Final author comments

Response to Referee #1 (received and published 7 June 2019).

Thank you for your comments on our manuscript. On behalf of my co-authors, I would like to respond to your suggestions as to how we could take this manuscript further.

1a) Referee #1; C2, item 1: "If there is one place that the manuscript could be taken to the next level, it would be a more sophisticated mass and isotope balance approach to modelling hillslope soil production and transport. However, the authors are 100% transparent about the variables in their lifespan analyses, and their approach is adequate."

1b) Response to Referee #1; C2, item 1: The primary aim of the paper is to report soil formation data. The employment of these data in a first-order lifespan model is an important secondary aim and we accept that our model is currently relatively simple. To enact a more sophisticated isotope balance approach, however, we would need to execute further sampling campaigns for both sites and conduct further laboratory analyses. Whilst this is interesting work, we felt it fell beyond the scope of this paper. However, we are considering this for future work (as addressed below).

1c) Change in manuscript after Referee #1; C2, item 1: We argue that no change is necessary.

2a) Referee #1; C2, item 2: "Given that RFF has been actively farmed for over a century and a half, how do you reconcile a still extant A horizon? Do you think that tens of centimetres of soil have been lost in that time?"

2b) Response to Referee #1; C2, item 2: Soil has been redistributed downslope. This is demonstrated by the fact that the soils at the toeslope comprise, in part, of colluvium and further supported by the increased depth to the Bunter Pebble Bed at the toeslope as discussed on Page 16, line 7. Further isotopic work, particularly down the profile at the toeslope, would begin to explore this process in more detail but this is beyond the scope of this paper. There are two reasons for the survival of the extant Ap horizon. First, as soil is lost downslope, subsequent tillage operations incorporate former, unconsolidated soil from the B horizon into the Ap horizon. This leads to the dilution of the Ap horizon with the result that more of the initial Ap matrix survives than if there was no replacement. In Quine and Van Oost (2007), erosion rates are calculated from ^{137}Cs data using the following equation:

$$R_p = R_f \left(1 - \frac{E}{P}\right)^{ts}$$

where R_f is the ^{137}Cs fallout reference inventory, R_p is the ^{137}Cs inventory at a point of interest, P is the cultivation layer depth, ts is the time between sampling and 1963, and E is the erosion rate. This equation can also be used to consider the survival of the Ap horizon, where R_f is the initial Ap matrix and R_p is the surviving Ap matrix. Using the data in Quine and Van Oost (2007), Ap survival is significant eve where erosion rates of 26 t ha^{-1} y^{-1} are experienced (57% after 50 years, and 32% after 100 years).

Second, we would suggest that the continuous removal of organic carbon is balanced by the dynamic replacement of new carbon input. Previous research has shown that for both water-based and tillage-based soil redistribution, this dynamic replacement rate in the upper ploughed layer exceeds that of carbon mineralisation in the sub-plough layer. (Please refer to: Van Oost *et al*. (2005) doi: 10.1029/2005GB002471 and papers cited therein, particularly those from Harden *et al.*).

2c) Change in manuscript after Referee #1; C2, item 2: We suggest that the following addition is made on Page 5, line 22: "Despite being subject to arable practices for over 150 years, the presence of a 30 cm Ap horizon may be explained in part by the incorporation of organic carbon from the B horizon, and the dynamic replacement of new carbon into the plough layer, which exceeds the rate of carbon mineralisation in the sub-plough layer (Van Oost *et al*., 2005) although further isotopic work is required to verify this for RFF."

3a) Referee #1; C2, item 3: "Stratigraphic evidence or isotopic (Cs-137) evidence could yield some insight into the effect of the past 1.5 centuries of tillage."

3b) Response to Referee #1; C2, item 3: We agree, and we are actively pursuing this at another site.

3c) Change in manuscript after Referee #1; C2, item 3: We argue that no change is necessary. Please note that we have signalled the need for further isotopic work within the previous 'change in manuscript' (see 2c).

Final author comments

Response to Referee #2 (received and published 17 June 2019).

Thank you for your comments on our manuscript. On behalf of my co-authors, I would like to respond to your suggestions as to how we could take this manuscript further.

1a) Referee #2; C2, item 1: “P5 line 19 Include the correct reference to WRB (2015). Please see recommended citation in the preface of the manual.”

1b) Response to Referee #2; C2, item 1: We agree.

1c) Change in manuscript after Referee #2; C2, item 1: We suggest that the citation on Page 5, lines 19 and 23 are changed to: “(IUSS Working Group WRB, 2015).” We will also provide a full reference in the bibliography.

2a) Referee #2; C2, item 2: “P5 L23 CW soil has 94% sand. This would classify the soil at this site in WRB as an Arenosol not a Cambisol.”

2b) Response to Referee #2; C2, item 2: We agree.

2c) Change in manuscript after Referee #2; C2, item 2: We suggest that “Cambisol” is changed to “Arenosol” on Page 5, line 23.

3a) Referee #2; C2, item 3: “P5 L19-20 Please refer to the methods used for the determination of the particle size distribution and LOI”.

3b) Response to Referee #2; C2, item 3: We agree.

3c) Change in manuscript after Referee #2; C2, item 3: We suggest the following addition is made on Page 8, line 9: “Soil samples were sub-sampled every 5 cm from each core at RFF and on each profile wall at CW. All samples were then oven dried overnight (105°C for 12 hours), grounded with a pestle and mortar, and sieved to discard the >2 mm fraction before being subject to particle size analysis and loss on ignition (LOI). Particle size analysis was conducted using a Beckman Coulter Laser Diffraction Particle Sizing Analyser LS 13 320 (pump speed: 70 %; sonication: 10 seconds; run-length: 30 seconds). For LOI, 5 g of each sample was placed in a Carbolite furnace CWF 1300 (550°C for 12 hours).” We then suggest that the text on Page 5, lines 19-26 (“The soils at RFF […] saprolitic sandstone”) are cut and are placed here on page 8, so that the description of the soil profiles follows the methods.

4a) Referee #2; C2, item 4: P7 L 5 "...observation on the competency of the extracted material…" is a bit vague - how was the Saprolite or the soil/saprolite boundary determined exactly? A change in colour, consolidation, grain size? Please provide some further details”.

4b) Response to Referee #2; C2, item 4: The methods we applied both in the field and in the laboratory were observations on the consolidation of the material supported by the penetrometer data.

4c) Change in manuscript after Referee #2; C2, item 4: We suggest a revision on Page 7, line 4: “…were later halved lengthways, and by observing the changes in the consolidation and physical integrity of the extracted material (i.e. whether it remained intact when removed from the core), together with the penetration resistance data acquired in the field, the soil-saprolite interface was demarcated.” We also suggest a revision on Page 7, line 9: “Observing the changes in the consolidation and physical integrity of the material down the profile wall, together with the penetration resistance data, the soil-saprolite interface was ascertained.”

5a) Referee #2; C2, item 5: “P7 L6 You sample at the soil-saprolite interface and 50cm below it in RFF. Please indicate the rationale for these paired samples. These samples are not differentiated in the results – so are they both used to be representative of this boundary and what are the implications for this? In table 1 the lower samples in some locations are showing active weathering indicated by greater soil formation rates”.

5b) Response to Referee #2; C2, item 5: They are not both representative of the boundary. The first sample (labelled A in Table 1) represents the soil-saprolite interface. Since reflecting on these responses, we have made revisions to Equation 1:

$$N = \sum_{i=sp,\mu_f,\mu^-} \frac{P_i(\theta)\ \cdot\ e^{-\frac{x}{\Lambda_i}}}{\lambda + \frac{\epsilon\rho}{\Lambda_i}} (1 - e^{-t\left(\lambda+\frac{\epsilon\rho}{\Lambda_i}\right)})$$

P are the annual production rates of ^{10}Be by spallation, fast muons and stopping muons (sp, μ_f and μ^-) at a surface with slope *Ɵ*; *x* is the mass sample depth (*ρ·z*); *p* is the density of overburden material; *z* is the depth of the sample; t is the age of the landscape (the age when the original surface was generated) λ is the decay constant of ^{10}Be with λ equalling In2/^{10}Be half-life; and Λ are the mean attenuation of cosmic radiations (Lal, 1991).

t is usually considered infinite. In this paper, we tested the best fit of *t* based on the data from RFF. To do this, we took two samples from the same depth profile and measured the concentration of ^{10}Be for both. At RFF, this showed that the landscape age (the time when the cosmogenic clock was reset) was >200 ka.

5c) Change in manuscript after Referee #2; C2, item 5: We suggest that Equation 1 is updated to:

$$N = \sum_{i=sp,\mu_f,\mu^-} \frac{P_i(\theta)\ \cdot\ e^{-\frac{x}{\Lambda_i}}}{\lambda + \frac{\epsilon\rho}{\Lambda_i}} \left(1 - e^{-t\left(\lambda+\frac{\epsilon\rho}{\Lambda_i}\right)}\right)$$

We also suggest that a revision is made to Page 7, lines 18-23: “where: *P* are the annual production rates of ^{10}Be by spallation, fast muons and stopping muons (sp, μ_f and μ^-) at a surface with slope *Ɵ*; *x* is the mass sample depth (*ρ·z*); *p* is the density of overburden material; *z* is the depth of the sample; *t* is the age of the bedrock surface (the age when the original surface was generated) λ is the decay constant of ^{10}Be with λ equalling In2/^{10}Be half-life; and Λ are the mean attenuation of cosmic radiations (Lal, 1991). *t* is usually considered infinite. In this paper, we took two samples from some of the sites to test if the data support this assumptions. RFF data is compatible with landscape ages >221 ka. Production rates, decay constants and attenuation lengths were calculated using field data and the CRONUS-

Earth online calculator v2.3 Matlab code for the St scheme (Balco, 2008). As *N* can be measured using Accelerator Mass Spectrometry (AMS), Eq. (1) can be solved for ε by simple interpolation of *N*."

6a) Referee #2; C2, item 6: "P8 L23 An additional statement needed here to indicate the exclusion of other potential soil forming inputs (e.g. organic matter and/or aeolian dust)."

6b) Response to Referee #2; C2, item 6: We agree.

6c) Change in manuscript after Referee #2; C2, item 6: We suggest the following addition is made to Page 8, line 24: "…sufficiently low, nor did we account for any allochthonous inputs to the profile such as aeolian additions and organic amendments."

7a) Referee #2; C2, item 7: "P8 line 25 depth to bedrock or depth to soil/saprolite boundary? Did you only use the samples labelled A from RFF to indicate depth to saprolite? Please confirm in the text".

7b) Response to Referee #2; C2, item 7: Yes, we used the depth to the soil-saprolite interface.

7c) Change in manuscript after Referee #2; C2, item 7: We suggest the following revision is made to Page 8, line 25: "the observed depth to the soil-saprolite interface at each catena position was employed".

8a) Referee #2; C2, item 8: "P13 6 Did you undertake any geochemical analysis on the samples (XRF or spectroscopy?) I guess you would have reported it but it would have been really good to see some data (perhaps in another paper)."

8b) Response to Referee #2; C2, item 8: We did not undertake any further analyses on the samples in this study. However, we are considering further isotopic work that may further our understanding of soil formation rates, erosion and particularly colluviation. Nevertheless, it would be beyond the primary aim of this paper to report such analysis here.

8c) Change in manuscript after Referee #2; C2, item 8: We argue that no change is necessary.

9a) Referee #2; C2, item 9: "P13 line 27, 31; P14 L5 and 14. Check the notation for p values for the Mann-Whitney tests. For significant difference $p < 0.05$; for no significant difference $p > 0.05$."

9b) Response to Referee #2; C2, item 9: We agree.

9c) Change in manuscript after Referee #2; C2, item 9: All reported *p* values should be revised (i.e: where $p < 0.05$ appears, these are replaced by $p > 0.05$, and vice versa).

10a) Referee #2; C3, item 10: "P14 L3 Can you clarify if the sandstone dataset is from the temperate subset or from the whole global database? If the latter, then there is an interaction between climate and differences in sandstone lithology."

10b) Response to Referee #2; C3, item 10: The sandstone dataset was derived from the whole global, soil-mantled database. Coincidentally, all but seven data points for the sandstone dataset stem from temperate climates (as classified by the Koppen system). The remaining seven stem from A_w (tropical/savannah) and we believe that these should be removed from the figure so that we limit the climate signal as much as possible. (Incidentally, your point can also be made for the temperate climate dataset, reported on Page 13, line 29 onwards. The temperate climate dataset comprises rates for no less than six different parent materials).

10c) Change in manuscript after Referee #2; C3, item 10: We suggest that the seven data points not from temperate climates are removed from Figure 4c. We then suggest the addition of the following on Page 14, line 5: “Although the sandstone-derived data were derived from the global soil-mantled database, all data stem from sites in temperate climates which reduces the influence that climate may have otherwise had in this analysis on lithology.” We also suggest the revision of Page 14, line 3: “(n = 57)”

11a) Referee #2; C3, item 11: “P16 L5. The toeslope also shows an Ap of 75 cm (p5 L20) which has also not been taken into account in the calculation due to the assumption that the top 30cm is representative of the current (active?) A horizon. If the top 30cm is removed then it could be argued there is still ‘viable’ topsoil at this location and thus the lifespan would be much greater than calculated (in addition to it also receiving colluvium).”

11b) Response to Referee #2; C3, item 11: We acknowledge that already on Page 16, line 9-10: “…lifespans at this position may be either longer than 2158 years or indefinite.” We should point out that the Ap horizon of 75 cm is most likely, in part, colluvium. But we will make this clearer also on Page 8, too. Finally, we will run the lifespan model again for the toeslope and report an additional lifespan for this position, taking into account the 75 cm depth.

