EMERGY SYNTHESIS 2: Theory and Applications of the Emergy Methodology


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ABSTRACT

A systems model of topsoil genesis was developed to explore the dynamics of various components of the soil system. The model was calibrated for long-term soil conditions in humid and semi-humid tropical Africa, but the model structure is sufficiently general to allow application to other climatic and biotic regions. Of specific interest was the addition of emergy to the simulation to arrive at transformity and specific emergy estimates for various internal components, including soil organic matter (SOM), soil nutrients, soil cation exchange capacity (CEC), and soil structure. Standard emergy simulation rules were applied to this multiple state variable system with one exception: material pathways that are recycled to a base storage add emergy to that storage based on the current transformity of the material in that storage. This allows material dispersal and re-concentration within a system without artificial transformity effects. The problem of simulating emergy in systems with recycled materials is explored using a two-tank mini-model before the new techniques are applied to the soil genesis model.

The calibrated model provided estimates of transformity and specific emergy values for a tropical savanna of 2.23E5 sej/J (SOM), 2.6E10 sej/gram (nutrients), 1.34E10 sej/gram (CEC), and 5.14E10 sej/J (Soil Structure). A Visual Basic module was added to the model to allow random draws from probability distributions for each parameter to be propagated through the model. Repeated cycles (~1000) of this Monte Carlo simulation ultimately provide confidence bounds for the computed transformities. Estimated probability distributions for this model resulted in the following standard deviations around the mean value reported above: 4.04E4 sej/J (SOM), 3.8E9 sej/gram (nutrients), 1.3E9 sej/gram (CEC) and 5.79E10 sej/J (soil structure). Data were also generated for tropical forest systems.

INTRODUCTION

Tropical agro-ecosystems are generally regions where significant levels of soil loss occur (Pimentel 1979). This is due primarily to the convergence of intense tropical rainfall patterns, low levels of soil subsidy (e.g. fertilizer, mulch) due to prevailing poverty, and large numbers of livestock reliant on small land parcels. As a result of this convergence of circumstances in western Kenya, soil erosion continues to be a formidable and charismatic problem (ICRAF, 2000). Within the context of an effort to study this problem using energy analysis, it became necessary to establish locally calibrated and highly reliable transformity values for soil functional features.

Soil degradation in the tropics takes several forms. Erosion is the most charismatic manifestation, but soil structure losses due to excessive grazing/trampling, nutrient export as a result of low-input agriculture, and oxidation of SOM due to tillage operations all represent a depreciation of the natural capital that is central to the livelihoods of rural farmers. Emergy analyses have historically used soil organic...
matter (SOM) as the value-bearer for the entire soil system. However, due to the multiple degradation mechanisms present in tropical Africa, it was deemed necessary to extend the valuations of soil to other functional components.

The conceptualization of soil genesis patterns is largely due to the work of Hans Jenny in the 1940’s. His forcing function heuristic model, that includes climate, organisms, topography (relief), parent material and time (the cl.o.r.p.t. model), has been widely used as a template for quantitative assessments of the process (Amundsen et al. 1994). To date, models of soil genesis fall into two broad categories: qualitative, functional models, such as Jenny’s work, which generally lack explicit mathematical descriptions, and quantitative mechanistic models (e.g. CENTURY – Parton et al. 1994 or ORTHOD – Hoosbeek and Bryant 1994) that are extremely complex due to over-compartmentalization. The modeled described herein represents an effort to greatly simplify the dynamics of soil formation without losing the essential functional relationships.

METHODS

Emergy Simulation Models

Simulation models typically begin by diagramming the system of interest. Using the symbolic systems language (Odum, 1984) components and sources are linked to create a visual pattern of the organization of the system. Once a pictorial representation of the system has been achieved, the mathematical equations for how the components and sources interact can be rigorously extracted and simulated.

Flows in the simulation model generally represent energy or materials. However, emergy values can be simulated along with these flows. This allows the computation of transformity (or specific emergy) values to be computed for each compartment within the system simultaneously. Standard rules for simulation of emergy are shown in Figure 1. These rules (Odum, 1996; Tilley 1999) can be verbally stated as follows: emergy accumulates in a storage as long as that storage is growing. Emergy is exported...
only on flows from that storage that are used by other components in the system, or exported to the next larger system. Any flow that represents 2nd Law dispersal carries no emergy. However, when a storage begins to decline, emergy is lost along all pathways, including those that represent dispersal. In all cases, transformity (or specific emergy) is the ratio of emergy to energy (or mass).

