]\underline{g}_{t_1} \qquad (2)$$

where W is the rate of weathering (which is depth dependent), and **B** is the non-dimensional weathering marginal transition matrix. Parameter W determines the rate of weathering while **B** determines the grading characteristics of the weathered particles.

For the armour layer the mass in the layer is kept constant so that as fines are preferentially removed by erosion, the mass removed is balanced by new material added from the layer below, and with the grading of the layer below. For each layer in the profile mass conservation is applied, and any net deficit in mass is (typically) made up from the layer below (i.e. by removing material in the layer below). The only exception to this rule is the case of deposition at the surface where material is pushed down. In this latter case the pushing down results from an excess of mass in the armour layer and this excess propagates down through the profile.

2.1. Constitutive Relationships for Erosion and Armouring

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The erosion rate (E) of the armour is calculated by a detachment-limited incision model,

$$E = e\frac{q^{\alpha_1} S^{\alpha_2}}{d_{50_a}^{\beta}} \qquad (3)$$

where e is the erodibility rate, q is discharge per unit width (m^3/s/m), S is slope, d_{50_a} is the median diameter of the material in the armour (m), α_1, α_2 and β are exponents governing the erosion process. It is possible to derive exponents α_1 and α_2 from the shear stress dependent erosion physics [*Willgoose et al.*, 1991b] or they can be calibrated to field data (e.g. *Willgoose and Riley*, 1998). In this paper for simplicity we will consider a one-dimensional hillslope with a unit width, constant gradient, and a 2m maximum soil depth. The discharge was calculated by

$$q = rx \qquad (4)$$

where r is the runoff excess generation (m^3/s) and x is the distance down the slope (m) from the slope apex to each node.

The implementation details of the erosion physics (e.g. how selective entrainment of fines is incorporated into the marginal transition matrix for erosion) are identical to that of *Cohen et al.* 2009 and will not be discussed here. The primary process of relevance here is that a size selective entrainment of fine fractions of the soil grading by erosion is used and it follows the approach of *Parker and Klingeman* 1982 as calibrated by *Willgoose and Sharmeen* 2006. The result is that for surfaces that are being eroded the surface becomes coarser with time (and thus why we call the top layer the armour layer).

2.2 Constitutive Relationships for Weathering

The fracturing geometry determines the weathering transition matrix **B**. Each grading size class will lose some of its mass to smaller grading size classes as larger parent particles are transformed into smaller daughter particles. The daughter products can fall in one or more smaller grading classes depending on the size range of particles produced by the breakdown of the larger parent particles. The amount of material received by each smaller size class is a

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function of size distribution of the grading classes, fracture mechanism, and the size characteristics of the daughter particles.

Wells et al. [2008] found that for his material (a mining waste product from Ranger Uranium Mine) a simple symmetric fracture model with two equal volume daughter products best fitted his experimental data. While the formulation of the weathering transition matrix in *Cohen et al.* [2009] allows a general fragmentation geometry, Cohen only used the symmetric fragmentation found experimentally by Wells. This paper will generalise these results and examine a broader range of fracture geometries.

To generalise the fracture geometries we will assume that a parent particle with a diameter d breaks into a single daughter particle with diameter d_1 and $n-1$ smaller daughters with diameter d_2 (the total number of daughters being n). For simplicity all the particles considered are assumed to be spherical. Mass conservation implies

$$d^3 = d_1^3 + (n-1)d_2^3 \qquad (5)$$

If the single larger daughter with diameter d_1 accounts for α fraction of the parent then

$$d_1 = \alpha^{\frac{1}{3}} d \qquad (6)$$

$$d_2 = \left(\frac{1-\alpha}{n-1}\right)^{\frac{1}{3}} d \qquad (7)$$

By changing the α fraction value and the number of daughters n we are able to simulate various fracture geometries such as symmetric fragmentation, asymmetric fragmentation, and granular disintegration [*Wells et al.*, 2008]. For instance α =0.5, n =2 represents symmetric fragmentation with 2 daughter particles, α =0.99, n=11 represents a fracture mechanism resembling granular disintegration where a large daughter retains 99% of the parent particle volume and 10 smaller daughters have 1% of the parent volume collectively.

The construction of the weathering transition matrix then follows the methodology outlined in Figure 1 in *Cohen et al.* [2009].

2.3 Soil profile development through depth-dependent weathering

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The weathering module of SSSPAM consists of 2 components. They are (1) the weathering geometry for the grading of the daughter particles discussed above, and (2) the weathering rate for the different soil layers which determines the rate at which the parent material is weathered. The weathering rate of each soil layer typically (though not always) depends on the depth below the soil surface.

To characterize the weathering rate with soil depth, depth-dependent weathering functions are used. In their mARM3D model *Cohen et al.* [2010] used 2 depth-dependent weathering functions (Figure 3), (1) exponential decline (called exponential) [Humphreys and *Wilkinson,* 2007] and (2) humped exponential decline (called humped) [*Ahnert*, 1977; *Minasny and McBratney*, 2006]. For the exponential, the weathering rate declines exponentially with depth. The rationale underpinning the exponential function is that the surface soil layer is subjected to the high rates of weathering because it is closer the surface where wetting and drying, and temperature fluctuations are greatest. The humped function has the maximum weathering rate at a finite depth below the surface instead of being at the surface itself and then declines exponentially below that depth. The rationale for the humped function is evidence that the weathering is highest at the water table surface which leads to a humped function.

We also examined another depth dependent weathering function we call the reversed exponential function. In this function the highest weathering rate is located at the soil-bedrock/saprolite interface and exponentially decreases upwards toward the surface and downwards into the underlying bedrock. The soil-bedrock interface is defined as that layer above which the porosity increases abruptly reflecting the transformation from bedrock/saprolite to soil (Anderson and Anderson, 2010). Unlike the exponential and humped functions the depth of the peak weathering rate in the dynamic reversed exponential function moves up and down with the ups and downs of the soil-bedrock interface. At the soil-bedrock interface the bedrock material is transformed from bedrock to soil. The bedrock has a higher potential for chemical weathering than the soil above the soil-bedrock interface that has been subjected to chemical weathering. The function declines below the soil-bedrock interface because of the reduced porosity of the bedrock inhibits water flow. Although we do not model chemical weathering in this paper, we believe that the dynamic reversed exponential function can be used to conceptualise chemical weathering.

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The three depth dependent weathering functions are graphically represented by Figure 3. The exponential function is [*Cohen et al.*, 2010]

$$w_h = \beta' e^{(-\delta_1 h)} \qquad (8)$$

where w_h is the weathering rate at the soil layer at a depth of h (m) below the surface and δ_1 is the depth scaling factor (here δ_1=1.738).

The humped function used is [*Minasny and McBratney*, 2006]

$$w_h = \frac{P_0\left[e^{(-\delta_2 h + P_a)} - e^{(-\delta_3 h)}\right]}{M} \qquad (9)$$

where P_0 and P_a are the maximum weathering rate and the steady state weathering rate respectively, δ_2 and δ_3 are constants used to characterise the shape of the function, and M is the maximum weathering rate at the hump which is used to normalize the function. Values we used here were P_0 = 0.25, P_a = 0.02, δ_2 = 4, δ_3 = 6, and M = 0.04.

The dynamic reversed exponential function is

$$w_h = \begin{cases} 1-\lambda\left[1-e^{-\delta_4 (H-h)}\right] & for \quad h \le H \\ 1-\lambda\left[1-e^{-\delta_5 (h-H)}\right] & for \quad h > H \end{cases} \qquad (10)$$

where H is the depth (m) to the soil bedrock interface from the surface which is calculated from the soil grading distribution at each iteration during the simulation, λ is a constant which determines the function value at the asymptote, δ_4 and δ_5 are constants used to characterise the rate of decline with depth of the function. We used λ = 0.98, δ_4=3, δ_5=10.

The non-zero weathering below the bedrock-soil interface in equation (10) represents a slower rate of chemical weathering within the bedrock due to its lower porosity and hydraulic conductivity. In general δ_5 > δ_4 .

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The weathering rate of each layer is determined by modifying the base weathering rate W_0 (Equation 2) and the depth dependent weathering function used, $f(h)$. The weathering rate of a soil layer at a depth of h from surface W_h is given by,

$$W_h = W_0 f(h) \quad (11).$$

3. Data used in this study

Four soil particle size distribution datasets were used as input data for SSSPAM simulations. Two particle size distribution datasets were collected from the Ranger Uranium Mine (Northern Territory, Australia) spoil site [*Willgoose and Riley*, 1998; *Sharmeen and Willgoose*, 2007; *Cohen et al.*, 2009; *Coulthard et al.*, 2012]. The third and fourth gradings were created from the previous two gradings to simulate the subsurface bedrock conditions. The naming convention used here is "a" for the actual grading dataset and "b" for the synthetic bedrock corresponding to the actual dataset (e.g. Ranger1a is the actual dataset and Ranger1b is the synthetic bedrock corresponding to Ranger1a actual dataset). Further details are given below (Table 1).

- Ranger1a: This grading distribution was first used by *Willgoose and Riley* [1998] for their landform evolution modelling experiments. This soil grading was subsequently used by *Sharmeen and Willgoose* [2007] and *Cohen et al.* [2009] for their armouring and weathering simulations. This grading distribution consists of stony metamorphic rocks of medium to coarse size produced by mechanical weathering breakdown, has a median diameter about 3.5mm, and has a maximum diameter of 19mm.
- Ranger2a: The second grading distribution was used by *Coulthard et al.* [2012] in their soil erosion modelling experiments and has a maximum diameter of 200mm. The Coulthard dataset includes a coarse fraction not included in Ranger1a, has a median diameter of 40mm, and has a maximum diameter of 200mm. Nominally Gradings 1a and 2a are for the same site but the gradings are not identical in the overlapping part of the grading below 19mm.
- Ranger1b and Ranger2b: These grading datasets were created using the particle distribution classes of Ranger1a and Ranger2a to represent the underlying bedrock for each of the grading distributions mentioned above. To represent the bedrock for these datasets 100% of the material was assumed to be in the largest diameter class for each grading classes (19mm for the 1b and 200mm for 2b).

