

Interactive comment on “Controls on slope-wash erosion rates in the Mojave Desert” by O. Crouvi et al.

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We thank anonymous referee #2 for the comprehensive review and detailed comments and suggestions that will improve the manuscript. Below we reply and discuss the comments and suggest changes and additions to the manuscript.

Q1: The paper can potentially have a much higher impact if the authors put their results in perspective by comparing and combining them with those findings under other climate and land cover conditions to be able to make further reaching conclusions about the driving forces behind soil erosion processes.

A1: We added comparison to additional studies.

Q2: Moreover, it would be interesting to add further discussion on the relevance of tem-

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poral scale of assessments and the interaction between soil erosion and soil formation processes (including soil disturbances).

A2: We discussed the issue of how soil erosion rates relate to soil development in 554/1-25. We have re-written this paragraph (see A9 here).

Q3: Also, the fact that higher rock fragment cover on steeper slopes is potentially an artefact of previous higher soil erosion rates on those steep slopes is not sufficiently elaborated by the authors (see for example Govers et al 2006; Poesen et al., 1998). The authors argue that they evaluate the factors determining soil erosion rates, but given the rather homogeneous land cover, lithology and climate between their study sites, in fact the paper only evaluates the relative role of rock fragment cover versus slope characteristics. The impact of these two factors may be completely over-ruled by other factors such as lithology, vegetation or climate, but we can't say that based on your results.

A3: The goal of our study was to determine controls on soil erosion rates over decadal time scales. The reviewer is correct that erosion on these slopes may be cyclical, such that faster erosion rates could lead to more armored slopes, which then have lower erosion rates until fines build up in the soil and initiate a return to higher erosion rates. Such cyclicity is theoretically possible but detecting it is beyond the capability of the ¹³⁷Cs tracer we used. We discuss reason for the rock cover – slope correlation in the text (552/27-29 to 553/1-4), with citation of Govers et al (2006). Anyway, we added more citations to this section. The climate in all four study sites is assumed to be similar on a decadal scale, as the maximal distance between sites is 30 km. Although rainfall can vary spatially in these spatial scales, over several dozens of years we can assume that the annual average rainfall is similar. Regarding lithology, three of the four lithologies are granite (or type of granite) – only one of the sites is of a different plutonic lithology (diorite). We analyzed the erosion rates with and without the dioritic site to learn on the effect of lithology (see also A30 here). About vegetation, we found different vegetation coverage between sites, but within sites there is limited variation in

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vegetation coverage (see also A24 here and A13 in the reply to reviewer 1). Thus, we can relate the rate of erosion to rock fragments in soils (i.e., rock coverage).

Q4: The author's justification of this study builds strongly on the argument that there are few data on erosion rates from arid regions around the world. While arid lands may be understudied for assessments of hillslope soil erosion rates, the paper would benefit from a more critical and in-depth discussion of those data that are available for arid lands around the world (see specific comments below) and contrasting them with data under more humid conditions. That may help to highlight the role of climate and provide an added value to your paper.

A4: A discussion regarding other studies that present erosion rates in arid regions, together with semi-arid regions, already appear in the text. Yet, we added and enhanced this discussion. It is important to emphasize that erosion rates determined over longer and shorter time scales may be driven by very different mechanisms than processes occurring over decadal time scales. As we noted in the manuscript, there is no published data on decadal-scale erosion rates in arid environments anywhere in the world. As such, comparing our data to data from other climates necessarily involves comparisons over different time scales. Such comparisons are beyond the scope of the paper.

Q5: It may also be interesting to include reference from the introduction and discussion section to the recently published pan-European database of soil erodibility that specifically accounts for stoniness, and highlights its strong reducing effect on soil erodibility (<http://eussoils.jrc.ec.europa.eu/library/themes/erosion/Erodibility/>).

A5: We added this reference.

Q6: There are several concerns about the methodology. Several of the replicate profiles taken at few meters distance show very different Cesium inventories (Figure 2), also for example for reference profile GM2. The author's explanation for this is that erosion rates are spatially very variable. However, there could be other explanations as

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well. It is not clear how you dealt with this and it potentially puts some serious doubts on the interpretation of your results.