11c) Change in manuscript after Referee #2; C3, item 11: First, we suggest the following addition on Page 8, line 22: “…D = 30 cm across the catena. At the toeslope, an additional lifespan was calculated to account for the greater depth (75 cm) of the A horizon.” Second, we suggest the following addition on Page 16, line 5: “…rather than thinning. This is supported by the fact that the depth of the Ap horizon at the toeslope is 75 cm, whereas it is 30 cm on all other observed landscape positions. Moreover, comprised within the upper stratigraphy of the soil profile down the catena is the Bunter Pebble Bed which can be found at approximately 30 cm on summit, shoulder and backslope positions but 70 cm at the toeslope. The depth to which this pebble bed occurs at the toeslope suggests that either colluviation has occurred or is still occurring. In a scenario where colluviation is no longer active, the lifespan of this 75 cm A horizon is finite and ranges from 345 – 4808 years, but lifespans here could be longer or indefinite is colluviation continues.”

12a) Referee #2; C3, item 12: “P16 L6 Could the pebble bed offer some surface armoury that would reduce the rate of soil erosion once material above it has been eroded?”

12b) Response to Referee #2; C3, item 12: An interesting idea. We discuss the potential differences in erodibility with soil removal on Page 18, line 3, but we only considered erodibility to increase. We shall acknowledge the pebble bed armoury.

12c) Change in manuscript after Referee #2; C3, item 12: We suggest the following addition on Page 18, line 3: “…neither reflects the increase in the erodibility of subsoil horizons, characterised by a relatively weaker soil structure (Tanner et al., 2018) nor the potential role that the Bunter Pebble Bed may play in armouring the soil surface in the future. Moreover, they do not reflect the expected shift in erosivity…"

13a) Referee #2; C3, item 13: "P16 line 15 this is the sampling depth, which is the soil-saprolite boundary, not depth to bedrock (be consistent with the descriptions you have used in other parts of the manuscript).

13b) Response to Referee #2; C3, item 13: We agree.

13c) Change in manuscript after Referee #2; C3, item 13: We suggest a revision to text on Page 16, line 15: "the soil thickness applied here is the depth to the soil-saprolite interface measured…" We also suggest a change to Figure 5 caption; "…(light brown) and the depth to the soil-saprolite interface (bricks)."

14a) Referee #2; C3, item 14: P18 L8. Is the last sentence incomplete?

14b) Response to Referee #2; C3, item 14: We agree; incomplete but also superfluous.

14c) Change in manuscript after Referee #2; C3, item 14: We suggest the deletion of the final sentence on Page 18, line 8.

15a) Referee #2; C3, item 15: Figure 2 Please indicate what the error bars show. Also include the sample numbers on the figure or in the caption.

15b) Response to Referee #2; C3, item 15: We agree.

15c) Change in manuscript after Referee #2; C3, item 15: We suggest that the caption for Figure 2 includes the words: "The error bars represent one standard deviation". Further, we suggest a revision to existing text: "Rufford Forest Farm (blue; n = 4) and Comer Woodland (green; n = 4)."

16a) Referee #2; C3, item 16: Figure 3 If I have interpreted the sampling correctly then 4 of these samples are from 50cm below the soil-saprolite boundary. Does this figure therefore show sampling depth rather than depth to saprolite (for RFF there would be 4 pairs of samples with the same saprolite-soil boundary depth, one sample at the boundary and one 50 cm below).

16b) Response to Referee #2; C3, item 16: Yes, that is correct and requires an axis label change.

16c) Change in manuscript after Referee #2; C3, item 16: We suggest that the x axis label is revised to: "Sampling Depth (cm)"

17a) Referee #2; C3, item 17: Table 1 You state the average sample density. If you have measured the BD for each sample then what is the justification for using the average for all samples rather than the specific sample bulk density in the Be10 calculations?

17b) Response to Referee #2; C3, item 17: We have developed a model as part of some sensitivity analysis to be published soon. We have run the model for all sites and have incorporated the new results throughout the paper.

17c) Change in manuscript after Referee #2; C3, item 17: We suggest that results from our new analyses are incorporated throughout the paper: in Table, figures, all written analyses, etc.

Final author comments

Response to Referee #3 (received and published 19 June 2019).

Thank you for your comments on our manuscript. On behalf of my co-authors, I would like to respond to your suggestions as to how we could take this manuscript further.

1a) Referee #3; C2-5, item 1: Equation 1 is the correct equation to use to determine the saprolite erosion rate, which then translates into the soil formation rate. However, I would like to suggest a different way to calculate the production rate at a sample's depth (the numerator in the equation). The authors have appropriately calculated surface production rates of cosmogenic 10Be due to spallation, fast muons, and stopping muons based on the Stone, 2000 scaling scheme. Then, to calculate the production rate of cosmogenic 10Be at the depth the samples were collected, the surface production rates are scaled with an exponential function based on the depth times the density of the overlying material. The product of depth times density is the "mass depth." In this paper, the authors appear to use the density of saprolite (2.2 g/cmˆ3) to calculate the mass depth of the samples. But the material that overlies the saprolite is soil, which should have a lower density than saprolite. I think the appropriate density to use to calculate the production rate at the sample's depth is that for soil because that represents the mass depth that overlies the soil-saprolite boundary, and the authors have (correctly) assumed that the soil thickness has not changed over time. If one were to use the density of soil as the overlying material, instead of saprolite, the mass depth of the samples would be lower because the density of soil is lower. This would then result in a higher production rate at the depth of the samples. Then, when calculating erosion rates from equation 1, this would result in higher erosion rates because an increase in the numerator in equation 1 would require an increase in the denominator (where the erosion rate goes) to result in the same concentration of 10Be that was measured in the sample. I would like to emphasize that this impact is small, is fairly uniform across all the sample sites, and does not change the main findings of the paper. I have recreated the authors' calculations, and performed my own calculations on the attached spreadsheet. In my experience with trying to measure soil density, soils typically have a density of 1.5 – 2.0 g/cmˆ3. In my calculations I used a value of 1.8 g/cmˆ3 as an approximate median value to my anecdotal evidence, but I would leave it to the authors to find an appropriate soil density value to use. There are two important things to note in how I have done my calculations: 1) To calculate the mass depth, you want the depth times the density of the overlying material. For the samples at the top of the saprolite, this is simple, and is just the depth times the density of the soil. But for the samples that are 50 cm below the top of the saprolite, this is the cumulative sum of the soil and the saprolite above the sample. This is also simple to calculate, it is the density of soil times the depth of the soil, plus the density of saprolite times 50 cm, because these samples were collected that far below the top of the saprolite. 2) This correction only applies to the numerator in equation 1. It does not apply to the denominator, which also has a depth times density term. In the case of the denominator, this is the place where erosion of the overlying material comes into the exposure model. The authors have concluded that the soil thickness does not change at a timescale that would affect the concentration of 10Be in the saprolite. I agree that this is a valid assumption, and the result is that only the saprolite changes depth with time in this exposure model. This means that only saprolite is "removed" as mass above the sample site, so the material that is eroded in equation 1 is saprolite. Thus, the density of the material in the denominator of equation 1 is correctly used at 2.2 g/cmˆ3. The spreadsheet I have included has two tabs. The first tab on the left (Evans et al. Calculation) recreates the authors' calculation to verify that they used 2.2 g/cmˆ3 in the numerator and denominator of equation 1. The second tab contains my calculations to determine the production rate at the depth of the sample, and each corresponding new saprolite erosion rate. I've also calculated the percent difference between my calculations and those from Evans et al. Using the method I propose, the saprolite erosion rates are 7 – 29% higher than determined by Evans et al. Although my proposed method results in higher saprolite erosion rates than those shown by the authors, the same trends discussed by the authors remain true, and the discussion and conclusions of the paper still hold. That is, the rates shown in figures 2, 3, and 5 would show the same general trends, but the numbers would be updated. Figure 4 that puts the calculated rates in context globally would have to be updated too, and that portion of the discussion could be quickly updated. Many of the tables would need to be updated. I suppose it's worth noting that Evans et al. have calculated the production rate of 10Be at the top of the saprolite sample. They could have made an additional correction for the sample thickness. I don't remember any discussion about sample thickness in the paper. This correction would be small, and would likely change all the numbers by only a percent or two Of course, this would depend on how thin or thick the samples were, and what the range of sample thicknesses was for the samples. I suppose that it is not necessary that they do this correction, especially if the samples are all about the same thickness and not more than a few centimeters thick. But it just occurred to me that this is missing. Please let me finish by welcoming any discussion about my method, or that used by the authors. I think I have correctly calculated the production rate at sample depth, but I am open to discussion on the topic. If the authors think that 2.2 g/cmˆ3 is the correct density to use for the numerator, I would love to hear their thoughts on the question and would consider the other number.

1b) Response to Referee #3; C2-5, item 1: We have developed a model as part of some sensitivity analysis, using multiple bulk density measurements down the soil profile. We have assumed that the density of the overburden (soil profile) has not changed with time. (The model itself is to be published soon, elsewhere). However, we have used the model to re-calculate soil formation rates for both RFF and CW and intend to incorporate these results in the paper. We have also used the model to assess the importance of sample thickness, by calculating soil formation rates for three different sampling depths: the top, middle and bottom of the sample.

1c) Change in manuscript after Referee #3; C2-5, item 1: We suggest that results from our new analyses are incorporated throughout the paper: in Table, figures, all written analyses, etc.

2a) Referee #3; C5, item 2: "P3, L28: You say only 252 of 1850 samples come from 10Be data. Did you compile all 1850 data points? This sounds like your compilation, and I wonder if there's more work that you've done that should be shared and part of this discussion".

2b) Response to Referee #3; C5, item 2: The compilation is our work, although it is largely based off existing inventories, namely Portenga and Bierman (2011), Stockmann et al. (2014) and Montgomery (2007). These are cited on Page 3, line 27.

2c) Change in manuscript after Referee #3; C5, item 2: We argue that no change is necessary.

3a) Referee #3; C5, item 3: "P4, L31: do you mean "small" instead of "soft" when describing the grain size of the sandstone at the CW site?"

3b) Response to Referee #3; C5, item 3: The word 'soft' here is an error.

3c) Change in manuscript after Referee #3; C5, item 3: We suggest the deletion of the word "soft" from Page 4, line 31.

4a) Referee #3; C5, item 4: P5, L3: What is the aspect of the sites? Is one north-facing and another south-facing? If you know this, it could be interesting to report as it could be a factor in the difference between the sites.

4b) Response to Referee #3; C5, item 4: Both are south-facing sites, although the effects of insolation are obviously dampened at CW due to the canopy cover.

4c) Change in manuscript after Referee #3; C5, item 4: We suggest the following addition on Page 5, line 1: "Both RFF and CW are south-facing slopes, and sit in a temperate…"

5a) Referee #3; C5, item 5: P5, L19: I don't think the citation for the FAO WRB is correctly formatted for this journal, but I'm not the expert. Is there a year?

5b) Response to Referee #3; C5, item 5: We agree.

5c) Change in manuscript after Referee #3; C5, item 5: We suggest that the citation on Page 5, lines 19 and 23 are changed to: "(IUSS Working Group WRB, 2015)." We will also provide a full reference in the bibliography.

6a) Referee #3; C6, item 6: P5, L24: I don't know what the acronym LFH stands for, and I'm not sure it's spelled out previously. If this is the first time it's used, please write it out fully.

6b) Response to Referee #3; C6, item 6: We agree.

6c) Change in manuscript after Referee #3; C6, item 6: We suggest that "LFH layer" on Page 5, line 24 is changed to "Litter Fermentation Humus layer".

7a) Referee #3; C6, item 7: P5, L25: This is simply a style thing, and certainly is due to my own biases. But as I read this page, I wanted to ask, "If the area had significant sediment transport from glacial outwash since the last glacial maximum, and there is a pebble layer in the stratigraphy, how certain are you that these soils are really derived from weathered saprolite?" I think the answer is, "These soils are still 82% and 94% sand, so there doesn't appear to be much input from glacial outwash into these soils." If I were writing this, I'd probably say something explicitly about this, but that's just my style and I don't think it's necessary to include this.

7b) Response to Referee #3; C6, item 7: We cite on Page 5, line 8 that "the prevalence of similar deposits on the study hillslope has not been studied." However, we accept that a soil with 84-94% sand suggests the absence of glacial outwash deposits; that the soils here are residual soils that have formed from sandstone rather than allochthonous sources.

7c) Change in manuscript after Referee #3; C6, item 7: We suggest the following addition to Page 5, line 25: "The sandy composition of these soils suggests that proglacial outwash deposits have not contributed to the soils of the study sites and that, instead, the soils are largely residual."

8a) Referee #3; C6, item 8: Also, what were the land-use practices at RFF? I thought something was written about tilling at that site, but I can't seem to find it now.

8b) Response to Referee #3; C6, item 8: Please refer to Page 5, line 15 where we state that "RFF has been under an arable regime and in the last twelve years, the dominant crops have been Winter Wheat and Rye." Unfortunately we are unable to provide precise details as to the tillage operations (plough depth, disc type, etc).

8c) Change in manuscript after Referee #3; C6, item 8: We argue that no change is necessary.

9a) Referee #3; C6, item 9: "P7, L17: Equation 1 is the correct equation to use, but it does not have a time element in it. So your description of the equation above this seems a bit confusing. I think what you're missing is that once enough time has passed, the system will approach an equilibrium nuclide concentration that is the balance between the production and erosion rates. Assuming this has been reached, you can use equation 1."

9b) Response to Referee #3; C6, item 9: We agree and have now incorporated a time element, as shown in 9c.

