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Josh West
Associate Editor, ESURF

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Dear Dr West,

Thank you for considering our manuscript "The CAIRN method: Automated, reproducible calculation of catchment-averaged denudation rates from cosmogenic radionuclide concentrations". We also thank reviewers for the two careful and considered reviews. We have attempted to answer all of the issues raised by the reviews, and where we have not modified the manuscript according to their suggestions, we explain why not.

Our responses are in *blue italics*.

Sincerely,

Simon M. Mudd

Reviewer 1

1. Assumptions of the method: To provide accurate denudation rates from cosmogenic nuclides, several assumptions must be strictly met. For instance, sediments should be well mixed, there should be a steady state between nuclide production and removal by erosion and decay, a uniform quartz yield etc. These assumptions should be briefly mentioned in the introduction of the ms along with a few references where readers can find more details (e.g. Dunai, 2010; already cited). As in many natural situations the required assumptions are partly violated, the general accuracy of denudation rates is probably limited to ±20 to ±30 % (Dunai, 2010, p. 124) and this should be mentioned. The general error of 10-20% (mentioned on line 429) is too optimistic in my opinion.
The second reviewer also raises this point. We agree that the computation invokes a number of assumptions (mentioned above) that are almost certainly not met and we do not wish to deceive users of the code that the results are more accurate than they in fact are. On the other hand, it is difficult to quantify the uncertainties generated by these assumptions. We thus have added a new section to make it clear that the general error is a minimum error that captures only known errors in AMS uncertainty, production rate uncertainty, etc. This new section follows the advice of reviewer 2.

2. Density: To calculate denudation rates in units of length per time one must make an assumption on density (as already pointed out by the Associate Editor). I agree with the editor that the authors

should elaborate on this issue in the discussion. From discussions I had in the past, I got the impression that it is not very clear what values are appropriate, because soil thickness varies within catchments and around the globe. Maybe the authors can suggest some recommendations.
We certainly agree with this comment and there is no good way to arrive at a density estimate of soils if you do not have measurements. However, in the discussion we have used density values for rock, which is less spatially variable than soil density, and thus the erosion rates reported in length per time are rock equivalent erosion rates (surface erosion rates will be significantly higher since soil is less dense). We now state this explicitly in the manuscript. In the summary of calculations section we now state explicitly that CAIRN reports denudation rates in g cm^{-2} yr^{-1} because this requires no assumption of density, and then in the discussion we add text with notes on what density means. We have separated this section on density in the discussion. Some figures still report denudation rates in length per time in order to remain consistent with rates reported in other papers.

3. Nuclide production by muons: The production of muons is mentioned in several places of the ms (e.g. lines 77ff, 298, 507, Fig. 9). As it is known since many years that the model of Heisinger overestimates muon production (shown by the depth-profiles published by Braucher et al. and other studies, which are already cited in the ms), I suggest to make this point clear from the beginning of the ms and not only at the end (507ff). Hence, on line 79 the authors could rephrase the respective sentence to "... field-based estimates of muon production demonstrate that Heisinger et al..." or something similar. Likewise, lines 297-300 should be rephrased to provide a clear picture of that issue.
We have stated more clearly on the former lines 77ff and 297ff that field studies show the Heisinger et al. model overestimates muon production, but have not made major changes based on the comments of reviewer 2.

Balco et al. (2008) provide a nice plot (their Fig. 8), which highlights that the importance of muons relative to neutrons depends on elevation and the rate of erosion. Muons are particularly important at low elevation and at high erosion rates. I think it would be worth stating this more clearly somewhere in the ms.
We now state this shortly after Equation (2).

4. Landsliding: Landsliding introduces considerable complications for interpreting cosmogenic nuclide concentrations in terms of denudation rates (see also comment made by Associate Editor). It seems to me that the approach which the authors propose in order to deal with the issue is too simplistic. In fact, they state on line 324 that their "landsliding module is admittedly rudimentary". Hence, I suggest to omit the respective parts from the ms (i.e. lines 149-158 and 251-254). It is sufficient to mention the landsliding issue and cite a few relevant studies (as the authors have done). I do not think that this will weaken the paper in any way.
We have followed the advice of reviewer 2 and now have a section devoted to transient scenarios. We removed text about landsliding from the former line 251 and 324.

5. Snow shielding: It is not yet widely acknowledged that water or snow have a significantly shorter neutron attenuation length than rocks (the value for the latter is ±160 g/cm^2). Therefore, I appreciate that the authors cite the work of Delunel et al. (2014) and Zweck et al (2013). In addition, I suggest to mention the value of 109 g/cm^2 for the neutron attenuation length of snow explicitely (cf. Zweck et al. 2013). Fig. 7 of Delunel et al. (2014) shows that the attenuation by snow may be even more significant, which could also be mentioned. In my opinion, it would strengthen the numerical code, if a lower attenuation length of snow (as compared to rock) would be implemented into CAIRN (and the user can thus make a choice). Remote sensing will most likely be increasingly used to map snow depth in mountains (e.g. Beniston et al. 2003 and references therein). Could the authors check the literature and cite 1-2 recent papers on this subject in lines 330ff (I am quite sure there are more recent studies than Beniston et al.).

We have now cited the Beniston paper and mention that Zweck has a reduced attenuation thickness in the section "Spatial averaging for the CRONUS calculators". There are papers more recent than Beniston but these mainly use GCMs to model changing snow conditions and we feel scientists who want to calculate denudation rates are unlikely to use such models to reconstruct snow thicknesses. We also refer to the comment of reviewer 2: the uncertainties in the snow thickness through time vastly outweighs the uncertainties in attenuation lengths so we do not feel that changing the code in regard to snow calculations will improve accuracy of the model. We do however add text stating that users can replicate the changing attenuation thickness suggested by Zweck by modifying the snow raster fed to CAIRN.

6. Hardware/software requirements and standardization: Are there any hardware or software requirements for running the code? (as the Associate Editor downloaded the code and it appeared to work, I did not check it myself). If yes, this should be described somewhere (maybe near line 59). When using the CronusEarth Online calculator, one has to chose an AMS standard. The authors should mention whether CAIRN has the same option.
Indeed CAIRN forces users to choose the AMS standard, we have now stated this in the section on "Summary of CAIRN parameters for denudation calculations". We have also included a short note on software/hardware requirements on the former line 59.

7. Change of production rate by seemingly ±20% (line 453ff): The 20% change in production rate mentioned here gives a somewhat negative impression. In fact, about half of this change is related to a new standardization, which was required after the study of Nishiizumi et al. (2007). In other words, a 10Be exposure age (or erosion rate) calculated with the OLD standardization and a production rate of ±5.0 at/g/yr yields basically the same age (or erosion rate) as a 10Be age calculated with the NEW standardization and a production rate of ±4.5 at/g/yr. Details can, for instance, be found on the website of PRIME Lab (Purdue University) at: http://www.physics.purdue.edu/primelab/News/news0907.php. This issue should be clarified.
Good point and also raised by reviewer 2. We have followed that reviewer's advice and simply reported that production rates have changed along with AMS standards over the last decade, and we have also included a figure that shows the differences between CAIRN and CRONUS2.2 are mainly due to different parameter values rather than factors related to the underlying mathematics.

8. In section 2.2, it may be useful to provide the simple equation 11 of Lal (1991) in the form: Denudation rate = (Prod. rate / Conc. lambda) (attenuation length / density)
We have added a modified version of this equation at the end of this section and have explained why it is inadequate for a catchment averaged calculation.

Line 63: The term "solution of CRN" in the title is a bit strange. One could rephrase e.g. as "Deriving/quantifying denudation rates at a single location" or something similar.
We have renamed this section "Quantifying denudation rates at a single location."

Line 71: maybe insert "local" or "site-specific" before production rate.
Added the word "local".

Line 113: I see that d is shielding depth, but what exactly is d0? (maybe I overlooked it).
It is the initial shielding depth, now stated in the manuscript.

Line 274: Typo, propAgation.
Fixed.

Line 294: Here a production ratio of 6.1 is mentioned. What does the factor of 1.106 mean? The 10Be and 26Al production rates given in Table 3 imply a production ratio of 7.2. Can the authors

explain the reasons for this discrepancy?
Thanks for highlighting this. We have corrected this passage to reflect what is actually happening in the code (basically we have a fixed production uncertainty of 8.7% which is taken from CRONUS2.2, but which we apply to our updated production rates. The production ratios stated earlier were taken from CRONUS, we now directly use production rates from the updated Braucher et al and CRONUScalc parameterizations. Instead of reporting ratios or factors, we simply report the exact numbers and where they have come from in the tables.

Line 413: Typo; to infer a(N) denudation rate.
Fixed.

Line 434: replace "geomagnetic" by "time-dependent".
Done.

Line 440: please refer to one of the studies by Riebe et al. (2001, 2003). Riebe, C.S. Kirchner, J.W., Finkel, R.C. (2003). Long-term rates of chemical weathering and physical erosion from cosmogenic nuclides and geochemical mass balance. Geochimica et Cosmochimica Acta, 67, 4411-4427. Riebe, C.S. Kirchner, J.W., Granger, D.E. (2001). Quantifying quartz enrichment and its consequences for cosmogenic measurements of erosion rates from alluvial sediment and regolith. Geomorphology, 40, 15-19.
We have included the 2001 Riebe et al paper.

Line 503: Typo; "denudation" is spelled wrongly.
Fixed.

Line 530: I guess "differences" would be more appropriate than the term "errors", which is used twice in this line.
Changed the wording from error to difference here and elsewhere.

FIGURES a) At the beginning of the captions for Figs. 2, 3, 7, 8, 11, 12 the term "Errors" is used. I believe that the word "Differences" would be more appropriate.
We agree this is a better word and have made these changes.

b) The colors of the symbols used in Figs 2, 3, 4 etc for the individual studies are inconsistent (i.e. different colors are used in different plots for one and the same study). Shouldn't the color coding be consistent?
Done.

c) I agree with the Associate Editor that some of the figures could be combined.
We have combined the former Figures 2 and 3, and the former Figures 7 and 8.

d) Fig. 5 needs to be increased in size.
Done.

TABLES As the first part of the ms is mainly focussed on the description of the equations parameters etc and the data from selected studies are only discussed later, I suggest to reverse the order of Table 2 and Tables 3, 4.
We have changed the order so the former Table 2 (the default parameters) appears before the data from selected study sites. Table 4 remains in the same place since we felt it only makes sense in the context of comparison of the different calculators, which sets the ordering of the tables.

Table 3: Should not the Braucher et al. 2011 EPSL paper be mentioned here (instead of Braucher et al. (2009)? It is the 2011 paper, which gives the SLHL muon prod. rates in Table 6.
Fixed.

Table 3 and 4: I suggest to also provide the absolute muon production rates at SLHL (not only the F values).
We have not made this change since it is simply one line multiplied by another and therefore redundant.

Algorithm 1: should the > not be reversed to < ?
We are glad you caught that! Fixed.

Reviewer 2 (Greg Balco)

Dr Balco has provided a number of contextual remarks that have helped us refine the paper. We won't reiterate all of these remarks here but instead will try to include responses to the components most obviously requiring modifications of the manuscript. Dr Balco's review was clearly carefully crafted, adds to the discourse surrounding computation of denudation rates based on cosmogenic nuclides, and provides evidence for why an open review process can be beneficial to the scientific process.

Pages C1 and C2 of the review provide contextual comments which we do not believe require a response, but we have adopted some of the language here in our correction of the former line 35 because it is a better statement of the problem than we had in the original manuscript.

Page C3 makes allusions to western cinema and the Star Wars franchise, which we very much appreciate. We are also glad the reviewer thinks our contribution is, in his words, not lame. The bottom of this page and page C4 goes on to discuss the dubious nature of assumptions required to calculate denudation rates, mirroring quite closely the comments of reviewer 1, in their first item. Please see our response to this reviewer about the various assumptions about the natural system we try to model and why they are imperfect. Specifically, we now have a section on how temporal and spatial variations in denudation rates add significantly to the uncertainty of the method, noting that this is not specific to our method, but rather endemic to all estimates of catchment averaged erosion.

Below are responses to itemized queries by the reviewer.

Abstract, first sentence. The first sentence can be removed it would be more useful for the abstract to begin with the second sentence, which describes what the authors actually did in the paper.
Sentence deleted.

Line 31. The word cosmogenic means originating from cosmic rays. The calculators dont originate from cosmic rays, so cosmogenic calculator makes no sense. Suggest just calculator here.
Done.

Line 35-ish. This is a bit oversimplified. In fact, there is not a lot of variation in approaches to computing the erosion rate (really there are only two: include muons, or dont). What there is a lot of variation in is how to compute P. Also, the phrase "representative parameters for the catchment" is unnecessarily complicated and also unhelpfully nonspecific. Specifically, what you are trying to estimate is just P. Be more specific here.
We have changed the text here to mirror what the reviewer has written on page C2 of his review, which succinctly states the process involved in calculating denudation rates.

Line 40-ish. Again, this is somewhat misleading as written. The mathematical definition of the catchment-averaged erosion rate (e.g., from Bierman and Steig, etc.) specifically has P in it, and there is no doubt about what this parameter is. Thus, it is incorrect to say that authors are trying to "choose a production rate that is representative of the catchment." Instead what they are doing is trying to estimate the mean production rate in the catchment, either by computing that in some pixel-based way or by fudging the input to the online calculators to force them to compute the mean production rate internally. In any case, it would be helpful to clarify this a bit.

We have rewritten this section, it now says: "Production rates vary spatially, thus users of online calculators must calculate the effective production rate within a catchment using a weighted mean of the production in individual pixels. The manner in which these are fed to existing calculators vary, for example one must feed a single weighted mean production, after shielding corrections to COSMOCALC. In contrast, one must calculate weighted mean shielding corrections and pass them to CRONUS-2.2, and in addition must calculate a pressure or elevation that reproduces the mean production rate before shielding."

Line 53. I was confused by this discussion of the landslide scenario, because this scenario violates the assumptions inherent in computing the catchment averaged erosion rate from a Be-10 concentration. Thus, if you are going to compute the erosion rate using the method in Bierman, Steig, etc., you have already assumed that erosion is steady over time (although not spatially uniform), which is equivalent to stating that landslides do not occur. Thus, landsliding doesnt cause a problem with computing P (as is implied by its inclusion in this section), it basically invalidates the entire method. To clear this up, I suggest dividing this section into two subsections: (i) issues that make it difficult to compute P (e.g., shielding, snow cover, etc.); and (ii) issues that invalidate the entire method by violating its basic assumptions (landsliding, sediment storage, etc.). Alternatively (and probably better), I suggest just pending the entire discussion of landsliding to a separate section at the end of the paper, in which you can discuss more generally the point that you could potentially use this code for all sorts of nonequilibrium scenarios.

We have chosen the latter option suggested here. We now append a separate section on transience and remove mention of landsliding from other parts of the manuscript.