A6: We acknowledge the fact that few adjacent profiles show very different inventories (see Figure 4 that summarizes these differences). We cannot explain the exact reason for each of these differences, beside the fact that their location at the same topographic position might suggest that the position along the hillslope is not the main control of rates of erosion. Rather, the local and upslope surface cover might be of more importance. We relate to this issue in the discussion (551/7-12). Regarding the spatial variability of inventories for reference profiles, see A7 in our reply to reviewer 1.

Q7: In relation to that, it would be interesting if you could discuss the assumptions made for Cesium as a tracer to assess soil erosion rates (see Parsons and Foster, 2011), and how these may affect your results.

A7: We added discussion on these assumptions in the discussion section.

Q8: Further, it is not clear from the methodology how rock fragment cover was determined. It somewhere mentions that rocks larger than 0.5m were counted, somewhere else it is mentioned that fractions > 2mm were considered as rocks?

A8: We stated clearly in the text that surficial rocks larger than 0.5 m were counted along transects (542/16-19). These were averaged into average rock cover (%) and presented in Table 1 as a rough estimation of the surficial properties at each site. On the other hand, the percentage of rock fragments in soil profile was estimated using sieving each soil sample through a 2 mm sieve (543/4-7). This value, for each soil profile, was used as proxy to estimate the relative presence of rock exposed upslope of the location of the soil profile (Nearing et al. 2005). All sediments that are larger than 2 mm are considered as rock fragments.

Q9: I am not convinced by the added value of paragraph 3.4. What exactly do these results tell us and how are they complementary to the Cesium results? It is not clear

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to me why greater heterogeneity in the degree of calcic soil development, higher soluble salt contents and less weathered C horizons in more gently sloping sites should be related to higher observed soil erosion rates. The authors suggest that these are indicators for higher runoff and therefore higher soil erosion rates, but convincing arguments or data to support this are not provided.

A9: We discussed these feedbacks in the discussion (554/1-25). We now added to the methodology section a more detailed explanation of the expected feedbacks between soil erosion rates and soil properties. We also have re-written the relevant results and discussion.

Q10: The discussion section is very chaotic and difficult to follow. Splitting up the discussion paragraph in 2-3 sub-paragraphs would make it a lot easier to read and extract the main messages. The whole discussion section can be reduced by about 50% by being more concise and bringing in more structure. You now bring the same message several times.

A10: We re-arranged the discussion and shorten it.

Specific comments:

Q11: The abstract can be written more concise.

A11: The abstract was rearranged.

Q12: L16-18: how do you explain the higher rock fragment cover for the semiarid sites as compared to arid sites?

A12: We relate to this in the discussion (556/14-24) and we re-written this part.

Q13: P537L4: what about erosion plots? Probably the most widely used method.

A13: We added 'erosion plots' to the text.

Q14: P537L9: you may want to add reference and discussion of results presented in

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Van-maercke et al (2012; 2014) and Cerdan et al (2010).

A14: We added only Cerdan et al. (2010) as it deals with the hillslope scale. The studies of Van-maercke are in catchment scale and were not discussed.

Q15: P537L9-12: This is not only the case in (semi-)arid regions, but generally valid for erosion processes.

A15: We re-phrased the sentence.

Q16: P537L18-20: Indeed that is also why the USLE and most other models use the C and K factor to describe soil erodibility and protection by land cover.

A16: We added a sentence at the introduction about the addition of stoniness to estimate soil erodibility (see A5).

Q17: P538L17-19: The paper would benefit from better discussion and reference to the results of work done by previous authors in arid lands like, Yair, Lavee, Sarah, and others (see reference list for some suggestions).

A17: We cite few of these studies in several places in the introduction (537/20-29 to 538/1-14; 538/18-19), and also in the discussion (553/9-29). Anyway, we added more references and discuss them in more detail in the discussion section. The papers by Lavee and Pariente (Sarah) focus on runoff generation and the effect of rock cover on runoff, rather than on erosion.

Q18: P538L21-23: Where does this characterization of arid regions come from? Is soil thickness and rock cover more variable than in semiarid areas? Is rainfall of higher intensity than in any other area?

A18: We added citations. See also A4 in the reply to reviewer 1.

Q19: P538L26-28: So you mean to say that studies based on cosmogenic nuclides represent average rates of large drainage areas and are therefore not suited to obtain information on slope and soil surface characteristics, which justifies your study based

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on Cesium 137? Please explain this.