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We divided our planar hillslope into nodes with 4m spacing downslope and the armouring and weathering was simulated at these nodes. The soil profile at each node was represented by 21 layers representing the armour layer and 20 subsurface layers. Initially the armour layer was set to either Ranger1a or Ranger2a grading dataset (depending on the type of simulation) and all the subsurface layers were set to the corresponding bedrock layer (for Ranger1a surface grading Ranger1b was set as the bedrock grading for all other subsurface layers). For brevity henceforth simulations run with the "Ranger1 dataset" used the Ranger1a grading for the initial surface layer and Ranger1b as the subsurface grading unless otherwise stated. Likewise "Ranger2 dataset" means, Ranger2a for the initial surface and Ranger2b for the subsurface). We have used 30 years of measured pluviograph data [*Willgoose and Riley* [1998] to calculate discharge. The 30 years of runoff was repeated to create a 100-year data set as was done in our earlier work [*Sharmeen and Willgoose*, 2006; *Cohen et al.*, 2009].

4. SSSPAM calibration

To provide a realistic nominal parameter set around which parameters could be varied in the parametric study SSSPAM was calibrated to mARM3D, which in turn had been calibrated to ARMOUR1D [*Willgoose and Sharmeen*, 2006] and we know ARMOUR1D corresponded well with field data.

Figure 5 shows a comparison between contour plots generated by mARM3D and SSSPAM using identical initial conditions (Ranger1 dataset) and model parameters. The figure shows that mARM3D and SSSPAM produce similar d_{50} values, though SSSPAM is very slightly coarser. The slight differences between the two contour plots result from the improved numerics of and an improved implementation of the matrix methodology in SSSPAM. We are thus confident that SSSPAM and mARM3D are comparable. The parameter values used for SSSPAM are $\alpha_1 = 1.0$, $\alpha_2 = 1.2$, $\beta = 1.0$, $m = 4$, $e = 2.5\text{x}10^{-8}$ and $n = 0.1$.

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5. SSSPAM Simulations and results

Cohen et al. [2009, 2010] found a strong log-log linear relationship between contributing area, slope and the d_{50} of the armour soil grading. They quantified the relationship between soil grading, local topographic gradient and drainage area by

$$\frac{A^{\alpha} S}{d_{50}{}^{\varepsilon}} = \text{constant} \qquad (12)$$

where A is the contributing area to the point of interest, S is the slope at the point of interest, d_{50} is the 50th percentile (i.e. median) of the soil grading, and α and ε are constants. Cohen used only one parent material grading and one parameter set for his analyses. To explore the generality of equation (12), we have examined the behaviour of the contour plots with changes to (1) weathering parameters, (2) grading of the parent material, (3) process and climate parameters, and (4) armouring mechanisms. We also examined a broader range of area-slope combinations that would typically occur in nature (since we are interested in man-made landforms which may have far from natural geomorphology), and which Cohen examined. For the initial conditions, unless otherwise indicated, in each simulation the 'a' grading was used for the initial surface layer and the corresponding 'b' bedrock grading for all the initial subsurface layers (e.g. Ranger1a for the surface and Ranger1b for the subsurface). To ensure that the hillslopes had reached equilibrium, the model simulated 100,000 years with output every 200 years. Equilibrium was assessed to occur when the grading of all nodes on the hillslope stopped changing, typically well before 100,000 years. Figure 4 shows a time series d_{50} evolution of all the nodes with lowest slope gradient (2.1%). It shows that equilibrium is reached well before 100,000 years. Hillslopes with higher gradients reached equilibrium even faster

5.1. Interpretation of the grading contour plots

Before discussing the parametric study and its myriad of contour plots, Figure 5 shows how the contour plots can be used to estimate soil properties for any hillslope type. Five profiles are illustrated:

1. This is a hillslope where the slope is increasing down the hillslope so is concave down in profile and looks like a rounded hilltop. The d_{50} increases down the hillslope (i.e. increasing area, moving from left to right in Figure 5).

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All our contour plots increase from left to right and from bottom to top, so in general concave hillslopes will always coarsen downslope.

2. This hillslope has constant slope downslope and, as for slope 1, will always coarsen downslope.
3. This hillslope has slopes that are decreasing downslope and is concave up. Importantly the gradient of the line in Figure 5 is less than the gradient of the contours so the hillslope coarsens downslope.
4. This hillslope is similar to 3 except that the rate of decrease of slope downstream is more severe (i.e. concavity is greater) so the gradient of the line in Figure 5 is steeper than the gradient of the contours. This hillslope fines downstream.
5. This hillslope is a classic catena profile with a rounded hilltop and a concave profile downstream of the hilltop. Tracking this hillslope downstream it will initially coarsen. As it transitions to concave up it will continue to coarsen until the rate of reduction of the hillslope slope is severe enough that is starts to fine downstream. Whether this latter region of fining occurs will depend on the concavity of the hillslope and whether it's strong enough relative to the gradient of the soil contours in Figure 5.

Note that the erosion model in SSSPAM is an incision model dependent on upstream area and slope. With this model the planar shape and slopes of the catchment upstream of the point are irrelevant, so while we derived Figure 5 for a planar hillslope it is equally valid for a natural two-dimensional catchment with flow divergence and convergence. Thus it should be clear that the spatial distribution of soils, and any questions of downslope fining or coarsening of those soils, must depend on the interaction between the pedogenesis processes that produce the soils (and thus drive the area-slope dependence of soil grading) and landform evolution processes that generate those profiles (and the area-slope relations for those slopes). Ultimately deeper understanding of these links will only come from a coupled landscape-soilscape evolution model, but in this paper we confine ourselves to better understanding of the soilscape processes and the area-slope dependence of grading. The coupled model will be discussed in a subsequent paper.

5.2. Parametric Study of SSSPAM

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All the nominal parameters used in the parametric study are presented in Table 2. In order to fully explore the area-slope-d_{50} relationship a parametric study was carried out using SSSPAM. The area-slope-diameter relationship was derived by evolving the soil on a number of one-dimensional, constant width, planar hillslopes, each with a different slope, with evolution continuing until the soil reached equilibrium. A contour plot was then created where the soil grading metric (usually the median diameter, d_{50}) was contoured for a range of slopes and area. Because of the planar slope, only erosion occurs, no deposition. Erosion is a function of local discharge, slope and soil surface grading as indicated in Equation (3), and is assumed to be detachment-limited. Detachment-limitation means that the upstream sediment loads do not impact on erosion rates. Hillslope elevations are not evolved (i.e. no landform evolution occurs) which is equivalent to assuming that the soil evolves more rapidly than the hillslope so that the soils equilibrate quickly to any landform changes.

5.2.1. Changing surface and subsurface gradings and weathering rate

Figure 6 shows the equilibrium contour plots generated for the two grading datasets and with different weathering rates. The equilibrium d_{50} decreases with increasing weathering rate. Higher weathering rates break down the larger particles more rapidly. The equilibrium d_{50} values were the same even if the initial surface grading was changed. For example, using the Ranger1a or Ranger2b grading data for the surface but with Ranger2b for the bedrock yielded identical equilibrium d_{50} results. As weathering broke down the surface layer and it was eroded it was replaced by the weathered bedrock material, which was identical when the same subsurface grading and weathering mechanism was used. Finally a coarser subsurface grading led to a coarser armour.

These trends with weathering rate are consistent with *Cohen et al.* [2010] where the log-log linear area-slope-d_{50} relationship was observed regardless of the weathering rate. Moreover the contour lines in Figure 6 all have the same slope. This implies that although the magnitude of the coarseness of the equilibrium armour depends on the underlying soil grading and weathering mechanism, the slope of the contours is independent of the subsurface grading and weathering process. This result demonstrates that the area-slope-d_{50} relationship is robust against changes in the grading of the source material, and the only change is in the absolute grading, not the grading trend with area and slope.

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5.2.2. Changing the Runoff Rate

Erosion is a function of the discharge, and the discharge depends on the climate and rainfall. The effect of changing the runoff is shown in Figure 7. To simulate a more arid climate the runoff generation parameter in Equation (4) was halved. Figure 7 shows that a reduced discharge produced a finer armour. While not shown, higher discharge rates produced coarser armour. For lower discharges (1) the Shield's Stress threshold decreases thus allowing smaller particles to be retained in the armour layer, and (2) the rate of erosion decreases while the weathering rate remains constant so that weathering (i.e. fining) becomes more dominant. Both of these processes work in tandem to produce finer armour. This conclusion is qualitatively consistent with *Cohen et al.* [2013], where they applied natural climate variability over several ice-age cycles and observed switching between fining and coarsening of the soil surface depending on the relative dominance of erosion and weathering at different stages in the climate cycle.

5.2.3. Changing the erosion discharge and slope exponents

The influence of the exponents on area and slope in the erosion equation (Equation 3), α_1 and α_2, is shown in Figure 8. These contour plots used the Ranger1a surface grading for the surface grading and Ranger1b bedrock grading for the initial subsurface layers. Figure 8 shows that although the d_{50} values changed with different α_1 and α_2 values, the slope of the contours only changed when α_1/α_2 was changed. To investigate the generality of this conclusion, contours were then plotted for different α_1/α_2. The slope of the contours was strongly correlated with α_1/α_2. The slope of the contours increased for higher α_1/α_2 ratios. Similar results were obtained for the Ranger2 dataset. The α_1/α_2 ratio not only influences the slope of the contour lines but also influences the equilibrium d_{50} values. For low α_1/α_2, the equilibrium d_{50} values at the hillslope nodes were coarser than for high α_1/α_2.

These relationships allow us to generalise the area-slope-d_{50} relationship

$$d_{50} = \left(cA^{\delta}S^{\gamma}\right)^{1/\varepsilon} \qquad (13)$$

where δ, γ and ε are exponents on contributing area, slope and d_{50} respectively, and c is a constant, and where the ratio δ/γ is a function of the erosion dependence on area and slope.

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Figure 9 show that δ / γ was strongly correlated with the model α_1/α_2 even though there was no correlation with the individual parameters (i.e. α_1 with δ, or α_2 with γ). In the regression analysis the parameter ε was assumed to be 1 in order to calculate δ and γ constants. This assumption does not affect the δ / γ ratio. This result was independent of the subsurface grading.

