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Interactive comment on "A probabilistic approach to quantifying soil property change through time integration of energy and mass input" *by* Christopher Shepard et al.

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Response to Editor Peter Finke

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We thank the editor for his comments and recommendations on the manuscript titled "A probabilistic approach to quantifying soil property change through time integration of mass and energy input." We have responded to and addressed the editor's comments and remarks below and in the revised version of the manuscript.

Response to general remarks: The model requires the inputs of time and effective energy and mass transfer (EEMT, Rasmussen et al., 2005; Rasmussen and Tabor, 2007; Rasmussen et al., 2011) to predict the probable range of a particular soil physical property at a given location. In this presentation, we focus on clay content as a physical property that reflects pedogenic change. EEMT is clearly rooted in the classical Jenny factorial approach for describing soil forming system, and as such does not describe any particular soil forming process. EEMT is a flux term, and is it not used here to parameterize a mechanistic model of pedogenesis as suggested by the editor. EEMT simply quantifies the energetic contributions from effective precipitation and net primary productivity as quantitative measures of climatic and biological forcing/input to the soil forming system. EEMT quantifies the energy transferred to the soil system that can perform pedogenic work, such as chemical weathering or carbon cycling, or any other soil forming process; it does not describe or quantify any one process, and this is indicated on lines 102-105.

Application of the present approach in the critical zone environment requires no soil information. Here we used an established geomorphically based numerical model that predicts local erosion rates, soil depth and local soil residence time from topography and a maximum rate of soil production (that can be assumed or based on local catchment derived denudation rates) (Pelletier and Rasmussen, 2009). The geomorphic model is mechanistic and process based, describing mass production and transport using established transport “laws”. The editor expressed doubt of the ability to predict soil information in the critical zone environment; however, we present clear model results that this approach can be used to predict clay content completely independent of soil data. This is a key piece of soil information to understanding critical zone function and evolution. We further argued that the present approach can greatly inform our understanding of the distributions of soil physical properties and facilitate further hypothesis generation. For example, the present approach did not accurately predict clay stocks at specific locations within the Santa Catalina Mountains-Jemez River Basin granite sub-catchment (Lines 329-339); any number of hypotheses and questions can be formulated and tested as to why the model failed to predict clay stocks at these locations, and the current model formulation can be updated to accommodate these findings. Further, the present results suggest an incomplete understanding of the soil-landscapes within these catchments, which may not have been found by using techniques such as digital soil mapping.

The strength of the current approach lies in the ability of the model to capture all soil forming factors into one relatively simple mathematical apparatus. We make no claims of modeling particular soil forming processes, a fact that we state clearly in lines 145-149 and in lines 151-152. As true of any factorial treatment of soil systems, the model captures either the net effect of all considered soil forming processes or rather the implicit result of soil forming processes, by considering all soil profiles equally. This is the same foundation for any number of digital soil mapping exercises, as typified by the SCORPAN statement of McBratney and others – the model uses factors to predict soil properties and is not a mechanistic model of process. The model only indirectly captures soil forming processes by not restricting the model to any particular spatial or temporal extent or any particular parent material. We disagree with the editor's comment about the delineation of the model domain. By restricting the model domain, either spatially, temporally, or with regards to parent material, entire suites of soil forming processes would not be captured, limiting the applicability of the present approach.

Response to Question 1. Why is the model forced to a bivariate pdf form? Techniques were on the shelf?

A bivariate normal density distribution was used for the present approach because it generally represents the mathematically simplest bivariate distribution and is easily parameterized. However, we did not consider other bivariate density functions, we wanted to demonstrate proof of concept before exploring complexities or refinements to the approach. We have added language to the revised manuscript at lines 131, indicating that we choose to force the data to a bivariate normal structure and that other density functions are available and may provide a better fit to the soil physical property of interest.

Response to Question 2. Question with regards to quantifying soil age and EEMT.