The application of these rules to systems with recycle pathways was explored through the simulation of mini-models before application to more complex models designed to simulate soil genesis.

**Confidence Interval Estimation**

Transformity estimates represent static computations of a systems status in a single location. As such, they should be accompanied by some estimate of the variance of the prediction. In general, there are insufficient numbers of comprehensive studies of the same phenomenon in the same location to allow meta-analysis of parallel studies. In this work, an alternative is proposed. Monte Carlo, or stochastic, simulation techniques applied to the parameter estimates in the model can allow uncertainty to be propagated through the model. By assessing the final status of the system after each simulation, and compiling the results, variance estimates for desired information can be calculated. A diagram of the process is shown in Figure 2, illustrating the critical difference between this method and standard sensitivity analyses. Centrally, Monte Carlo simulations allow the interactive (or multivariate) effects of uncertainty to be predicted, whereas sensitivity analysis evaluates univariate uncertainty. In this work, the Monte Carlo process was written as a Visual Basic module that can be overlayed on any simulation model (or emergy table) constructed in Microsoft Excel.

In all cases presented, mean and standard deviation estimates for each parameter were used to create the probability density function from which random samples were drawn. Normal distributions were throughout for illustrative purposes, but any continuous distribution (e.g. Weibull, Gamma, Log-normal etc.) could be used. Random draws were based on the following function:

\[ Z = m + s \sqrt{-2 \log(U_1)} \cos(2\pi U_2) \]  

(1)
where $Z$ is a normally distributed random variable with mean $m$ and variance $s^2$, and $U_1$ and $U_2$ are random numbers between 0 and 1.

**RESULTS**

**Emergy Simulation with Recycling**

First, emergy simulation summary results from the simple single-tank model are presented in Figure 3. This chart shows the effects on steady state transformity, and the time required to reach steady state, due to changes in the dispersal:flow (proportion dispersal) ratio. The greater the proportion of total inflow dispersed (flow J4 in Figure 1), the larger the transformity of the material at steady state and the longer the time required to reach steady state. This is considered the expected behavior for emergy accumulating in a storage (Tilley, 1999), and illustrates the importance of distinguishing between yield and dispersal pathways in the system of interest.

The second model that was tested is only slightly more complicated than the single tank model used to formulate the emergy simulation rules. In this model, shown in Figure 4, the two tanks represent some low quality abundant resource (T) and an upgraded storage of the same material (Q). An example might be nutrients in the soil (T) and nutrients bound in plants (Q). One energy source (S1) drives the upgrade process, while another (S2) replenishes material dispersed from T. Export and dispersal pathways are included for both storages.

A simulation model of this system was constructed to include the emergy rules previously presented. However, as Figure 5a indicates, the transformity of the storage T, to which dispersed materials flow, behaves in an unexpected manner. Specifically, the transformity value appears not to be a function of the proportion of the inflow that is dispersed, which is the expected behavior established using the single
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The observed behavior indicates that steady state transformity is a function of the ratio between inflow and use (where use can exceed inflow because of the recycle pathway). This problem arises because it was previously assumed that no emergy flowed on the recycle pathway (and therefore, $E_mJ_4 = 0$), and, therefore, the emergy used to drive the upgrade process ($E_mJ_2$) is not replaced when the material is recycled. There is, as shown, an artificial decrease in $T_{rT}$ such that at steady state, the value of $T_{rT}$ is an artificial function of the inflow:use ratio:

$$T_{rT} = \frac{S_2}{J_2} \times T_{rS_2}$$

Figure 4. Simple two-tank model simulated to explore the dynamics of emergy in systems with material recycle pathways. Recycle is shown as dispersal from high quality storage ($Q$), where energy is degraded but materials are returned to their lower quality storage ($T$).