Line 60. Dont you want to continue here to mention that in addition to computing production rates, the software also does the implicit solution for erosion rate given a measured nuclide concentration? Because as written this paragraph doesnt indicate that any erosion rate estimate happens. Needs improvement. In general, also, it would be helpful for the reader at this stage if you were to explain the overall procedure of inverting a forward model for nuclide concentrations to obtain an estimate of the erosion rate, as a preview of coming attractions.

Yes, now that you mention it, we do want to say that. The text now reads "Based on these calculations the software can then calculate the expected cosmogenic nuclide concentration from a basin given a spatially homogenous denudation rate. Finally, the software uses Newton iteration to calculate the denudation rate that best reproduces the measured cosmogenic nuclide concentration."

Line 80-ish. This brings up the subject of muons. In this work as in others, muons are responsible for 2% of surface production and 98% of suffering. The decision in this paper to use an exponential scheme for muon production for computational simplicity is, in fact, sensible. Unfortunately I found the explanation here to be incomplete and confusing.

We have attempted to follow the reviewer's comments within our manuscript, since they contain succinct statements of why the muon approximation may erroneous and also why errors in muogenic production do not play a significant role in overall uncertainty. See specific changes below.

Basically, the difference between the Heisinger integration scheme and a simple exponential approximation la Braucher is that the latter is incorrectly representing the physics. What is really happening physically is that as depth increases, the mean energy of the remaining muons increases, so the instantaneous e-folding length for muon production continually increases with depth. You cant represent that with a finite sum of exponentials. If you have a bunch of summed exponentials, you can do pretty well at shallow depths, but there is some depth below which you are quite wrong. So that is

what the actual difference is.
We now specifically state this: "The advantage of the Heisinger et al. (2002) scheme is that it tries to capture the physics of muon passage through the near surface, and specifically models how the mean energy of muons increases as one moves to greater depths in the subsurface. This affects muon production at depth in a way that is not captured by exponential approximations. Recent work by Marrero et al. (2016) has updated the scheme of (Heisinger et al., 2002) reflecting the muon production rates inferred from field studies. This method still has the disadvantage that it is computationally expensive, to the extent that this computational cost is prohibitive if one is to calculate muon production in numerous pixels across a catchment."

However, there are two reasons the exponential approximation is OK here. (The reviewer goes on to state why the approximation is okay).
We have added some text reflecting the reviewer's comments about why the approximation is okay, which hopefully will encourage skeptical readers to keep going: "Our approach is to approximate muon production using a sum of exponential functions. This approach has the advantage of being computationally efficient, but has the disadvantage of not reflecting the physics of muon production and therefore failing to capture muon production well at depths beyond a few meters. This is unlikely to lead to large errors, however, because muon production makes up a very small percentage of the overall nuclide production at the depths where the physics-based models diverge from the exponential models. We specifically quantify this difference in Section 6.3, finding the exponential approximation to lead to differences between the physics-based approximation that are relatively small (for a wide range of denudation rates these differences are less than 2%)."

A final point here is that there would potentially be lots of other ways to speed up the computation whilst still using the Heisinger scheme, if you wanted. Mainly this is because the production rate due to muons will not be very different between adjacent cells. Thus, it is a big waste of time computing muon production separately in each pixel. You can probably get away with doing the muon calculations in a very small minority of cells in a typical watershed and extending those results to the other cells simply by a regression formula in elevation, without loss of accuracy. Or do muon production on a much coarser grid than spallogenic production. Of course, this would be a big rewrite of the code, but if you really want it to run maximum fast it would be the next obvious strategy. If muons are 2% of surface production, why give them more than 2% of processor time?
These are all interesting suggestions for speeding up the Heisinger approximations, but our testing suggests the difference between the Heisinger method and our exponential method is around 2%, which is completely dwarfed by the rest of the uncertainties, so we don't think it would be particularly useful to spend the time optimizing this part of the code.

Line 105. Again, equations are not cosmogenic.
Removed "cosmogenic".

Line 120. Note again the implications of assuming that muon production is in steady state. Not likely to be true.
We now refer readers to our section on transience here.

Line 130, "self-shielding." I am not sure I understand what is going on here because under normal circumstances, the sediment leaving the catchment would be assumed to be from an infinitesimally small surface layer, so no integration in depth would be required. So this appears to me to be overly complex. My understanding of what is happening in this part of the paper is that the authors have just put in this capability to facilitate later use of the same code for a patchy-erosion model where finite thicknesses of sediment are removed at once (e.g., landslides). And then the discussion of steady state is confusing here as well, because, of course, if landslides are occurring then there is by definition not a

steady state. Overall, more explanation needed here. As noted above, I think this would be clearer if all discussion related to the landsliding issue was deferred to a separate section.
We now state explicitly that for most applications an infinitesimal layer will be used ($d_t = 0$, but we have included it so that future users can devise clever ways to explore landsliding. We then state that landsliding is beyond the scope of this paper, but we acknowledge the uncertainties it introduces.

Line 160 and below. Topographic shielding. This is another example where the calculation is an precise representation of simplified physics, so gives illusory precision. Specifically, this code includes a quite precise calculation of topographic shielding under the assumptions that (i) the cosmic-ray flux is totally attenuated below the apparent horizon, and (ii) the zenith angle dependence of the cosmic-ray flux responsible for production is a cosine to a constant power. Neither (i) or (ii) is actually true. Because secondary particle production takes place throughout the atmosphere (including that part of the atmosphere that is between you and the apparent horizon on the other side of the valley), a nonzero amount of production will actually be due to cosmic rays originating below the visible horizon. In addition, the cosine-to-a-power dependence is highly approximate. See this paper: Argento, D.C., Stone, J.O., Reedy, R.C. and OBrien, K., 2015. Physics-based modeling of cosmogenic nuclides part IIKey aspects of in-situ cosmogenic nuclide production. Quaternary Geochronology, 26, pp.44-55.
We now state explicitly the two assumptions that underpin our shielding model and cite the Argento et al. paper noting that our method is an incomplete description of the physics in question.

The point being that the very comprehensive analysis of discretization errors in the shielding calculation here clouds the fact that there exist larger systematic errors due to simplified physics. This issue has basically no practical relevance to the erosion rate calculation overall (because it is still much less important than violations of the basic method assumptions). However, the authors should note here that they are concerned with the precision of a representation of simplified physics, which may or may not be the same as the precision of the calculation relative to real life.
We now say this so there can be no doubt about what we have done. "Thus our model, while precise, contains a simplified version of the true physics of topographic shielding."

In addition, this could also be sped up a lot if you really wanted to... but although of historical interest, that is beside the point here.
Because this is open-source software, future authors can fork our code and make such improvements. Refactoring the code at this point, however, would take several months of effort not only rewriting this component but recalculating every measurement reported here, for minimal gain in accuracy. We don't think the reviewer is asking us to do this so we haven't.

A final important issue here is that it was not clear to me whether telescoping of the mean free path length on dipping surfaces (see Dunne, also Fig. 5 in Balco, 2014 in Quaternary Geochronology) is included in this calculation.
It isn't. We say so.

Line 200 et al. The issue of non-time-dependent vs. time-dependent scaling is actually more important than described here. The reason for that is that production rates are calibrated using data mostly from the last 20,000 years, and the Earths magnetic field has been stronger than its long-term average during that time. Thus, at erosion rates low enough that the residence time of material in the soil profile is much longer than this (e.g., most normal erosion rates), the use of a non-time-dependent scheme likely creates a systematic error due to an underestimate of the long-term production rate. Basically this is yet another violation of the steady-state assumption. Again, this is a non-issue compared to much bigger issues in the application of this method, but the text is somewhat inaccurate here as written.
At the end of the paragraph containing the former line 200, we have inserted a few sentences explaining

that for slow denudation rates the assumption of time-invariant production rates will introduce some uncertainty because of the high magnetic field intensity of the past 20 kyrs.

Line 215, section 2.6. Unfortunately, I simply dont understand why the calculation described in this section is necessary. I didnt look back at the Vermeesch paper, but if I am remembering correctly this whole procedure was just needed to make the equation relating erosion rate to concentration explicit so it could be solved analytically?? Here you dont need to worry about that, because you are only doing the forward calculation, so why are you doing this? I may not be remembering this correctly, but in other words, it seems to me that all the Ss and Fs needed for Equation 13 are known a priori, or should be. Typically one would compute scaling for spallogenic production and muons separately (for example, this is in the Stone (2000) scheme as published), and because they are different, that should take care of the fact that muons are less important at higher elevation. Each pathway has already been assigned its own attenuation length, so you can compute mass shielding for each pathway. Then it seems like all you need to do is decide how to compute topographic shielding for muons (I dont know the answer...in the 2008 online calculators it is just disregarded), and you are done. What am I missing here? In any case, this needs to be better explained.
We added two sentences explaining why this is done, but in short, in the equations you have an S term for each production mechanism, but our calculation of the production mechanisms is lumped. So this calculation is to convert lumped scaling terms into four separate scaling terms. There might be a better way to do this, but this way we reproduce cosmocalc exactly, and judging by the minimal differences between CAIRN and CRONUScalc this procedure does not seem to be biasing the results.

Line 270-ish. I should point out (in response to the editor's comments) that the issue of asymmetry of uncertainty distributions is really a total non-issue from the geological perspective. Anything with an e in it will have an asymmetric uncertainty distribution, of course, but its hard to think of any cases where its actually important from the geological perspective.
This comment will be useful to readers of the discussion, but does not seem to require a change to our text.

Line 280-ish. Numerical partial differentiation by repeatedly doing the full calculation is almost certainly overkill (especially because youve already linearized it). I would do this simply by assuming that the basin has one pixel with the effective P derived from the whole basin. I agree that it is interesting to do it once, though.
We agree that it is overkill but we did not know it would be overkill when we were writing the code (we expected the nonlinearities to be larger) and so programmed in the uncertainties the brute-force way. Changing that now would require significant changes to the code, and the uncertainty calculations are not the rate limiting step.

Line 300. In physical science, 'conservative' is typically used to mean that something is being conserved, e.g., mass or energy. This use in the context of uncertainty analysis is common but incorrect. Instead one should state that the uncertainty estimate is supposed to be an upper bound.
We have reworded this sentence to reflect that the uncertainty is an upper bound.

Line 315. This is an excellent point, that the divergence among various theoretical expectations of how snow shielding works is much less important than the practical difficulty of actually measuring the mean snow depth distribution throughout the year. Frankly, in my view it is not even necessary to mention the various models here, because that issue is pretty much totally unrelated to this paper. As an aside, I found the Delunel paper to not be persuasive because, as far as I can tell from reading the paper, we dont know the effect of snow cover on the energy dependence of the neutron monitors (snow is basically like changing the amount of polyethylene on the outside, which affects the spectral response). This would imply that it is likewise unknown whether or not the variation in monitor count

rate with snow cover is applicable to cosmogenic nuclide production at all. But that is totally off topic.
The other reviewer seems keen on keeping this bit, so we have.

Line 320-ish. Again, I suggest moving all discussion related to landsliding and nonsteady/ nonuniform erosion to a separate section at the end. First, implement the basic model; then, at the end, introduce the abilities to deal with complications that are half-baked at present, but potentially useful in future.
We have followed this advice and separated the discussion of nonsteady/nonuniform cases from the rest of the model description.

Line 345-ish. It is probably overkill to generate separate effective elevations and average shielding factors for input to the 2008 online calculator. I know that technically its required because the elevation affects the muon proportion of total production and the shielding factor doesnt, but this issue is well down in the noise.
In other cases where we have made a computation that is more robust than really necessary: we don't feel the gain in computational time is worth the effort of refactoring the code at this point. We might do that in a future project to bring the tool online, but feel this level of tweaking is beyond the scope of the current paper.

Line 370. Again, no need to get into the details of snow shielding here. The point remains that it is unclear whether one can estimate the snow depth accurately in any case.
We have briefly mentioned the results of Zweck et al here in light of reviewer 1's comments but add no further details.

In general, in this part of the discussion (i.e., all of section 5) I think it would be easier to understand if you break down the discussion into two parts: things that are linear with respect to the production rate (e.g., topographic shielding), so can be pixel-averaged by themselves; and things that are nonlinear with respect to the production rate (e.g., elevation, latitude, snow shielding), that have to be converted into production rates, averaged, and then unconverted into an effective summary value. At present these two things are mixed up and its hard to understand what is happening. Overall, this section could be made more clear.
We have edited this section and added subheadings to make it more clear. The basic structure remains unchanged because we follow the sequence of calculations that our software actually computes. Firstly, we must calculate self and snow shielding separately, because in CAIRN these are subsumed within the depth-averaging. So we start with a section based on those calculations. We then need to discuss how the different calculators ingest lumped parameters, since they do it differently. Thus we have followed the format of dealing with lumping for each calculator in sequence. To address the comments of the reviewer, we do specifically allude to the nonlinearity and the reason for calculating the effective pressure with the text: "The CRONUS calculators then calculate production using either an elevation or pressure. Production rates are nonlinear with either elevation or pressure, so we must compute an effective pressure that reproduces the mean production rate in the catchment. This is because the arithmetic average of either elevations or pressures within the catchment, when converted to production rate, will not result in the average production rate due to this nonlinearity. CAIRN calculates an effective pressure that reproduces the effective production rate over the catchment. The average production rate is calculated with: ".

Section 6. This sort of comparison is a terrible mess because of the need to sort out the differences between inherent properties of the algorithm (e.g., point approximation vs. full-basin calculation) and the input parameters (mainly the production rate and the muon interaction parameters). Overall, however, it is accomplished fairly well in this paper; I like the approach of selecting a few representative data sets rather than trying to show a global comparison over all of scaling and erosion rate space, and

the explanation is quite clear as regards which errors apply where in which comparisons. I only have a couple of comments about this section. Line 470. It is quite interesting that there is a systematic difference in shielding factors vs. those originally reported. Do you think this really is because of the averaging a- nonlinear-thing effect? But in any case, as discussed above, the precision of this measurement is overstated in any case due to simplification of the physics.
We have changed the wording here to simply state that our method produces greater shielding than the other studies. Since the details of those shielding calculations are not reported, we can't exactly diagnose why they are different, so merely mention that our greater shielding values are consistent with the results of our sensitivity analysis on the spacing of azimuth and inclination for the shielding calculation.

Line 480. I think production rate differences are much more likely responsible here than anything to do with shielding calculations.
We changed the working so that the production rate differences are mentioned first and topographic shielding is mentioned as a secondary concern.

Line 486. The snapping issue is by far the biggest problem I can think of in wholesale automation of this process. Especially potentially disastrous for literature data.
Yes, this is nasty. That is why the repository for CAIRN contains some tools for checking if your sampling point is in the right place.