The editor is correct in that the model assumes EEMT is constant over the duration of pedogenesis. Further, we agree with the reviewer that climate throughout the Quaternary has not been constant (Zachos et al., 2001), and that this inconsistency likely has influenced our predicted soil property values. We directly addressed this model limitation in section 4.3, lines 503-514:

"Furthermore, global climate patterns have shifted dramatically over the last 65 Mya (Zachos et al., 2001). The majority of soils observed in the compiled chronosequence database span the Quaternary, including both the Holocene and Pleistocene. The Pleistocene was marked by a number of major glacial-interglacial cycles at approximately 100,000-year intervals (Imbrie et al., 1992; Wallace and Hobbs, 2006), which corresponded with shifting climatic conditions, e.g., for large portions of the northern mid-latitudes glacial periods were generally cooler and wetter, and interglacial periods were warmer and drier (Connin et al., 1998; Petit et al., 1999). Further, the Pleistocene climate shifts likely influenced the rates of weathering and clay production (Hotchkiss et al., 2000). Taking into account the differences in past and modern climate would likely diminish disparities between observed and modeled soil physical properties. Reconstructed global paleo-EEMT values would improve model accuracy, and limit uncertainty in the probabilistic ranges of soil properties for soils older than Holocene age."

Further, we discussed a possible model correction in which paleo-EEMT values could be calculated and used to provide better estimates of TPE. However, in order to calculate an accurate accounting of paleo-EEMT values would require datasets of about past mean monthly air temperature, mean monthly precipitation and monthly net primary productivity (Rasmussen et al., 2005, 2011; Rasmussen and Tabor, 2007) for the entire duration of pedogenesis. Unfortunately, few, if any, locations on the planet have spatially explicit paleoclimatic records with all the necessary data requirements to perform this calculation, although paleoclimate predictions are improving, e.g. the recent CIMP4 general circulation model application to predict global LGM climates, which

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represents an ongoing opportunity to incorporate such data into pedogenic models. As such, we made the simplifying assumption that the current climate can be used to represent of climates that many of the included soils evolved under. This is true of any factorial approach and representation of soil data that includes soils older than the Holocene. Any representation of soil properties relative to mean annual temperature or precipitation or any plot of soil property change vs time invariably includes past climate variation influence of soil property evolution. We clearly stated and recognized this in the text.

Defining soil age is a challenge in many landscapes as the editor suggests; however, there are simple techniques that can be used to estimate soil age without the need for expensive cosmogenic radionuclide dating. The age of geomorphic landforms can be estimated by using the cross-sectional shape of gully cuts or scarp-like surfaces and hillslopes and a known hillslope diffusivity value (Bucknam and Anderson, 1979; Hsu and Pelletier, 2004; Pelletier et al., 2006; Pelletier and Cline, 2007). Estimating geomorphic landform age requires only the use of either a digital elevation model (DEM), or profiles of scarp elevation, both of which are easily and inexpensively attained. Further, relative age dating is widely used in chronosequence studies and provides general estimates and constraints of soil-geomorphic surface ages (Schaetzl and Anderson, 2005). With regards to upland catchments, catchment averaged denudation rates can be estimated from cosmogenic radionuclides (CRN) using a smaller number of samples than would be necessary for quantifying full CRN depth profiles (Granger et al., 1996). Using a geomorphically based model of soil depth, spatially explicit soil ages can be calculated was discussed in lines 220-224. As such, we do not agree with the editor the target variables are more easily determined than soil age; for any chronosequence study, soil age would have to be determined regardless of the target variables of interest, assuming soil age is too expensive or indeterminable is not an appropriate or accurate critique of the presented model.

Response to Question 3. Removal of buried horizons.

Buried horizons were removed from the dataset, as we assumed that these buried horizons were not reflective of the relationship between the modern climate and the subaerial soil horizons. We decided to remove buried horizons, as the subaerial soil horizons likely are more correlated with the current climate, as compared to the buried horizons. Eolian horizons were removed from soils described in McFadden et al. (1986), because these horizons are likely significantly younger than the basaltic flow dates that were used to represent the soil age; however, based on the reviewer's suggestion we have removed these soils from the current dataset and updated lines 194 to reflect this change. Only buried horizon have been removed from the dataset presented in the revised manuscript.