The proposed resolution of this problem is to explicitly account for the emergy value of the recycled materials. This model can be linked to a real system by expanding on the nutrient analogy. In the environment, nutrients are recycled to some larger storage at some lower concentration than the upgraded product. However, that concentration in the environment still represents a gradient from background states, implying that the storage has a transformity (i.e. it is higher quality). Therefore, in a material cycle, the emergy on the recycle pathway should reflect that quality, which can be computed by multiplying the
Figure 5. Transformity Output for simulation of energy with recycle. a) The response of steady state transformity to changes in the proportion of flow dispersal for a variety of input-to-use ratios under the standard emergy rules applied to the system in Figure 2. b) The response of steady state transformity to changes in the input-to-use ratio for a variety of proportion dispersal levels using new network emergy rules (note the different x-axis from 5a). c) The transformity of steady state transformity to changes in proportion dispersal using network emergy rules (as in Figure 3).
recycled material flow by the transformity of the destination storage (in the example model, Tr2*J4). We continue to assume, however, that no emergy is drained from the upgraded stock by the dispersal flow.

Using this approach, hereafter called the network emergy rule, the results presented in Figure 5b are achieved. The transformity of the storage is now dependant only on the ratio between the use and dispersal (proportion dispersal), as in the single-tank model (Figure 1), and not on the inflow to use (I:U) ratio. Note that the x-axes in figures 5a and 5b are different, with the axis in figure 5b presenting the ratio of inflow to use, and the character of the response indicating the independence of transformity from this ratio. Figure 5c shows the response of the steady state transformity to the change in the dispersal proportion (as in Figure 3), which replicates exactly the functional behavior of the single tank storage. Note that the geometry of the response is the same regardless of the input-to-use ratio, hence the presence of only one line.

**Topsoil Genesis**

*Model Configuration*

![Image of systems model of soil genesis in tropical grasslands and forests. Shown are the stocks of biomass (B), detritus (litter), soil organic matter (OM), nutrients (N), clay cation exchange capacity (Clay/CEC) and soil structure (SS). Sources are sun, wind, rain, nutrients in rain (Nrain), and parent material (PMat) and associated flows of clay (Clay/CEC) and nutrients (Nmin). Flows labeled “ox” are oxidation pathways representing dispersal and material recycling.](image)

Figure 6. Systems model of soil genesis in tropical grasslands and forests. Shown are the stocks of biomass (B), detritus (litter), soil organic matter (OM), nutrients (N), clay cation exchange capacity (Clay/CEC) and soil structure (SS). Sources are sun, wind, rain, nutrients in rain (Nrain), and parent material (PMat) and associated flows of clay (Clay/CEC) and nutrients (Nmin). Flows labeled “ox” are oxidation pathways representing dispersal and material recycling.
Figure 6 shows the diagram that was conceived to model topsoil genesis based on a review of the literature (Jenny, 1941; Bryant and Arnold, 1994; Young 1976; Amundsen and Tandarich 1994; Nye and Greenland, 1961; Bolker et al. 1997). The model, verbally, represents the use of three energy sources – sun, rain, and geologic inputs – in the process of creating saprolite or topsoil. The components in the model are vegetative biomass, detritus (litter), soil organic carbon (active and passive pools aggregated), soil nutrients, cation exchange capacity and soil structure. The model is designed to represent soil processes on a yearly basis, and model is simulated for 500 years. Several critical features of the model construction should be noted:

1) All interactions in the diagram are multiplicative unless otherwise stated. In general, associations between soil variables are understood only in a conceptual sense (e.g. the cl.o.p.r.t. model of Jenny, 1941), and little quantitative rationale was found in the literature for interactions that are more complex.

2) Biomass production is a function of sunlight, infiltration, nutrient storage and soil structure. It is not autocatalytic because of the long time increment.

3) There are three chemical oxidation pathways (i.e. organic matter dispersal). They are drawn from the storages of biomass, litter and organic matter, and are linear functions of those storages.

4) Nutrient content and cation exchange capacity (CEC) are functions of time and parent material quality. For the simulation results presented here, the quality of parent material is considered constant. CEC is measured in standard units cmol/kg of mineral soil, measured as the sum of exchangeable acidity and exchangeable bases during standard titrations. Nutrient content cannot exceed CEC (i.e. 100% base saturation).