A19: Yes. We simplified this in the text.

Q20: P539L1: moreover, I assume we would like to know which factors determine these soil erosion rates.

A20: Added to the text.

Q21: P539L14: please explain where this dust comes from. You refer to higher wind erosion rates? If these are so high, how does this affect your water erosion assessments? Maybe part of your estimated water erosion is actually wind driven? This might explain that steep slopes exposed opposite to the dominant wind direction result in lower erosion rates than flat terrain exposed to any wind direction?

A21: See A5 in the reply to reviewer 1.

Q22: P539L12-14: Can you explain how hypothesis 1 relates to the classical Langbein and Schumm (1958) curve suggesting a maximum erosion rate around about 300mm of effective annual rainfall, with decreasing erosion rates below that threshold due to a lack of rainfall to provoke high erosion rates?

A22: We added this to the discussion.

Q23: P539L15-16: I am not sure if we can say that erosion rates are 'mainly' controlled by rock coverage in semiarid regions. Indeed rock coverage plays an important role, but so do vegetation cover, lithology, rainfall intensity and duration characteristics. So maybe trim down the statement somewhat or simply refer to the relative role of rock coverage as compared to slope gradient.

A23: We changed the text accordingly.

Q24: P539L18-20: What about vegetation cover, generally considered one of the most important factors controlling erosion rates? Or is your study limited to controlling factors under equal vegetation cover? Your objectives suggest you will also include the role

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of vegetation cover, but apart from the numbers in Table 1, no analysis are performed with vegetation cover.

A24: We do not assume equal vegetation cover – we report the overall coverage of vegetation in Table 1 as a general characteristic of each site. We did not observe clear spatial trends in vegetation within sites; see also A13 in our reply to reviewer 1. Thus, when we discuss the differences between sites, we wrote that the reason is the combined effect of rock and vegetation cover as we indeed cannot differentiate between the two here (552/1-4). Since we did not observe any downslope change in vegetation cover within sites, vegetation cannot explain the variability in soil erosion rates within sites. Thus, our interpretation of the significant relationship between rock fragments content in individual soil profile vs. erosion rates, for all sites, is that the rates of soil erosion can be explained, at least partly, by rock coverage percentage.

Q25: P539L21-23: What exactly is 'floral bioturbation'? In fact, the cited paper by Kaste et al (2007) seems to suggest that physical soil mixing (bioturbation) was found to be an important process in some of their study sites (grasslands in California). So, how does this support your assumption that floral bioturbation is not expected to be of relevance for the evaluated timescales?

A25: We re-phrased these sentences.

Q26: P539L24-25: what about wind erosion here?

A26: See A58 here.

Q27: P539L25: what is meant by 'erosion by colluvial processes'? You mean deposition processes and interpret that as a negative erosion process? Please clarify.

A27: Erosion by colluvial processes refer to diffusion-like processes like bioturbation and creep (539/21-23). We re-phrased these sentences.

Q28: P540L15: what is meant with residuum?

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A28: Residuum is residual of rock/soil material.

Q29: P540L27: what does the 50-100% stand for? The % of sediments with Aeolian origin? The same for the 11-33% later on? What does this mean?

A29: Yes. We simplified these sentences in the text.

Q30: P541L14: It is interesting that you included a less weathering resistant lithology in case soil formation rates might affect trends in your soil erosion rates. However, this aspect is not dealt with in your paper so it remains unclear why you included this less weathering resistant lithology and what is the added value.

A30: We added a short paragraph regarding the results of the less-resistant site to the discussion.

Q31: P542L2: so what about wind erosion deposits?

A31: See A5 in the reply to reviewer 1.

Q32: P542L15-20: method used to assess rock fragment cover is unclear. Why were only rocks larger than 0.5 meters (diameter?) included? How was rock fragment cover determined 'visually' in the other two sites with less rocks? Both methods seem to be 'visual'?

A32: We chose the value of > 0.5 m as a threshold for rocks that has considerable effect on the surficial hydrology. As we wrote in detail in the text (542/16-20), the rock coverage for the two rocky hills was determined quantitatively, by counting the number of rocks (> 0.5 m) in a 1 m interval along 50 m transect along the topographic contours. For the two other sites, we visually estimated the rock coverage (i.e., looking at the surface and estimating the rock coverage percentage). See also A8.