5.2.4. Changing the erodibility and selectivity exponent, *β* and *e*

This section examines the effect of changing erosion equation parameters, (1) the d_{50} exponent β (Equation 3) which relates the erosion rate to median sediment diameter, and (2) the erodibility rate e. The slope of the contours was independent of these parameters. The parameters β and e influence (1) the absolute value of d_{50}, and (2) the spacing of the contours. These impact on the value of c in Equation 13. For higher β, the equilibrium d_{50} was coarser than for low β values. Increasing the erodibility factor e yields similar results.

5.2.5. Different weathering fragmentation geometries

To study different weathering mechanisms we used a fragmentation geometry (Figure 2), that has two parameters, n and α (Equations 5-7). The simulations in the previous sections used symmetric fragmentation with n=2 and α=0.5 (i.e. where a parent particle breaks down to two equal volume daughter particles). Here we examine four other geometries, (1) symmetric fragmentation with multiple daughter products (n=5, α =0.2; i.e. the parent breaks into five equal daughters each having 20% of the volume of the parent), (2) moderately asymmetric (n=2, α=0.75; the parent breaks into two daughters, with 75% and 25% of the parent volume), (3) granular disintegration (n=11, α=0.9; the parent breaks into 11 daughters, one with 90% of the parent volume and the other 10 daughters each have 1% of the parent volume), and (4) as for Geometry 3 but with the large daughter having 99% of the parent particle volume (n=11, α=0.99). Figure 10 shows results using the Ranger1 dataset. The corresponding symmetric results are in Figure 6. Symmetric fragmentation with five equal daughter particles (Geometry 1) leads to the finest equilibrium contour plot but the contours are otherwise unchanged. The granular disintegration geometries produced coarser results with the coarsest armour from Geometry 4. We conclude that when fragmentation produces a number of symmetric daughters the equilibrium grading of a hillslope is finest. Finally the slope of the contours did not change for different fragmentation geometries.

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5.2.6. Effect of initial conditions

The simulations in the sections above used the same grading for the initial surface and the subsurface. To explore the initial conditions we changed the initial surface and subsurface datasets. The equilibrium grading contour plot generated using Ranger2a surface grading and Ranger1b subsurface gradings was identical to the equilibrium grading contour plot generated using Ranger1a surface and Ranger1b subsurface grading. Likewise the equilibrium grading contour plot generated using Ranger1a surface and Ranger2b subsurface gradings was identical to the equilibrium grading contour plot generated using Ranger2a surface and Ranger2b for subsurface gradings. The results were slightly different for different subsurface gradings. These results also show that, as expected, there was no effect of the initial conditions on the equilibrium grading. Though not shown the influence of the initial grading is only felt during the dynamic phase of the simulation before the armour reaches equilibrium.

5.3. Generalising beyond median grain size

The results above have focussed on d_{50} as a measure of soil grading. However, the model can provide any particle percentile or statistic of interest. Figure 11 shows area-slope results for d_{10} (i.e. 10% by mass is smaller than this diameter). It shows that the general trends observed in the d_{50} contour plots (Figure 6b2) are also evident in d_{10}. Though not shown, similar results were found for d_{90}. The slope of the contours is independent of diameter but as expected the d_{10} and d_{90} values are ranked $d_{10} < d_{50} < d_{90}$. We conclude that the area-slope-diameter relationship we have observed in our simulations is robust across the grading profile.

5.4. Influence of the depth dependent weathering functions

In this section we consider the three different depth dependent weathering functions (Figure 3, Equations 8 to 10) for the weathering rate in the subsurface soil layers. All the simulations in the previous sections used the exponential function (Equation 8). Figures 5 and 12 show that the contour plots for all weathering functions are very similar. However, as slope and area are increased the humped function produces a more rapidly coarsening armour. Overall the reversed exponential produces the coarsest armour. For the reversed exponential after an initially high weathering rate at the surface, the weathering rate reduces rapidly as the soil-bedrock interface moves deeper into the soil profile. This low near surface weathering decreases the rate of fining of the armour and dramatically reduces the erosion. This reduction in erosion rate prevents weathered fine particles from reaching the surface.

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We also analysed the subsurface soil profile. Figure 13 shows the d_{50} through the soil profile for our one-dimensional hillslope of length 32m, divided in to 8 nodes at 4 m intervals, and with 10% slope, and Ranger1 dataset. The bedrock layers are those layers near the base of the profile with the d_{50}=19mm. The exponential and humped functions produce similar soil profiles except that the humped function produces a shallower soil and a coarser armour compared with the exponential. In contrast, the reversed exponential produces a markedly different soil profile. It produces very coarse armour, a soil thickness beyond the modelled 2000mm limit, and a more uniform soil grading through the profile. This latter result is because the weathering is greatest at the bedrock-soil interface so most of the soil grading change is focussed at the base of the profile and relatively less occurs within the profile.

A final question is whether the area-slope-grading relationship occurs only in the armour or exists throughout the profile using the exponential weathering function. We generated area-slope-d_{50} contours for four different depths within the profile extending down to the base of the soil profile (Figure 14). The slope of the contours is the same for all depths and hence we believe that the area-slope-grading log-log linear relationship is exhibited for the entire soil profile, with the only change being the coarseness of the soil (which reflects the maturity of weathering of the soils) at any particular depth. This result is intriguing because while the armouring from erosion occurs at the surface it has an impact throughout the profile, it is not simply a property of the near surface layer directly impacted by erosion. Thus the act of soil profile generation, which is solely driven by the depth dependent weathering function, couples the spatial organisation of the surface with the spatial organisation of the soil profile at depth. Therefore what happens at the surface affects the entire profile.

6. Discussion

Here we have used a new pedogenesis model, SSSPAM, to analyse the equilibrium soil grading and spatial organisation of soil profiles. This model extends the mARM3D model of *Cohen et al.* [2010] and improves the numerics. Our results have generalised previous studies [*Cohen et al.*, 2009, 2010, 2013] that have found a log-log linear relationship between d_{50}, contributing area and slope. Using a broader range of environmental conditions, we have found that log-log linear relationship for grading is robust against changes in environment and underlying geology and for hillslopes where the dominant processes are surface fluvial erosion and in-profile weathering. The main factors influencing the

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quantitative form of the relationship are the area and slope dependency of the erosion equation, and the relative rates of the weathering and erosion processes. Coarsening of the downslope nodes was observed in all the simulations.

Our parametric study has demonstrated the versatility of our model for studying the influence of different process parameters and the dynamics of hillslope evolution. Our d_{10} and d_{90} contour plots show that the area-slope-diameter relationship is not only true for d_{50} but is also true for other aspects of the particle size grading of the soil. This strengthens our confidence in the generality of the area-slope-diameter relationship. This relationship provides us with a methodology to predict the characteristics of soil grading on a hillslope as a function of geomorphology. It also allows us to interpolate between field measurements. Furthermore, our parametric study showed how parameters of the armouring component affect the area-slope-diameter relationship. Particularly interesting was that the ratio of the erosion exponents (α_1/α_2) changes the slope of the contours. This observation also hints at the importance of topographic and process characteristics in soil evolution and hillslope catena and how these topographical units may be used for predictive soil mapping and inference of erosion process.

Previous work (e.g. *Willgoose, et al.*, 1991b; *Tucker and Whipple*, 2002) has shown that topography is also a function of α_1/α_2 and this suggests a strong underlying process link between the spatial distribution of topography and the spatial distribution of soil grading that goes beyond the concept of soil catena. The soil catena concept says that systematic changes occur in soils as a function of their position on the hillslope. Our results suggest that the same processes that influence the equilibrium distribution of topography (e.g. the erosion process that determines α_1/α_2) also influence the equilibrium distribution of soils. Thus while a soil catena presumes a causal link from topography, we postulate a causal link for both topography and soils from erosion processes.

Using our model we were able to explore the soil profile characteristics and how the soil profile will change depending on the weathering characteristics of the bedrock material. Another important insight is that the area-slope-d_{50} relationship is present in all the subsurface layers as well as the surface armour.

In this paper SSSPAM did not model transport-limited erosion. The implication is that the eroded sediment from nodes upslope did not impact the erosion on the downslope nodes. We also did not model an interaction between grading and the infiltration of water so no

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coupled behaviour with hydrology was modelled. In this paper we have only considered erosion from overland fluid flow and physical weathering mechanisms to predict the equilibrium soil distribution of hillslopes. There is a need to explicitly incorporate chemical and biological weathering [*Green et al.*, 2006; *Lin*, 2011; *Riebe et al.*, 2004; *Roering et al.*, 2002; *Vanwalleghem et al.*, 2013]. Another important aspect needed is accounting for deposition of sediments so that we can model alluvial soils which requires a transport-limited erosion model. A future task is to incorporate a soils model like SSSPAM into a landform evolution model such as SIBERIA [*Willgoose et al.*, 1991a]. This would allow the modelling of the interaction between the pedogenesis process in this paper with hillslope transport processes such as creep and bioturbation. If soils evolve rapidly then it may be possible to use the equilibrium grading results from this paper as the soilscape model, on the basis that the soil evolves fast enough to always be at, or near, equilibrium with the evolving landform. If soils evolve slowly then it may be necessary to fully couple the soils and landform evolution models. This is a subtle, and not fully resolved, question of relative response times of the soils and the landforms [*Willgoose et al*., 2012].

7. Conclusions

The most important insight from this paper is that the area-slope-grading relationship observed from a earlier generation soil profile pedogenesis model by previous authors [*Cohen et al.*, 2009, 2010] is general and robust across a range of climate and geologic conditions. Despite the wide range of parameters we used in our simulations, we always observed the log-log linear area-slope-diameter relationship in our simulations although the soil coarseness depended on the parameters used. In addition, contour plots of d_{10} and d_{90} indicated that the area-slope-diameter relationship is valid throughout the soil grading range, not just for d_{50}. It was also true for depths below the surface. The parametric study conducted on the area-slope-diameter relationship demonstrated how this relationship would change with changes in the pedogenic processes. We found that the ratio of the erosion exponents on discharge and slope, α_1/α_2, changes the angle of the contours in the log-log contour plots (Figures 7). This has application in the field of digital soil mapping where easily measurable topographical properties can be used to predict the characteristics of soil properties. Importantly, the contributing area and the slope data can be easily derived from a digital elevation model, which can be produced using remote sensing and GIS techniques. Coupling SSSPAM with a GIS system can potentially improve the field of digital soil mapping by providing a physical basis to existing empirical methods and potentially streamlining existing resource intensive

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and time-consuming soil mapping techniques as, for example, in the current initiatives in global digital soil mapping [*Sanchez et al*., 2009].