9c) Change in manuscript after Referee #3; C6, item 9: First, we suggest the following addition is made to Page 7, line 16: "…smaller concentrations (Lal, 1991; Stockmann et al., 2014). We assume here that the production of ^{10}Be and the erosion of the bedrock is at an equilibrium:" Second, we also suggest that Equation 1 is updated to:

$$N = \sum_{i=sp,\mu_f,\mu^-} \frac{P_i(\theta)\ \cdot\ e^{-\frac{x}{\Lambda_i}}}{\lambda + \frac{\epsilon\rho}{\Lambda_i}} \left(1 - e^{-t\left(\lambda + \frac{\epsilon\rho}{\Lambda_i}\right)}\right)$$

Third, we also suggest that a revision is made to Page 7, lines 18-23: "where: *P* are the annual production rates of ^{10}Be by spallation, fast muons and stopping muons (sp, μ_f and μ^-) at a surface with slope *Θ*; *x* is the mass sample depth (*ρ·z*); *p* is the density of overburden material; *z* is the depth of the sample; *t* is the age of the bedrock surface (the age when the original surface was generated) λ is the decay constant of ^{10}Be with λ equalling In2/^{10}Be half-life; and Λ are the mean attenuation of cosmic radiations (Lal, 1991). *t* is usually considered infinite. In this paper, we took two samples from some of the sites to test if the data support this assumptions. RFF data is compatible with landscape ages >221 ka. Production rates, decay constants and attenuation lengths were calculated using field data and the CRONUS-Earth online calculator v2.3 Matlab code for the St scheme (Balco, 2008). As *N* can be measured using Accelerator Mass Spectrometry (AMS), Eq. (1) can be solved for ε by simple interpolation of *N*."

10a) Referee #3; C6, item 10: You could also be more explicit that the saprolite erosion rate directly translates into the soil formation rate.

10b) Response to Referee #3; C6, item 10: For the purposes of using cosmogenic radionuclide analysis for deriving soil formation, we agree it does. However, we must (and do) consider that there are other extraneous inputs that may up-build soil profiles, which are not necessarily taken into account in a bedrock weathering rate.

10c) Change in manuscript after Referee #3; C6, item 10: We suggest the following addition is made on Page 3, line 20: "…measured and assumed to equal the rates of soil formation."

11a) Referee #3; C6, item 11: P7, L24: Were the soil pits dug and the samples collected from a vertical profile? Or were they collected from a slope perpendicular profile? Another way to put this is, was depth measured vertically or perpendicular to slope?

11b) Response to Referee #3; C6, item 11: They were vertical. We shall add this detail.

11c) Change in manuscript after Referee #3; C6, item 11: We suggest the following addition is made to Page 7, line 4: "…then proceeded to extract a series of vertical undisturbed core samples…" We also suggest that a similar addition is made to Page 7, line 8: "…a soil pit was manually dug vertically at each of the four sampling locations."

12a) Referee #3; C6, item 12: P8, L27: It may be worth adding a little discussion about the timescales of these measurements. The 10Be measurements represent soil formation rates that have been going on for order of 10ˆ4 years, and the Cs-137 measurements represent erosion rates for the past 75 years.

12b) Response to Referee #3; C6, item 12: We agree.

12c) Change in manuscript after Referee #3; C6, item 12: We suggest the following addition is made to Page 8, line 30: "It should be acknowledged here that the rates of soil formation represent timescales four orders of magnitude greater than those of soil erosion. However, if lifespans are to provide an insight into the sustainability of the soil profiles at RFF, the soil erosion rates must represent those from contemporary arable agriculture."

13a) Referee #3; C7, item 13: P9, L1: I'll admit that I'm not entirely sure why equation 2 is introduced. In this line you say you're going to derive equation 2 from the data, but you don't really ever come back to this equation with the results. I think the equation that shows up in figure 3 could be slightly altered to fit this form. It would be interesting to see something in your discussion that comes back to this equation and the values of W and gamma that you derive, rather than seem to just assign (next note).

13b) Response to Referee #3; C7, item 13: Equation 2 is introduced to test whether the rates of soil formation are sensitive to changes in soil depth, and therefore, whether a constant formation rate should be used in the denominator of Equation 3 (Page 9, line 11) or whether the formation rate should change with decreasing soil depth. It is merely a preliminary test to best formulate Equation 3. To ensure maximum transparency and accessibility, we would argue that combining this into the lifespan equation is not the best course of action.

13c) Change in manuscript after Referee #3; C7, item 13: We argue that no change is necessary.

14a) Referee #3; C7, item 14: P9, L5: How was gamma calculated? Did it come from your data? Please elaborate. And if it came from your results, then please put it there. It is important to make your assumption that soil thickness does not impact soil production rates as sound as possible. And ultimately, you have to have that assumption to use equation 1.

14b) Response to Referee #3; C7, item 14: We cite in the paper that gamma is a parameter that determines the thickness of soil when soil formation falls off by 1/e. Here, *e* is the exponent of the best fit exponential trend line that runs through our soil formation rate data.

14c) Change in manuscript after Referee #3; C7, item 14: We suggest the following addition to Page 9, line 5: "The data for both the production rate (*P*) and the thickness of the soil (*h*) was used to calculate *W* and gamma using least squares regression."

15a) Referee #3; C7, item 15: P10, Figure2: Something seems off between the graph and the data presented in Table 1. The summit of CW has a soil formation rate of 36 mm/ka in Table 1, but this appears to plot as just 30 mm/ka in Figure 2.

15b) Response to Referee #3; C7, item 15: This is something we need to address. We have also noticed the inconsistency between Table 1 and Figure 2, and will make the necessary changes.

15c) Change in manuscript after Referee #3; C7, item 15: We shall prepare a revised figure and ensure that the data match Table 1.

16a) Referee #3; C7-8, item 16: P13, L19: You're correct that the 10Be concentrations you measured would not be impacted by a recent landuse change, but the thickness of the soil could be changed, and this would throw off the production rate at the sample depth. As a simple example, at RFF, suppose that in the last 150 years of agriculture at the RFF site 20 cm of soil had been removed (reasonable for the Cs-137 rate, I think). The proper depth to use for the production rate would be 20 cm more than the current depth because that was the depth to the top of the saprolite for the tens of thousands of years the soil has been developing. That is a really interesting thing to pursue. I suppose there isn't much to go on to support or negate this, but it might be worth a little bit of "error analysis" to pursue this. You could calculate the amount of soil that has been lost at RFF since agriculture started there, and include that as the steady-state soil thickness and recalculate the production rates at the sample depths. The production rates would be lower, and the resulting soil formation rates would be lower too. You could then say something about "if we're wrong about the soil depths today being representative of the long-term soil depth, then the results would change by X percent."

16b) Response to Referee #3; C7-8, item 16: As part of the development of a new model to address the earlier comment on bulk density, we have also re-calculated soil formation rates assuming non-steady soil thicknesses, making use of Cs-137 derived soil erosion rates.

16c) Change in manuscript after Referee #3; C7-8, item 16: We suggest that results from our new analyses are incorporated throughout the paper: in Table, figures, all written analyses, etc.

17a) Referee #3; C8, item 17: P13, L26: do you want to say "soil mantled" or just mantled?

17b) Response to Referee #3; C8, item 17: Yes, soil mantled.

17c) Change in manuscript after Referee #3; C8, item 17: We suggest the following revision is made to Page 13, line 26: "…that of the soil mantled inventory…"

18a) Referee #3; C8, item 18: P13, L32: It would be interesting to see the data you've compiled plotted with precipitation rate. I'm also not sure I understand the discussion in this paragraph. To me, it seems like your median rate matches the median rate for the temperate climate subset. And if 44% of the temperate-based data are from regions with lower mean annual precipitation rates, that sounds like your sites are really close to the median precipitation rate of the data set. So it seems like both your precipitation rate and soil formation rate are close to this subset's median rates too. When you say there is no significant difference between the two data sets, do you mean between your results and the temperate climate subset? If so, then you do you really need to take much time explaining why you think they are different?

18b) Response to Referee #3; C8, item 18: We will add clarity to this section.

18c) Change in manuscript after Referee #3; C8, item 18: We suggest the following addition to Page 13, line 30: "…although there is no statistically significant difference between those data and those we have measured for our UK study sites."

19a) Referee #3; C8, item 19: P14, L5: Similar to the last comment, if the data aren't statistically different, do you need to explain why you think there are differences?

19b) Response to Referee #3; C8, item 19: We argue that it is important to place our UK data into context. With regards to this particular example, whilst no statistical difference was found, lithological variation may still influence soil formation rates. It may be that Type 2 errors are present here.

19c) Change in manuscript after Referee #3; C8, item 19: We argue no changes are necessary.

20a) Referee #3; C8-9, item 20: P14: There does not appear to be any discussion about the results from the samples collected 50 cm below the soil-saprolite interface. These results are interesting and should be discussed. In some cases, they show faster rates than the samples from the top of the saprolite, and in other cases they are slower. In theory, they should show the same rates if soil production has been constant for a long enough time. The fact that they are different indicates that soil production hasn't been constant on the timescales these measurements record. The differences may be explained by something that has happened within the last order of 10ˆ5 years. This is because the muon attenuation lengths are much longer than that for spallation, and muons are produced at much lower rates than by spallation. The result is that muons average over much longer timescales than spallation. Thus, when the rate in the sample 50 sample below the soil saprolite boundary are lower than from the top of the, that may indicate that recently (order 10ˆ5 years) soil production rates increased. And vice-versa if the rate from the lower sample is higher than from the top of the saprolite. You might double-check my logic, but I think that's really cool and warrants a paragraph in this paper!

20b) Response to Referee #3; C8-9, item 20: Yes, that would be a very interesting output from the paired samples. However, our measurements are not precise enough to solve a model with an accelerated or decelerated soil production. Actually, the calculated erosion rates from the paired samples agree within one sigma, meaning that we would not be able to prove soil formation acceleration/deceleration from these data. Also, slight changes of other factors (e.g. the actual position of the surface before farming, density uncertainties, etc.) can also affect these apparent offsets, and we have no data to rule them out.

20c) Change in manuscript after Referee #3; C8, item 20: We argue that no change is necessary.

21a) Referee #3; C9, item 21: P15, Figure 4: I'm a bit confused by "depth" in this figure. Is it depth to the top of the saprolite? Or just depth below the surface? It may be helpful to know how most of the samples in this global compilation were collected. Were most from the soil-saprolite interface? Or a mix of that and below the interface like you've done?

21b) Response to Referee #3; C9, item 21: Invariably, it is sampling depth. Many papers do not specify whether this is a depth to saprolite or to bedrock, so the best practice here is to put 'sampling depth'.

21c) Change in manuscript after Referee #3; C9, item 21: We suggest that the x axis labels are changed on all four panes to: "Sampling depth (cm)". We also suggest a revision in the caption: "…plotted against sampling depth."

22a) Referee #3; C9, item 22: P18: It may be appropriate to include something in your conclusion about how your results compare to the global data set you compiled.

22b) Response to Referee #3; C9, item 22: We agree.

22c) Change in manuscript after Referee #3; C9, item 22: We suggest that the following addition is made to Page 18, line 22: "Soil formation rates were found to fall within the range of those previously published for soils in temperate climates and on sandstone lithologies, but were found to be significantly greater than those measured previously at Bodmin Moor. This is explained by the fact that the parent material at Bodmin Moor is a coarse-grained granite and therefore less susceptible to weathering than the sandstone materials underlying Rufford Forest Farm and Comer Wood."

Arable soil formation and erosion: a hillslope-based cosmogenic-nuclide study in the United Kingdom

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Abstract

Arable soils are critical resources that support multiple ecosystem services. They are frequently threatened, however, by accelerated erosion. Subsequently, policy to ensure their long-term security is an urgent societal priority. Although long-term security relies upon a balance between the rates of soil loss and formation, there have been few investigations of the formation rates of soils supporting arable agriculture. This paper addresses this knowledge gap by presenting the first isotopically-constrained soil formation rates for an arable (Nottinghamshire, UK) and coniferous woodland hillslope (Shropshire, UK). Rates ranged from 0.~~023~~ 026 mm year^{-1} to 0.~~064~~ 096 mm year^{-1} across the two sites. These rates fall within the range of previously published rates for soils in temperate climates and on sandstone lithologies but significantly differed to those measured in the only other UK-based study. We suggest this is due to the parent material at our sites being more susceptible to weathering. Furthermore, soil formation rates were found to be greatest for aeolian-derived sandstone when compared with fluvially-derived lithology raising questions about the extent to which the petrographic composition of the parent material governs rates of soil formation. On the hillslope currently supporting arable agriculture, we utilised cosmogenically-derived rates of soil formation and erosion in a first-order lifespan model and found, in a worst-case scenario, that the backslope A horizon could be eroded in ~~137~~ 138 years with bedrock exposure occurring in ~~209~~ 212 years under the current management regime. These findings represent the first quantitative estimate of cultivated soil lifespans in the UK.

1 Introduction

Soil erosion is a significant threat to society (Pimentel et al., 1995; UNCCD, 2017). Whilst uncultivated 'pristine' soils may develop steady-state thicknesses, where erosion and production are in dynamic equilibrium (Phillips, 2010), human-induced erosion has led to soil thinning across many landscapes (Montgomery, 2007). Soil erosion, left unchecked, can ultimately lead to the removal of the soil cover and the exposure of the underlying parent material (Amundson et al., 2015). The development of soil conservation strategies has long been an active field for research and practice (Panagos et al., 2016; Govers et al., 2017). Given any long-term strategy to preserve soil resources relies upon a balance between the rates of soil loss and soil renewal (Hancock et al., 2015), the measurement of soil formation is a fundamental component in these conservation efforts.