Line 500+ and Figures 7-8. As noted by the other reviewer, this effect is nearly all due to differences in the input parameters (production rate and muon interaction crosssections) and very little due to the spatial-averaging issue or any other aspects of the various algorithms. In large part this is my fault because I have been too much of a slacker to update these parameters in the online code (that is, make v 2.3), which is, frankly, embarrassing. Sorry. However, the need here for the purposes of this paper is to clearly separate these issues. I can think of two ways to do this. One, change the parameters in the CAIRN code to increase spallogenic production by a factor of (4.5/4) and muon production by a factor of (1/0.44). That will very nearly account for the various input parameter differences. Then do the comparison on that basis. Two, leave these figures unchanged but add in the background some lines showing the expected effect of those changes in the parameters (for elevations vaguely resembling the input data). In any case, this would be extremely helpful in distinguishing the various effects of differences in the algorithm itself vs. differences in the calibrated parameters. This would also make the discussion in lines 520+ more clear as well.
We have followed this advice and generated another figure that shows that the differences between CAIRN and CRONUS2.2 are almost entirely due to the different parameters, and that about a third of this difference is due to the different spallogenic parameters, with the rest being from muons. There still is a small difference between CAIRN and CRONUS2.2 but this is dwarfed by all the other uncertainties.

1. Reviewers comment 3. It is not correct to say that the model of Heisinger overestimates muon production. The model accurately estimates muon fluxes; the problem is that the cross-sections for production of Be-10 and Al-26 by muon interactions, when applied to those flux estimates, overestimate Be-10 and Al-26 production. In other words, its not the model thats wrong, its the cross-section measurements needed to convert the model prediction to a production rate. I think the present paper is mostly correct on this point.
See our response to reviewer 1's comment 3.

2. Reviewers comment 7. The reviewer is correct here, and this is important. The options here are (i) to get all numbers properly standardized in this discussion, or (ii) preferably, to not get into the details here and simply note that best estimates of production rates are about 10% lower than they were 10 years ago because of improved calibration data.
We have changed the text following suggestion (ii) above.

Use of acronym CRN. Do you really want to exclude stable cosmogenic nuclides? Because this code would work for them too. Perhaps, having written the paper, the authors could just globally search and replace CRN with cosmogenic nuclide?
Done.

CAIRN acronym.
In our group we amuse ourselves by coming up with acronyms that are Scots words. This is why we eventually rejected the previous acronym frontrunner of Dr NUT (readers can try to guess what that one stands for). Readers can look forward to future models and methods called NUMPTY and GLAIKIT. Readers who disagree with this approach are welcome to come to Edinburgh and discuss the issue over a dram of whisky.

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The CAIRN method: Automated, reproducible calculation of catchment-averaged denudation rates from cosmogenic radionuclide concentrations

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Abstract. The use of cosmogenic radionuclides to calculate catchment-averaged denudation rates has become a widely adopted technique in the last two decades, yet the methodology varies between studies and is not always reproducible. We report a new program for calculating catchment-averaged denudation rates from cosmogenic radionuclide nuclide concentrations. The method (Catchment-Averaged denudatIon Rates from cosmogenic Nuclides: CAIRN) bundles previously reported production scaling and topographic shielding algorithms. In addition, it calculates production and shielding on a pixel-by-pixel basis. We explore the sampling frequency across both azimuth ($\Delta\theta$) and altitude ($\Delta\phi$) angles for topographic shielding and show that in high relief terrain a relatively high sampling frequency is required, with a good balance achieved between accuracy and computational expense at $\Delta\theta = 8°$ and $\Delta\phi = 5°$. The method includes both internal and external uncertainty analysis, and is packaged in freely available software in order to facilitate easily reproducible denudation rate estimates. CAIRN calculates denudation rates but also automates catchment averaging of shielding and production, and thus can be used to provide reproducible input parameters for the CRONUS family of online calculators.

1 Introduction

In-situ cosmogenic radionuclides (CRNs)nuclides, such as ^{10}Be and ^{26}Al, are widely used to determine both exposure ages and denudation rates (e.g., Dunai, 2010; Granger et al., 2013; von Blanckenburg and Willenbring, 2014; Granger and Schaller, 2014). A denudation rate is the sum of the chemical weathering rate and physical erosion rate. Since the publication of the seminal papers by Brown et al. (1995), Granger et al. (1996) and Bierman and Steig (1996), dozens of studies have used concentrations of CRNs cosmogenic nuclides in stream sediments to quantify denudation rates that are spatially averaged over eroding drainage basins. There are now more than 1000 published catchment-averaged denudation rates (e.g., Portenga and Bierman, 2011; Willenbring et al., 2013a), with many new studies published each year.

Several authors have provided standardized methods for calculating denudation rates from CRN cosmogenic nuclide concentrations, notably the COSMOCALC package (Vermeesch, 2007) and the CRONUS-Earth online calculator (Balco et al., 2008). Here we make comparisons with the CRONUS calculator version 2.2, so we refer to it as CRONUS-2.2 for clarity. These calculators have been widely adopted by the cosmogenic, quaternary science and geomorphic communities, in large part because they are easily accessible and their methods are transparent (i.e., the source files are available online). These previously published cosmogenic calculators are ideal for calculating denudation rates or ages from a particular site (e.g., an exposed surface or a glacial moraine). However, using these calculators to determine catchment-averaged denudation rates necessitates the user selecting representative parameters for the catchment These calculators rely on the principle that there is an inverse relationship between denudation rate and the concentration of a nuclide (slower erosion means more exposure to cosmic rays) and that the concentration of a nuclide can be inverted for denudation rate if one estimates the production of the nuclide. In the context of catchment-averaged denudation rates, nuclide production rates will vary in space, and an open-source method of making these choices calculating production and inverting nuclide concentration for denudation rate has yet to emerge. Due to the lack of an open-source tool, a wide variety of approaches to calculating catchment-averaged denudation rates are used in the literature, which makes intercomparison studies challenging (c.f., Portenga and Bierman, 2011; Willenbring et al., 2013a) (cf., Portenga and Bierman, 2011;

Several factors determine the concentration of a CRN cosmogenic nuclide in a sample. For instance, elevation and latitude control the production rate of different CRNs cosmogenic nuclides (e.g., Lal, 1991; Dunai, 2000; Stone, 2000; Desilets and Zreda, 2003; Lifton et al., 2005). Production rates vary within a basin and spatially, thus users of online calculators frequently choose values representative of the entire catchment . As such, online calculators ingest single parameters representative of an entire catchment for production rates and scaling factors, either in combination (COSMOCALC) or separately (must calculate the effective production rate within a catchment using a weighted mean of the production in individual pixels. The manner in which these are provided to existing calculators vary, for example one must feed a single weighted mean production, after shielding corrections to COSMOCALC. In contrast, one must calculate weighted mean shielding corrections and pass them to CRONUS-2.2). For example, many , and in addition must calculate a pressure or elevation that reproduces the mean production rate before shielding. Many authors use an averaging scheme for production where production is calculated in each pixel , and a representative value which is then passed to an online a calculator (e.g., Kirchner et al., 2001; Hurst et al., 2012; Munack et al., 2014; Scherler et al., 2014). In addition, CRN nuclide concentrations can be affected by partial shielding caused by snow cover, surrounding topography, and overlying layers of sediment (e.g., Balco et al., 2008). These again are spatially distributed and so authors reporting catchment-averaged denudation rates frequently report averaged shielding values. Although software packages do exist for calculating spatially averaged topographic shielding (e.g., Codilean, 2006) and snow shielding (e.g., Schildgen et al., 2005), results from these models are not integrated with spatially varying production rates. Finally, in landslide dominated terrain, removal of thick layers of sediment can dilute ~~CRN~~ cosmogenic nuclide concentrations in river sediment (Niemi et al., 2005; Yanites et al., 2009; West et al., 2014). This factor is often not included in denudation calculations. For these reasons, Balco et al. (2008) specifically urged development of tools dedicated to the calculation of catchment-averaged denudation rates from ~~CRN~~ cosmogenic nuclide concentrations.

Here we present software that estimates production and shielding of the ~~CRNs~~ cosmogenic nuclides ^{10}Be and ^{26}Al on a pixel-by-pixel basis, and propagates uncertainty in AMS measurement and ~~CRN production.~~ cosmogenic nuclide production. Based on these calculations the software can then calculate the expected cosmogenic nuclide concentration from a basin given a spatially homogenous denudation rate. Finally, the software uses Newton iteration to calculate the denudation rate that best reproduces the measured cosmogenic nuclide concentration. We have made this software available through an open-source platform at https://github.com/LSDtopotools/LSDTopoTools_CRNBasinwide to allow community modification and scrutiny, with the goal of allowing users to report denudation rates that can be easily reproduced by other scientists. The software distribution includes instructions for building the software on a virtual machine that can function on common operating systems.

2 ~~Solution of CRN concentration~~ Quantifying denudation rates at a single location

We derive a solution that tracks the concentration of a ~~CRN~~ cosmogenic nuclide as it is exposed, exhumed or buried. This approach is adopted because ~~we feel~~ it is the most general: specific scenarios of both steady and transient denudation and burial may therefore be derived. Our approach is broadly similar to that of Parker and Perg (2005), but results are equivalent to those of more widely used derivations (e.g., Lal, 1991; Granger and Smith, 2000).

We begin by conserving the concentration of ~~CRN~~ cosmogenic nuclide i through time t:

$$\frac{dC_i}{dt} = P_i - \lambda_i C_i \tag{1}$$

where C_i is the concentration of ~~CRN~~ cosmogenic nuclide i (C_i is typically reported in atoms g^{-1}, i could be ^{10}Be or ^{26}Al, for example), P_i is the local production rate of ~~CRN~~ cosmogenic nuclide i (in atoms g^{-1} yr^{-1}) and λ_i (yr^{-1}) is the decay constant of ~~CRN~~ cosmogenic nuclide i. Production can be a function of latitude, altitude (or atmospheric pressure), magnetic field strength and shielding by rock, soil, water or snow (e.g., Balco et al., 2008).

CRNs Cosmogenic nuclides can be produced by both neutrons and muons (e.g., Gosse and Phillips, 2001). Production by neutrons is widely modelled using a simple function in which production decays exponentially with depth (e.g., Lal, 1991). Muons, on the other hand, are modelled using a variety of schemes. The CRONUS-2.2 calculator (Balco et al., 2008) implements the scheme of Heisinger et al. (2002a, b), which requires computationally expensive integration of muon stopping over a depth profile. Recent field-based Field-based estimates of muon production suggest that Heisinger et al. demonstrate that Heisinger et al. (2002a) significantly overestimates production by muons (Braucher et al., 2011, 2013; Phillips et al., 2016a). For both computational efficiency and flexibility in selecting muon production scaling terms, we use a model similar to those used by Granger and Smith (2000) , Braucher et al. (2009) , Schaller et al. (2009) , and Vermeesch (2007) where the production rate is the sum of four exponential functions Other authors have used empirical fits of cosmogenic profiles from the field, typically using a sum of exponential functions, to describe muon production (e.g., Granger and Smith, 2000; Vermeesch, 2007; Braucher et al., 2009; Schaller et al., 2009) .

The advantage of the Heisinger et al. (2002a) scheme is that it tries to capture the physics of muon passage through the near surface, and specifically models how the mean energy of muons increases as one moves to greater depths in the subsurface. This affects muon production at depth in a way that is not captured by exponential approximations. Recent work by Marrero et al. (2016) has updated the scheme of Heisinger et al. (2002a, b) , reflecting the muon production rates inferred from field studies. This method still has the disadvantage that it is computationally expensive, to the extent that this computational cost is prohibitive if one is to calculate muon production in numerous pixels across a catchment.

Our approach is to approximate muon production using a sum of exponential functions (e.g., Granger and Smith, 2000; Vermeesch This approach has the advantage of being computationally efficient, but it does not reflect the physics of muon production and therefore failing to capture muon production well at depths beyond a few meters. This is unlikely to lead to large errors, however, because muon production makes up a very small percentage of the overall nuclide production at the depths where the physics-based models (Heisinger et al., 2002a, b; Marrero et al., 2016) diverge from the exponential models. We specifically quantify this difference in Section 6.3, finding that the exponential approximation leads to differences between the physics-based approximation that are relatively small (for a wide range of denudation rates these differences are less than 2%).

The exponential approximation for nuclide production used in CAIRN is:

$$P_i(d) = P_{i,SLHL} \sum_{j=0}^{3} S_{i,j} F_{i,j} e^{\frac{-d}{\Lambda_j}} \quad (2)$$

where $P_{i,SLHL}$ is the surface production rate (atoms g^{-1} yr^{-1}) at sea level and high latitude, $F_{i,j}$ is a dimensionless scaling that relates the relative production of neutron spallation and muon production,

$S_{i,j}$ is a dimensionless scaling factor that lumps the effects of production scaling and shielding of cosmic rays, d is a mass per unit area which represents the mass overlying a point under the surface (g cm^{-2} typically), and Λ_j is the attenuation length for reaction type j (g cm^{-2}). The reaction types are $j = 0$ for neutrons and $j = 1-3$ for muons; these muons can be either slow or fastmuons. In general, production from muons relative to neutrons is greater in landscapes with a high denudation rate or at low elevation (Balco et al., 2008) .

The depth d, called shielding depth, is related to depth below the surface as:

$$d = \int_{\zeta-h}^{\zeta} \rho(z)\,\mathrm{d}z \tag{3}$$

where ζ (cm) is the elevation of the surface, h (cm) is the depth in the subsurface of the sample, z (cm) is the elevation in a fixed reference frame and ρ (g cm^{-3}) is the material density, which may be a function of depth. For a constant density, $d = \rho h$.

2.1 Solving the governing equation

The governing equation (Eq. 1) has the general form:

$$\frac{dC}{dt} + p(t)C = g(t) \tag{4}$$

In our case, $p(t)$ simply equals λ_i, which is a constant in this case, and $g(t)$ is equal to P_i, which is a function of t.

Equations of this form have the solution:

$$C = \frac{1}{h(t)} \int h(t)g(t)\,\mathrm{d}t + const \tag{5}$$

where $const$ is an integration constant and

$$h(t) = \exp\left(\int p(t)\,\mathrm{d}t\right) \tag{6}$$

which in the case of the cosmogenic governing equation reduces to:

$$h(t) = e^{\lambda_i t} \tag{7}$$

The term $g(t)$ is equal to:

$$g(t) = P_{i,SLHL} \sum_{j=0}^{3} S_{i,j} F_{i,j} e^{\frac{-d}{\Lambda_j}} \tag{8}$$

The shielding depth, d, is a function of time:

$$d(t) = d_0 + \int_{t_0}^{t} \epsilon(\tau)\mathrm{d}\tau \tag{9}$$

where τ is a dummy variable for time that is replaced by the limits after integration. Here t_0 is the initial time and d_0 is the initial shielding depth. In the case where denudation, denoted ϵ (g cm^{-2} yr^{-1}), is steady in time this becomes

$$d(t) = d_0 + \epsilon(t_0 - t) \tag{10}$$

~~where t_0 is the initial time.~~ Here denudation is the rate of removal of mass from above the sample per unit area. If we let the concentration of the ~~CRN~~ cosmogenic nuclide equal C_0 at the initial time, t_0, and combine Eqs. (5), (7), (8), and (10), we can solve for the integration constant ($const$) and arrive at a solution for ~~CRN~~ cosmogenic nuclide i at time t:

$$C_i(t) = C_0 e^{-(t-t_0)\lambda_i} + P_{i,SLHL}\left[\sum_{j=0}^{3} \frac{S_{i,j}F_{i,j}\Lambda_{i,j}}{\epsilon + \Lambda_{i,j}\lambda} e^{\frac{-d_0}{\Lambda_{i,j}}}\left(e^{\frac{\epsilon(t-t_0)}{\Lambda_{i,j}}} - e^{-(t-t_0)\lambda}\right)\right] \tag{11}$$

Equation (11) is the full governing equation from which scenario-specific solutions may be derived.