5) Nutrient, organic matter and CEC are all reduced through leaching. Nutrients, however,
are retained in the system by the existing exchange capacity of clay, and - of central importance in highly weathered tropical soils - by the large effective exchange capacity provided by organic material.

6) Soil structure is created by the growth of plants, and by the litter humification process, which represents, among other organic consumption, the important activity of organisms such as termites and earthworms.

7) Erosion is a quadratic function of runoff (transport capacity) and a negative exponential function of vegetative cover (detachment capacity). Enrichment, the preferential entrainment of clay, silt, and organic material, is governed by an enrichment ratio in the model of 2.5. This value, gleaned from the erosion modeling literature (Byne, 2000) indicates that for each gram of soil eroded, the various enrichment components are proportionally augmented 250%.

8) Soil structure is a unitless storage where 1 represents maximal structure and 0 represents completely structureless soil (i.e. parent rock). This can be converted roughly to bulk density by dividing by 0.8. In simulating emergy, the energy value of the soil structure is defined as shown in Figure 7, where the vertical displacement of the soil (due to increased pore space) offsets the center of gravity of the original rock material by some height (\(h_{\text{diff}}\)), which can be translated into gravitational potential energy. The use of bulk density as a proxy for the nebulous quality “soil structure” ignores many of the inherent complexities of a soil physical condition (particle size hierarchy, macropores, structural shapes – Brady and Weil, 2002), but is the most quantitatively accessible measure of the ability of a soil to perform hydrologic and biological function. Moreover, the association between bulk density and other functional structural characteristics is widely

\[\text{Figure 8. Simulated output of soil genesis under tropical savanna conditions. All stocks are shown on the left y-axis except soil structure which is shown on the right y-axis.}\]
assumed (e.g. Biswas and Mukherjee, 1994). Furthermore, for the transformity to be computed, the chosen measure of soil structure must be convertible to energy units, which is the case for bulk density (using the method described in Figure 7) but is less readily computable for other potential measures.

**Simulation Results**

The simulation results for the mass storage values are shown for one scenario, a tropical moist savanna, in Figure 8. As shown, when all of the function soil components are absent (biomass, detritus, SOM and soil structure) it takes long period of time for steady state to be reached. Several key features should be noted:

1) SOM takes nearly 250 years to reach steady state, illustrating the value of that component. Biomass and detritus peak after less than 20 years (typical of grasslands).

2) Nutrients and exchange capacity initially decrease rapidly (relative to their long turnover times - \( \sim 1000 \) years) due to the lack of organic material to mitigate leaching effects, but stabilize once that stock stabilizes.

3) Soil structure requires nearly as long as organic matter to reach steady state despite the internal model assumption that bulk density can be created in 40 years. This reflects the intimate relationship between soil organic carbon and soil structure.

4) A steady state is reached in the system between the weathering rate, replenishing lost nutrients and exchange capacity, and the losses due to leaching and erosion. This output assumes a moderate quality parent material (30 cmol/kg clay and 50% base saturation). However, tropical systems often have highly weathered parent material resulting in lower quality geologic inputs, which in turn force ecosystems to be more efficient with nutrients.

*Figure 9. Emergy dynamics of the model under tropical savanna conditions. Biomass, litter and SOM transformity levels are shown on the right y-axis while soil structure transformity and nutrient and CEC specific emergy levels are shown in the left y-axis.*
Emergy Dynamics

When emergy is added to the model according the network emergy rule, transformity dynamics can be explored. These are shown in Figure 9 for the tropical savanna. Table 1 shows the transformity and specific emergy output for both forest and savanna ecosystems. Notable in the output:

1) Soil organic matter stabilizes at a transformity of 2.25E6 sej/J after 300 years. This value is approximately 4 times larger than previous computations (Odum 1996; Buranakarn, 1997).
2) Transformity values of nutrients and CEC were started at their anticipated steady-state specific emergy values because of effects on the dynamics of the rest of system due to the extremely long turnover times (~1500 years) of these stocks.
3) Soil structure has a transformity value (based on the energy calculation presented above) of 3.55E10 sej/J. This is due to the low energy storage represented in the vertical displacement, and the high environmental investment (and feedback potential).