The simple physical processes currently implemented in SSSPAM also enables it to model the evolution of hillslope soil grading. A subsequent paper will focus on the dynamics of the soil profile evolution process. Although we used only armouring and weathering as soil forming factors in this study, other processes such as chemical weathering or biological influence on soil formation can also be included in our state-space matrix modelling framework (e.g. Willgoose, “Models of Soilscape and Landscape Evolution”, in prep). With its high computational efficiency and ability to incorporate various processes in to its modelling framework, SSSPAM has the potential to be a powerful tool for understanding and modelling pedogenesis and its morphological implications.

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Acknowledgements

This work was supported by Australian Research Council Discovery Grant DP110101216.

The SSSPAM model and the parameters used in this paper are available on request from the authors.

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Figures

Figure 1

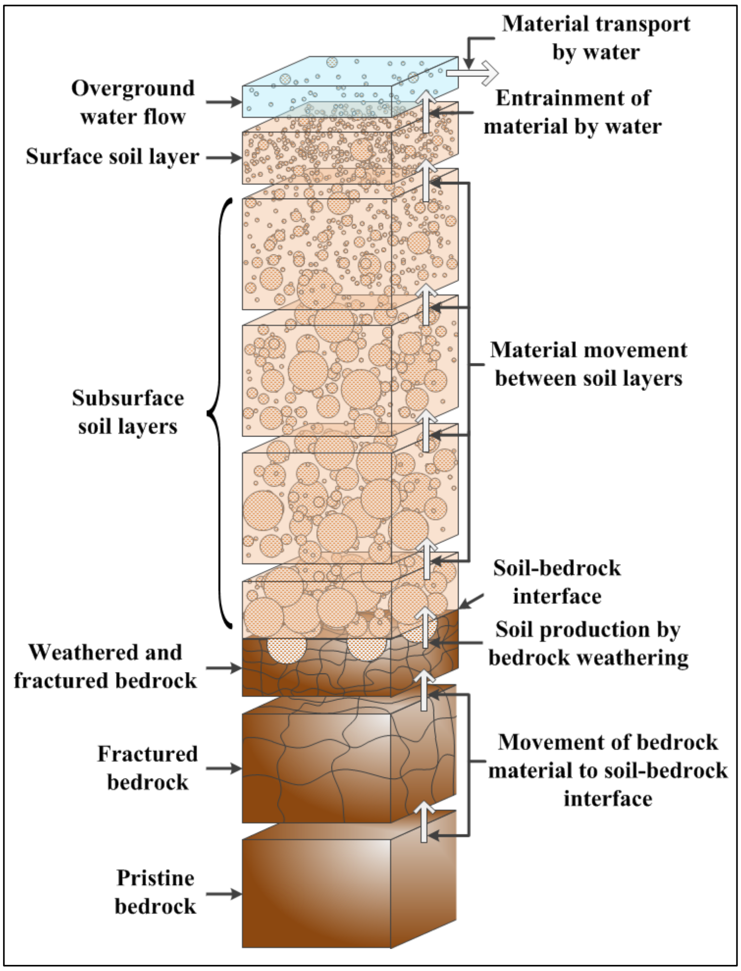

Figure 1: Schematic diagram of the SSSPAM model (from Cohen et al., 2010).

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Figure 2

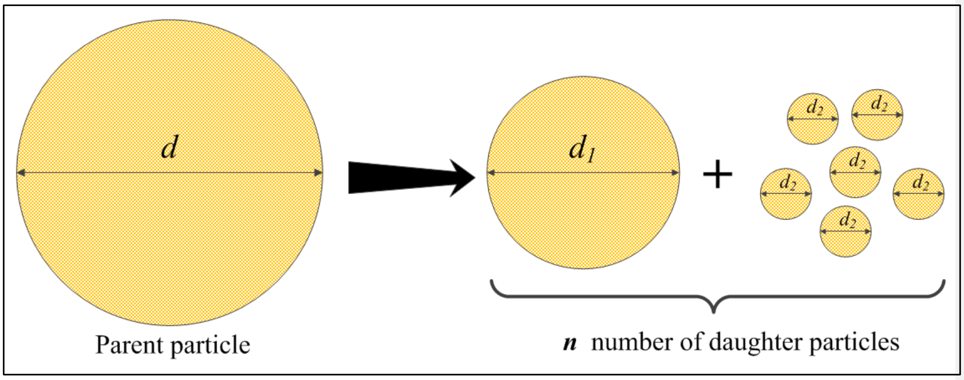

Figure 2: The fragmentation geometry used in SSSPAM (after Wells, et al., 2008).

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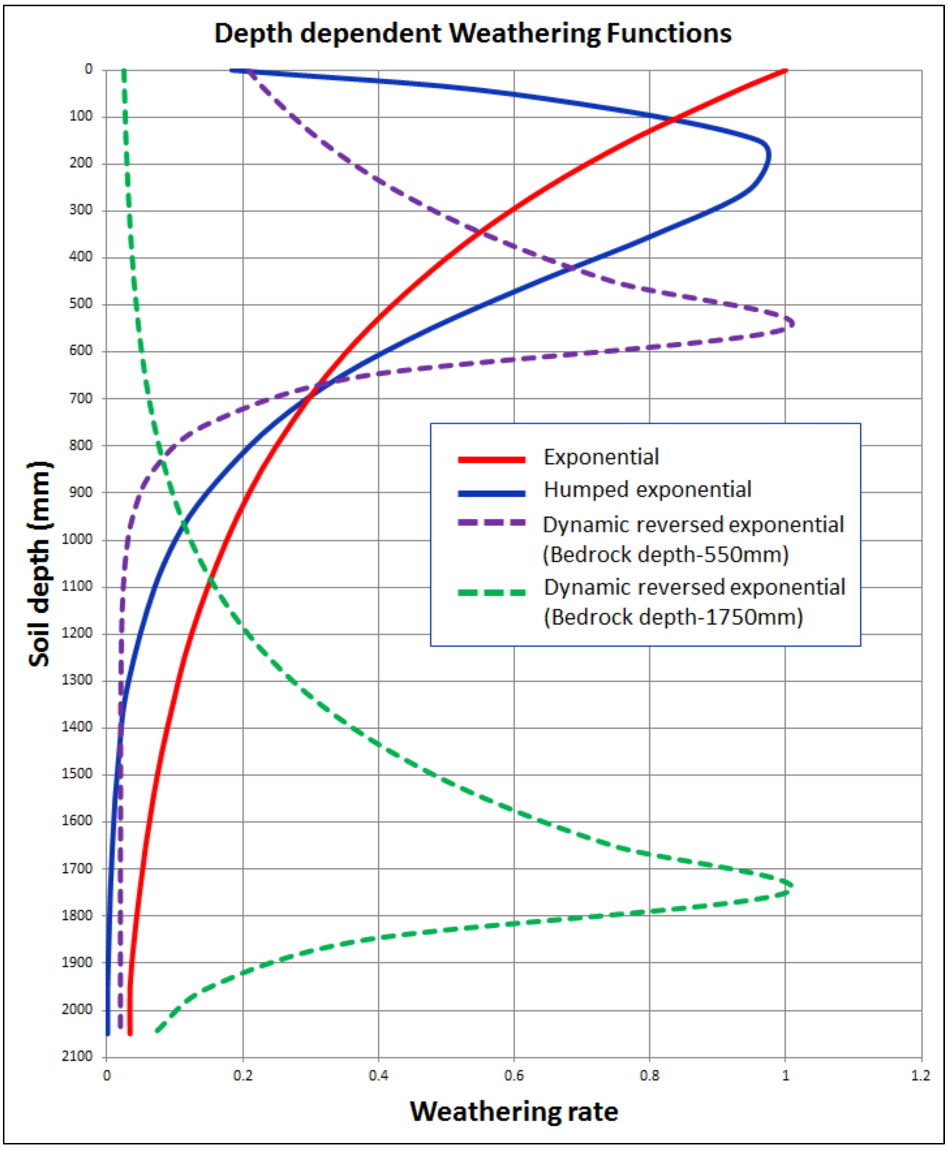

Figure 3: Graphical representation of all the depth dependent weathering functions used in SSSPAM

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Figure 4

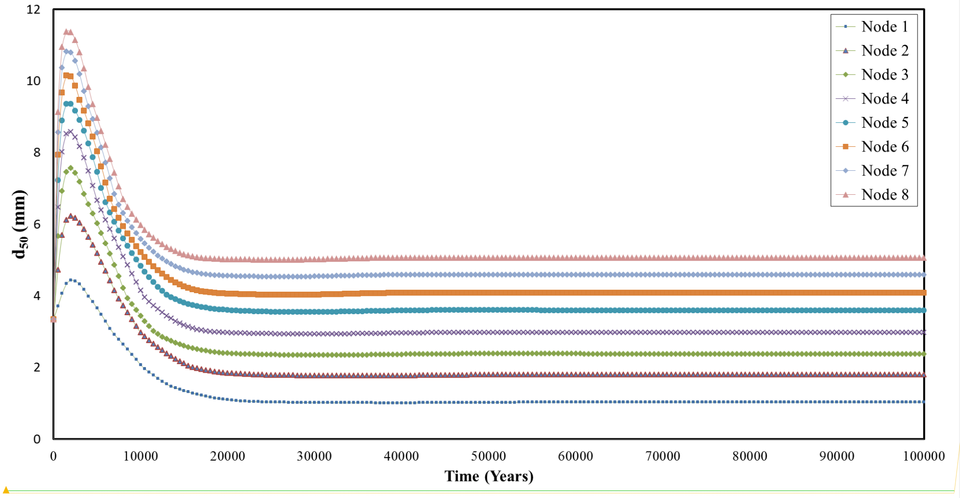

Figure 4: d_{50} Evolution of the nodes with lowest slope gradient (2.1%)