2.2 Steady state solution

By convention, we consider the cosmogenic profile to be steady in time. This allows analytical solution of the ~~CRN~~ cosmogenic nuclide concentration at any point in the basin. At steady state, the particles near the surface have been removed (either through erosion or chemical weathering) at the same rate for a very long time, so we set $t_0 = 0$ and $t = \infty$. This results in a simplified form:

$$C_i(d) = P_{i,SLHL} \sum_{j=0}^{3} \cancel{\frac{S_{i,j}F_{i,j}\Lambda_{i,j}e^{-d/\Lambda}}{\epsilon + \lambda_i \Lambda_{i,j}}} \frac{S_{i,j}F_{i,j}\Lambda_{i,j}e^{-d/\Lambda_{i,j}}}{\epsilon + \lambda_i \Lambda_{i,j}} \tag{12}$$

where ϵ is the denudation rate (g cm^{-2} yr^{-1}). If we set $d = 0$ (that is, we solve for material being eroded from the surface, with no distributed mass loss via weathering), Eq. (12) reduces to Eq. (6) from Granger and Smith (2000) for denudation only (i.e., no burial or exposure), and reduces to Eq. (8) of Lal (1991) if production is due exclusively to neutrons. If Eq. (12) is simplified to neutron only production, assumes the sample is taken from the surface ($d = 0$), and is solved for erosion rate, one arrives at

$$\epsilon = \Lambda_i \left(\frac{P_{i,SLHL}S_i}{C_i} - \lambda_i\right) \tag{13}$$

which is equivalent to the widely used Eq. (11) from Lal (1991) . However Eq. (13) requires adjustment for catchment averaged estimates of denudation rates because each point in the landscape from which sediment is derived will have its own local production and shielding factors. This is why a spatially distributed approach is required.

2.3 Snow and ~~self-shielding~~self shielding

Equation (12) is restrictive in that it only considers material removed from a specific depth, i.e. removed for a single value of d. In reality samples may come from a zone of finite thickness. This finite thickness can contribute some shielding to the sample, i.e. the bottom of a sample is shielded by the mass of the sample that overlies. This shielding is called ~~self-shielding~~ self shielding and is generally implemented by assuming that ~~self-shielding~~ self shielding can simply be approximated by a reduction in neutron production (e.g., Vermeesch, 2007; Balco et al., 2008). Snow can also reduce production of ~~CRNs~~ cosmogenic nuclides (e.g., Gosse and Phillips, 2001). Typically these two forms of shielding (snow and self) are typically incorporated in denudation rate calculators as a scaling coefficient calculated before ~~solution of~~ solving the governing equations (e.g., Vermeesch, 2007; Balco et al., 2008), i.e. snow and ~~self-shielding~~ self shielding are incorporated into the $S_{i,j}$ term.

Our strategy is slightly different: we calculate snow and ~~self-shielding~~ self shielding by integrating the ~~CRN~~ cosmogenic nuclide concentration over a finite depth in eroded material. For example, if there is no snow, the concentration of ~~CRNs~~ cosmogenic nuclides at a given location is obtained by depth-averaging the steady concentrations from zero depth (the surface) to the thickness of eroded material. If snow is present, the concentration is determined by depth-averaging from the mean snow depth (d_s) to the thickness of the removed material (d_t). Both d_s and d_t are shielding thicknesses, therefore they are in units of g cm^{-2} and thus differences in material density are taken into account. The depth-averaged concentration is then:

$$C_i(d) = \frac{P_{i,SLHL}}{d_t} \sum_{j=0}^{3} \frac{S_{i,j} F_{i,j} \Lambda_{i,j}^2 \left(e^{-d_s/\Lambda_{i,j}} - e^{-(d_s+d_t)/\Lambda_{i,j}}\right)}{\epsilon + \lambda_i \Lambda_{i,j}} \quad (14)$$

~~This approach also allows the computation of CRN concentration dilution due to landslides by setting~~ In most applications, the thickness of ~~removed material to the landslide thickness. Thicknesses can either be measured in the field, modelled (e.g., Niemi et al., 2005; Yanites et al., 2009) , or approximated using mapped landslide inventories (e.g., Hovius et al., 1997; Korup, 2005) . These may be combined with data on landslide area-volume relationships (e.g., Guzzetti et al., 2009) . Our formulation (~~the removed material will be 0, i.e. the particles from which nuclide concentrations are measured in detrital sediment are derived from a thin layer removed from the surface of the catchment. However, the solution described by Eq. ~~14) is still a steady state approximation in that it is assumed that material exhumed by landslides has a concentration profile obtained from a single constant denudation~~

~~rate, similar to Niemi et al. (2005) . We do not explore landsliding further as it is beyond the scope of this contribution, but simply note here that our depth averaged approach allows calculation of dilution due to mass wasting~~(14) allows some flexibility so that future users can explore different erosion scenarios, for example removal of sediment through mass wasting. We discuss this in Sect. 5.4, but for the current contribution we focus on steady-state scenarios.

2.4 Topographic shielding

In addition to snow and ~~self-shielding~~self shielding, locations in hilly or mountainous areas can also receive a reduced flux of cosmic rays because these have been shielded by surrounding topography (Dunne et al., 1999). We adopt the method of Codilean (2006), in which both the effect of dipping sample surfaces and shielding by topography blocking incoming cosmic rays are computed. The Codilean (2006) method is spatially distributed: each pixel in a digital elevation model (DEM) has its own topographic shielding correction that varies from 0 (completely shielded) to 1 (no topographic shielding). These correction values are calculated by modelling shadows cast upon each pixel in the DEM from every point in the sky. This is achieved by modelling shadows incrementally for a range of zenith (ϕ) values from 0° to 90° and azimuth (θ) values from 0° to 360°.

As $\Delta\theta$ and $\Delta\phi$ values decrease, the accuracy with which the shielding is calculated is expected to increase, as we are modelling shielding at finer resolutions. However, this benefit is attenuated by increasing computational cost when these values tend towards (1°, 1°). Codilean (2006) compared the accuracy of different $\Delta\theta$ and $\Delta\phi$ by comparing them to a minimum step size of (5°, 5°). Here we exploit the efficiency of our software and the considerable increase in computing power since 2006 to explore smaller step sizes. We make the assumption that a step size of (1°, 1°), corresponding to 32 400 iterations of the shielding algorithm, is an accurate representation of the true shielding factor to the extent that any further refinement in the measurements would not yield a significant change in the results of the ~~CRN~~ cosmogenic nuclide calculations.

In order to determine the optimal balance between measurement accuracy and computational efficiency, the full range of ($\Delta\theta$, $\Delta\phi$) pairs were used to derive shielding values for each cell of a worst-case scenario: a high-relief section of the Himalaya (650 km^2 with a 7000 m range in elevation). Table 1 presents the maximum absolute residual value (the error of the pixel with the greatest error) for topographic shielding of the corresponding step sizes when compared to the shielding derived for (1°, 1°). Using values below Codilean (2006)'s suggested threshold of (5°, 5°) gives increasingly small returns for a larger computational burden. We suggest that a ($\Delta\theta$, $\Delta\phi$) pair of (8°, 5°), requiring 810 iterations, is an optimal value for any high relief landscape, yielding a maximum absolute error in our test site of 0.018. On lower relief landscapes the ($\Delta\theta$, $\Delta\phi$) values could be increased to achieve the same level of accuracy. We note that these data are determined using a 90 m resolution DEM, and errors will be higher for finer resolution DEMs (Norton and Vanacker, 2009).

Our topographic shielding calculations rely on two approximations that can lead to some uncertainty. First, the method of Codilean (2006) assumes the horizon attenuates all cosmic rays, and secondly the production of cosmogenic nuclides obeys a power law relationship between the cosine of the zenith angle. Argento et al. (2015) have shown these assumptions to be inaccurate. In addition, the Codilean (2006) method does not include changes to the flux penetration distance on the gradient of the topographic surface (e.g., Dunne et al., 1999; Balco, 2014) . Thus our model, while precise, contains a simplified version of the true physics of topographic shielding.

2.5 Production scaling

Production of CRNs cosmogenic nuclides varies as a function of both elevation (defined via atmospheric pressure) and latitude and these variations are accounted for by using one of several possible scaling schemes. The classic scaling model of Lal (1991), later modified by Stone (2000), is the simplest and is referred to herein as Lal/Stone. Later scaling models (Dunai, 2000, 2001; Desilets and Zreda, 2003; Lifton et al., 2005, 2014) have incorporated various other parameters such as time-dependent geomagnetic field variations, solar modulation, and nuclide-specific information, resulting in a total of seven possible scaling models in the most recent CRONUS calculator (Marrero et al., 2016).

These scaling schemes vary in complexity and therefore computational expense. Time-dependent scaling schemes are far more computationally expensive than the time-independent scheme of Lal/Stone, which does not consider variations in geomagnetic field strength. Recent calibration results (Borchers et al., 2016; Phillips et al., 2016a), including a low-latitude, high-altitude site in Peru (Kelly et al., 2015; Phillips et al., 2016b) suggest that the time-independent Lal/Stone scheme performs similarly to the physics-based schemes presented in Lifton et al. (2014) and fits the data better than several other scaling schemes (Dunai, 2000; Desilets and Zreda, 2003; Lifton et al., 2005). For these reasons, we scale production rates using the Lal/Stone scheme. This may lead to some uncertainty because production rates are scaled by the intensity of the Earth's geomagnetic field (e.g., Dunai, 2010) , and this intensity has been relatively high over the last 20 kyrs (Valet et al., 2005; Lifton et al., 2014) , meaning that this approximation could lead to some uncertainty in samples with slow denudation rates. For example, a rock removal rate of 0.03 mm/yr would remove 60 cm in 20 kyrs, and most of production of nuclides occurs in the top 60 cm of rock Lal (1991) . However, in cases with faster denudation rates, the uncertainty introduced by assuming time-invariant production rates is likely to be much smaller than other sources of uncertainty.

The Lal/Stone scaling scheme requires air pressure, whereas most published studies include only elevation information. We follow the approach of Balco et al. (2008) and convert latitude and elevation data to pressure using the NCEP2 climate reanalysis data (Compo et al., 2011). In certain areas, the ERA-40 reanalysis (Uppala et al., 2005) has been shown to provide more accurate results and due to CAIRN's open source design new models can be readily incorporated into the software. Here we retain the NCEP2 reanalysis to better compare our results with CRONUS-2.2. We note that if users deploy CAIRN as a spatial averaging front end to online calculators, they should be vigilant to use the same air pressure conversion method in both CAIRN and the online calculator.

2.6 Combining scaling and shielding

To calculate the concentration of a CRNcosmogenic nuclide, the scaling factors for each pathway ($S_{i,j}$) must be computed. Both topographic shielding and production rate scaling are subsumed within the scaling terms ($S_{i,j}$), whereas snow and self-shielding self shielding are computed separately (see Sect. 2.3). We These scaling terms are not computed for each production pathway, but rather are lumped into a single value. We therefore need to compute the values of the individual scaling factors, $S_{i,j}$. To do this, we follow the method of Vermeesch (2007) and calculate scaling factors using an effective attenuation depth. We must do this This is necessary because, when considering multiple production pathways, the scaling terms for individual production mechanisms may vary depending on elevation, shielding, sample thickness, or denudation rates. For example, muogenic pathways will contribute relatively more to production when there is more shielding since muogenic reactions penetrate deeper than spallation.

To determine the scaling terms for the individual production mechanisms ($S_{i,j}$), we first compute the total scaling at a location (S_{tot}), which we define as the product of the production rate scaling (S_p) and the topographic shielding (S_t), that is S_{tot} = $S_t S_p$. Production scaling (S_p) is estimated using the Lal/Stone scaling scheme and (S_t) is calculated using our topographic shielding algorithms. We then derive the scaling factors for the individual production mechanisms, S_i, j, by employing a virtual attenuation length, Λ_v, in units of g cm^{-2}, following the method of Vermeesch (2007):

$$S_{i,j} = e^{\frac{\Lambda_v}{\Lambda_i} \frac{-\Lambda_v}{\Lambda_i}} \tag{15}$$

We must therefore calculate Λ_v based on S_{tot}. The individual production mechanisms must be set such that:

$$S_{tot} = \sum_{j=0}^{3} S_{i,j} F_{i,j} \tag{16}$$

In Eq. (16), S_{tot} and $F_{i,j}$ are known, whereas $S_{i,j}$ are functions of Λ_v. We thus iterate upon Λ_v, calculating $S_{i,j}$ using Eq. (15) using Newton's method until Eq. (16) converges on a solution for Λ_v. Once the virtual attenuation length is solved, the $S_{i,j}$ terms are then used in Eq. (14).

3 Denudation rates across a catchment

So far we have described the calculations that predict the concentration of a CRN cosmogenic nuclide at one specific location in a basin. Some form of this method is embedded within existing

~~CRN calculators~~ All existing cosmogenic nuclide calculators contain some form of these calculations. A wide variety of approaches to scale calculations of ~~CRN~~ cosmogenic nuclide concentrations within a single location to the concentration across entire catchments have been used in the literature. Some authors have averaged production rates on a pixel-by-pixel basis but have not considered topographic shielding (e.g., Belmont et al., 2007; DiBiase et al., 2010; Portenga and Bierman, 2011). Others have calculated an average scaling by integrating the product of topographic shielding and production on a pixel-by-pixel basis (e.g., Ouimet et al., 2009; Hurst et al., 2012; Lupker et al., 2012; Scherler et al., 2014). Another strategy is to calculate both averaged topographic shielding and production scaling values for a basin (e.g., Abbühl et al., 2010). All of these approaches involve some degree of spatial averaging of production, shielding, or a combination of the two before catchment-averaged denudation rates are estimated.

The approach we take in the CAIRN method differs in that shielding and production rates are not averaged: these are calculated locally at each pixel. For a given denudation rate, ϵ, the concentration of ~~CRNs~~ cosmogenic nuclides from each pixel is calculated, then the catchment-averaged concentration is the average of the concentrations from all pixels. ~~In applications without landsliding, this~~ This concentration requires no weighting because the denudation rate is considered to be spatially homogenous. ~~In the event of mass removal (i.e., by setting d_t in Eq. 14), the average concentration is weighted by the local thickness of mass removed to account for increased volumes derived from material delivered to the basin through mass wasting.~~ The denudation rate for the basin is then iterated upon with Newton's method until the predicted concentration of ~~CRNs~~ cosmogenic nuclides emerging from the catchment matches the measured concentration (see Algorithm 1).