The mechanisms associated with soil formation have been studied for over a century, with a focus on the development of soil horizons and the evolution of soil properties (Dokuchaev, 1879; Jenny, 1941; Bryan and Teakle, 1949; Tugel et al., 2005). Efforts to quantify the rates at which soils form from parent materials have included studying how soil properties change across chronosequences (Turner et al., 2018), developing chemical weathering models (Burke et al., 2007) and, in particular, employing terrestrial cosmogenic radionuclide analysis (Heimsath et al., 1997). In the latter, the concentrations of radioactive isotopes in the bedrock, which are partly dependent upon the rate at which bedrock transforms into soil, are measured and assumed to equal the rates of soil formation.

Despite the recent advancements in cosmogenic radionuclide analysis, their application in soil science has, arguably, not been fully realized. Moreover, there are three research challenges that may explain this. First, there is a dearth of soil formation rate data. Whilst there have been many attempts at calculating a global average soil formation rate from collating multiple inventories (Alexander, 1988; Montgomery, 2007; Stockmann et al., 2014; Minasny et al., 2015), these datasets often omit more than 100 countries, particularly in Africa and Europe, presenting a clear rationale for more studies to take place in these areas of the world. Second, over 80% of the soil formation rate inventory, comprising data from Montgomery (2007), Portenga and Bierman (2011) and Stockmann et al. (2014), is attributed to samples taken from outcrops and stream sediments procured from drainage basins. Moreover, only 252 ^{10}Be-derived rates from this inventory of 1850 stem from samples extracted from underneath the soil mantle. In addition, the majority of these stem from mountain regions and deserts (Heimsath et al., 1997; Wilkinson et al., 2005; Zhao et al., 2018; Struck et al., 2018). This is partly because the observation and estimation of bedrock weathering rates is most commonly carried out by the geomorphological community, principally to identify the mechanisms behind long-term landscape evolution (Heimsath, 2006; Heimsath and Burke, 2013; Ackerer et al., 2016; Zhao et al., 2018). As a result, there has been no investment in deriving rates of soil formation for soils that support arable agriculture (Heimsath, 2014), despite these soils being identified as a societal priority (FAO, 2015). Such soils are critical to the delivery of multiple ecosystem services and, for many countries, are one of the most critical resources in ensuring the health of society and sustained economic growth. They are also often intensely managed and thus the loci for accelerated erosion (Quinton et al., 2010; Borrelli et al., 2017). However, in the absence of soil formation rate data, the magnitude of the threat erosion places on the sustainability of soils and arable production is unknown, amounting to a critical knowledge gap. Third, although the distributions of inventoried soil erosion and formation rates are often presented together to demonstrate the severity of soil erosion (Montgomery, 2007; Minasny et al., 2015), the spread of globally-compiled data is such that it cannot offer a useful forecast of the sustainability of soil at a site scale. Both distributions are platykurtic and there is substantial overlap in these rates: 0—28.8 mm $year^{-1}$ for soil formation (Minasny et al., 2015) and 0—52.9 mm $year^{-1}$ for soil erosion (Montgomery, 2007). For a greater understanding into the sustainability of soil resources at the local scale, we argue that soil scientists should undertake empirical measurements of both soil formation and erosion in parallel.

In this UK-based study, we present ^{10}Be-derived soil formation rates for two catena sequences in an arable and coniferous woodland setting. The former are the first of their kind globally and the latter are the first of their kind in Europe. We place our results in the context of the rates previously derived in similar climatic and petrographic settings around the world. Finally, using previously measured soil erosion rates at the arable site, we calculate first-order soil productive lifespans to infer the long-term sustainability of the soil resource.

2.0 Materials and Methods

2.1 Site Description

This study measures soil formation down two catena sequences (Figure 1). The first is an arable hillslope at Rufford Forest Farm (RFF), east of Mansfield in Nottinghamshire, UK (53°7’13.43” N, 1°4’39.61” W). The second is a woodland hillslope at Comer Wood (CW), north of Quatford in Shropshire, UK (52°30’30.43” N, 2°22’45.68” W). RFF was selected as it is the site of previous tillage and water-based erosion studies (Quine and Walling, 1991; Walling and Quine, 1991; Govers et al., 1996). Electing CW as a sister site is justified based on its similarities in parent geology, macroclimate and soil physical properties with RFF as detailed below. A Trimble S6 Total Station was used to measure the relative elevation and slope of the catenas at both sites (Figure 1b).

A reconnaissance study of the parent materials and their feasibility for cosmogenic radionuclide analysis was undertaken in spring 2017. Both sites are underlain by Triassic sandstone. In RFF, the Sherwood sandstone (Chester formation; Olenekian, 247—251 Ma) is described as pinkish to red, medium to coarse grained, pebbly, cross-bedded, and friable. In CW, the New Red sandstone (Bridgnorth formation; Cisuralian, 273—299 Ma) is described as brick-red, ~~soft to~~ medium grained, cross-bedded and aeolian based. Both RFF and CW are south-facing slopes, and sit in a temperate oceanic climate (Cfb), between 96—99 m a.s.l. and 50—71 m a.s.l., respectively. The mean annual precipitation and temperature is 709 mm and 9.8°C at RFF and 668 mm and 9.9°C at CW, respectively (Met Office, 2018).

Both sites are positioned beyond the areal limits of the Late Devensian ice sheet, but studies conducted on similar formations of Triassic Sherwood Sandstone nearby suggest that the weathering of the parent material was partly induced by freeze-thaw processes associated with periglacial active layer development possibly during this period (Tye et al., 2012). Although proglacial glaciogenic deposits have been found in the vicinity of CW, the prevalence of similar deposits on the study hillslope has not been studied. However, unpublished work conducted by the authors suggests that the upper (3—5 m) of the lithosphere at both sites was subject to high-magnitude sediment transport at least 200,000 BP or before, potentially during the Anglian glaciation (~450,000 BP). The complex land-use and vegetation change in the Sherwood Sandstone outcrop, within which RFF is based, has been extensively studied and mapped by Tye et al. (2013). Following the onset of the Holocene, the area has been dominated by a complex sequence of land-use change including broadleaf woodland (6000—2000 BC), heathland (43—409 AD) and landscaped heathland for hunting (1600 AD). From at least 1855 AD, RFF has been under an arable regime and in the last twelve years, the dominant crops have been Winter Wheat and Rye. CW is understood to have been an open field until 1903—1926 and then heathland until 1954. Between 1954 and the present day, however, the site has been continuously occupied by coniferous forest (Evans, 2018).

~~The soils at RFF are classified as Arenosols (FAO WRB) with weak horizonisation. An Ap loamy-sand horizon (82% sand, 16% silt, 2% clay) thickens from 30 to 75 cm and increases in LOI content from 3.65 to 3.91% from summit to toeslope, respectively. This Ap horizon is underlain by a 5 cm fluvial pebble-bed, typical of the Bunter pebble-beds found in the vicinity (Ambrose et al., 2014). An undifferentiated, weakly-consolidated subsoil steadily grades into saprolitic, moderately-consolidated sandstone. The soils at CW are classified as Cambisols (FAO WRB). Similar to RFF, there is little evidence for horizonisation down the profile at CW. A thin (<5 cm) LFH layer overlays an undifferentiated, weakly-consolidated, sandy subsoil (94% sand, 5% silt, 1% clay) and grades into moderately-consolidated saprolitic sandstone.~~

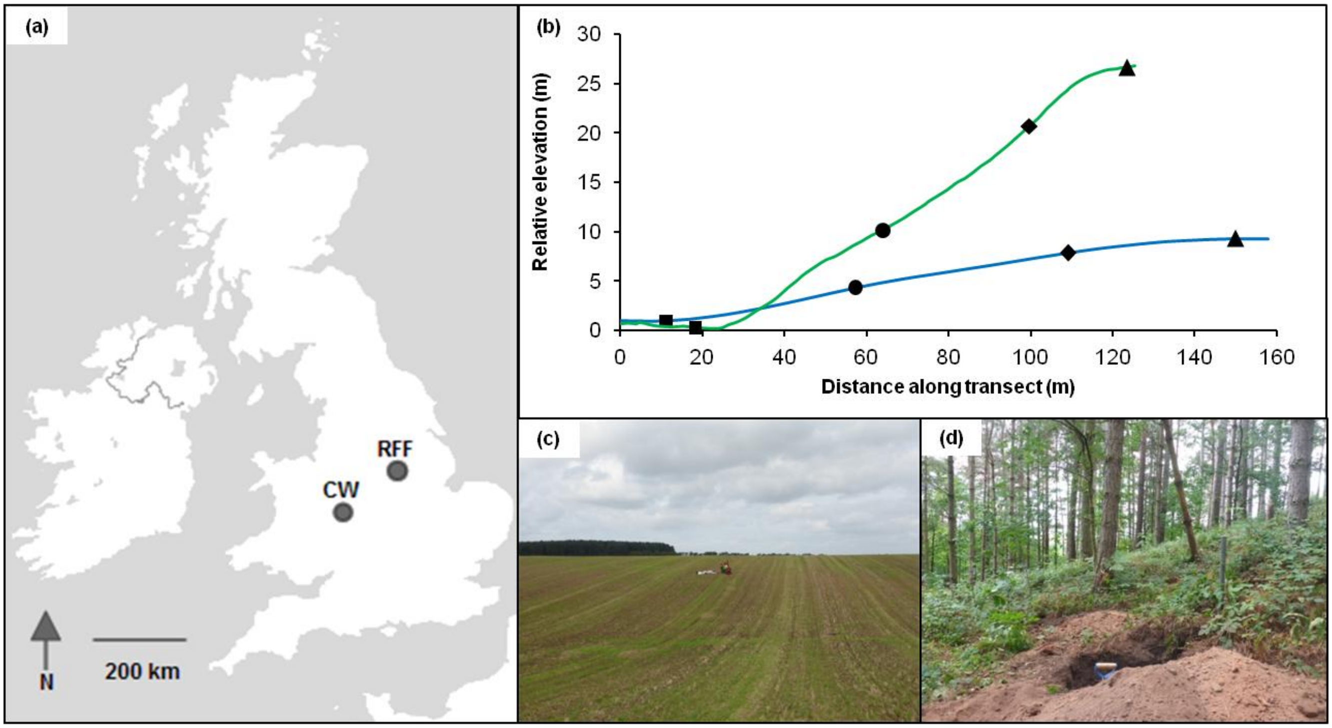


Figure 1: Locations of the study sites in this paper (a) with elevation profiles (b) for both Comer Woodland (CW; green) and Rufford Forest Farm (RFF; blue). The position of summit (triangles), shoulder (diamonds), backslope (circles) and toeslope (squares) sampling positions are indicated on each profile. Photographs of RFF (c) and CW (d) were taken by the author at the time of sampling.

2.2 Saprolite Extraction ~~and Processing~~and Soil Sampling

Four positions (summit, shoulder, backslope and toeslope) along a catena transect were selected for depth to bedrock surveys and saprolite extraction. First, a dynamic cone penetrometer was used to estimate the depth of the soil-saprolite interface. At RFF, a percussion drilling rig then proceeded to extract a series of vertical undisturbed core samples of the soil and saprolite. Cores were later halved lengthways, and by observing the changes in the consolidation and physical integrity of the extracted material (i.e. whether it remained intact when removed from the core), together with the penetration resistance data acquired in the field, the soil-saprolite interface was demarcated.~~were later halved lengthways and, using both the penetrometer data and observations on the competency of the extracted material, the soil-saprolite interface was demarcated.~~ Two samples of saprolite (5 cm thickness) were then subsampled for cosmogenic radionuclide analysis; one at this interface and one from 50 cm below. At CW, following the use of the dynamic cone penetrometer to locate suitable sites, a soil pit was manually dug vertically at each of the four sampling locations. Observing the changes in the consolidation and physical integrity of the material down the profile wall, together with the penetration resistance data, the soil-saprolite interface was ascertained.~~The data derived from the penetrometer and observations of differentiating competency down the profile wall were used to ascertain the position of the soil-saprolite interface.~~ A sample of saprolite (5 cm thickness) was then extracted from this interface for cosmogenic isotope analysis.