Response to Question 4. Non-linear or transient soil formation.

We specifically addressed non-linear soil formation and internal or intrinsic feedbacks driving soil development in section 4.3, lines 490-502: "Internal or intrinsic feedbacks and thresholds within the soil system drive pedogenic development without changes in the external state factors (Muhs, 1984; Chadwick and Chorover, 2001). For example, greater chemical weathering and clay production due to increased water residence time caused by argillic horizon development is the result of an internal feedback that is independent of the external climatic and biological system (Schaetzl and Anderson, 2005). These thresholds can operate as progressive or regressive processes, driving soil formation forward or hindering further development (Johnson and Watson-Stegner, 1987; Phillips, 1993). Internal soil development feedbacks were not explicitly considered in the present model formulation. The presence of these internal feedbacks may partially explain error within the model predictions. Changes in EEMT would not explain all observed differences in soil properties over the age of the soil. However, if these feedbacks were operating in the included soils, the influence of intrinsic thresholds was implicitly captured within the probability distributions, partially accounting for the role of internal soil development feedbacks on soil formation."

The model does capture all soil forming processes implicitly, in that no one process

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is explicit expressed or quantified. Further, we agree with the reviewer that the model does produce a prediction of soil physical properties based on the net effect of these soil forming processes. We have edited lines 149-153 by removing the word “implicitly”.

Response to Question 5. Human impacts on soil formation.

We did not address human impacts within the current manuscript or even discuss anthropogenically driven changes in land use or climate. Here we demonstrate the use of a probabilistic model for quantifying the distribution of soil properties we observe currently on the Earth’s surface that has arisen during the Quaternary. Furthermore, the energetic contributions from human impacts and dust influx can and have been incorporated within the EEMT apparatus (Rasmussen et al., 2011). The energetic inputs from dust or fertilizer additions, for example, are generally orders of magnitude smaller than the energetic inputs from solar radiation, precipitation, or primary productivity into the soil system. The energetic inputs to the soil from other direct human activities such as the compression of soil due to farming equipment or the increased erosion due to construction or plowing (Rasmussen et al., 2011). We have added language to indicate the adaptability of the EEMT model for differing soil environments at lines 212-215 in the revised manuscript. In specific systems, both dust inputs and human impacts may be significant, however, the vast majority of the soils included in the presented dataset are not directly impacted by human activities or modern dust influx. As the model is probabilistic in nature, the model can simply predict a probable range of target soil physical properties, the domain is generally unconfined. As stated above, human and dust inputs to the soil system can be incorporated into EEMT allowing the inclusion of these soils within the model. Furthermore, the application of the model in this manuscript was to predict clay content, this is a soil property that does not readily change over human time-scales – but rather reflects geologic time scale pedogenic change.

Response to Question 6. Regards to use of energetic models.

Energetic approaches to quantifying soil physical properties and soil formation are able to deal with differing mixtures of the soil forming factors. The soil state factor model has the potential to be expanded beyond the classical five soil forming factors to include influences from site-specific soil forming factors such as the addition of fertilizer to soils or increased erosion due to human activity (Jenny, 1941, 1961). All energetic pedogenic models are derived from the soil state factor model (Minasny et al., 2008), and as such have the potential to be expanded to accommodate additional soil forming factors. Energetic approaches account for the potential fluxes of matter and energy into the soil system that are associated with the soil forming factors, relating the energetics of the fluxes into the soil system to soil physical properties and structures (Volobuyev, 1964; Runge, 1973; Smeck et al., 1983; Rasmussen et al., 2005, 2011; Rasmussen and Tabor, 2007). The energetic input from fertilizer can be easily quantified and included with the model scheme for EEMT when appropriate, however, the energetic additions to the soil from fertilizer are orders of magnitude smaller when compared to the energetic additions of soil radiation, effective precipitation, and net primary productivity (Rasmussen et al., 2011).