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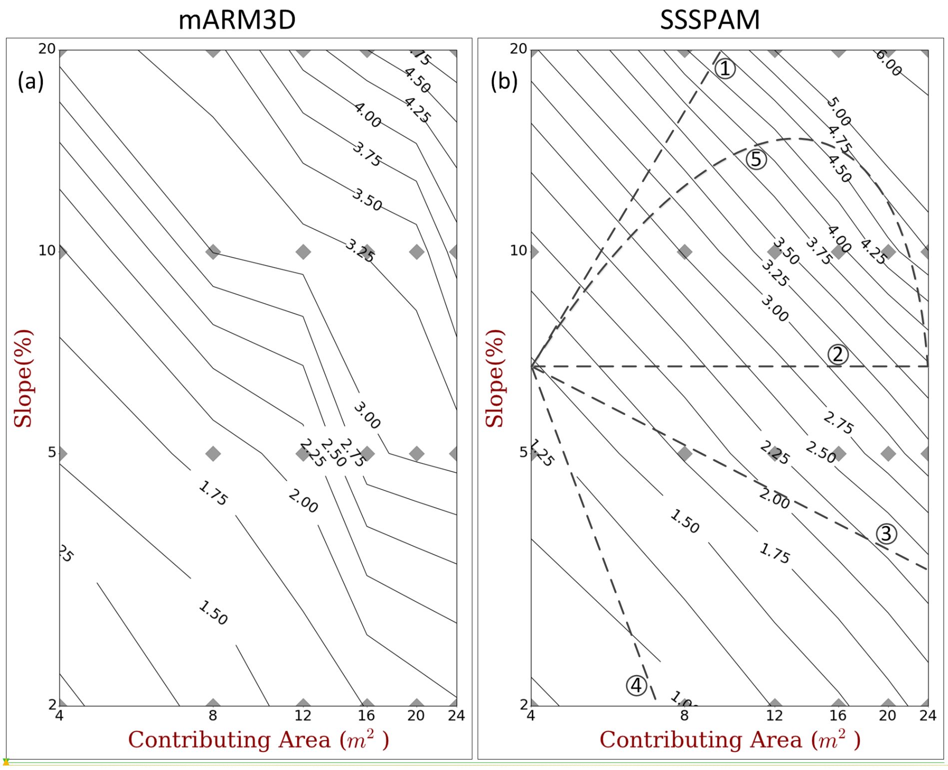

Figure 5: Log-log Area-Slope-d_{50} contour plots generated using the Ranger1 dataset. (a) mARM3D [*Cohen et al.*, 2009], (b) SSSPAM. The dotted lines in (b) are hypothetical long profiles down a drainage line showing how the contour figure can be used to generate soil properties down a drainage line. See the text for more detail.

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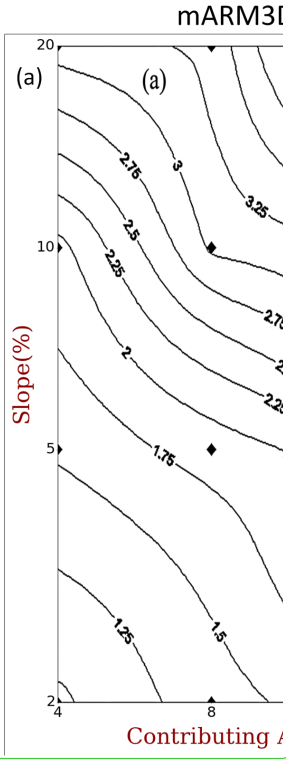

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Figure 6

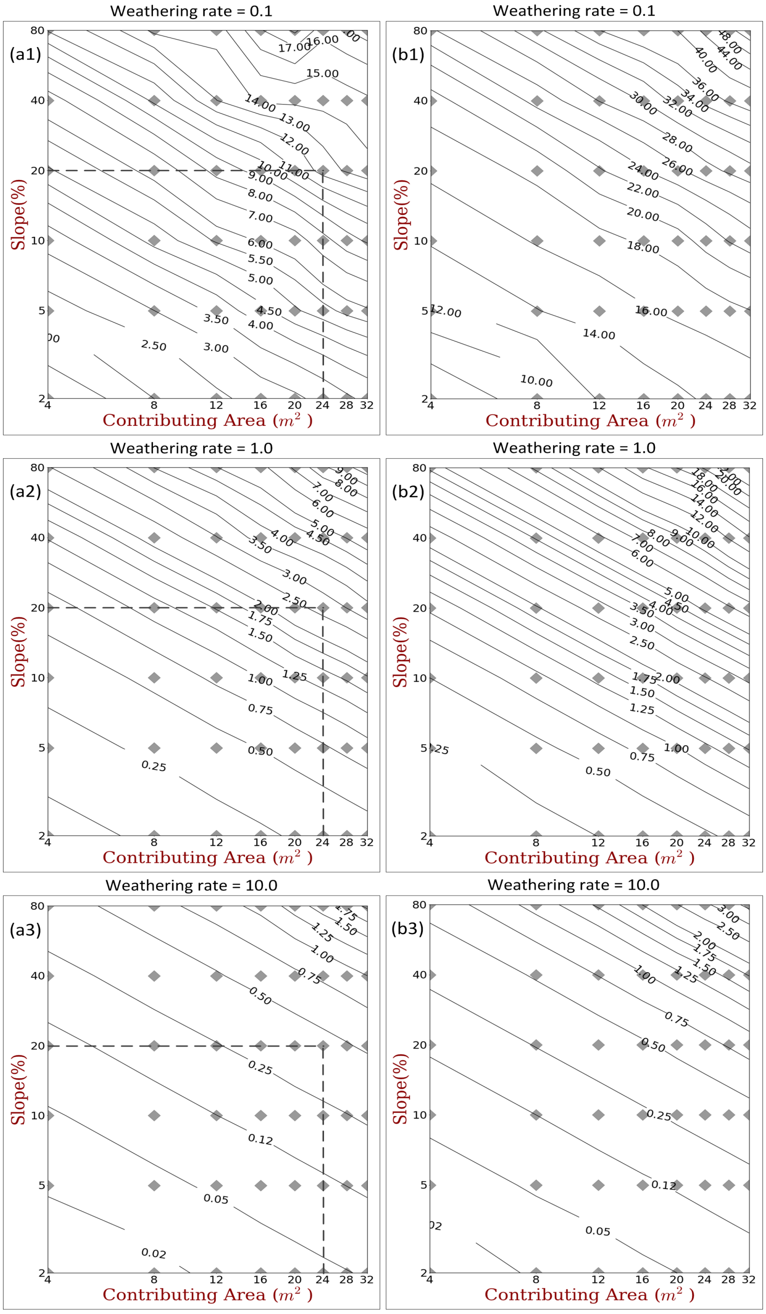

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Figure 6: Equilibrium contour plots of d_{50} values (interpolated from 48 data values, the diamonds) simulated by SSSPAM for different surface and subsurface grading data and different weathering rates (Top to Bottom: 0.1, 1.0, 10.0). (Left Column) Ranger1 dataset, (Right Column) Ranger2 dataset.

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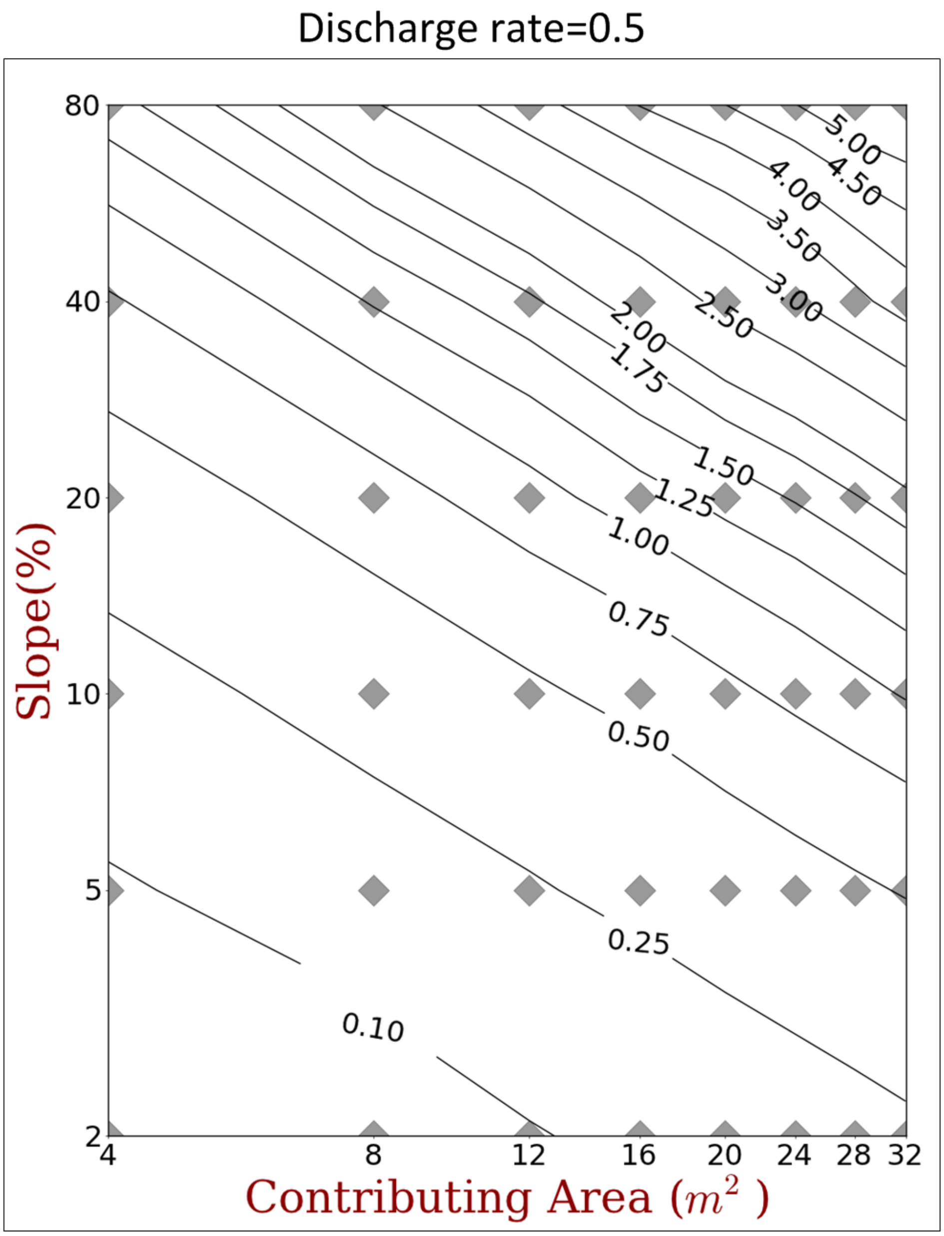