We should note here that the version of CAIRN reported in this contribution calculates the denudation rate across an entire catchment required to produce the observed concentration of the target ~~CRN~~cosmogenic nuclide. That is, CAIRN assumes denudation rates are the same everywhere in the catchment. ~~Even in the case of removal of spatially heterogeneous mass of known thickness from the surface (i.e.,~~ Users can explore the effect of instantaneously removing mass by setting d_t Eq. 14 ~~), CAIRN still calculates~~ and d_t can be spatially heterogeneous, but even when users choose this option CAIRN will still calculate the spatially homogenous background denudation rate in light of dilution by mass wasting or stripping of material from the landscape. Future adaptations of the ~~(open source)~~ code could account for nested basins~~(~~, as this sampling strategy common in many studies of basin averaged erosion rates~~)~~, or changes in the concentration of target minerals ~~(usually quartz)~~ as employed by, for example Safran et al. (2006). Our software is open source so other groups can make adjustments to CAIRN to suit their needs. These potential future developments, however, are beyond the scope of this contribution.

4 Uncertainty propagation

We calculate uncertainty from both internal (nuclide concentration uncertainties from accelerator mass spectrometry (AMS) measurements) and external (shielding and production rate) sources using Gaussian error propagation propagation of uncertainty following Balco et al. (2008). We do note that some authors have used a Monte Carlo approach in determining CRN-derived cosmogenic nuclide-derived denudation rates because parameter uncertainties can have non-gaussian distributions (e.g., West et al., 2015). CAIRN, at present, does not implement a Monte Carlo uncertainty approach but rather follows conventional Gaussian error propigationpropagation of uncertainty.

4.1 Gaussian error propagation of uncertainty

Uncertainties are calculated in terms of the denudation rate, ϵ, in units of g cm^{-2} yr^{-1}, so that no assumption about bedrock material density is necessary. The standard deviation of the denudation rate, s_ϵ, is calculated with

$$s_\epsilon = \sqrt{(\frac{\partial \epsilon}{\partial x})^2 s_x^2 + (\frac{\partial \epsilon}{\partial y})^2 s_y^2 + \ldots} \tag{17}$$

where s_x is the standard deviation of x, s_y is the standard deviation of y, and so on. The variables x and y can represent any uncertain parameter, such as the measurement uncertainty or the production rate of the nuclide. All uncertainties (e.g., nuclide concentration) are assumed to be at the one sigma level unless otherwise stated. The derivatives in Eq. (17) are calculated using the nominal value plus the associated uncertainty and then recalculating the denudation rate in the original, pixel-by-pixel fashion.

Three uncertainties are included in the calculation: i) the uncertainty in CRN cosmogenic nuclide concentration, ii) the uncertainty in the production rate at sea level, high latitude ($P_{i,SLHL}$), and iii) uncertainty in muon production. Uncertainty in CRN cosmogenic nuclide concentration is reported by authors alongside concentrations. For the CRN cosmogenic nuclide concentration uncertainty, the concentration is used directly to determine the denudation rate uncertainty. For all other parameters, the uncertainty values help to predict a new concentration in each pixel, which is then used to determine denudation rate uncertainty.

The uncertainty on the production rate ($P_{i,SLHL}$) is the same as based on that used in the CRONUS-2.2 calculator (Balco et al., 2008): in CRONUS-2.2 the uncertainty is 0.39 atoms cm^{-2} yr^{-1} for ^{10}Be and 2.63 based on a production rate of 4.49 atoms cm^{-2} yr^{-1}. This means the uncertainty in CRONUS-2.2 is 8.7% of $P_{i,SLHL}$ for ^{26}Al (based on a ratio of production between ^{26}Al and ^{10}Be of 6.1×1.106Be. We use this uncertainty for both ^{10}Be and ^{26}Al based on our the production rates reported in Table (2). Although the recent CRONUS-Earth calibration (Borchers et al., 2016) has produced new production rates for both ^{10}Be and ^{26}Al, the production rate uncertainties remain in the same range as those used here (Phillips et al., 2016a).

Even though recent studies seem to agree Field studies have shown that muon production based on laboratory experiments (Heisinger et al., 2002a, b) overestimate muon production observed in deep samples (Braucher et al., 2003, 2011, 2013; Balco et al., 2013; Phillips et al., 2016a), there is still some uncertainty over the exact muon production profile. CAIRN employs the exponential scaling method from Braucher et al. (2009). However, we use a very conservative estimate of uncertainty by calculating the contribution of muon models to overall uncertainty based on It then calculates the upper bound of uncertainty derived uncertainty in muon models by calculating the difference between the default CAIRN muon model and those from the Schaller et al. (2009) scheme, which approximates the original Heisinger results (Heisinger et al., 2002a, b).

4.2 Uncertainty from snow and self-shielding (including landsliding)shielding

Uncertainties from nuclide concentration, muon production, and production rates are calculated internally by our software. Uncertainties from snow and self-shielding self shielding rely on user-supplied information and therefore must be estimated separately.

Snow shielding can be supplied as a constant effective snow thickness (in g cm^{-2}) or spatially distributed information in the form of a raster. Most snow shielding calculations reported in the literature are based on an effective attenuation estimated by the thickness of snow (e.g. Balco et al., 2008) (e.g., Balco et al., 2008) , but recent field-based measurement indicate that snow may attenuate fluxes of cosmic rays to a greater extent than assumed in simple mass-based snow shielding calculations (Zweck et al., 2013; Delunel et al., 2014). However these uncertainties are small compared to the extreme uncertainties of the thickness, extent and duration of snow over millennial timescales, which are unlikely to ever be well constrained. If no snow shielding values are provided, the software assumes that there is no snow cover.

Similarly, self-shielding thickness can be supplied as a single value (in g cm^{-2}) or as spatially distributed thicknesses. For landsliding, the assumption is that there is a steady background denudation rate and then material with a steady cosmogenic depth profile is removed suddenly, which is the approach taken by Niemi et al. (2005) . We do not account for re-equilibration of cosmogenic concentration that takes place in the years after a landslide (e.g., Schaller and Ehlers, 2006; Muzikar, 2009; Yanites et al., 2009) . This would require a model or reconstruction of past landslides, which is beyond the scope of this contribution. Our landsliding module is admittedly rudimentary and is provided primarily as a tool for exploration. It allows users to calculate a spatially homogenous background denudation rate given a spatially distributed episode of instantaneous mass removal. This is obviously a contrived scenario but does allow users to probe whether the dilution by landslides of different sizes is likely to alter the inferred denudation rate within a catchment.

To calculate uncertainties, users must supply two scenarios for these shielding factors. For example, the user could provide two snow thickness rasters representing variation in snow thickness with 1σ uncertainty (how an author might calculate this could fill another paper and is beyond the scope of our study). The denudation rates of these two scenarios would then be calculated, and the square of the difference in these two denudation rates would then be inserted into Eq. (17). In this way users can calculate shielding uncertainties manually.

4.3 Summary of CAIRN parameters for denudation calculations

To summarize, the CAIRN method predicts ~~CRN~~ cosmogenic nuclide production from neutrons and muons using a four exponential approximation of data from Braucher et al. (2009). These production rates are scaled using Lal/Stone time-independent scaling. Production is calculated at every pixel, with atmospheric pressure calculated via interpolation from the NCEP2 reanalysis data (Compo et al., 2011). Topographic shielding is calculated using the method of Codilean (2006), and scaled production rates are multiplied by topographic, snow, and ~~self-shielding~~ self shielding at each pixel. Decay rates, attenuation lengths, and parameters for production are reported in Table 2. Denudation rates are reported in g cm^{-2} yr^{-1} because in these units no assumptions about density, which is spatially heterogeneous, are required. In addition, users must report the AMS standard when supplying nuclide concentrations to CAIRN and the concentrations are then normalized following the same scheme as Balco et al. (2008) . The CAIRN software prints these parameters to a file so that if they change in the future based on new calibration datasets, users will be able to both view and report these updated values.

5 Spatial averaging for ingestion by other denudation rate calculators

In addition to producing denudation rates, CAIRN also provides spatially-averaged production rates and effective catchment-averaged pressure (see below), so that users can compute denudation rates using other available calculators. Programs such as the CRONUS-Earth calculators (referred to as CRONUS-2.2 for Balco et al. (2008) and CRONUScalc for Marrero et al. (2016)) and COSMOCALC do not have the ability to calculate catchment-averaged parameters. CAIRN can be used independently to determine production rates or in conjunction with these other calculators, which allows for the possibility of using time-dependent scaling and other new features in the future.

~~The calculators require slightly different input parameters than those used directly in CAIRN . Because our depth-integrated treatment of cosmogenic concentrations (i.e. ,~~

5.1 Conversion of depth integrated parameters for calculator ingestion

CAIRN iterates on denudation rate until the predicted cosmogenic concentrations from Eq. (14) is reached. Eq. ~~14) differs from that of~~ (14) is a depth integrated approach that is a direct solution of the production equations. This depth-integrated solution subsumes both snow and self shielding. This is different from from COSMOCALC and the CRONUS calculators, ~~we calculate snow and self-shielding using more traditional shielding terms for spatial averaging for use in these~~ which take separate values for shielding. Thus to pass results from CAIRN to calculators we must first calculate equivalent snow and self shielding values for each pixel. Note that these values are not used within denudation rate calculation in CAIRN, they are only used when shielding values are passed to the COSMOCALC and the CRONUS calculators.

Self-shielding Self shielding used for spatial averaging is calculated for each pixel k with:

$$S_{self,k} = \frac{\Lambda_{i,0}}{d_{t,k}} \left(1 - e^{-\frac{d_{t,k}}{\Lambda_{i,0}}} \right) \tag{18}$$

where $S_{self,k}$ is the self-shielding self shielding correction for the k^{th} pixel, $d_{t,k}$ is the shielding thickness for the k^{th} pixel (in g cm^{-2}). Equation (18) is used in both COSMOCALC and CRONUS. In the CRONUS calculators, snow shielding is lumped with topographic shielding, therefore the CRONUS calculators presumes presume the user will determine the product of snow and topographic shielding at a site with a method of their choice. COSMOCALC includes a snow shielding calculator which assumes that the equivalent depth of snow (in g cm^{-2}) attenuates neutron production following the formula:

$$S_{snow,k} = e^{-\frac{d_{s,k}}{\Lambda_{i,0}}} \tag{19}$$

where $S_{snow,k}$ is the snow shielding correction of the k^{th} pixel and $d_{s,k}$ is the time-averaged depth of snow water equivalent in g cm^{-2}. We adopt this approximation when performing spatial averaging. Although recent Recent work suggests snow may attenuate spallation to a greater degree than predicted by Eq. (19) (Delunel et al., 2014), and Zweck et al. (2013) suggest that the attenuation length for snow is reduced compared to rock (they report an attenuation length of 109 g cm^{-2} for snow). However, the uncertainty in historic snow thickness will outweigh vastly outweighs uncertainties from the snow shielding equation. We Although there have been methods suggested to model the evolution of snow thickness through time (e.g., Beniston et al., 2003) , the averaging time for eroded particles that accumulate cosmogenic nuclides is on the order of thousands to tens of thousands of years (e.g., Lal, 1991) , and reconstructing snow thickness over this timescale is highly uncertain. Users wishing to approximate the Zweck et al. (2013) attenuation lengths can feed CAIRN snow rasters with a thicker apparent snow layer. Overall, we therefore recommend that users include a large range of snow thickness in their uncertainty analysis, guided by historical observations of snow depth.

5.2 Spatial averaging for COSMOCALC

In COSMOCALC's erosion calculator (which calculates denudation), the required inputs are a combined shielding and scaling term, the CRN cosmogenic nuclide concentration and the uncertainty in the CRN concentration. cosmogenic nuclide concentration. That is, scaling and shielding are combined in a single, spatially averaged term. We calculate the scaling factor S_{CCtot}, which is a lumped shielding and scaling term, with

$$S_{CCtot} = \frac{1}{N}\sum_{k=0}^{N} S_{snow,k} S_{topo,k} S_{self,k} S_{i,k} \tag{20}$$

where terms are calculated on a pixel-by-pixel basis. Snow shielding is calculated from Eq. (19), self-shielding self shielding is calculated from Eq. (18), and topographic shielding is calculated accounting for the effects of sloping samples and topography blocking cosmic rays (see Sect. 2.4). We wish to emphasize that CAIRN reports S_{CCtot} for users that wish to use it in COSMOCALC, whereas the denudation rates reported by CAIRN use Eq. 14 for snow and self shielding. Production scaling for CRN cosmogenic nuclide i at pixel k, $S_{i,k}$, is calculated using Eq. (16) and Lal/Stone scaling (Sect. 2.5).

5.3 Spatial averaging for the CRONUS calculators

The CRONUS calculators (CRONUS-2.2 and CRONUScalc) require a lumped shielding value and information about either the elevation or pressure of the sample. Spatial averaging of the lumped shielding value, $S_{CRshield}$, is calculated with:

$$S_{CRshield} = \frac{1}{N}\sum_{k=0}^{N} S_{snow,k} S_{topo,k} S_{self,k} \tag{21}$$

Note that we fold the self-shielding self shielding into the lumped shielding term so that when transferring data to the CRONUS calculator the sample thickness should be set to 0. We also calculate

The CRONUS calculators then calculate production using either an elevation or pressure. Production rates are nonlinear with either elevation or pressure, so we must compute an effective pressure by taking the average that reproduces the mean production rate in the catchment. This is because the arithmetic average of either elevations or pressures within the catchment, when converted to production rate, will not result in the average production rate due to this nonlinearity. CAIRN calculates an effective pressure that reproduces the effective production rate over the basincatchment. The average production rate is calculated with:

$$S_{effp} = \frac{1}{N}\sum_{k=0}^{N} S_{i,k} \tag{22}$$

We then use the Newton iteration on the Lal/Stone scaling scheme to find the pressure which reproduces the basin average production rate (S_{effp}). That way, results from our method can be compared to results from the CRONUS calculator and, if users are so inclined, they can use time varying production scalings via the CRONUS calculator (which CAIRN does not include for reasons outlined in Sect. 2.5).

5.4 Uncertainties introduced by spatial and temporal variability

CAIRN provides uncertainty estimates based on uncertainties in the measurement of nuclide concentrations, and uncertainties in production rates. It does, however, make an assumption of steady erosion, and assumptions likely to be violated almost everywhere on Earth due to the long timescales of geomorphic adjustment, which are on the order of tens of thousands to millions of years (e.g., Fernandes and Dietrich, 1997; Roering climate oscillations that are tens to hundreds of thousands of years (e.g., Lisiecki and Raymo, 2005) . In addition, spatial heterogeneity in lithology and target mineral concentrations can lead to additional uncertainty to denudation rate estimates (e.g., Safran et al., 2006; Carretier et al., 2015) . Mass wasting can also perturb the concentration of cosmogenic nuclides (e.g., Niemi et al., 2005; Yanites et al., 2009) , leading to further uncertainties. Finally, as noted above, if snow shielding is to be taken into account, one must estimate the shielding provided by snow over millennial timescales, which, to put it mildly, are difficult to constrain.