The impact of anthropogenic climate change on soil physical properties can be incorporated into the EEMT model space. EEMT can be updated to include the impacts of increased atmospheric CO2 on the fluxes of matter and to the soil system. Local changes in air temperature, precipitation, evapotranspiration, and net primary productivity due to increased atmospheric CO2 are quantifiable, and can be easily incorporated into the EEMT model. Further, EEMT can be calculated on a range of temporal scales from near-real time through the use of eddy flux tower and meteorological flux measurements to annually (Rasmussen et al., 2015). With EEMT values updated to include the impacts of anthropogenic climate change, the presented model structure is capable of incorporating these influences on soil formation. As such, we disagree with the reviewer that energetic-based pedogenic models are not capable of handling changing earth surface conditions, and can be updated to accommodate human influences on the climate and landscapes.

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Response to specific remarks

Response to remarks on Lines 94-97, interchangeability of Px and Lo:

The soil state factor model developed by Jenny (S=f(cl,o,r,p,t)) was later formulated by Jenny as S=f(Px,Lo,t), recognizing that climate and biology are generally flux inputs into the soil system and relief and parent material are site factors. Px influences pedogenesis and soil evolution over the lifetime of the soil and may be time dependent, whereas Lo generally represents the initial state of the soil forming system and is not time dependent (Jenny, 1961). Interchanging the influence of Px and Lo is not possible. Relief or topography can vary over time, and in certain formulations of the soil state factor model may be considered time dependent, however, the chronosequence data used to parameterize the present approach are sited on low sloping surfaces, and changes in topography were minimized. Furthermore, as described by Jenny, and approximately 70 decades of soil science, the soil state factors do not describe soil forming processes, the state factors only describe the soil forming environment, i.e. climate is not a soil forming process, but a description of the conditions under which certain soil properties are observed and soil processes operate.

Response to remarks on Lines 182-183: Depth weighted percent clay calculation and bulk density values

We used depth weighted average percent clay in the prediction of clay stocks to account for the greater influence of thicker soil horizons on the account of clay stocks. By calculating a depth weighted average we are accounting for the distribution clay with depth, and summarizing those values into one value. Our model was trained on depth weighted average clay percentages from the chronosequence database; consequently, we also used depth weighted average clay values for predicting clay on a mass per area basis. We agree with the editor, bulk density is not constant throughout a profile, unfortunately, bulk density is difficult to measure, or is often not measured in the field. Further, bulk density data are not commonly reported within the soil science literature or in the available chronosequence literature. Without the necessary data, we chose to assume a constant value of 1500 kg m-3 for all soil profiles used in the calculation of predicted mass per area clay. If bulk density data were available, those data could be easily included in the prediction of mass per area, and likely the presented probabilistic-energetic would likely better predict clay stocks.

Response to remarks on Lines 238-240: Assumption of 1500 kg m-3 bulk density and use of RF% for calculating clay stocks.

Bulk density is not a commonly measured soil variable as it is often difficult to obtain measurements for bulk density from soil profiles, and values for bulk density are highly method dependent; there was low reporting of bulk density estimate in the available chronosequence literature. Due to a lack of measured values, a constant value was chosen for all profiles; if bulk density measurements are available than the measured values should be used in the predictions of clay stocks. Further, RF% data were used in the predicted clay stocks, as (1-RF%) in Eq. 9 describes the volume or fraction of the soil profile in which clay sized particles accumulate. Additionally, RF% did not influence the prediction of clay stocks (line 326); if RF% data were unavailable, a standard or constant value could be assumed for predicting clay stocks. Further, these simplifications for calculating soil properties on a mass per area basis are standard corrections and assumptions that are made throughout the available literature. With missing or incomplete data, the complexities of measuring soil properties in the field, educated assumptions are usually required.