The bombardment of quartz minerals in the uppermost metres of bedrock with cosmic rays leads to the production of ^{10}Be. Assuming the intensity of these cosmic rays and the in situ weathering of bedrock (ε) is constant, the concentration of ^{10}Be (N) in a sample of bedrock, Eq. (1), is dependent upon the balance of two factors: the time that the bedrock has been exposed to cosmic rays with longer durations leading to greater concentrations and the weathering of this bedrock into mobile regolith (soil) with greater rates of bedrock weathering leading to smaller concentrations (Lal, 1991; Stockmann et al., 2014). We assume here that the production of ^{10}Be and the erosion of the bedrock is at an equilibrium:~~:~~

$$N = \sum_{i=sp,\mu_f,\mu^-} \frac{P_i(\theta)\ \cdot\ e^{-\frac{x}{\Lambda_i}}}{\lambda + \frac{\epsilon\rho}{\Lambda_i}} \left(1 - e^{-t\left(\lambda + \frac{\epsilon\rho}{\Lambda_i}\right)}\right)$$

$$\cancel{N = \sum_{i=sp,\mu_f,\mu^-} \frac{P_i(\theta)\cdot e^{-z\rho/\Lambda_i}}{\lambda + \epsilon\rho/\Lambda_i}} \qquad (1)$$

where: P are the annual production rates of ^{10}Be by spallation, fast muons and stopping muons (sp, μf and μ-) at a surface with slope Θ; x is the mass sample depth (ρ·z); p is the density of overburden material; z is the depth of the sample; t is the age of the bedrock surface (the age when the original surface was generated) λ is the decay constant of ^{10}Be with λ equalling

In2/^{10}Be half-life; and Λ are the mean attenuation of cosmic radiations (Lal, 1991). t is usually considered infinite. At RFF paper, we took two samples from the same depth profile at each catena position to test if the data support these assumptions. RFF data is compatible with landscape ages >200 ka. Production rates, decay constants and attenuation lengths were calculated using field data and the CRONUS-Earth online calculator v2.3 Matlab code for the St scheme (Balco, 2008). As N can be measured using Accelerator Mass Spectrometry (AMS), Eq. (1) can be solved for ε by simple interpolation of N.~~where: P are the annual production rates of ^{10}Be by spallation, fast muons and stopping muons (sp, μf and μ-) at a surface with slope Θ; z is the sample depth; ρ is the mean density of parent material; λ is the decay constant of ^{10}Be with λ equalling In2/^{10}Be half-life; and Λ are the mean attenuation of cosmic radiations (Lal, 1991). Production rates, decay constants and attenuation lengths were calculated using field data and the CRONUS-Earth online calculator v2.3 Matlab code for the St scheme (Balco, 2008). As N can be measured using Accelerator Mass Spectrometry (AMS), Eq. (1) can be solved for ε by simple interpolation of N.~~

A total of twelve samples of saprolite (eight from RFF and four from CW) were prepared for AMS at the Cosmogenic Isotope Analysis Facility, East Kilbride, Scotland. This comprised of mineral separation, quartz cleaning and procedures leading to the preparation of BeO sample cathodes (Kohl and Nishiizumi, 1992; Fifield, 1999; Corbett et al., 2016). The AMS measurements were carried out at the SUERC AMS laboratory (Xu et al., 2010). ^{10}Be concentrations are based on 2.79 x10^{-11} ^{10}Be/^{9}Be ratio for the NIST Standard Reference Material 4325. The processed blank ratio ranged between 6 and 13% of the sample ^{10}Be/^{9}Be ratios. The uncertainty of this correction is included in the stated standard uncertainties. Concentrations of ^{10}Be were subsequently determined, following Balco (2006) (see Supplementary Table 1).

Previous work (e.g. Heimsath, 1997) has assumed that the bulk density of the soil above the bedrock surface is either equal to that of the bedrock, or constant with depth. For this paper, we developed a model called 'coSOILcal' to calculate soil formation rates using empirically measured bulk density data from each catena position at both RFF and CW. The local annual production rate of ^{10}Be at each study site must also account for any obstructions that reduce the cosmic ray flux to the parent material (Phillips et al., 2016). For an obstruction to cause this reduction, it is required to be several metres thick which equates, in practice, to topographic features at the scale of tens of meters or greater. The shielding factor, therefore, is a ratio of the ^{10}Be production rate at the obstructed site to that at an identical site but with a flat surface and a clear horizon (Balco, 2008). To calculate both shielding factors and subsequently normalize local ^{10}Be production rates, site elevation, latitude and longitude were inputted into the CRONUS-Earth Matlab code v2.3 using Lal/Stone (St) scaling (Balco, 2008).

Soil samples were sub-sampled every 5 cm from each core at RFF and on each profile wall at CW. All samples were then oven dried overnight (105°C for 12 hours), grounded with a pestle and mortar, and sieved to discard the >2 mm fraction before being subject to particle size analysis and loss on ignition (LOI). Particle size analysis was conducted using a

Beckman Coulter Laser Diffraction Particle Sizing Analyser LS 13 320 (pump speed: 70 %; sonication: 10 seconds; run-length: 30 seconds). For LOI, 5 g of each sample was placed in a Carbolite furnace CWF 1300 (550°C for 12 hours).

The soils at RFF are classified as Arenosols (IUSS Working Group WRB, 2015) with weak horizonisation. An Ap loamy-sand horizon (82% sand, 16% silt, 2% clay) thickens from 30 to 75 cm and increases in LOI content from 3.65 to 3.91% from summit to toeslope, respectively. Despite being subject to arable practices for over 150 years, the presence of a 30 cm Ap horizon may be explained in part by the incorporation of mineral matter with the remaining organic material after harvest, although further isotopic work is required to verify this for RFF. This Ap horizon is underlain by a 5 cm fluvial pebble-bed, typical of the Bunter pebble-beds found in the vicinity (Ambrose et al., 2014). An undifferentiated, weakly-consolidated subsoil steadily grades into saprolitic, moderately-consolidated sandstone. The soils at CW are classified as Arenosols (IUSS Working Group WRB, 2015). Similar to RFF, there is little evidence for horizonisation down the profile at CW. A thin (<5 cm) litter-fermentation-humus layer overlays an undifferentiated, weakly-consolidated, sandy subsoil (94% sand, 5% silt, 1% clay) and grades into moderately-consolidated saprolitic sandstone. The sandy composition of these soils suggests that proglacial outwash deposits have not contributed to the soils of the study sites and that, instead, the soils are largely residual.

2.3 Lifespan analysis at Rufford Forest Farm

To provide an insight into the sustainability of the soil profiles at RFF under arable agriculture, in terms of the balance of erosion and formation, a first-order lifespan model was employed. Calculating the sustainability of a net-eroding soil in first-order terms has been attempted in the past (Elwell and Stocking, 1984; Sparovek and Schnug, 2001; Montgomery, 2007; Medeiros et al. 2016). Early models (Stocking and Pain, 1983), however, did not account for mass inputs into the soil system, such as that derived from bedrock weathering. In this study, this omission was addressed by using soil formation rates empirically measured at RFF. Furthermore, in previous models, the solum thickness used to calculate the soil lifespan is not universally consistent. Some authors constrain the lifespan by the minimum depth required for primary production (Stocking and Pain, 1983; Elwell and Stocking, 1984). Notwithstanding the fact that this soil threshold depth will, in part, be crop-dependent, soils that fall below this threshold may still be able to fulfil some of the ecosystem services, such as the sequestration of carbon. To address this here, two lifespan (L) scenarios were calculated, both of which are based on the continuation of contemporary arable agriculture. The first referred to the expected lifespan of the current A horizon (D = 30 cm across the catena). At the toeslope, an additional lifespan was calculated to account for the greater depth (75 cm) of the A horizon. Here, we did not account for any transformation of subsoil into topsoil, which could occur if erosion rates are sufficiently low, nor did we account for any allochthonous inputs to the profile such as aeolian additions and organic amendments. The second estimated the time until the underlying parent material is exposed. Here, the observed depth to ~~bedrock~~ the soil-saprolite interface at each catena position was employed.

Both lifespan scenarios were calculated for summit, shoulder, backslope and toeslope catena positions. Three different erosion rates (E) were applied. First, a mean annual erosion rate of 1.19 mm $year^{-1}$ was used based on ^{137}Cs-based data (n = 103) measured by Quine and Walling (1991) at RFF. This mean value represents all erosion processes, including water-based and tillage-based erosion. Two additional lifespans were calculated using rates from the 5th and 95th percentiles of this dataset (0.19 mm $year^{-1}$ and 2.2 mm $year^{-1}$, respectively). It should be acknowledged here that the rates of soil formation represent timescales four orders of magnitude greater than those of soil erosion. However, if lifespans are to provide an insight into the sustainability of the soil profiles at RFF, the soil erosion rates must represent those from contemporary arable agriculture.

The soil formation rates, as empirically measured in this paper, were then plotted to derive the soil production function *P*; Eq. (2):

$$P = W\, e^{\left(\frac{-h}{\gamma}\right)} \tag{2}$$

where W is the production rate at zero soil thickness (h) and γ is a parameter that determines the thickness of soil when soil formation falls off by 1/e. The data for both the production rate (*P*) and the thickness of the soil (*h*) was used to calculate *W* and gamma using least squares regression. In this study, γ was calculated as being 2.~~25~~ 26 m, which is substantially greater than that previously reported (e.g. Heimsath, 1997). It was therefore concluded that soil formation rates at RFF are relatively insensitive to changes in soil thickness. As a result, constant soil formation rates (F) for each catena position, together with two additional rates representing upper and lower standard deviations, were used to calculate soil lifespans. Furthermore, the expected increase in soil formation rates as a result of soil thinning were captured within these upper and lower uncertainties. Soil lifespans were thus calculated using Eq. (3):

$$L = \frac{D}{E - F} \tag{3}$$

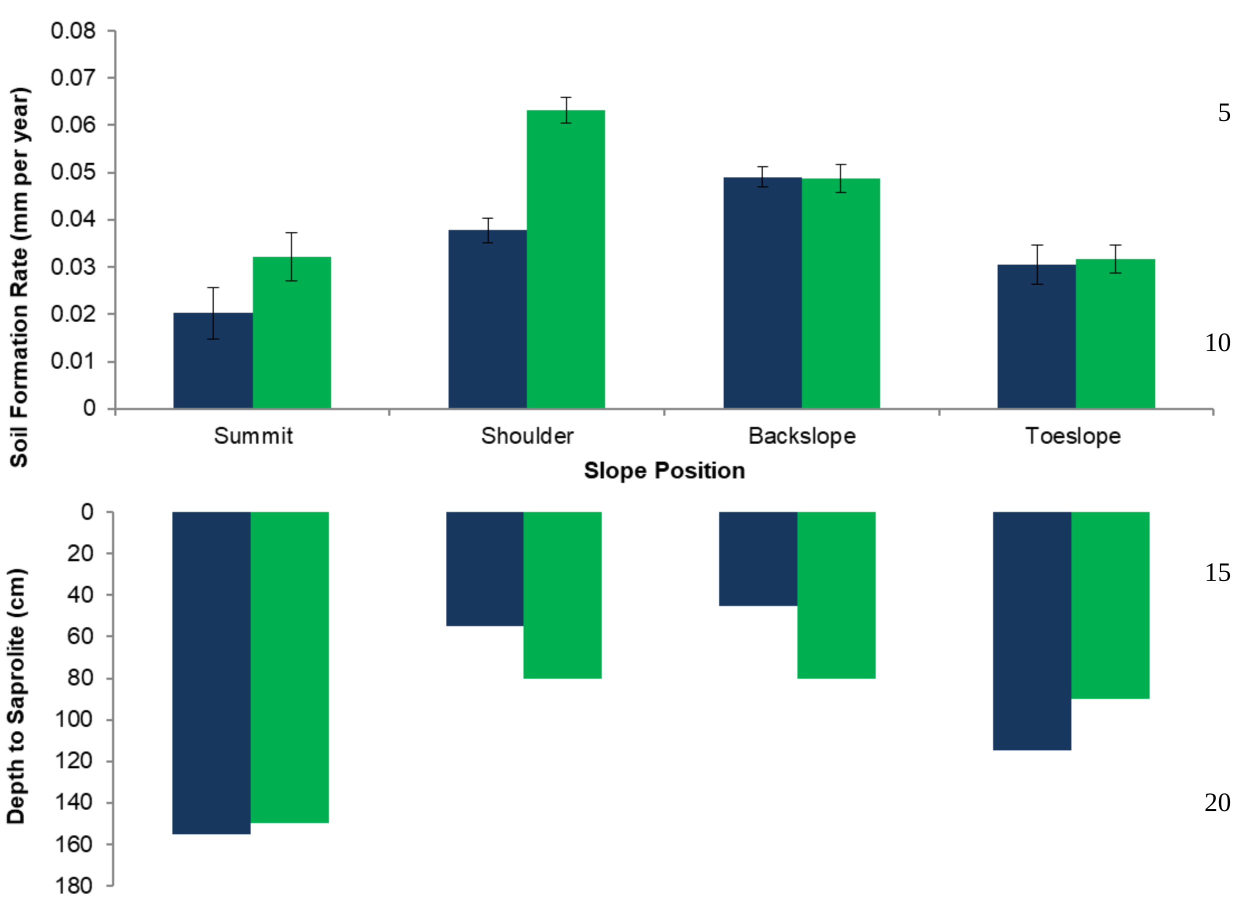
where D is depth in mm, E is gross annual soil erosion rate in mm year^{-1} and F is gross annual soil formation rate in mm year^{-1}.