Confidence Intervals

The Monte Carlo simulation technique was applied to the soil genesis model to explore the effects of uncertainty on the transformity estimates. Table 2 shows a selection of the parameter means and variances that were used for both forest and savanna simulations. The summary results are presented in Table 3, which shows the mean transformity values for each component and error bars representing one standard deviation from the mean. The probability distributions that were used to produce the computed confidence intervals were all normal, and based on literature values and estimates. The output (Table 3) shows the relative confidence in the transformity estimates for all components except soil structure, for which the standard deviation is larger than the mean. Soil structure had a higher mean value in forest soils (1.11E11 sej/J) than in savanna soils (5.14E10) both of which were higher than the computed value of 3.55E10 using the dynamic emergy approach without error propagation (Table 1).
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**DISCUSSION**

The examination of emergy dynamics in the context of a system with material recycling is an ongoing thread of research in emergy science. Buranakarn (1997) explored the emergetics of various recycling schemes within the economy (e.g. paper, glass, aluminum) and proposed the emergy retrograding concept that is central to this study. That is, when materials are recycled to a lower quality state they lose the embodied information that represents the upgrade in quality. However, because the stocks are still highly concentrated relative to the background states in the environment, the recycled material is not devoid of emergy. Simply put, flows of materials to the left in systems models represent a decrease in the specific emergy until the environmental base state is reached at which point the specific emergy is zero. Likewise, with dynamic simulation it was necessary to make the assumption that recycled materials maintain some emergy value; specifically they take on the transformity of the storage to which they are flowing. It should be noted that while the distinction between dispersal and recycle is clear in this conceptualization, these flows may be difficult to distinguish in real systems.

Exploration of the soil genesis model that was beyond the scope of this paper indicates that the model structure is generally sound, and sufficiently general to allow exploration of soil development under a variety of climatic conditions. However, the literature revealed a relative paucity of numeric or experimental data to validate the model. Those studies for which there were data were used to calibrate the model, making proper validation unfeasible. However, the model appears to conform well to the conceptual models of soil development, and matched calibration data effectively. The addition of model

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**Table 2.** Selected model parameter means and standard deviations as used in Monte Carlo simulation for transformity variance estimation.

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Mean Parameter Values</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Parameters</td>
<td>Savanna</td>
<td>Forest</td>
</tr>
<tr>
<td>Veg Biomass (g/m^2/yr)</td>
<td>3700</td>
<td>12200</td>
</tr>
<tr>
<td>Structural Litter (g/m^2/yr)</td>
<td>660</td>
<td>3700</td>
</tr>
<tr>
<td>Soil Organic Matter (g/m^2/yr)</td>
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<td>7000</td>
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<tr>
<td>Clay (%)</td>
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<td>30%</td>
</tr>
<tr>
<td>CEC-Clay (cmol/kg)</td>
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<td>30</td>
</tr>
<tr>
<td>Base Saturation (%)</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Sunlight (J/yr)</td>
<td>1.83E+06</td>
<td>1.83E+06</td>
</tr>
<tr>
<td>Rain (m/yr)</td>
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<td>2.20E+00</td>
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<tr>
<td>Weathering Rate (g/m^2/yr)</td>
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<td>0.024</td>
</tr>
<tr>
<td>Sunlight remainder (J/yr)</td>
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<td>1.83E+05</td>
</tr>
<tr>
<td>Runoff (m^3/m^2/yr)</td>
<td>1.10E-01</td>
<td>1.10E-01</td>
</tr>
<tr>
<td>Seepage (m^3/m^2/yr)</td>
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<td>Biomass Production (g/m^2/yr)</td>
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<tr>
<td>Litterfall (g/m^2/yr)</td>
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<td>850</td>
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<td>Soil Structure Creation (unit/yr)</td>
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<td>0.05</td>
</tr>
<tr>
<td>CEC of Organic Matter (cmol/kg)</td>
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<td>800</td>
</tr>
<tr>
<td>Transformity Sun (sej/J)</td>
<td>1.00E+00</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>Transformity Rain (sej/J)</td>
<td>3.10E+04</td>
<td>3.10E+04</td>
</tr>
</tbody>
</table>
flows to represent agriculture, forestry, and pasture will allow exploration of the behavior of the soil resource, and associated costs of human management. However, it is important to recognize that the system of soil genesis presented here ignores significant formative factors in landscapes: specifically the accumulation of eroded sediments in topographically lower pedons. The resulting catena (topographic soil sequence) has significant implications on the types of ecosystems and human systems that can persist at a site. By ignoring the larger spatial dimension of soil genesis (temporarily; there are plans to include inflowing sediments) there are risks of not adequately capturing the process.