Figure 7: Equilibrium contour plots of d_{50} generated using the Ranger1 dataset with identical model parameters as used in Figure 6(a2) except changing the runoff rate, half the nominal runoff rate

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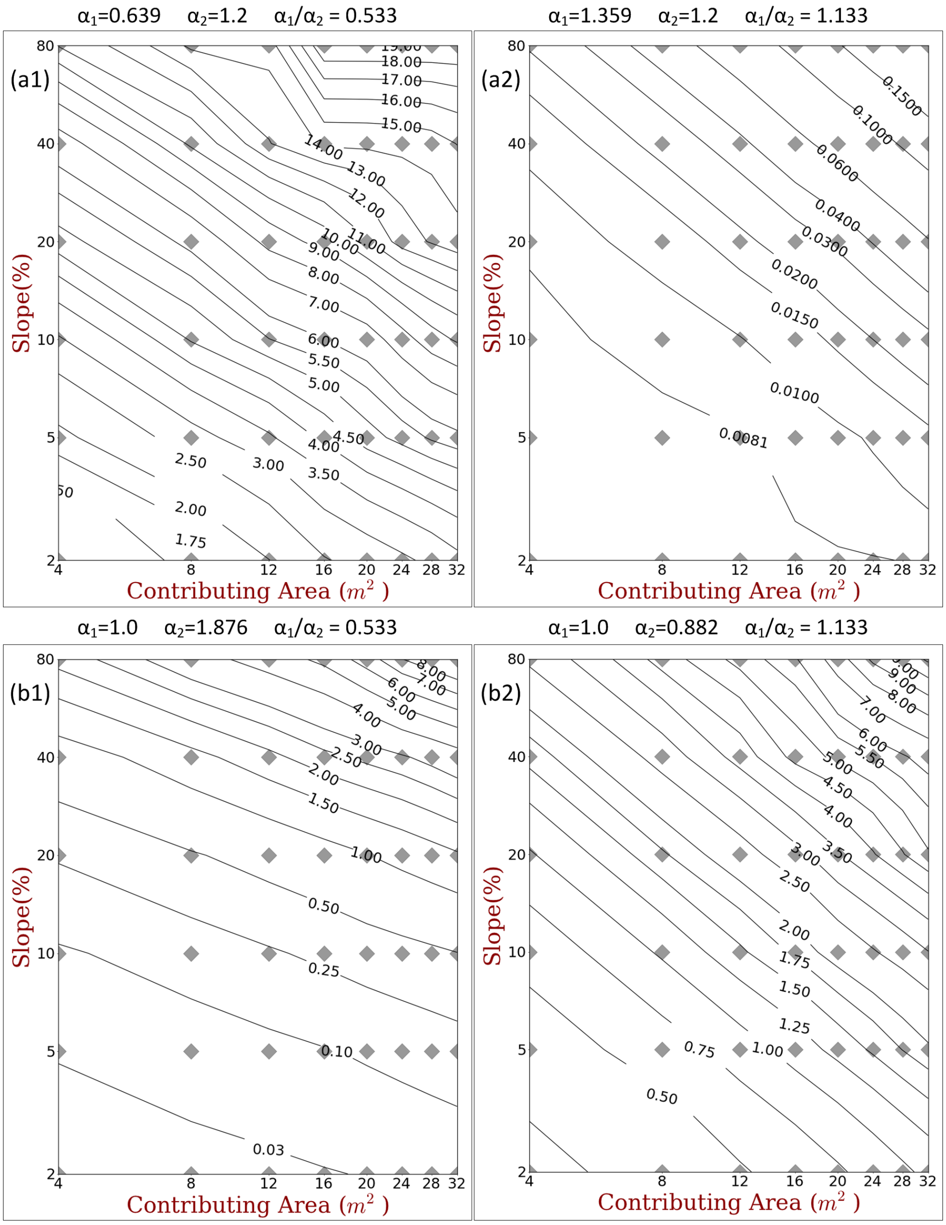

Figure 8: Equilibrium contour plots of d_{50} generated using Ranger1 dataset with identical model parameters as Figure 6(a2) (i.e. α_1=1.0, α_2=1.2, α_1/α_2=0.833) except changing $\alpha_1$and α_2 values generated using (a1, b1) different α_1 and constant α_2 values, (a2, b2) different α_2 and constant α_1 values.

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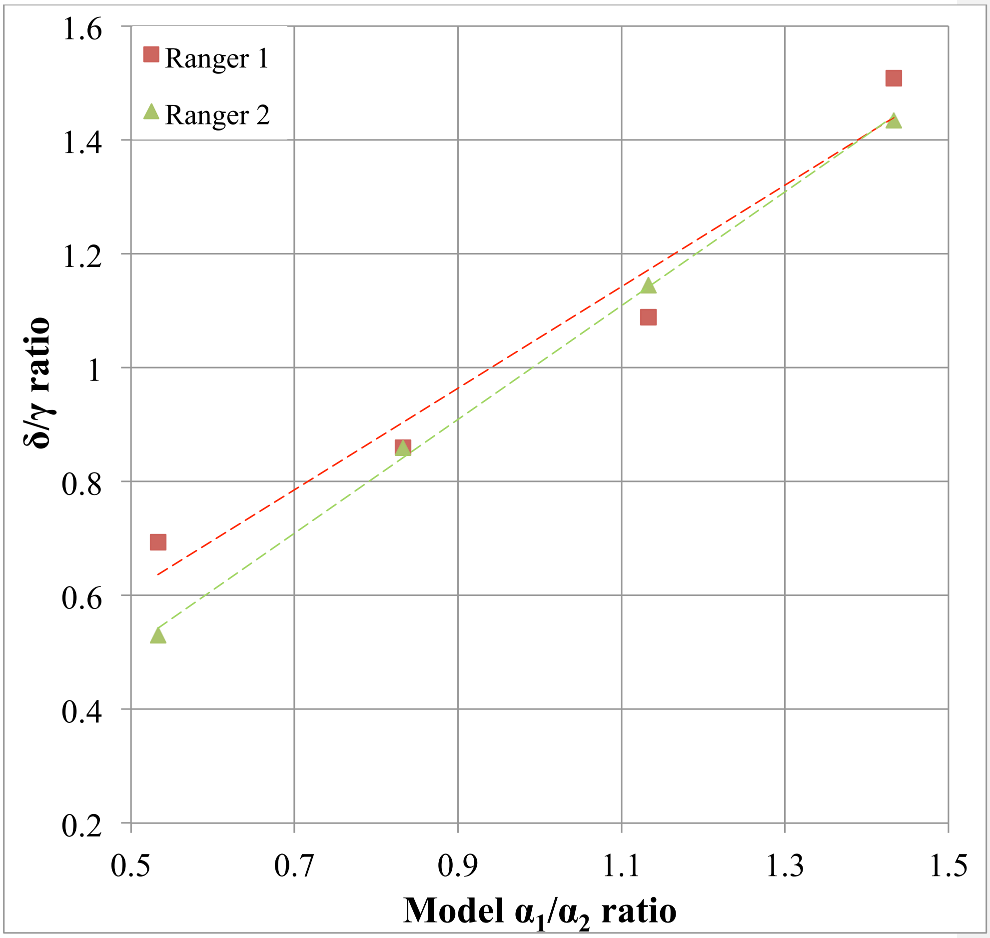

Figure 9: Correlation between the model α_1/α_2 and δ/γ

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Figure 10

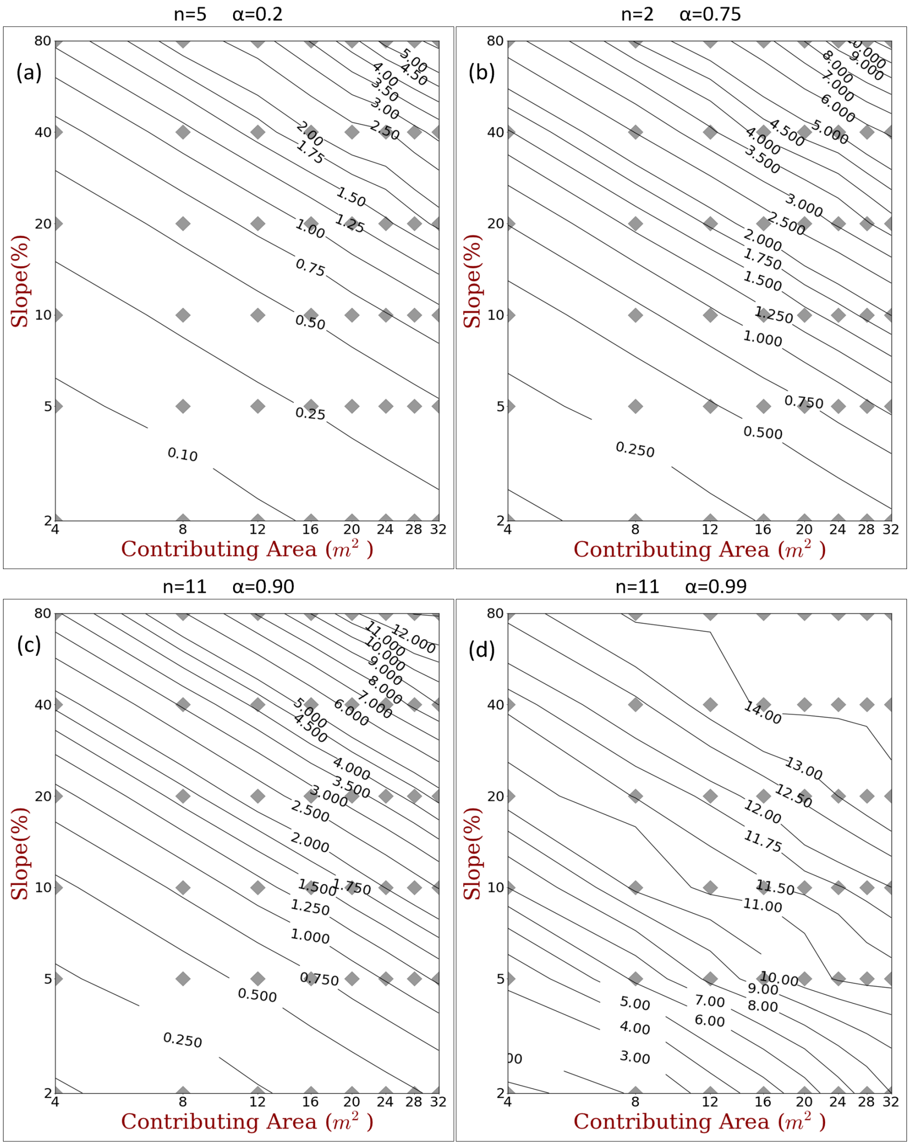

Figure 10: Equilibrium contour plots of d_{50} generated using Ranger1 dataset with identical model parameters as Figure 6(a2) (i.e. n=2, α=0.5; symmetric fragmentation with 2 daughter particles) except changing the weathering geometry, n-number of daughter particles and α - material fraction retained by largest daughter particle (a) symmetric fragmentation with n=5 and α=0.2 (b) asymmetric fragmentation with n=2 and α=0.75 (c) granular disintegration with n=11 and α=0.9, (d) granular disintegration with n=11 and α=0.99.