For the problem of spatially heterogeneous lithology, careful geologic mapping, such as that done by Safran et al. (2006) and Carretier et al. (2015) can alleviate some of the uncertainty, but such mapping is logistically challenging. For landsliding, mass removal can be measured in the field, modelled (e.g., Niemi et al., 2005; Yanites et al., 2009) , or approximated using mapped landslide inventories (e.g., Hovius et al., 1997; Korup, 2005) . These may be combined with data on landslide area-volume relationships (e.g., Guzzetti et al., 2009) . The main difficulty here is that it takes some time for the cosmogenic nuclide concentration to readjust after mass removal (e.g., Schaller and Ehlers, 2006; Muzikar, 2009; Mudd, thus one must make some estimate of not only the spatial distribution of landslides but their evolution through time (Yanites et al., 2009) . Simulating nuclide concentrations in settings where denudation rates vary is possible (Mudd, 2016) , but computationally intensive and one must have some confidence that one can accurately reconstruct the temporal evolution of denudation rates. Although recent progress has been made in this area (e.g., Whittaker et al., 2008; Pritchard et al., 2009; Hurst et al., 2013; Goren et al., 2014; Fox et a it still suffers from the fact that we lack devices for time travel and struggle to test these reconstructions.

Ultimately, this means that the uncertainties reported by CAIRN are the minimum uncertainties and do not take into account transience, lithology, or variation in snow shielding. The fact that catchment-averaged denudation rates carry additional uncertainties is well known, and Dunai (2010) estimates that any catchment-averaged denudation rate carries with it a minimum 30% uncertainty. Because the uncertainties mentioned in this section are difficult, if not impossible to constrain, our approach with CAIRN is to report the uncertainties that can be constrained and caution users that there are large additional unconstrained uncertainties related to the assumptions underpinning the method.

6 Method comparison

Comparison with other methods is difficult because authors reporting ~~CRN-derived~~ cosmogenic nuclide-derived catchment-averaged denudation rates have not made their algorithms available as open-source tools. Our spatially-averaged production scaling and shielding estimates are approximations of spatial averaging reported by other authors. We compare our data to both published denudation rate estimates, and to estimates of denudation rates generated by the CRONUS calculator given the spatial averaging described in Section 5.3. In our comparisons we use seven published cosmogenic datasets (Table 3). These datasets were chosen to span a wide range of locations (i.e., differing latitudes and elevations) and denudation rates. The parameters used by CAIRN for these comparisons are reported in Table 2.

It will perhaps aid the reader to explain how denudation rate estimates may vary between methods. Firstly, production rates are nonlinearly related to elevation, and thus spatial averaging of the product of production scaling and shielding is not the same as the product of the spatial averages of production scaling and shielding. In addition, previous studies and other calculators have chosen different parameters for ~~CRN~~ cosmogenic nuclide production and shielding. For example, past publications have used a wide variety of methods for estimating topographic shielding (e.g., see Table 3). Choices of spallation and muon production rates also affect the final denudation rate. Consider a measured nuclide concentration that one uses to infer ~~an~~ a denudation rate. If one assumes a high production rate (via either muons or spallation), it means that for a given denudation rate the predicted nuclide concentration is higher. Thus, for a given nuclide concentration, the inferred denudation rate is higher if the assumed production rate is higher (see dashed lines in Figure 1). If the inferred shielding is higher, then for a given denudation rate the production is lower, and the inferred denudation for a given concentration will be lower.

6.1 Spatial averaging of production and shielding vs pixel-by-pixel calculations

First, we compare results of two methods using the exponential approximation of muon production (Eq. 12), used in both COSMOCALC and the CAIRN calculator. The difference in calculating denudation rates by iterating upon ~~CRN~~ cosmogenic nuclide concentration from all pixels in a basin (the CAIRN method) and calculating it by using a spatial average of the production of scaling and production terms (Eq. 20) is virtually zero if snow and ~~self-shielding~~ self shielding are spatially homogenous (Figure ~~??~~2a). Thus we find that combining all scaling and shielding terms in a single lumped term is adequate for calculating denudation rates if computational power is limited.

Separating production rate scaling from shielding leads to slightly larger uncertainty (Figure ~~??~~2b), but in terms of the total uncertainty this averaging also leads to small uncertainties (on the order of 1-2% compared to 10-20% from other sources of uncertainty). Many users will want to compare rates determined by our software with the popular CRONUS calculators (Balco et al., 2008; Marrero et al., 2016). The CRONUS calculators internally scale production rates while shielding is a user input. Consequently, the uncertainties plotted in Figure ?? 2b approximate the uncertainties that will arise from the spatial averaging process that users must pass to the CRONUS calculators. Some users may wish to calculate denudation rates using geomagnetic time-dependent scaling schemes, which is not possible in CAIRN, but CAIRN can be used as a front end to the CRONUS calculators via its spatial averaging capabilities with the confidence that this will only introduce relatively small errors.

6.2 Comparison with existing denudation rate estimates

Denudation rates reported in the literature from catchment-averaged CRN cosmogenic nuclide concentrations are calculated using a wide variety of methods. The term erosion rate is often substituted for denudation rate although few studies attempt to account for chemical weathering (cf., Kirchner et al., 2001) (cf., Kirchner et al., 2 Studies differ in their strategies for production rate scaling, topographic, snow, and self-shieldingself shielding, and the manner in which spatial averaging is performed. In many cases there is insufficient detail reported that might enable other groups to reproduce reported denudation rates. A primary motivation of the CAIRN calculator is to provide an open-source means of computing denudation rates that may then be reproduced by other groups. We have incorporated reported snow shielding from previous studies by inverting Eq. 19 for an annual average snow thickness and then distributing this thickness over the entire DEM. We acknowledge this is a poor representation of snow thickness but snow shielding rasters are rarely available and in most cases there is little reported snow shielding.

The diversity in methods for calculating denudation rates reported in the literature means that it is difficult to compare denudation rates when they come from different studies. This problem has been highlighted by previous data intercomparison studies (Portenga and Bierman, 2011; Willenbring et al., 2013a). Estimated sea level, high High latitude production rates under Lal/Stone scaling of ^{10}Be have changed significantly over the last 15 years as more calibration sites are reported. For example Stone (2000) reported a value of 5.1 atoms g^{-1} yr^{-1}, whereas the current estimates are closer to 4.0 atoms g^{-1} yr^{-1} (Borchers et al., 2016; Phillips et al., 2016a) . This difference alone can lead to up to 20differences in derived denudation ratesin the last 10 years due to an ever increasing number of calibration sites (e.g., Phillips et al., 2016a) and changing AMS standards (Nishiizumi, 2004) . In some cases, muons are not considered, whereas other studies use a variety of different muon production schemes (e.g., Table 3). Studies typically report erosion or denudation rates in dimensions of length per time, but this requires an assumption about rock density, which can vary and is sometimes not reported. Topographic shielding is occasionally not considered (particularly in older studies). In some cases the horizon elevation is recorded from a limited number of directions (e.g., COSMOCALC includes a calculator using 8 directions), and in other instances the computational method of Codilean (2006) is used. Studies also cite Dunne et al. (1999) for shielding but this paper lists several methods for calculating shielding: the equations therein depend on the number and geometry of shielding objects and this information is seldom reported. Even when the more robust method of Codilean is used, the spacing of azimuth and angle of elevation is often not reported.

Studies typically report erosion or denudation rates in dimensions of length per time, but this requires an assumption about density, which can vary and is sometimes not reported. Most studies use a rock equivalent denudation rate (as opposed to a regolith or soil denudation rate) and thus densities assumed are typically rock densities (see Table 3). Because denudation rates are traditionally reported in dimensions of length per time, we do not suggest future authors cease reporting denudation in these dimensions, but we do recommend also reporting denudation rates in dimensions of mass per area per time (e.g., g cm^{-2} yr^{-1}) because these units allow simpler comparison between sites as they require no assumptions about spatially heterogeneous density.

Of our seven example datasets (Table 3), only 3 of the original authors reported topographic shielding factors. We calculated shielding using the CAIRN method with $\Delta\phi$ = 5°, $\Delta\theta$ = 8° in these three high relief landscapes using a 90 meter resolution DEM. Our small values of $\Delta\phi$ and $\Delta\theta$ systematically resulted in calculated topographic shielding well above (up to 20more shielding) the shielding factors used in previous studies lead to variations in shielding between CAIRN and reported values (Figure 3). At the time of its publication, the Codilean (2006) algorithm was severely limited by computational power. Codilean reported a computing time of 46 hours for $\Delta\phi$ = 5and $\Delta\theta$ = 5on a relatively small DEMs (15 km^2 at 10 m resolution). Authors Authors typically do not give enough information to reproduce their shielding calculations, but we note that authors using Dunne et al.'s algorithm have used use a limited number of horizon measurements to calculate shielding. For example in COSMOCALC (Vermeesch, 2007), users are expected to input horizon values at 45° intervals, which . Our calculations suggest that this can lead to errors of 10-40in high relief landscapes lower maximum shielding differences between this method and the CAIRN method (Table 1). An example of the potential underestimates of topographic shielding is shown in Figure 4.

The denudation rates predicted by CAIRN are plotted against reported denudation rates in Figure 5. These data are scattered about the 1:1 line, but for most samples the CAIRN denudation rate is lower than the reported denudation rate. Reasons for this vary for each study since the method used to calculate denudation rates vary in each example study, but one unifying factor is that CAIRN calculates topographic shielding at much higher resolution than virtually all previous studies and as a result differences are likely to be due to the higher production rates used in previous studies (Table 3) and slightly greater topographic shielding in CAIRN is significantly higher (i.e. lower S_t values), resulting in lower denudation rate estimates (see Figure 1). Higher production rates used in previous studies (Table 3) also lead to higher reported denudation rates than those calculated by CAIRN. One component of CAIRN that requires some caution is that the snapping of cosmogenic samples to channels is automated: if errors in the DEM place the main channel in the wrong location, or GPS coordiantes coordinates of the sampling location contain large errors (common in older datasets), there is a chance the basin selected by CAIRN will not be the same as the sampled basin. This can result in large errors as production rates vary significantly with elevation. We have provided a tool in the github repository that allows users to check the basins that are associated with ~~CRN~~ cosmogenic nuclide samples. If these do not match the expected basins, then users will need to manually change the latitude and longitude of the samples until they are located near the correct channel.

We wish to emphasize that the relative denudation rates do not change significantly between CAIRN and reported values (as evidenced by a clustering about the 1:1 line in Figure 5). In addition previous studies contain elements modulating denudation rates that are not contained within the current version of CAIRN. For example, Kirchner et al. (2001) reports true physical erosion rather than denudation and Safran et al. (2006) modified their denudation rates based on the quartz content of the source areas.

6.3 Comparison with the CRONUS calculators

The results from CAIRN are compared to results from both CRONUS calculators. When comparing output from the CAIRN calculator with output from the online CRONUS-2.2 calculator, far larger uncertainties (up to to 40% of the denudation rate) occur. These ~~errors~~ differences are not controlled by ~~deundation~~ denudation rate (Figure ~~??~~7a) but are instead mainly a function of the production rate (Figure ~~??~~7b). In the previous section, we found that ~~errors~~ differences due to spatial averaging and separation of shielding from production scaling are small. The large difference is primarily due to the difference in spallation production rates and the over-production of muons in CRONUS version 2.2, as described by Balco et al. (2013). According to Balco et al., future versions of this CRONUS calculator will be updated to have significantly reduced muogenic production consistent with recent studies (Braucher et al., 2003; Phillips et al., 2016a; Braucher et al., 2011, 2013). If production rates in CRONUS are changed to reflect the production rates from Braucher et al. (2011) , we find that differences are quite small (Figure 7). We see from this figure that in locations with high production rates just under half of these differences between CAIRN and CRONUS-2.2 are from the different spallation rates, whereas in locations with low production rates, most of the differences are due to the higher muon production present in CRONUS-2.2.

The other CRONUS calculator, CRONUScalc, incorporates new spallation production rates and muon production is calculated using production rates based on a deep core from Antarctica (Marrero et al., 2016; Phillips et al., 2016a). In order to examine the underlying source of discrepancies between the three calculators, we plot the total and muon production rates for the CAIRN, CRONUS-2.2, and CRONUScalc calculators in Figure (8). The production rates for CRONUS-2.2 are calculated directly from the MATLAB scripts available online. The CRONUScalc production rates are approximated as a three exponential analytical function with parameters shown in Table 4. Although total production rates appear relatively similar, CRONUScalc and CAIRN predict significantly smaller muon contributions that CRONUS-2.2. The result is that for the same denudation rate, the CRONUS-2.2 calculator produces signifcantly more (in some ~~case~~ cases 40% more) atoms than using CAIRN or CRONUScalc (Figure 9). This discrepancy between muon production is important because rapidly eroding samples accumulate a significant proportion of their nuclide concentrations below 100 g cm^{-2}, leading to a large discrepancy in calculated denudation rates between CRONUS-2.2 and the other two calculators (CAIRN and CRONUScalc), which both incorporate more recent muon models. The CAIRN outputs of topographic shielding, as well as the spatial averaging of both production scaling and shielding, are independent of these calculators and will still provide spatial averaging for use with future calculator versions, even as production rates and mechanisms are updated.

We have used the spatially averaged shielding and scaling outputs from CAIRN to determine ~~errors~~ differences between CAIRN and CRONUScalc. We find that there is a 2.5% to 5% ~~error~~ difference between the denudation rates predicted by CAIRN and those predicted by CRONUScalc (Figure 10). Currently CRONUScalc is not able to calculate very high denudation rates (for rates greater than ~0.06 g cm^{-2} yr^{-1} the current version of CRONUScalc crashes; it was designed for exposure ages and becomes computationally unstable at high erosion rates) so we cannot compare CAIRN to CRONUScalc for all of the example datasets. The ~~errors~~ differences in Figure (10) arise from two sources: first, we must pass the product of the scaling (S_{effp}) and shielding ($S_{CRshield}$) to CRONUScalc rather than calculating pixel by pixel values. Second, the default muon production in CAIRN is derived from the Braucher et al. (2009) scheme, which is slightly different than the production schemes derived from Marrero et al. (2016) and Phillips et al. (2016a) (see Figure 8). In CAIRN, users can choose the muon production scheme, and we have implemented an approximation of the muon production scheme from Marrero et al. (2016) that uses the exponential form of Eq. 2 (see Table 4). It is important to note that the CAIRN implementation of muons from Marrero et al. (2016) assumes that Λ = 160 g cm^{-2} for spallation, whereas in CRONUScalc this attenuation length can vary as a function of latitude and pressure. We compare the denudation rates from CAIRN using the production parameters in Table 4 ($\epsilon_{CAIRN-CRC}$) with the default production scheme of Braucher et al. (2009) in Figure (11). The ~~errors~~ differences here are smaller (mostly less than 2%) suggesting that much of the ~~error~~ difference seen in Figure (10) is due to spatial averaging.