3.0 Results and Discussion

3.1 Soil Formation Rates

Soil formation rates calculated from measured ^{10}Be concentrations at RFF range from 0.~~023~~ 026 ~~± 0.002~~ mm year^{-1} to 0.~~051~~ 084 ~~± 0.002~~ mm year^{-1}, with the mean soil formation rate being 0.~~037~~ 048 ± 0.~~003~~ 008 mm year^{-1} (Table 1). At CW, soil formation rates range from 0.~~034~~ 053 ~~± 0.001~~ mm year^{-1} to 0.~~064~~ 096 ~~± 0.004~~ mm year^{-1}, with the mean soil formation rate being 0.~~046~~ 070 ± 0.~~007~~ 010 mm year^{-1}, which is 0.~~009~~ 022 mm year^{-1} greater than that at RFF. These rates indicate declining soil formation rates with increasing soil thickness (Fig. 2—3). In accordance with geomorphological theory (Conacher and Dalrymple, 1977; King et al., 1983; Pennock, 2003; Schaetzl, 2013), soils are thinner on the slope convexities and the steepest gradients where surface erosion is considered most prevalent. In contrast, soil thicknesses are greater at the summit where surface erosion has been less extensive and the toeslope zone where sediment is deposited. In RFF, the fastest soil formation rates were found on the backslope where soils are thinnest.~~formation rates are 0.018 mm year^{-1} faster for shoulder and backslope positions where soils are thinner.~~ These results are consistent with many theorized mechanisms that demonstrate how parent material overlain by shallower soils is more affected by diurnal thermal stresses, contact with water and physical disturbance which can together proliferate physical and chemical weathering processes and thus the conversion of saprolite into soil. Conversely, it was found the slowest formation rates were associated with the deepest soils at the summit ~~that formation rates are slower at summit and toeslope positions~~ where the increasing thickness of the soil mantle buffers the parent material from any subaerial factors that may otherwise proliferate weathering (Carson and Kirby, 1972; Cox et al., 1980; Dietrich et al., 1995; Minasny and McBratney, 1999; Wilkinson and Humphreys, 2005). At CW, the difference in soil thickness between eroding and non-eroding zones is less pronounced. On the shoulder and backslope positions, where soils are thinnest, the soil formation rates were 0.03 mm year^{-1} faster than summit and toeslope positions. ~~but similarly soil formation rates are faster by 0.017 mm year^{-1} where soils are thinnest.~~

[Table 1]



~~**Figure 2: Soil formation rates and the depths to saprolite for the four sampling positions along the catena transects at Rufford Forest Farm (blue) and Comer Woodland (green).**~~

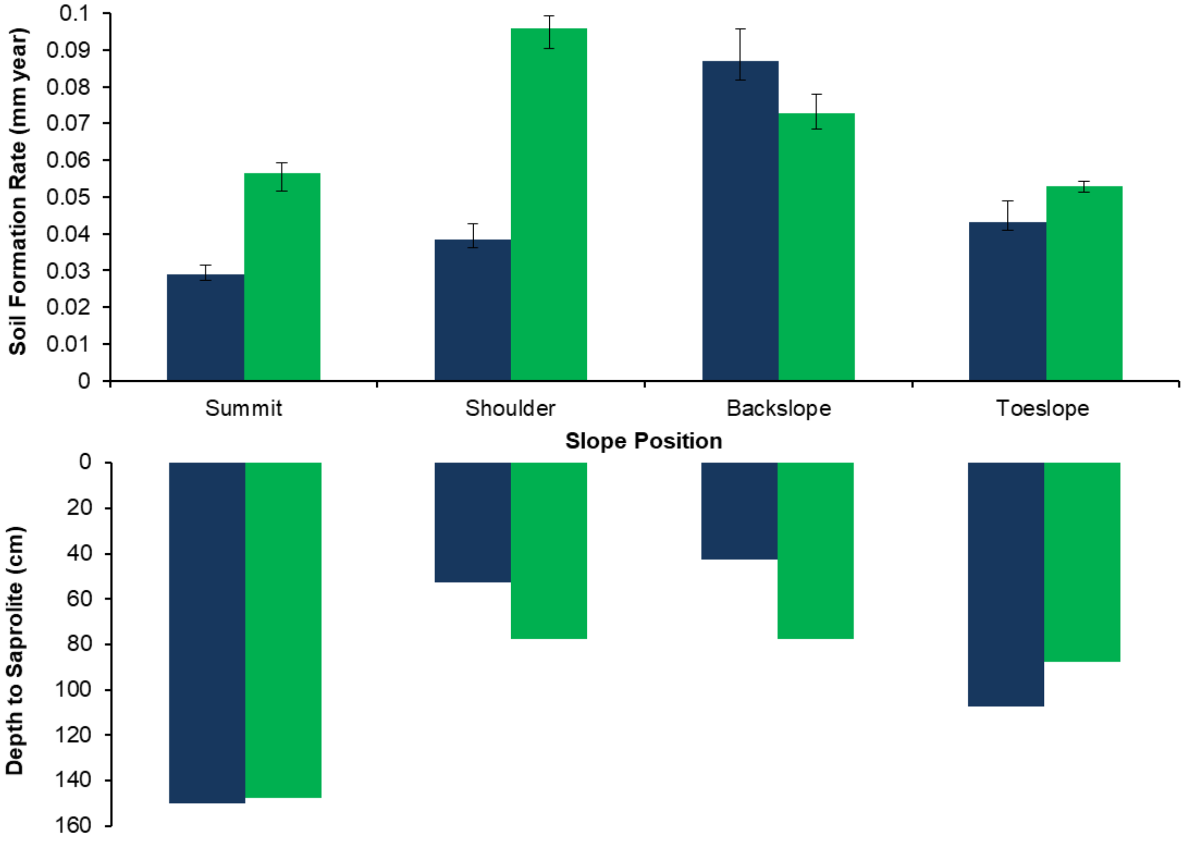
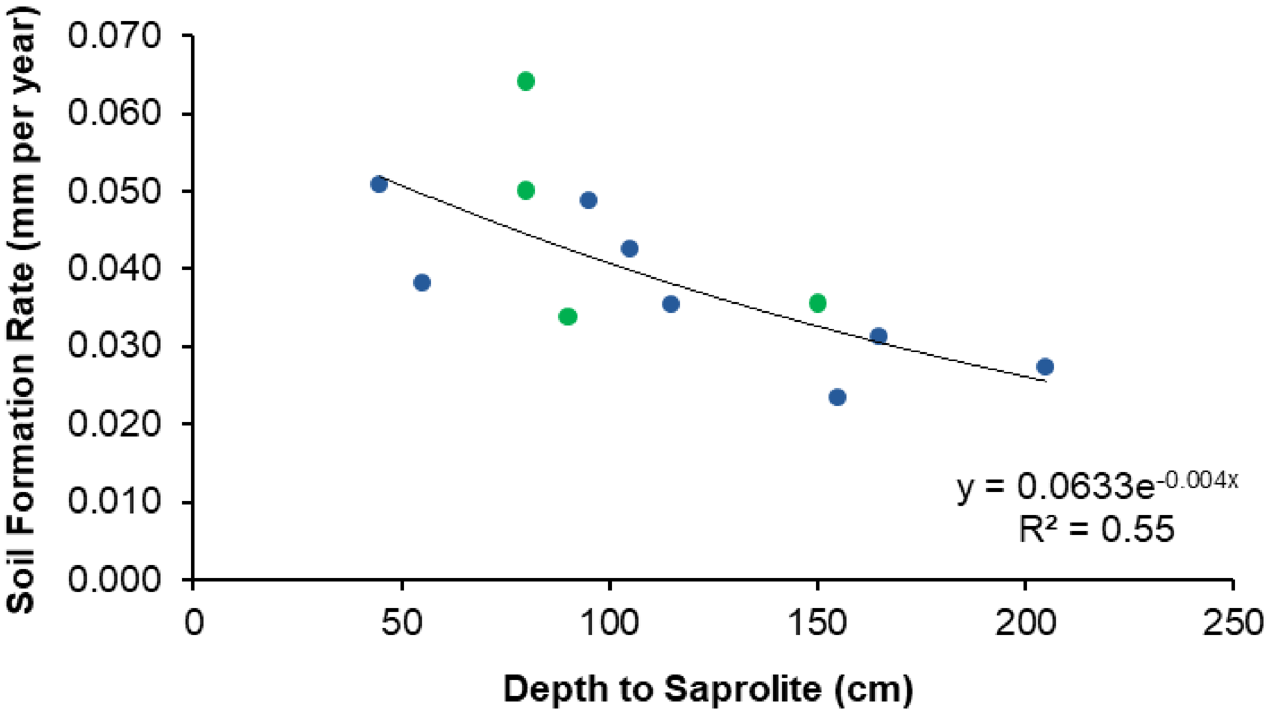


Figure 2: Soil formation rates and the depths to saprolite for the four sampling positions along the catena transects at Rufford Forest Farm (blue; n = 4) and Comer Woodland (green; n = 4). The error bars represent one sigma uncertainties. At RFF, two ^{10}Be concentrations down the same depth profile have been used in the coSOILcal model to derive a 'best fit' soil formation rate. Depth here refers to that for the midpoint (between the top and bottom) of the sample.



~~Figure 3: Soil formation rates against the depths to saprolite for Rufford Forest Farm (blue) and Comer Woodland (green).~~

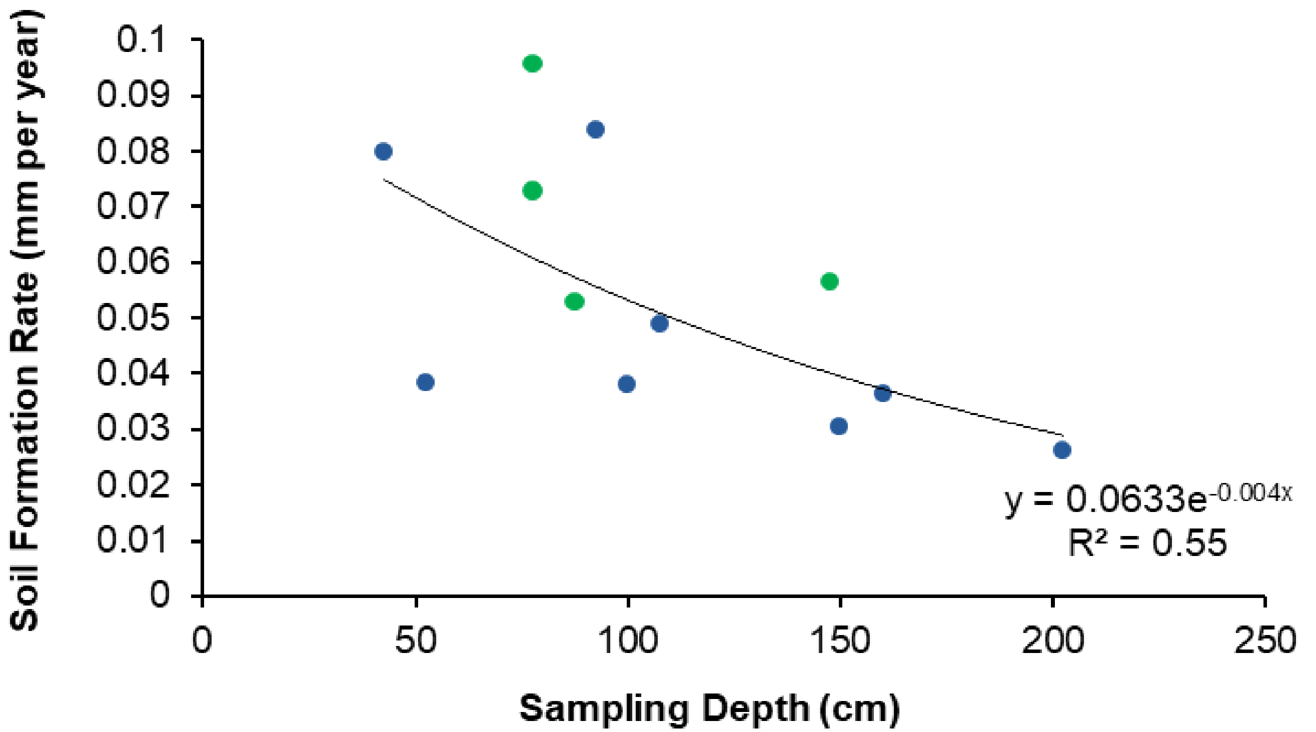


Figure 3: Soil formation rates against sampling depth for Rufford Forest Farm (blue; n = 8) and Comer Woodland (green; n = 4). Depth here refers to that for the midpoint (between the top and bottom) of the sample.

Comparing data between RFF and CW demonstrates that there are other factors besides soil thickness that govern soil formation rates. For example, at the shoulder the soil thickness at CW is greater by 25 cm than that at RFF which would suggest slower formation rates. Instead soil formation rates are faster by 0.~~025~~ 038 mm year^{-1} at CW. One possible explanation is the petrographic composition of the parent material and the susceptibility of that parent material to weathering. Whilst both RFF and CW are underlain by sandstone, the bedrock at RFF is fluvially-derived whereas that at CW is aeolian-derived. Petrological studies on fluvially-derived sandstone report a greater concentration of cementing clays in the matrix material which ultimately reduces the porosity and decreases its susceptibility to particle detachment, leading to slower soil formation rates (Wakatsuki et al., 2005; Mareschal et al., 2015).

In studies where cosmogenic methodologies have not been applied, it has been found that land use regime can promote or retard rates of bedrock weathering. Humphreys (1994) found that root channels and mesofaunal pedotubles in both the topsoil and subsoil can enhance the surface to bedrock hydrological connectivity. Similarly, Dong et al. (2018) demonstrated how an interconnected network of ecohydrologic interactions controls the supply and transport of acid to the bedrock. When a greater proportion of root mass was distributed in the uppermost horizons of the soil profile, CO_2 was predominantly emitted as gas whereas when roots were distributed in the subsoil, more CO_2 moved downwards to increase acid production and enhance chemical weathering. Other work has sought to identify the mechanisms that affect the thermal regime of soil profiles and the consequential impacts on the weathering susceptibility of the parent material (Ahnert, 1967; Minasny and McBratney, 1999). At CW, the roots are deeper than those found observed at RFF and this is likely to proliferate weathering processes. However, given the fact that the ^{10}Be derived soil formation rates are millennial scale averages, it is unlikely that relatively recent (decadal-centennial) variances in the site's land use regime would be captured in the isotopic data (Darvill et al., 2013).