Response to remarks on Section 3.1 Bias in sampling and stratification of Lo:

The editor did not fully understand the model background as presented in the manuscript. Lo was not used for stratification; Lo is not directly expressed within the model structure. We removed Lo from Eq. 4 to produce Eq. 5, justifying this simplification as time partially accounts for the influence of topography and parent material variation. Soil residence time on a landscape is proportional to slope or curvature

(Heimsath et al., 1997, 2002; Yoo et al., 2007). Additionally, the degree of weathering or alteration of the parent material and the presence of secondary minerals and products are also proportional to the soil residence time (Brimhall and Dietrich, 1987; Chadwick et al., 1990; Brimhall et al., 1992). We chose to break down model predictions using leave one out cross validation by parent material in Fig 4 to demonstrate the model was insensitive to different parent materials or landforms, the predictive ability of the model did not vary significantly between the 3 broad parent material categories. We did not calculate model parameters based on parent material, we presented global parameter values in Table 2. We have updated lines 124 and lines 155-157 to clarify this point.

Biased sampling due the use of chronosequence studies is an issue faced in all of soil science. Soil pits are generally preferentially sited in locations where it is possible to dig a soil pit of sufficient depth to sample the soil profile. Any chronosequence study or synthesis of chronosequence data is hampered by biases within soil sampling and presentation of selected data in the literature. Biases in estimated model parameters are based upon sampling techniques and availability of chronosequence data in the literature not due to selective sampling of chronosequence data used to calculate model parameters. We did not limit the data used to calculate the model parameters from the chronosequence literature as a way to minimize errors within the presented model.

Response to remarks on Line 346, clay content change:

In lines 151-152 we stated: “The model assumes all changes in soil physical properties are due to pedogenic processes.”, and in lines 345-348 we stated: “Weathering and clay production are primary pedogenic processes (Birkeland, 1999; Schaetzl and Anderson, 2005), and because the model assumed all changes in the soil profile are due to these processes, the model was the most effective at predicting clay content.” These statements are in agreement with each other. The model implicitly captures the net effect of all pedogenic processes, we assumed that all changes in the soil profiles are due to pedogenic processes, and the primary pedogenic processes are weathering and clay production, amongst a suite of other processes (Schaetzl and Anderson, 2005), meaning the model captures the influence of weathering and clay production in soil property change. There is no “pretending”, we are not misrepresenting the model or its predictive power in any way. We did not claim to model soil forming process, only the end result of all soil forming processes at specific times and energetic inputs based on the available chronosequence literature; this is true for any chronosequence or time based representation of soil data that has been published over the last 70+ years.

Response to remarks on Section 4.1.1, and where the model underperformed:

In many areas, estimated TPE values likely do not account for the total flux of mass and energy into the soil system. Error in predicted clay percentages are likely partially a function of error in TPE estimates. We discussed underestimations of TPE due to changing climate, topography, parent material differences and intrinsic thresholds in soil formation in Section 4.3. Further, we did not constrain the chronosequence data set used to calculate the model parameters, as the formulated model is capable of handling soil data from a wide range of environments and locations due to its probabilistic component. We highlighted where the model failed to predict soil property values as a way to highlight locations where we still have an incomplete understanding of soil formation, or places where parent material greatly influences resultant soil formation (i.e. coral reef terraces). The inability of the model to predict soil properties in particular areas, suggests that a soil-forming factor not included in EEMT or TPE is highly influencing soil formation in this area, not that input data used to calculate model parameters need to be constrained. Models are only representations of reality and there is no logical need for a model to perform perfectly. It is generally beneficial to identify locations and conditions under which models do not work, as a way to identify potential model refinements.

We did not highlight model failures as an excuse to selectively choose data to achieve the best model predictions as suggested by the editor. Further, constraining data to achieve a successful model prediction is uninteresting, as one cannot identify locations or conditions under which the model breaks. Without the inclusion of coral reef terrace chronosequence, we would not have identified that the model has an inability to predict resultant soil formation under fine textured parent materials and tropical climates.