Q33: P542L20: what characteristics of vegetation cover were determined? The type of vegetation, surface cover, how was this done? What did you do with the information?

A33: For the two rocky sites we visually estimated the percentage of vegetation cov-

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erage, including the areal size of the crown for each soil pit (e.g., looking at the area surrounding each soil pit and estimating the areal coverage of the vegetation). For the two less-rocky and less vegetated sites we visually estimated the vegetation coverage of the entire hillslope. We did not account for different vegetation species. See also A24 for usage of vegetation data. We added relevant information in the text.

Q34: P543L5: So everything larger than 2mm is considered to be a rock fragment? That is a very low threshold! How does this compare with rocks larger than 0.5 meter above?

A34: See A8.

Q35: P544L23: what kind of LiDAR? Airborn, groundbased?

A35: "airborne" was added to the sentence.

Q36: P544L25: can we expect these animal burrows to affect our bioturbation and Cs profiles?

A36: When we sampled for Cesium-137 we avoided places with clear signs of animal burrows. In addition, the Cesium-137 depth profiles do not show any evidence for bioturbation.

Q37: P545L9: grid=grid

A37: Corrected.

Q38: P545L20: why is it that we see higher values in Figure 2 (over 800 Bqm-2)?

A38: The value range that appear in 545/18-20 refer to individual soil samples (see also supplement material), whereas the values presented in Figure 2 are total inventories for each soil profile.

Q39: P546L5: the large variation between replicates at the summit position is especially worrying as this is your reference profile.

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A39: See A6 here and A7 in the reply to reviewer 1.

Q40: P546L10-25: This description of results is a bit chaotic, some information is documented twice (e.g. fact that only in 4 profiles Cs was detected between 3–6 cm), and results could be described more systematic and more concise.

A40: We reorganized the results section.

Q41: P547L3: it makes sense that if you don't find Cesium, high erosion rates are to be expected, assuming the assumptions of the Cesium methodology are valid.

A41: We deleted this sentence.

Q42: P547L4: What exactly is the value or information we obtain from an average soil erosion rate per site if variation is so large?

A42: Despite the fact that variation of rates is large, we use the average and range of rates to examine the general differences between sites, together with differences in average rock cover and vegetation per site.

Q43: P548LL8 what do you mean by 'high and only minimal erosion rates'? Are they high or minimal?

A43: Rephrased.

Q44: P548L21: Please rephrase 'mean value of volume fraction of rocks'. Not clear what is meant now.

A44: We clarify this in the text.

Q45: P549-P550: Did you also find an A horizon in the profiles with no detectable Cesium? I suppose that the presence of an A horizon would not agree with a high erosion rate (>50t ha⁻¹ yr⁻¹), where I would expect truncated profiles and shallow soils and no A horizon.

A45: We did not use the thickness of A horizon as a sole indicator for high erosion rates

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as it might be that the thickness of A horizon is relatively thick due to past episodes of dust accumulation (e.g., BRH site). We use combination of various soil properties to learn on the relationship between erosion rates and soil development. See A9 here.

Q46: P549L23-24: how are cobbles and stones defined?

A46: We changed "stones" to "gravels". Cobbles size range is 6.4-25.6 cm, whereas gravels size range is 2 mm to 6.4 cm.

Q47: P551L13-14: Didn't you just show in your previous paragraph that soil thickness was rather constant?

A47: We stress here (and in Crouvi et al., 2013) that in general there is a great spatial variation in soil thickness along the hillslopes, including areas with no soil at all due to the presence of rocks. Yet, we show here that for some hillslope (i.e., GM2), in places where there are soils, their thickness can be rather constant.

Q48: P551L17-18: Indeed, selection of reference sites is the most crucial step. But how do you explain that only 2 out of 8 summit positions showed useful reference profiles? What happened in the others? What does this tell us about the reliability of reference profiles?

A48: See A7 in the reply to reviewer 1.

Q49: P552L25: simply quantify this by the correlation between rock fragment cover and slope gradient.

A49: We added the correlation.

Q50: P553L4-7: please rephrase this sentence, very difficult to follow. For example what do you mean by 'slope-velocity equilibrium the develops on slopes'?