7 Conclusions

We present an automated, open-source method for calculating catchment-averaged denudation rates based on the concentrations of *in-situ* ~~CRNs~~ cosmogenic nuclides collected in stream sediment. Our catchment-averaged denudation rate method (CAIRN) predicts ~~CRN~~ cosmogenic nuclide concentrations based on pixel-by-pixel scaling and shielding. These concentrations are then averaged to predict the catchment-averaged concentration. Newton iteration is later used to find the denudation rate for which the predicted concentration matches the measured concentration and to derive associated uncertainties. In addition, CAIRN provides spatially averaged shielding and scaling values that can be used by other popular calculators (which do not provide spatial averaging, e.g. CRONUS and COSMOCALC). The CAIRN method is provided as open-source software so that reported denudation rates can be easily reproduced.

The CAIRN method is intended to streamline the computation and reporting of catchment-averaged denudation rates, but it has limitations that may be the subject of future developments. At the moment CAIRN assumes steady erosion; there is no facility for incorporating transient erosion rates which might affect nuclide concentrations in transient landscapes (e.g., Willenbring et al., 2013b; Mudd, 2016). In addition, the method does not include a facility for nesting basins in which the denudation rate in a large basin incorporates the denudation rates from smaller basins that it contains. The calculator cannot account for differing source areas of material, so at the moment it is not capable of using ~~differencing~~ different particle size fractions to identify denudation hot spots (e.g., Riebe et al., 2015; Carretier et al., 2016). Despite these limitations, the CAIRN method addresses the need to provide transparent, reproducible estimates of denudation rates.

Our open source framework allows other users to update the algorithms (e.g., a nesting function could be built on top of the current CAIRN architecture) and different atmospheric reanalysis data or new muon scaling schemes can be added as needed in the future. Thus we hope it will provide a platform for more nuanced estimates of denudation rates from cosmogenic nuclides in the future.

Software and data availability

The software is available at the LSDTopoTools Github website (https://github.com/LSDtopotools/). The data files containing formatted cosmogenic data, parameter values and results, and scripts for plotting figures used in this paper are also located on the Github site. All DEMs used in the analysis were derived from Shuttle Radar Topography Mission 3 arc second data available from the United States Geological Survey digital globe website (http://earthexplorer.usgs.gov/).

Author contributions

S.M. Mudd (SMM), MDH and SWDG wrote the software. MAH, SMM and S.M. Marrero analyzed the data. SMM wrote the paper with contributions from other authors.

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Table 1. Absolute maximum residuals (i.e., greatest residual within the DEM) for different combinations of $\Delta\theta$ and $\Delta\phi$ used in shielding calculations for a high relief basin in the Himalayas.

	$\Delta\theta$, degrees									
$\Delta\phi$, degrees	1	2	3	5	8	10	15	30	45	60
1	0.000	0.002	0.004	0.009	0.010	0.011	0.027	0.053	0.063	0.081
2	0.004	0.004	0.005	0.009	0.010	0.012	0.029	0.057	0.064	0.080
3	0.008	0.008	0.008	0.010	0.011	0.012	0.027	0.053	0.062	0.081
5	0.014	0.015	0.016	0.017	0.018	0.018	0.030	0.056	0.065	0.087
8	0.023	0.023	0.026	0.025	0.027	0.030	0.039	0.064	0.082	0.093
10	0.036	0.037	0.033	0.040	0.035	0.040	0.037	0.063	0.074	0.104
15	0.057	0.059	0.058	0.060	0.060	0.058	0.065	0.084	0.100	0.122
20	0.072	0.071	0.073	0.075	0.077	0.076	0.083	0.111	0.109	0.138
30	0.171	0.172	0.168	0.176	0.167	0.167	0.173	0.188	0.160	0.242
45	0.337	0.340	0.332	0.335	0.346	0.335	0.332	0.393	0.385	0.430
60	0.352	0.352	0.352	0.352	0.352	0.352	0.352	0.352	0.385	0.418

Table 2. Default parameters used in the CAIRN model.

Parameter	Value	Source
λ_{10Be}	500*10^{-9} $yr^{-}1$	Chmeleff et al. (2010); Korschinek et al. (2010)
λ_{26Al}	980*10^{-9} $yr^{-}1$	Nishiizumi (2004)
Λ_i	160;1500;4320 g cm^{-2}	From COSMOCALC version 2.0 to mimic Braucher et al. (2011)
^{10}Be P_{SLHL}	4.30 atoms g^{-1} yr^{-1}	From COSMOCALC version 2.0 to mimic Braucher et al. (2011)
^{10}Be F_i	0.9887; 0.0027; 0.0086 (dimensionless)	From COSMOCALC version 2.0 to mimic Braucher et al. (2011)
^{26}Al P_{SLHL}	31.10 atoms g^{-1} yr^{-1}	From COSMOCALC version 2.0
^{26}Al F_i	0.9699; 0.00275; 0.0026 (dimensionless)	From COSMOCALC version 2.0 to mimic Braucher et al. (2011)

Table 3. Datasets used for method comparisons. ^{10}Be production rate (Prod rate) is given for sea level, high latitude and in units of atoms g^{-1} yr^{-1}. 'CR' or 'CR muons' refers to the spallation or muon calculation methods and production rates used in CRONUS-2.2 (Balco et al., 2008). The scaling values, production rates, topographic shielding and notes reported in this table are for the original studies: CAIRN uses the same settings (see Table (2) for its calculations regardless of site location.

Study	Location	Scaling	Prod rate	Topo Shielding	Other Notes
Bierman et al. (2005)	New Mexico, USA	Lal/Stone	5.2	None.	ρ = 2.7 g cm^{-3}, no muons.
Dethier et al. (2014)	Colorado, USA	Lal/Stone	4.49 (CR)	None.	ρ = 2.7 g cm^{-3}, fast muons only.
Kirchner et al. (2001)	Idaho, USA	Lal/Stone	4.72	Dunne et al. (1999), details not given.	Corrections for chemical weathering.
Munack et al. (2014)	Ladakh, India	Lal magnetic	4.49 (CR)	Pixel-by-pixel, but details not given.	CR muons. Snow and ice shielding considered.
Palumbo et al. (2010) and Palumbo et al. (2011)	Tibet	Dunai (2000)	5.12	Codilean (2006), $\Delta\phi$, $\Delta\theta$ not reported.	Muons using Granger and Smith (2000) scheme. ρ = 2.65 g cm^{-3}.
Safran et al. (2006)	Bolivia	Dunai (2000)	None.	No muons. ρ not reported. Corrections for quartz fraction.	
Scherler et al. (2014)	Garwahl Himalaya	Lal magnetic	4.49 (CR)	Pixel-by-pixel, but details not given.	CR muons. Snow and ice shielding considered.

~~Default parameters used in the CAIRN model. ParameterValueSourceλ_{10Be}500*10^{-9} yr^{-}1Chmeleff et al. (2010); Korschinek et al. (2010) λ_{26Al}980*10^{-9} yr^{-}1Nishiizumi (2004) Λ_i160;1500;4320 g cm^{-2}From COSMOCALC version 2.0 to mimic Braucher et al. (2009) ^{10}Be P_{SLHL}4.30 atoms g^{-1} yr^{-1}From COSMOCALC version 2.0 to mimic Braucher et al. (2009) ^{10}Be F_i0.9887; 0.0027; 0.0086 (dimensionless)From COSMOCALC version 2.0 to mimic Braucher et al. (2009) ^{26}Al P_{SLHL}31.10 atoms g^{-1} yr^{-1}From COSMOCALC version 2.0^{26}Al F_i0.9699; 0.00275; 0.0026 (dimensionless)From COSMOCALC version 2.0 to mimic Braucher et al. (2009)~~

Table 4. Parameters used for production of ^{10}Be which approximate the scheme in CRONUScalc (Marrero et al., 2016). λ_{10Be} values are the same as defaults listed previously. The F_i values represent spallation and fast and slow muons, respectively.

Parameter	Value
Λ_i	160;1460;11040 g cm^{-2}
^{10}Be P_{SLHL}	4.075 atoms g^{-1} yr^{-1}
^{10}Be F_i	0.9837; 0.0137; 0.0025 (dimensionless.)

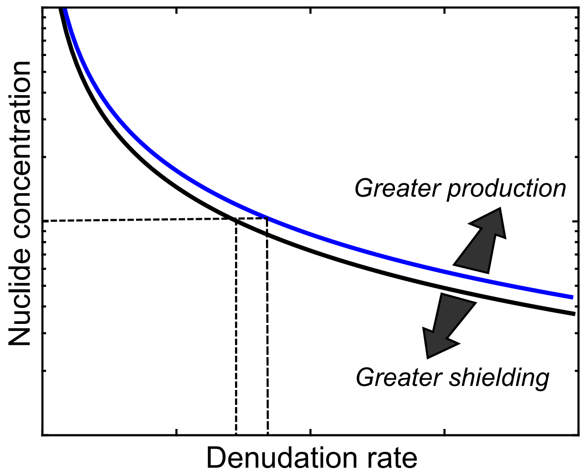


Figure 1. A schematic drawing of the predicted concentration of a nuclide as a function of denudation rate. If production rates are assumed to be higher, the predicted concentration will be higher for a given denudation rate. If shielding is greater, the predicted concentration is lower for a predicted denudation rate. Thus assumptions about production and shielding will affect the inferred denudation rate given a sample with fixed concentration, shown with the dashed lines.

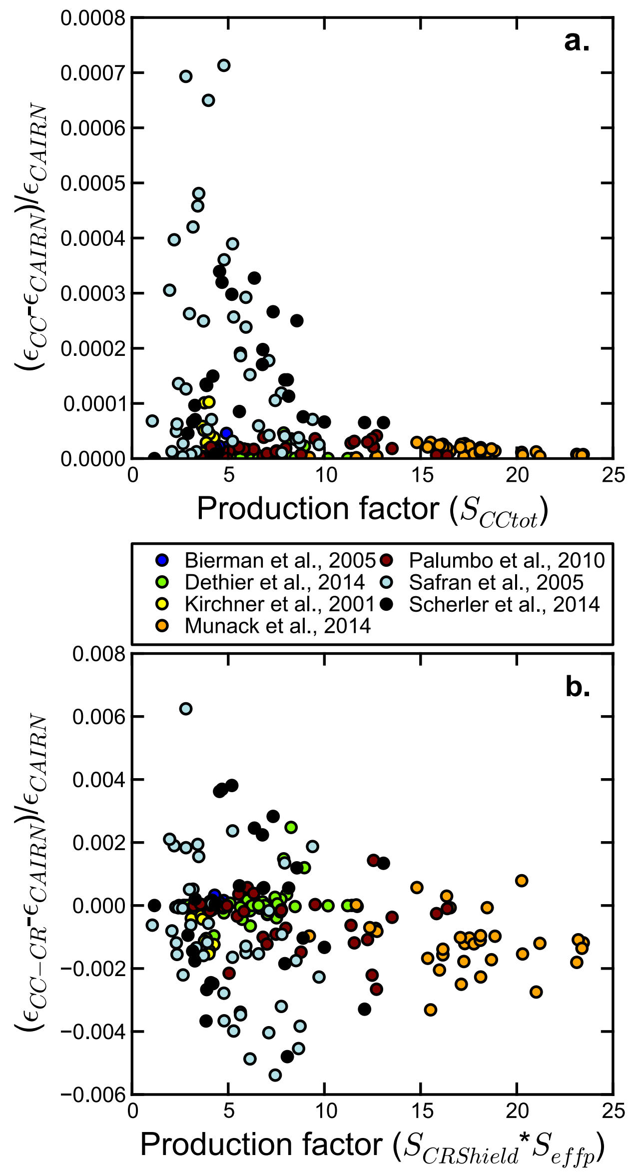


Figure 2. Errors Differences between the denudation rate calculated by CAIRN (ϵ_{CAIRN}) and the denudation rate using the production factor (S_{CCtot}) (which includes production scaling and shielding) passed to COSMOCALC (ϵ_{CC}) (**a.**), and differences between the denudation rate calculated by CAIRN (ϵ_{CAIRN}) and the denudation rate using separate spatial averages for shielding and production scaling that are then averaged ($\epsilon_{CC-CRONUS}$) as a function of production factor **b.**. In this case the production factor is calculated by multiplying the separately averaged shielding ($S_{CRShield}$) and scaling (S_{effp}) factors. This approach emulates the data requirements for CRONUS-2.2, which calculates production scaling and accepts a single shielding factor (for snow and topography combined). Although the shielding and scaling emulate data requirements for CRONUS-2.2, the denudation rate is calculated using the exponential production method of CAIRN and COSMOCALC.

Errors between the denudation rate calculated by CAIRN (ϵ_{CAIRN}) and the denudation rate using separate spatial averages for shielding and production scaling that are then averaged ($\epsilon_{CC-CRONUS}$) as a function of production factor. In this case the production factor is calculated by multiplying the separately averaged shielding ($S_{CRShield}$) and scaling (S_{effp}) factors. This approach emulates the data requirements for CRONUS-2.2, which calculates production scaling and accepts a single shielding factor (for snow and

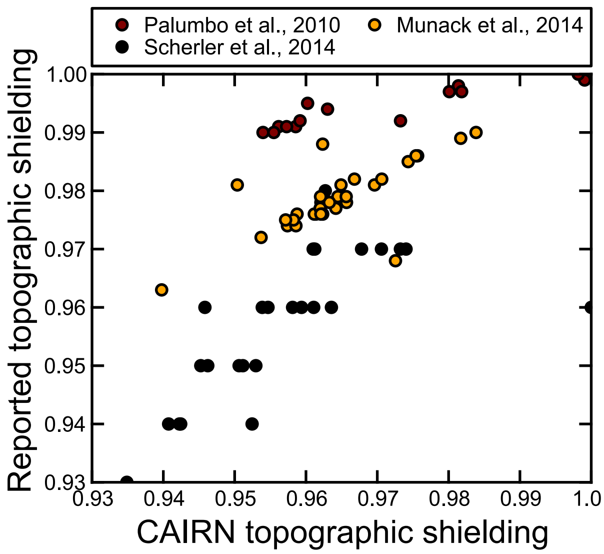


Figure 3. Topographic shielding (S_t) calculated using $\Delta\phi$ = 5, $\Delta\theta$ = 8 plotted as a function of reported shielding.