Response to remarks on Line 439, model assumptions about initial conditions:

The editor did not understand the model background as written in lines 115-127, we did not stratify the data by parent material:

“Explicitly including time in Eq. 4 through TPE partially captures variation in soil property change attributable to topography and parent material. Soil residence time may be directly related to landscape position through topographic control on soil production and sediment transport/deposition (Heimsath et al., 1997, 2002; Yoo et al., 2007). Additionally, parent material modulates soil residence time through control on soil depth (Rasmussen et al., 2005; Heckman and Rasmussen, 2011), soil production, and sediment transport rates (Andre and Anderson, 1961; Portenga and Bierman, 2011). The initial conditions of the soil forming system (Lo) are never fully known; however, representing the state of the soil system as a probable distribution of values, implicitly accounting for soil age, and not constraining the initial soil forming conditions, Eq. 4 can be stated simply as: P(s_1≤S≤s_2)=f(TPE) (5) where the probability state of the soil, P(s_1≤S≤s_2), bounded by a lower and upper limit, is a function of one quantifiable variable.”

We simply removed Lo from Eq. 4 to write Eq. 5, TPE partially accounts for variation in Lo due to the influence of topography and parent material on soil residence time, as discussed above. We did not use parent material to stratify model parameter estimates; we calculated model parameters for the entire chronosequence dataset. We did not make assumptions about the soil parent material, or include any data about the parent material within the presented model. The statement in Line 439 is accurate. We have updated lines 124 and lines 155-157 to clarify this point.

Response to remarks on Line 459, potential to model landscape evolution:

We strongly disagree with this statement. First, the application of the model that couples the geomorphic model of Pelletier and Rasmussen (2009) explicitly includes soil production and sediment transport to predict landscape variation in soil depth and residence time – these values coupled with TPE yield estimates of soil physical properties completely independent of any soil data. This coupled model may be used to predict soil and landscape evolution across any range of topographic and/or climate scenarios, and yield probabilistic estimates of soil clay content. As stated throughout the manuscript, the model was designed to capture Quaternary soil evolution; additionally, the focus on clay content necessitates a geologic time scale perspective as this property changes not on human scales, but on pedogenic time scales. Changes induced by human activity could be incorporated into the sediment transport of the Pelletier and Rasmussen (2009) model, as well as incorporated into the energy and mas transfer terms, but in terms of changes in clay content over human time scales these changes will likely be insignificant. As stated in the manuscript, this approach could be used to investigate potential landscape scenarios. Using the geomorphic model (Pelletier and Rasmussen, 2009), potential landscape evolution scenarios could be investigated where changes in topography and soil thickness are used to determine changes in soil properties across small watersheds. We stress that potential landscape evolution scenarios could be investigated, assuming the landscape is at steady state, soil development and evolution could be teased apart using the presented approach; any predictions drawn from such hypothetical modeling exercises would only be a potential future for any landscape. Furthermore, as discussed in this review EEMT can be updated to include the influence from human impacts on the atmosphere and landscapes, and TPE can also be calculated to include the influence of a changing climate (Rasmussen et al., 2011).

As stated in the manuscript and repeatedly above, we used modern EEMT integrated over the age of the soil as the estimate of "total" pedogenic energy input as the best available data that we have. We clearly recognize that this does not incorporate past climate change, leading to what could be under/over estimates of TPE depending on how

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the local climate system changed at each included location during glacial periods. The majority of sites were from northern hemisphere mid-latitude sites suggesting modern EEMT, and hence, TPE likely underestimates the total pedogenic energy transferred to each location. As noted spatially explicit estimates of LGM climate conditions are now available, but we currently lack a time resolved estimate of paleoclimate variation. As such, we used modern values as proxies for soil forming factors. This is true for any study of soil properties relative to modern climate. Based on the editor suggestion we have removed the reference to investigation of potential soil forming environments at lines 540-541 in the revised manuscript.

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