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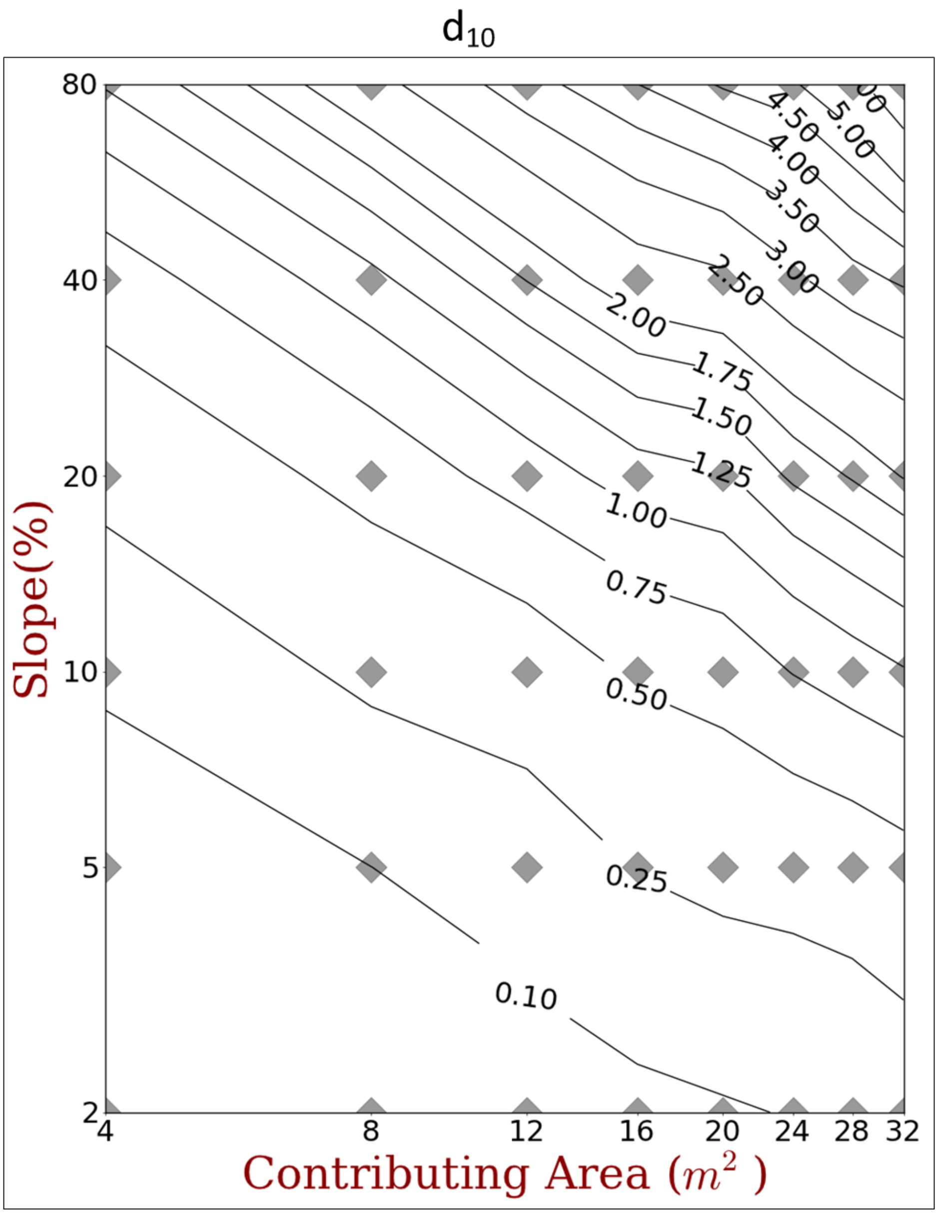

Figure 11: Equilibrium contour plots of d_{10} generated using Ranger1 dataset with identical model parameters as Figure 6(a2) (where the d_{50} results are presented).

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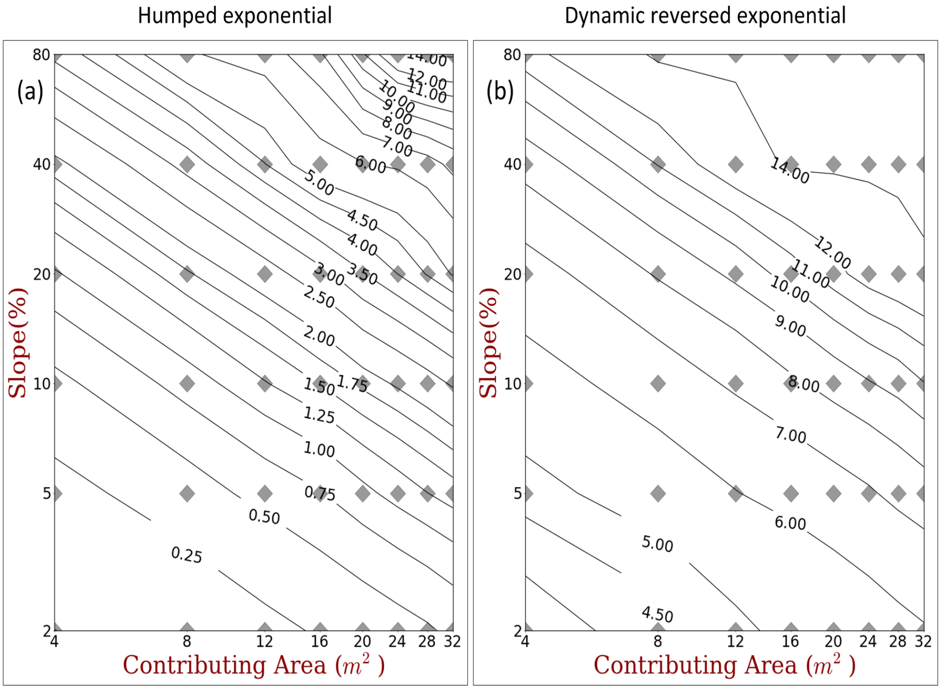

Figure 12: Equilibrium contour plots of d_{50} generated using Ranger1 dataset with identical model parameters as Figure 6(a2) except changing the depth dependent weathering function to (a) Humped, (b) Dynamic reversed exponential.

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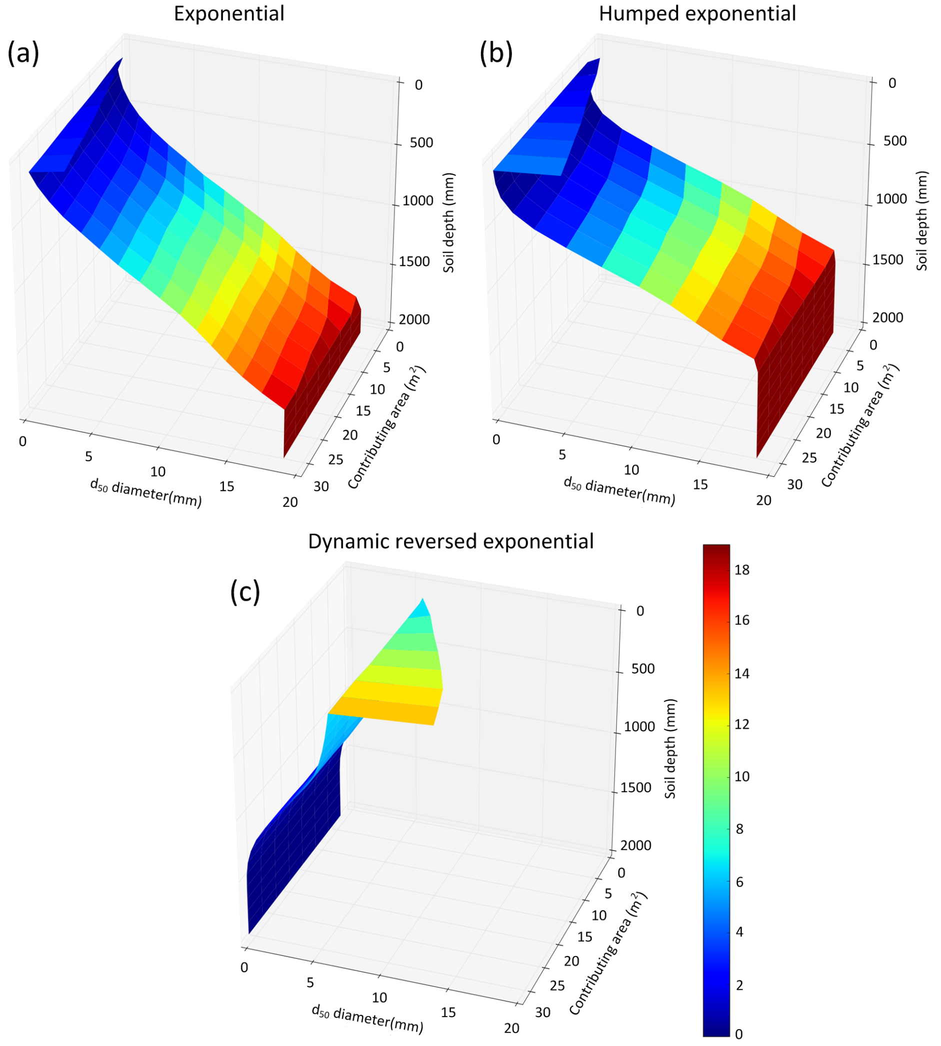

Figure 13: Equilibrium soil profile d_{50} generated using the Ranger1 dataset with a one-dimensional hillslope with 10% slope and 32m length using (a) Exponential, (b) Humped, (c) Reversed exponential weathering functions.