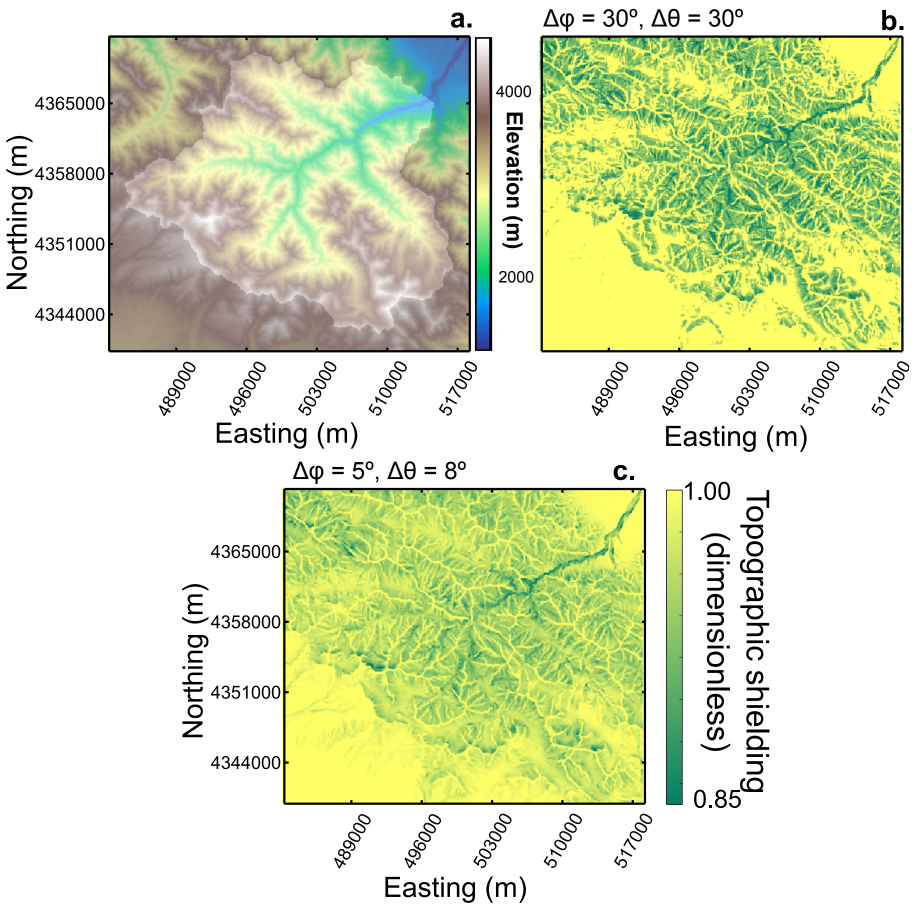


Figure 4. Comparison of the topographic shielding for different values of $\Delta\phi$ and $\Delta\theta$. The Tibetan basin is for sample 07C13 in Palumbo et al. (2011). Maps are projected into WGS1984, UTM zone 47N. The basin is shown in plot **a**, whereas the topographic shielding factor is shown in plots **b** and **c**.

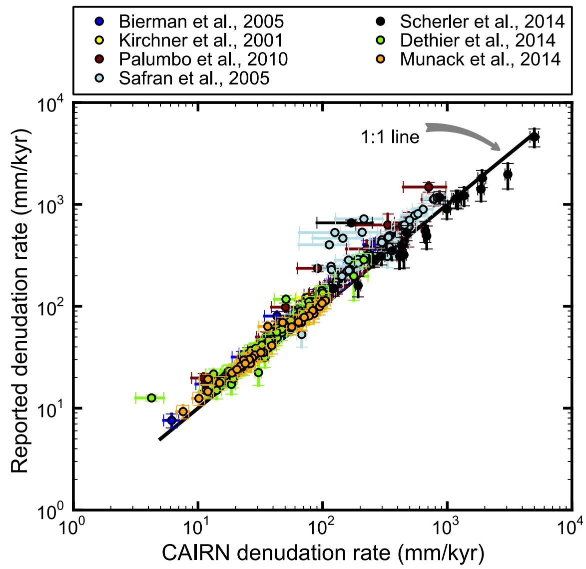
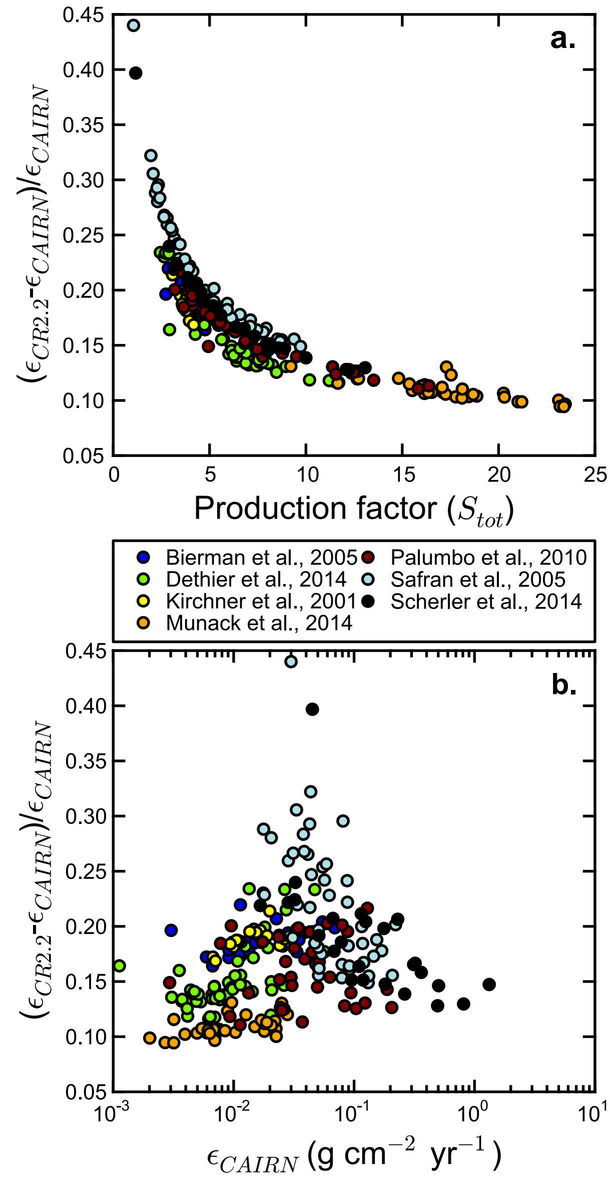


Figure 5. Comparison of denudation rates reported by selected studies plotted against denudation rates predicted by CAIRN. The denudation rates for individual studies use their original assumptions of the density of the surface material, as reported in Table 3. The results from CAIRN in this plot use a density of 2.65 g cm^{-2}.



Errors a., and differences between the denudation rate calculated by CAIRN (ϵ_{CAIRN}) and the denudation rate calculated with CRONUS-2.2 ($\epsilon_{CR2.2}$) as a function of the total scaling(, S_{tot} (**b.**).

Errors a., and differences between the denudation rate calculated by CAIRN (ϵ_{CAIRN}) and the denudation rate calculated with CRONUS-2.2 ($\epsilon_{CR2.2}$) as a function of the total scaling(, S_{tot} (**b.**).

Figure 6. Errors Differences between the denudation rate calculated by CAIRN (ϵ_{CAIRN}) and the denudation rate calculated with CRONUS-2.2 ($\epsilon_{CR2.2}$) as a function of CAIRN denudation rate .

Errors a., and differences between the denudation rate calculated by CAIRN (ϵ_{CAIRN}) and the denudation rate calculated with CRONUS-2.2 ($\epsilon_{CR2.2}$) as a function of the total scaling(, S_{tot} (**b.**).

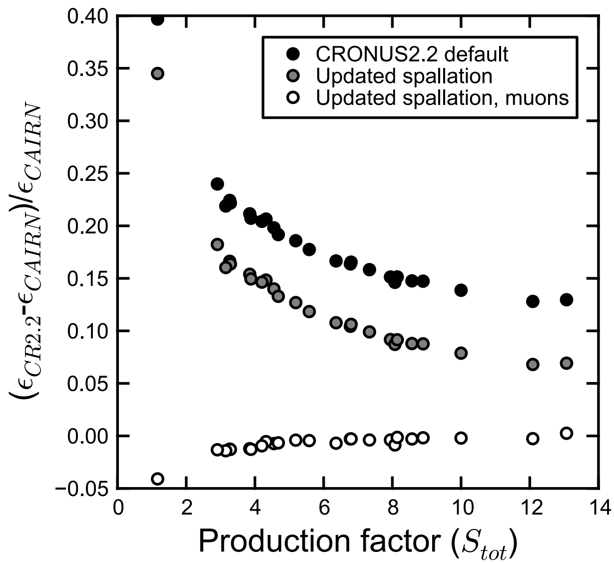


Figure 7. Difference between denudation rate calculated by CAIRN (ϵ_{CAIRN}) and the denudation rates calculated by CRONUS-2.2 ($\epsilon_{CR2.2}$), but with CRONUS-2.2. parameters updated to have spallation and muon production reflecting production in CAIRN, which is based on (Braucher et al., 2011) . Data are from the Scherler et al. (2014) study.

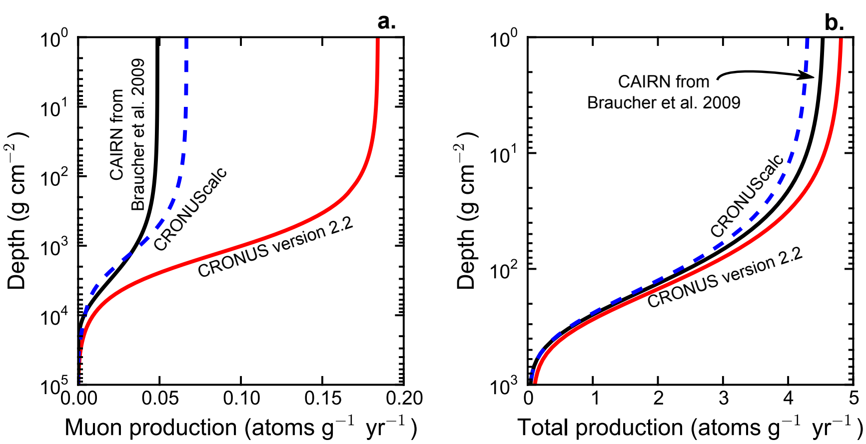


Figure 8. Production rates of ^{10}Be as a function of depth for muons only (**a.**) and total production (**b.**). These production rates are calculated using the Lal/Stone scaling at 70 degrees North and with a pressure of 1007 hPa (near sea level). Note the logarithmic depth scale: eroding particles spend a large amount of their exposure history below 100 g cm^{-2} and so increased muon production at these depths, despite being a small fraction of the total production, plays a significant role in determining the total nuclide concentration (see Figure 9).

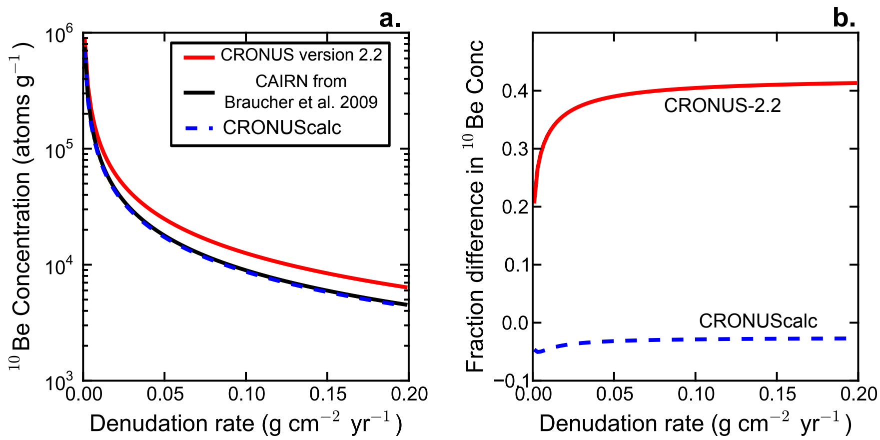


Figure 9. Concentrations as a function of denudation rate (**a.**) and the fractional differences between the predicted concentration from the Braucher et al. (2009) approximation used in CAIRN and both CRONUS-2.2 Balco et al. (2008) (Balco et al., 2008) and CRONUScalc Marrero et al. (2016) (Marrero et al., 2016) . These concentrations are calculated for a hypothetical site at 70 degrees North and near sea level (1007 hPa). Note that although the default production scheme in CAIRN is the Braucher et al. (2009) scheme, the production from CRONUScalc (Marrero et al., 2016) can also be used (see Table (4).

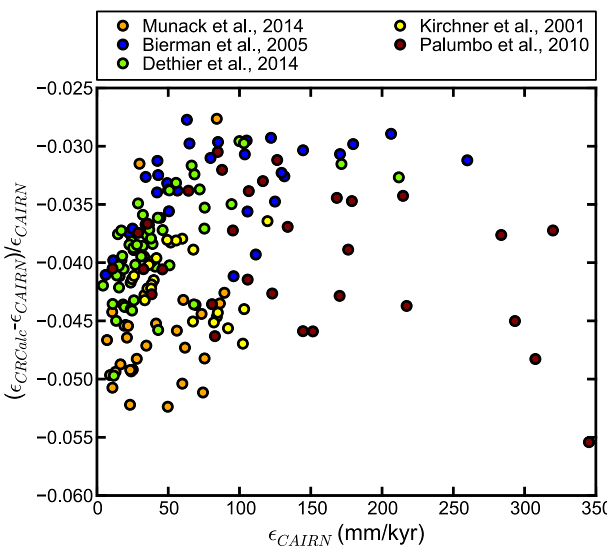


Figure 10. Errors Differences between the denudation rate calculated by CAIRN (ϵ_{CAIRN}) and the denudation rate calculated with CRONUScalc (ϵ_{CRCalc}) as a function of CAIRN denudation rate for selected studies.

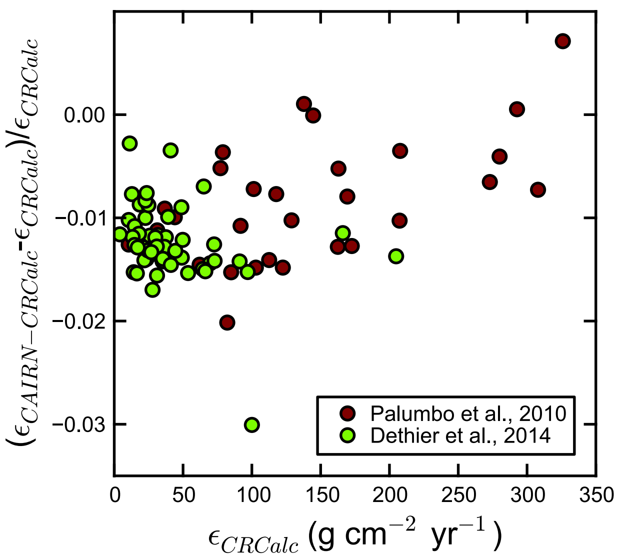


Figure 11. ~~Errors~~ Differences between the denudation rate calculated by CAIRN using the parameters in Table 4 to approximate CRONUScalc production ($\epsilon_{CAIRN-CRCalc}$) and the denudation rate calculated with CRONUScalc (ϵ_{CRCalc}) as a function of CAIRN denudation rate for selected studies.

Algorithm 1 Calculating denudation rates on a pixel-by-pixel basis

```
Make initial denudation rate guess based on spallation only at outlet pressure and latitude.
repeat
    for all Pixels in basin do
        Calculate cosmogenic nuclide flux based on denudation rate using Eq. 14
    end for
    Average the cosmogenic nuclide concentration over the basin
    Change denudation rate by small increment
    for all Pixels in basin do
        Calculate cosmogenic nuclide flux based on updated denudation rate using Eq. 14
    end for
    Calculate new denudation rate based on the change in error between calculated and measured cosmo-
    genic nuclide concentrations (i.e., Newton's method).
    Calculate change in effective denudation rate
until Change in effective denudation rate < tolerance
```