3.2 Derived soil formation rates in reference to the global inventory

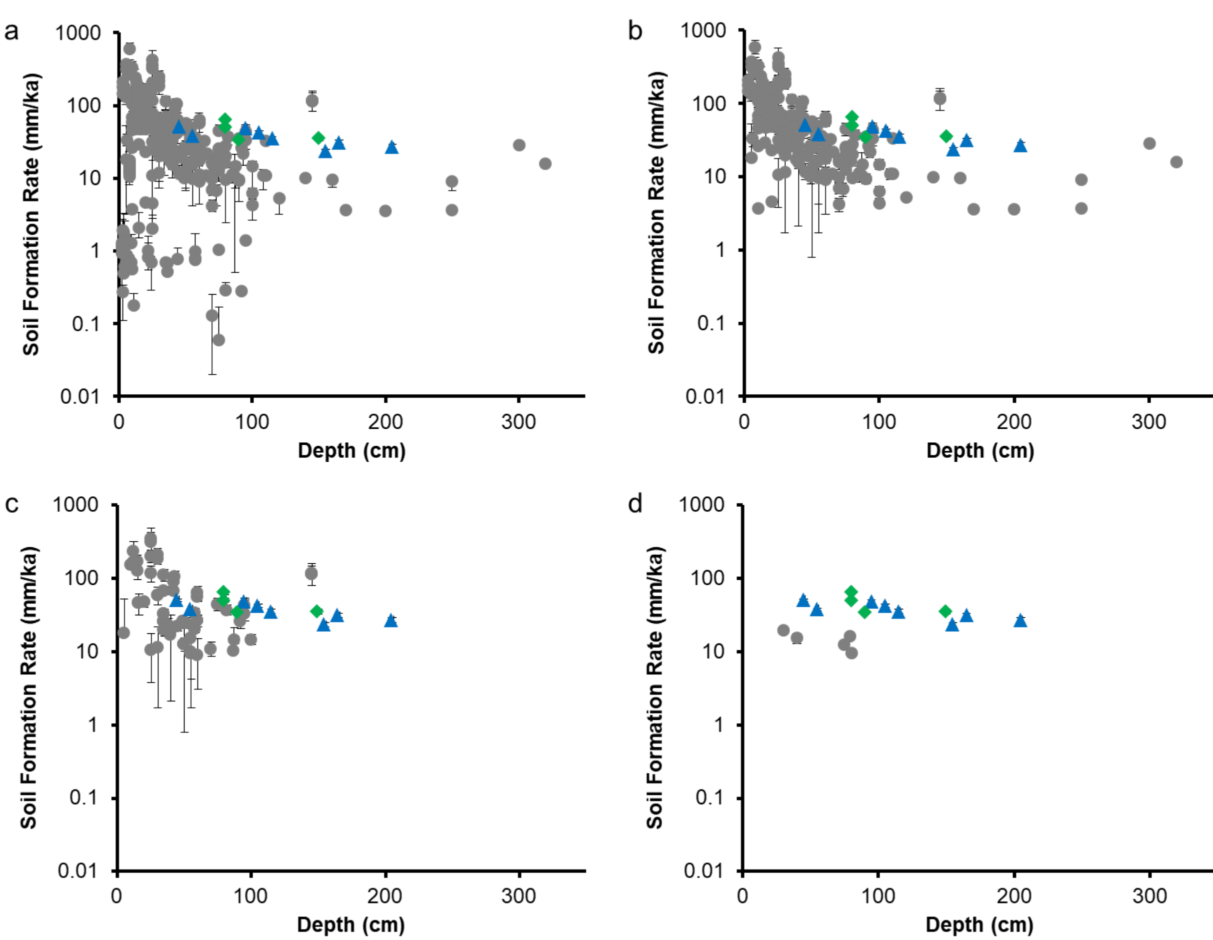
Figure 4 compares soil formation rates for the study sites to an inventory of soil formation rates extracted from the published literature (n = 252; Fig. 4a; Supplementary Table 2). The median soil formation rate in this study (0.~~037~~ 051 mm year^{-1}) is

0.~~011~~ 028 mm year^{-1} faster than that of the mantled inventory ~~but there is no~~, a statistically significant difference ~~between the two datasets~~ (U test; P ~~<~~ < 0.05). ~~-~~However, this global inventory comprises studies conducted on a range of geologies and climates, which are both influences on bedrock weathering rates.

Isolating the data from temperate climates (n = 187; Fig. 4b) presents a median soil formation rate of 0.035 mm year^{-1}, which is 0.~~002~~ 016 mm year^{-1} slower than that measured for RFF and CW, although there is no statistically significant difference between ~~the two datasets~~those data and those we have measured at the UK study sites presented in this paper (U test; P ~~<~~ > 0.05). It is likely that the inventory's median soil formation rate for temperate climates is slower as 44% of the temperate-based data has been collected from regions that have lower mean annual precipitation than RFF and CW which can lead to less weathering activity at the parent material (Heimsath et al., 2001; Heimsath et al., 2005; Dixon et al., 2009; Heimsath et al., 2012).

Isolating the sandstone-derived data from the inventory (n = ~~64~~57; Fig. 4c) presents a median soil formation rate of 0.~~034~~ 045 mm year^{-1} which is 0.~~003~~ 006 mm year^{-1} slower than that measured for RFF and CW, although there is no statistically significant difference (U test; P ~~<~~ > 0.05). Although the sandstone-derived data were derived from the global soil-mantled database, all data stem from sites in temperate climates which reduces the influence that climate may have otherwise had in this analysis on lithology. We suggest that faster formation rates at RFF and CW may be explained by the fact that the specific varieties of sandstone at these study sites are generally more susceptible to weathering than those within the sandstone-based inventory, of which the dominant form is the greywacke, characterised by a hard, fine-grained argillaceous matrix, with greater resistance to weathering (Cummins et al., 1962). Although there has been substantial work on the susceptibilities of major geological rock types to weathering (Stockmann et al., 2014; Wilson et al., 2017), we do not know of any study which seeks to identify whether the susceptibility of specific varieties of sandstone have an influence on soil formation rates.

The only other study to measure soil formation rates in the UK is that of Riggins et al. (2011) where rates were derived for Bodmin Moor, Cornwall (n = 5; Fig. 4d). In that study, the median soil formation rate was 0.015 mm year^{-1}, which is 0.~~022~~ 036 mm year^{-1} slower than that for RFF and CW and statistically significant (U test; P ~~>~~ < 0.05), despite the fact that Bodmin Moor receives about 300 mm more precipitation per year than the sites in this study which should increase soil formation rates (Riggins et al., 2011). This is explained by the parent material at Bodmin Moor (coarse-grained granite) being generally less prone to weathering than the varieties of sandstone evident at RFF and CW (Portenga and Bierman, 2011).


a
b
c
d
Soil Formation Rate (mm/ka)
Depth (cm)
1000
100
10
1
0.1
0.01
0
100
200
300

~~Figure 4: Soil formation rates from a globally compiled inventory (grey circles) and from this study at Rufford Forest Farm (blue triangles) and Comer Woodland (green diamonds) plotted against soil depth. Rates in grey are from (a) the total mantled inventory (n = 252); (b) studies from temperate climates (n = 187); (c) studies on sandstone geology (n = 64) and (d) the UK, exclusively from Riggins et al. (2011) (n = 5). Error bars indicate the standard error.~~

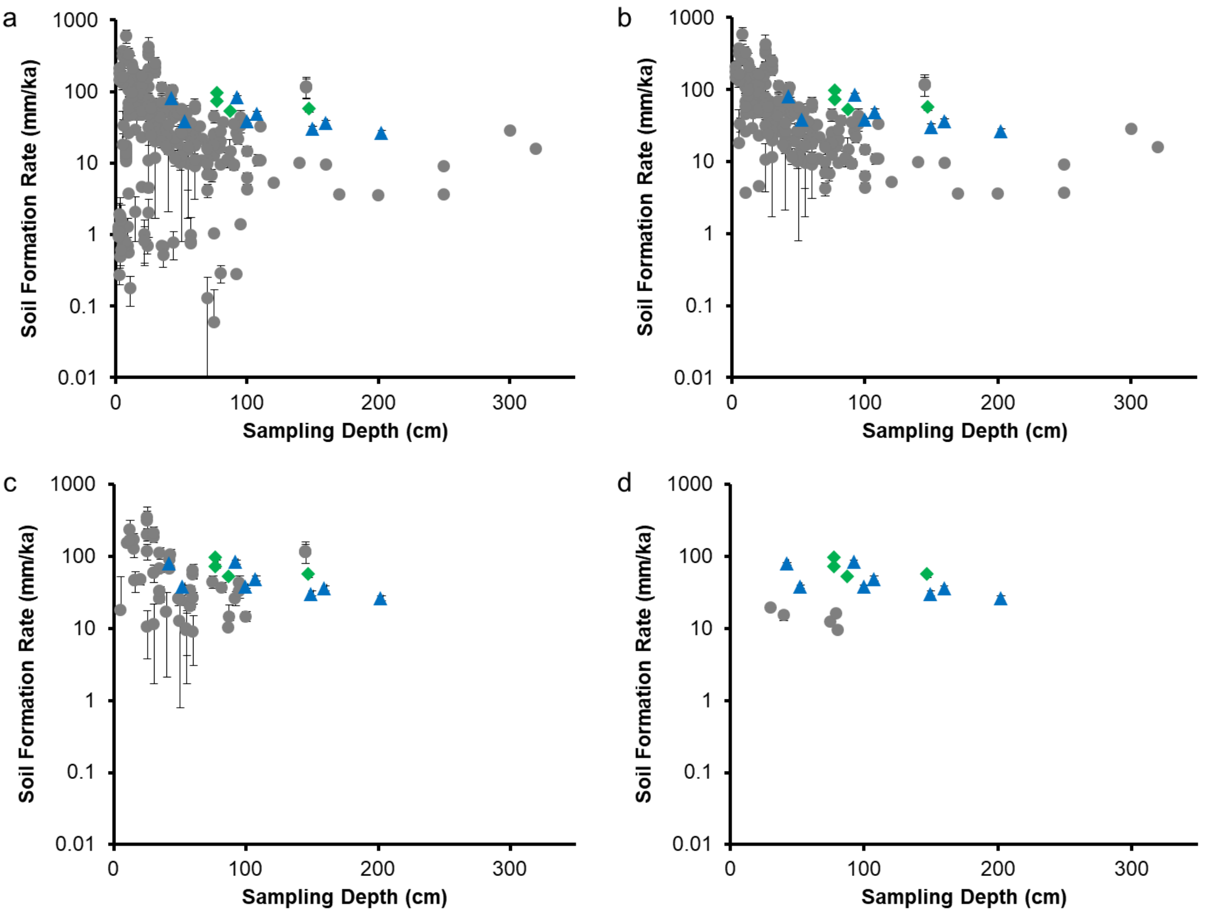
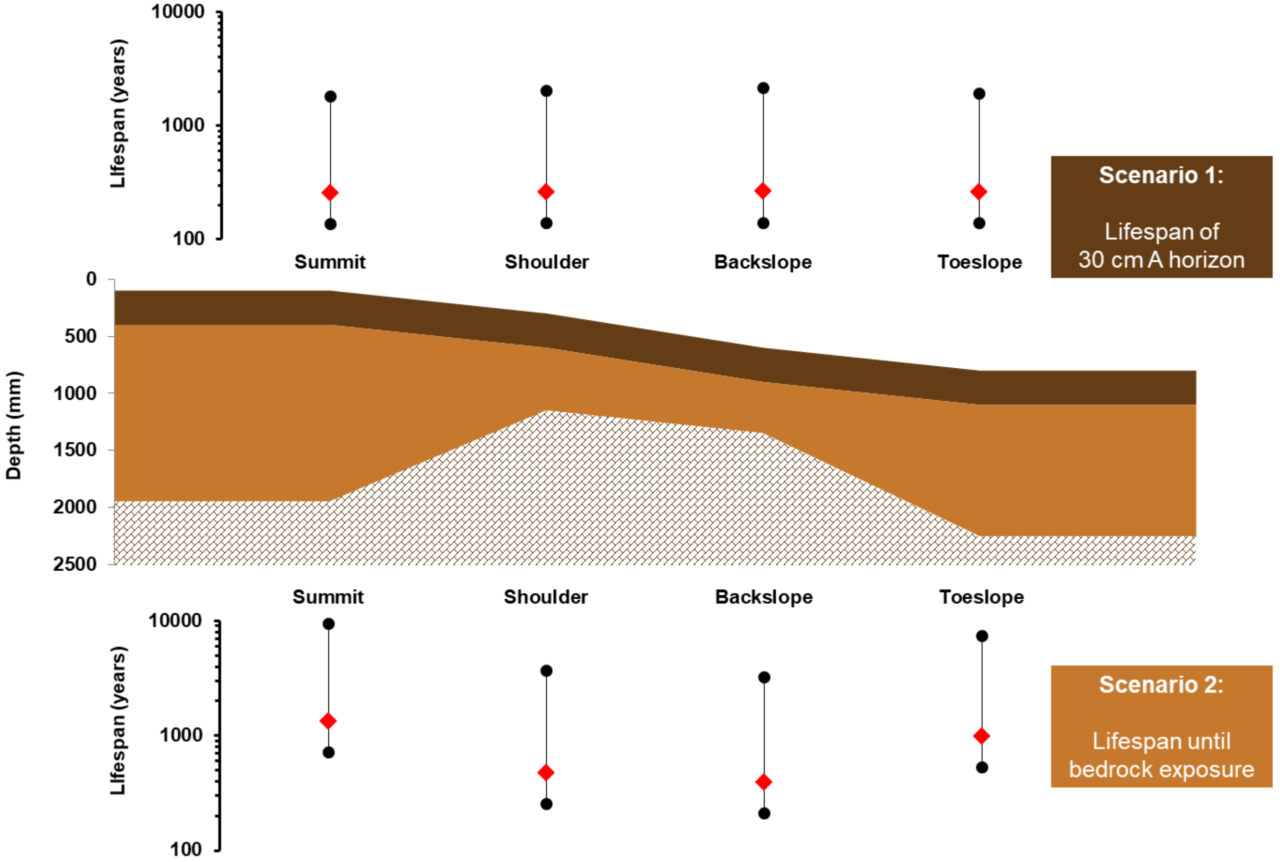


Figure 4: Soil formation rates from a globally compiled inventory (grey circles) and from this study at Rufford Forest Farm (blue triangles) and Comer Woodland (green diamonds) plotted against sampling depth. The depth here refers to that for the midpoint (between the top and bottom) of the sample. Rates in grey are from (a) the total mantled inventory (n = 252); (b) studies from temperate climates (n = 187); (c) studies on sandstone geology (n = 57); and (d) the UK, exclusively from Riggins et al. (2011) (n = 5). Error bars indicate the standard error.