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Figure 14

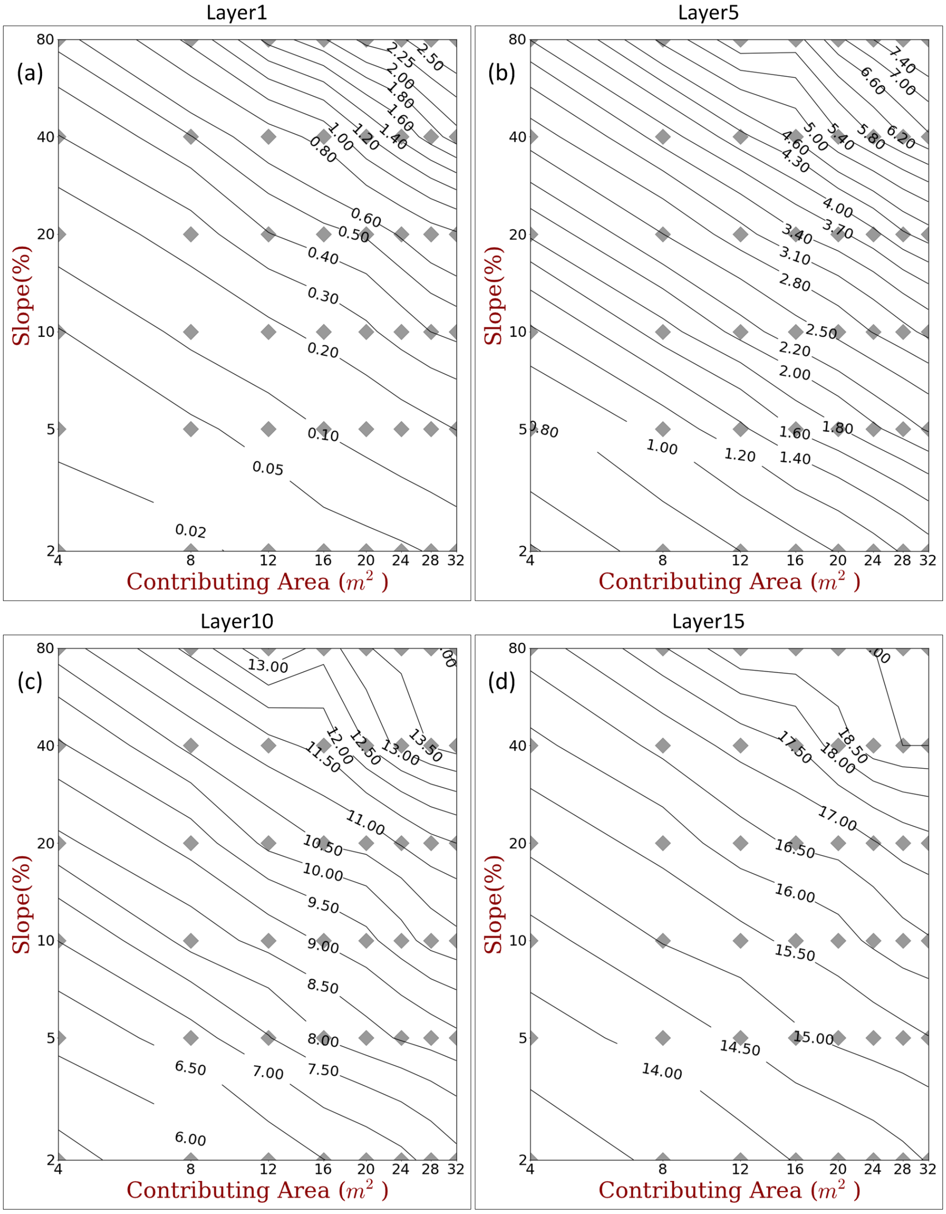

Figure 14: Equilibrium contour plots of d_{50} generated using the Ranger1 dataset with identical model parameters as used in Figure 6(a2) for different subsurface soil layers (a) layer 1 (100mm depth), (b) layer 5 (500mm depth), (c) layer 10 (1000mm depth), (b) layer 15 (1500mm depth)

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Tables

Table 1. Size distribution of soil gradings used for SSSPAM4D simulations

Grading Range (mm)			Ranger1a	Ranger1b	Ranger2a	Ranger2b
0	-	0.063	1.40 %	0.0%	8.75 %	0.0%
0.063	-	0.111	2.25 %	0.0%	2.19 %	0.0%
0.111	-	0.125	0.75 %	0.0%	1.46 %	0.0%
0.125	-	0.187	1.15 %	0.0%	1.72 %	0.0%
0.187	-	0.25	1.15 %	0.0%	0.86 %	0.0%
0.25	-	0.5	10.20 %	0.0%	0.86 %	0.0%
0.5	-	1	9.60 %	0.0%	0.86 %	0.0%
1	-	2	12.50 %	0.0%	0.86 %	0.0%
2	-	4	16.40 %	0.0%	5.70 %	0.0%
4	-	9.5	20.00 %	0.0%	6.35 %	0.0%
9.5	-	19	24.60 %	100.0%	7.65 %	0.0%
19	-	40	0.00 %	0.0%	8.70 %	0.0%
40	-	95	0.00 %	0.0%	12.85 %	0.0%
95	-	200	0.00 %	0.0%	41.20 %	100.0%

Table 2. Parameters used in the simulations generate Figure 6(a2)

Equation No	Parameter	Value
3	α_1	1.0
	α_2	1.2
	β	1.0
	e	0.025
5,6,7	α	0.5
	n	2.0
8	β'	1.0
	δ_1	1.738
9	P_0	0.25
	P_a	0.02
	δ_2	4.0
	δ_3	6.0
	M	0.04
10	λ	0.98
	δ_4	3
	δ_5	10

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However at the present state of technology, these gamma ray spectral imaging devices are used as hand held devices or airborne survey instruments. For this reason, although the spatial resolution of

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Products of GIS technology such as digital elevation models (DEM) have revolutionized the study of geomorphological processes through physically based numerical modelling

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Methodologies to predict the soil characteristics using morphological attributes and models of physical processes derived from digital elevation models (e.g. contributing area, slope) were

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1.1 Armouring

The first important process is armouring as a result of fluvial erosion. Armouring in river beds has been widely understood and studied extensively for mostly streams and rivers [*Gessler*, 1970; *Gomez*, 1983; *Lisle and Madej*, 1992; *Little and Mayer*, 1976; *Parker and Klingeman*, 1982]. The majority of these armouring models employ time varying simulations to calculate the particle distribution of the armour layer by selective entrainment of the smaller bed material by the transport medium.

Armouring of the surface soil layer is a by-product of erosion by either overland water flow (fluvial erosion) or wind (aeolian erosion). Depending on the energy of the erosion medium, transportable fine particles are preferentially entrained and transported from the surface soil layer. This process coarsens the remaining surface soil layer enriching it with coarser, less mobile, material. With time, if the energy of the transport medium remains constant, an armoured layer is formed with all the transportable material removed. At this time the sediment transport reaches zero. This armour, where all the materials are larger than the largest grains which the transport medium can entrain, prevents erosion of material from the subsurface. If the energy of the transport medium increases, the existing armour can be disrupted, and a newer stable armour with coarser material can be formed [*Sharmeen and Willgoose*, 2006].

1.2 Weathering

The second important process is weathering. Weathering is a general term used to describe all the processes which cause rocks or rock fragments to disintegrate or alter through physical, chemical or biological means [*Strahler and Strahler*, 2006]. Disintegration of rock material through physical weathering can occur by (1) unloading, (2) expansion and contraction of rock through heating and cooling cycles, (3) stress developing in rock fractures due to freezing water, (4) salt crystal growth or tree root intrusions, and (4) abrasion of rock by harder materials transported by flowing water or glaciers [*Thornbury*, 1969]. Physical weathering where larger soil particles are broken down into smaller particles is dominant in the surface layer of material where it is more exposed. Weathering also occurs underneath the surface and the weathering rate at these subsurface layers can be modelled with depth dependent weathering functions.

There is considerable literature concentrating on different aspects of rock weathering such as physical weathering [*Ollier*, 1984; *Wells et al.*, 2006; *Wells et al.*, 2008; *Yokoyama and Matsukura*, 2006] and chemical weathering [*Green et al.*, 2006; *Ollier*, 1984]. However the significance of the combination of armouring and weathering, and the influence on soil erosion in landform evolution models has only recently been quantitatively studied [*Sharmeen and Willgoose*, 2006].

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The soil grading at any specific time, and for any specific layer, is given by a vector, the state vector. Each entry in the state vector is the mass of sediment in each grading size range in that layer. The transition from the state at any given time to the state at the next time step (i.e. the change in soil grading from one timestep to the next) is described by a matrix equation.

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Table 3. Parameters of the d_{50}-Area-Slope relationship calculated from regression analysis for different data sets and different model α_1/α_2 ratios.

α_1	α_2	α_1/α_2	δ	γ	δ/γ
Ranger grading data set 1					
0.800	1.500	**0.533**	0.620	0.894	**0.694**
1.000	1.200	**0.833**	0.805	0.936	**0.859**
1.020	0.900	**1.133**	0.798	0.733	**1.088**
1.200	0.837	**1.433**	0.725	0.480	**1.509**
Ranger grading dataset 2					
0.800	1.500	**0.533**	0.701	1.322	**0.530**
1.000	1.200	**0.833**	0.437	0.509	**0.859**
1.020	0.900	**1.133**	0.909	0.794	**1.145**
1.200	0.837	**1.433**	0.843	0.588	**1.434**