One interesting feature of the emergy portion of the model output can be observed by comparing Tables 1 and 3. Table 1 represents the calculation of transformity using the deterministic approach while Table 3 shows the mean of the ~1000 Monte Carlo simulations that were done. For all stocks except soil structure, the values are nearly identical reflecting the stability of the model within the range of parameter values and the overall linearity of the model structure. However, the significant differences that exist between predicted values for soil structure indicate that this portion of the model may have some inherent bias or non-linearity that is unanticipated. The uncertainty in the soil structure parameters in the model, due to the scant quantitative literature on the subject, also leads to extremely large standard deviation estimates (i.e. greater than the mean value) around the predicted mean. This uncertainty should be reflected and propagated in any application of the transformity values presented here.

The implications of the Monte Carlo approach to propagating error can be widespread. First, the addition of confidence intervals to each transformity estimate will help silence critics of the approach that suggest that the lack of statistical rigor compromises any conclusions. Second, and most importantly, the output from each analysis can be assessed more effectively when, for example, competing policy options have variance bounds. Since Monte Carlo techniques can be applied to any spreadsheet analysis, not just dynamic simulations, the potential to integrate this process into standard protocols is large, and the method is remarkably simple. It is important to note, however, that this technique can only address uncertainty with specified model parameters. It cannot address the larger questions of uncertainty that arise with the manner in which the model is formulated. Uncertainty because of errors and omissions in the diagram, a source of considerable potential error, remain unknown.

**CONCLUSIONS**

Three undertakings form the foundation of this research. The first is an effort to understand and devise rules for the simulation of emergy in systems that contain material cycles. This subset of systems models is not adequately addressed by the current emergy dynamics rules. The second part of the research was the description and simulation of a simplified soil genesis model to explore the dynamics of the critical soil stocks and their transformities. Critical soil stocks were considered to be vegetative
biomass, litter (unincorporated organic material), soil organic carbon, nutrients, cation exchange capacity and soil structure. The third portion of the work was the application of error propagation tools to the simulation. A Monte Carlo simulation approach was proposed not only for simulation models, but for all emergy tables as a means for assessing the confidence in the output and for enhanced ability to interpret analysis results.

Central conclusions are:

1) Emergy dynamics in systems with material recycle pathways require the addition of network emergy rules to the standard emergy simulation rules for realistic results. The network emergy rule simply allows the material on a recycle (dispersal) pathway to embody emergy. The specific emergy of the recycle flow is set at the level of the storage to which the flow is directed.

2) The soil genesis model proposed herein appears to capture the behavior expected in the system. Additional modules to allow human management and extractive harvest (i.e. farming, forestry, animal grazing) will allow the dynamics and emergy costs to be explored further.

3) Transformity estimates were made using the network emergy rules applied to the soil genesis model. Values for soil structure were 3.35e10 sej/J based on an energy computing method that accounts for the gravitational potential energy that accrues when saprolite is formed. Biomass and litter transformities were in the expected range, but the transformity for soil organic matter was found to be 4 times larger than previously computed.

4) The propagation of parameter uncertainty through the model was successfully undertaken, and confidence intervals for the transformity estimates were computed. Simple overlay modules for Microsoft Excel spreadsheets were constructed that can be applied to any simulation model or emergy table for propagating error. Additionally, any probability distribution can be used in this manner, though normal distributions were assumed throughout.

5) The discrepancy between the predicted transformities using the deterministic simulation approach versus those gleaned from the Monte Carlo simulation must be explained by non-linearities in the model structure, and potential instability in the model due to the large uncertainty associated with the soil structure parameters.

REFERENCES


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