A50: Corrected: we meant to write 'slope-velocity equilibrium that develops on slopes'. The concept of slope-velocity equilibrium is a standard one in hillslope erosion studies (i.e. see Nearing et al. (2005)).

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Q51: P554L4 & L13: slats= salts

A51: Corrected.

Q52: P554L13: I am not so convinced by the direct relationship between the absence of a weathered C horizon and high erosion rates.

A52: See A9 here.

Q53: P554L27: what is colluvial erosion? You mean creep? Also, previously you that wind erosion in these sites may be important.

A53: A detailed explanation on colluvial erosion appears in 539/21-25 (also re-phrased in the new text). We did not say that wind erosion is important at these sites, rather aeolian deposition (accretion). See also A58 here.

Q54: P555L1: what about concentrated flow erosion? This is often mentioned to be responsible for large parts of total erosion, especially in areas with high intensity rainfall, in areas with high runoff rates etc.

A54: We see some rills in the study area but these are located at the lower part of the slopes; where rills are evident, we avoided sampling near these features.

Q55: P555L4: bioturbation is likely to act on a shorter timescale than 50 years.

A55: There is no published estimation on soil mixing time in the Mojave Desert. Yet, we assume that diffusion-like processes (e.g., bioturbation, creep) are barely active on short time scales in areas not adjacent to perennial shrubs, as most faunal and floral activities occur up to 1.3 times the canopy radius in the Mojave desert (Caldwell et al., 2012). Thus, erosion by colluvial processes is likely not accounted for in 137Cs inventories whereas the decadal-scale soil erosion rates estimated here are mostly due to slope wash. This assumption is strengthened by two observations: 1) most Cesium-137 depth profiles do not show evidence for soil mixing, and 2) no significant linear relationship was found between topographic curvature and erosion rate, as expected

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in the case of soil erosion by flowing water.

Q56: P555L23: what do you mean with 'diffusion like erosion'?

A56: See A53.

Q57: P555L28-29: Please refer also to these studies in your intro where you stress the absence of studies in these environments. At least mention and discuss all studies available.

A57: We added discussion with these studies.

Q58: P556L4: again, this contrasts your previous statement that wind erosion is not relevant here due to crusts. So, do we have wind erosion and Aeolian sediments or not?

A58: There is no conflict. The hillslopes serve as a sink not as a source of dust. According to previous studies, most sources of eolian material (i.e., wind erosion) in the Mojave Desert are alluvial fans, washes and playas (Sweeney et al., 2013). Moreover, our previous paper (Crouvi et al., 2013) suggest that most of the fine fraction of the soil (<2 mm) in the studied hillslope is of aeolian origin. See also A5 in the reply to reviewer 1.

Q59: P557L10-12: what is the size of the source area of this study (km²)?

A59: The size is <1km². We added this information to the text.

Q60: Figure 2: the yellow triangles and numbers stand for Cs inventories (totals over 9 cm depth?)?

A60: Yes, we added this to the caption.

Q61: Figure 6: what does the +/- values after the erosion rates stand for? Standard deviation based on only 2 numbers?? The EC profiles are unclear/too small to interpret.

A61: The figure is now larger. We deleted the average value and present the two

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values of the two soil pits. We also deleted the averages from the text.

Q62: Figure 7: why are profiles with no detectable Cs not included, and why would these refer to minimal erosion rates? Wouldn't this be the other way around (extremely high erosion rates left no Cs in the profile)?

A62: Profiles with no detectable Cesium-137 were not included in the regressions as we do not know their exact values of erosion rate – for these profiles we only know that erosion rate is higher than $-51.85 \text{ t ha}^{-1} \text{ yr}^{-1}$. We rephrased accordingly in the text.

Q63: Table 2: which profiles are included here? All replicate profiles? On figure 2 some profiles show inventory 0, which is not included in this Table.

A63: All 46 soil profiles are included in Table 2, divided according to sites. The 2 reference profiles appear again in a separate column. The soil profiles with inventory 0 that appear in Figure 2 do appear in Table 2 (note 0 inventories as a minimum value for sites EPR3 and BRH).

Sweeney, M. R., McDonald, E., and Markley, C. E.: Alluvial sediment or playas: What is the dominant source of sand and silt in desert soil vesicular A horizons, southwest USA, *Journal of Geophysical Research*, 118, 257-275, 0.1002/jgrf.20030, 2013.

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