3.3 Lifespan analysis at Rufford Forest Farm

Based on a mean annual erosion rate of 1.19 mm $year^{-1}$ under arable agriculture, the lifespans of the A horizon across the catena at RFF range between ~~256~~258–~~263~~ 272 years (Figure 5). This range expands to ~~137~~138–~~2158~~ 3000 years when the 5th and 95th percentile soil erosion rates are applied. However, further examination of the A horizon from cores extracted down the catena suggest that the toeslope is in a phase of aggradation rather than thinning. This is supported by the fact that the depth of the Ap horizon at the toeslope is 75 cm, whereas it is 30 cm on all other observed landscape positions. Moreover, comprised within the upper stratigraphy of the soil profile down the catena is the Bunter Pebble Bed which can be found at approximately 30 cm on summit, shoulder and backslope positions but 70 cm at the toeslope. The depth to which this pebble bed occurs at the toeslope suggests that either colluviation has occurred or is still occurring. In a scenario where colluviation is no longer active, the lifespan of this 75 cm A horizon is finite and ranges from 347 – 5245 years, but lifespans here could be longer or indefinite if colluviation continues. ~~Moreover, comprised within the upper stratigraphy of the soil profile down the catena is the Bunter Pebble Bed which can be found at approximately 30 cm on summit, shoulder and backslope positions but 70 cm at the toeslope. The depth to which this pebble bed occurs at the toeslope suggests that either colluviation has occurred or is still occurring, or that lifespans at this position may be either longer than 2158 years or indefinite.~~ This demonstrates the difficulty of calculating lifespans using soil formation rates derived from bedrock alone and not from other system inflows of soil mass such as that from colluviation and soil carbon additions.

Soil lifespans indicating the time until the exposure of the parent material span between ~~394~~407–~~1325~~ 1334 years. The range of these lifespans can be explained by the fact that unlike scenario one, where a constant A horizon thickness of 30 cm was applied across the catena, the soil thickness applied here is the depth to ~~bedrock~~ the soil-saprolite interface measured at each catena position (see Table 1). Applying upper and lower confidence intervals in the soil formation term and the 5th and 95th percentiles in the soil erosion term further widens the breadth of lifespans to ~~209~~212–~~9394~~ 9688 years. The shortest lifespans are found on the backslope where bedrock exposure is expected to occur between ~~209~~212–~~3237~~ 4500 years. In contrast, the greatest lifespans are found at the summit where soil thickness is 155 cm (~~709~~713–~~9394~~ 9688 years). Although soil formation rates are greater at the toeslope, the depth to bedrock is 40 cm greater at the summit and, as a result, longer durations are required for bedrock to become exposed at this position. The soil detached and transported from the backslope is expected, in part, to continue to be a contributory source of the colluvium observed at the toeslope. Although the growth of soil profiles due to colluvium is not considered in the lifespan equation, it suggests that lifespans at the toeslope may either be longer than the calculated maximum of ~~7372~~ 8042 years or indefinite.


Lifespan (years)
10000
1000
100
Summit
Shoulder
Backslope
Toeslope
Scenario 1:
Lifespan of
30 cm A horizon
Depth (mm)
0
500
1000
1500
2000
2500
Summit
Shoulder
Backslope
Toeslope
Lifespan (years)
10000
1000
100
Scenario 2:
Lifespan until
bedrock exposure

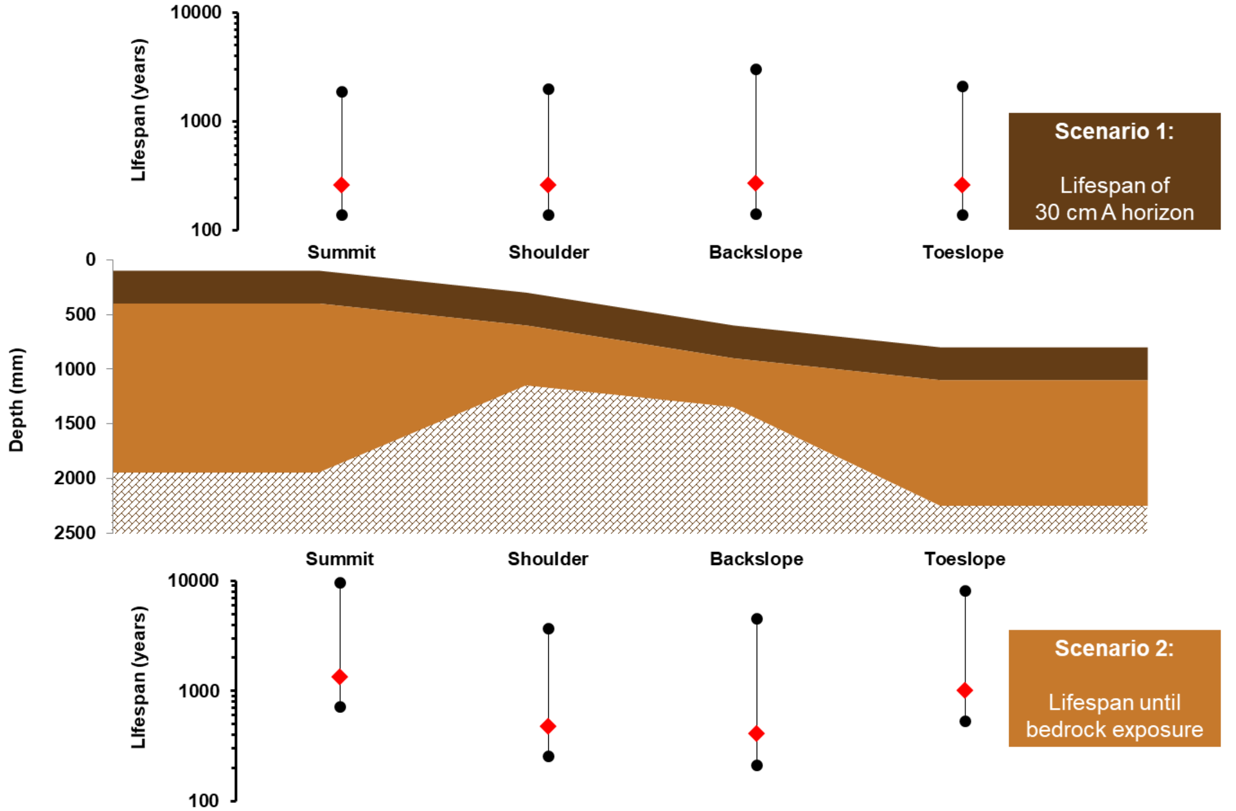


Figure 5: First-order soil lifespans calculated at four catena positions at Rufford Forest Farm for Scenario 1 (the time until the erosion of a 30 cm A horizon) and Scenario 2 (the time until bedrock exposure). The centre diagram indicates the thickness of the A horizon (dark brown), the subsoil (light brown) and the depth to ~~bedrock~~ the soil-saprolite interface (bricks). Red diamonds denote lifespans calculated using a mean annual soil erosion rate of 1.19 mm year^{-1} from Quine and Walling (1991) and soil formation rates from this study. Black dots denote the minimum and maximum lifespans calculated using the 5th and 95th percentile of the soil erosion dataset and the one sigma uncertainties in the soil formation dataset.

The first-order lifespans presented here are based on a number of assumptions. Notwithstanding the fact that the land management regime may change within the cited time spans altering the protection the soils receive from wind and water, the erosion rates employed neither reflects the increase in the erodibility of subsoil horizons, characterised by a relatively weaker soil structure (Tanner et al., 2018) nor the potential role that the Bunter Pebble Bed may play in armouring the soil surface in the future. Moreover, they do not reflect the expected shift in erosivity ~~the increase in the erodibility of subsoil horizons, characterised by a relatively weaker soil structure (Tanner et al., 2018) nor do they account for an expected shift in erosivity~~, commensurate with more intense precipitation events (Burt et al., 2015). Acknowledging these factors, the lifespans presented here are likely to be overestimated. However, the fate of eroded soil upslope may contribute to the up-building of soil profiles in downslope concavities, extending the lifespans in the colluvial zone. In this respect the lifespans presented here, particularly those for the toeslope, are likely to be underestimated. ~~Similarly, the soil formation rates employed.~~

4.0 Conclusions

We have presented the first isotopically-derived rates of soil formation for soils currently supporting arable agriculture. Rates derived for two UK catena sequences using cosmogenic radionuclide analysis range from 0.~~023~~ 026 ~~± 0.002~~ mm year^{-1} to 0.~~064~~ 084 ~~± 0.002~~ mm year^{-1}, with mean rates being 0.~~037~~ 048 ± 0.~~003~~ 008 mm year^{-1} and 0.~~046~~ 070 ± 0.~~007~~ 010 mm year^{-1} for Rufford Forest Farm and Comer Wood, respectively. By combining soil formation rates from Rufford Forest Farm with soil erosion rates derived from a prior isotopic study in a first-order lifespan model, we estimate that in a worst-case scenario the soil that currently comprises the A horizon on the backslope may be eroded in ~~137~~ 138 years and bedrock exposure may occur in ~~209~~ 212 years. Assessing gross soil erosion with measured rates of soil formation is important because soils that support arable agriculture are under threat from accelerated soil erosion. We have therefore shown that both the derivation and application of soil formation rates must become a fundamental component in future discussions of soil sustainability.

This work also represents the second of all isotopic studies of soil formation in the UK and therefore a significant contribution to our knowledge of pedogenesis. Soil formation rates were found to fall within the range of those previously published for soils in temperate climates and on sandstone lithologies, but were found to be significantly greater than those measured previously at Bodmin Moor. This is explained by the fact that the parent material at Bodmin Moor is a coarse-grained granite and therefore less susceptible to weathering than the sandstone materials underlying Rufford Forest Farm and Comer Wood. ~~Soil formation rates were found to be significantly greater than those measured previously at Bodmin Moor which is explained by the fact that the parent material at Bodmin Moor is a coarse-grained granite and therefore less susceptible to weathering than the sandstone materials underlying Rufford Forest Farm and Comer Wood.~~ Such petrographic controls may also explain the greater rates of soil formation at Comer Wood where the sandstone matrix is largely devoid of the cementing agents present at Rufford Forest Farm and, therefore, more susceptible to particle detachment during physical and chemical weathering. Given that petrographic variability has not been thoroughly investigated in pedogenesis work, greater investment is warranted to better understand how the geochemical composition of the parent material governs the rates of soil formation.

Data availability

The authors declare no restrictions on the availability of materials or information.

Supplement link

Author contribution

D. L. E., J. N. Q., A. M. T. and J. A. C. D. designed research. D. L. E. and A. M. T. conducted sampling. D. L. E. and A. R. conducted laboratory work and analysed results. D. L. E. prepared the manuscript with contributions from all co-authors.

Competing interests

J. N. Q is a member of the editorial board of the journal.

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Table 1: ^{10}Be concentrations and calculated maximum soil formation rates for Rufford Forest Farm (RFF) and Comer Wood (CW)

Site	Catena Position	Elevation, m	Horizon Position	Depth, cm	^{10}Be atoms, g	Uncertainty of ^{10}Be atoms, g	^{10}Be production rate at surface, g^{-1} year^{-1}	Soil Formation Rates, (Best Fit) mm ka^{-1}	Uncertainty, mm ka^{-1}
RFF	Summit	98.7	A	~~155~~150	35266	2364	4.63	30~~23~~	29 - 33~~2~~
RFF	Summit	98.7	B	203~~205~~	22683	1586	4.63	26~~27~~	24 - 28~~2~~
RFF	Shoulder	99.3	A	53~~55~~	54380	2030	4.63	38~~38~~	36 - 41 ~~1~~
RFF	Shoulder	99.3	B	100~~105~~	30064	1850	4.63	38~~43~~	36 - 40~~3~~
RFF	Backslope	97.9	A	43~~45~~	45603	1833	4.63	80~~51~~	77 - 83~~2~~
RFF	Backslope	97.9	B	93~~95~~	28876	1661	4.63	84~~49~~	77 - 88~~3~~
RFF	Toeslope	95.7	A	108~~115~~	32738	2006	4.62	49~~35~~	46 - 53~~2~~
RFF	Toeslope	95.7	B	160~~5~~	25237	1562	4.62	36~~31~~	34 - 39~~2~~
CW	Summit	70.6	A	148~~150~~	24507	1696	4.49	57~~36~~	52 - 59~~3~~
CW	Shoulder	65.3	A	78~~80~~	24811	1333	4.46	96~~64~~	90 - 99~~4~~
CW	Backslope	58.9	A	78~~80~~	31263	2035	4.42	73~~50~~	69 - 78~~3~~
CW	Toeslope	50.1	A	88~~90~~	41276	1522	4.39	53~~34~~	51 - 54~~1~~

Horizon Position 'A' denotes the sample was taken at the soil-saprolite interface. Horizon Position 'B' denotes an additional sample was taken ~50cm below the interface from the same depth profile. The depth here refers to that for the midpoint (between the top and bottom) of the sample. The shielding correction was calculated as 1.0 (to 1 d.p) for all samples and ^{10}Be production rates are corrected for elevation and location (see Supplementary Table 1). All uncertainties are one standard deviation and are based on uncertainties in the measurement of ^{10}Be concentration as outlined in Rodés et al. (2011). ~~Average sample density is 2.2 g cm^{-3}.~~