A Rudimentary Mechanistic Model for Soil Production and Landscape Development in Qazvin Area, Northwest of Iran

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Abstract: In this research, a primary and basic soil production model was utilized. This model has considered soil formation in a landscape conditioned by a digital elevation model. The model demonstrated the application in quantifying pedogenesis. The model stated the changes in soil thickness with respect to time duration; it depends on physical weathering rate of rock, the loss due to chemical weathering and transport of the soil through erosion. The rate of physical weathering or lowering of the bedrock surface is represented by an exponential decline with soil thickness. The movement of materials in the landscape was characterized by diffusive transport, leaching and dissolution. Dissolution, authigenesis and hydration of soil were considered as losses by chemical weathering. The model was solved numerically using finite difference approach and applied to a digital elevation model. The obtained results showed that the soil thickness is highly related to the profile curvature. The effect of climate, rock type and land management were presented by different combinations of weathering rate and erosive diffusivity. The model also exhibits the characteristics of a nonlinear dynamic system. Simulation of soil development in Qazvin plain for different time scales was illustrated. Finally, results showed promising progress in evaluation of quantitative pedogenesis.

Key words: Pedogenesis · Quantitative Analysis · Soil Production · Landscape · Digital Elevation Model · Exponential Decline

INTRODUCTION

Soil is not renewed during length of human life, so it should be protected. Soil evaluation resulted in a method of using lands, agriculture activities and climate changes. In order to combine agriculture activities including various uses of land and other management activities for the soil protection, one has to consider the effect of these activities and environmental changes on soil evaluation. If possible, soil formation and evaluation has to be predicted by means of modeling. The quantitative modeling allows us to evaluate the long-term effects of human activities and environmental changes on soil and landscape. There has been a growing development of applying empirical quantitative techniques to predict soil properties from landscape attributes at specific sites, so-called digital soil mapping [1, 2]. The ever increasing environmental problems have created a need for a better understanding of soil landscape relationships. In the past, traditional soil survey methods have been criticized for their qualitative characters. In response to these criticisms, quantitative modeling has been proposed. Hoosbeek and Bryant [3] pointed out about quantitative models which are related to numerical observations. It was suggested that a mechanistic model was suitable for this work. Minasny and Mc Bratney [4] presented a rudimentary mechanistic model that preceded the other models and considered the soil formation at the catena scale for time periods greater than 10 years. In their earliest form, quantitative models mainly took on an empirical approach, related soil formation to soil processes, such as erosions, soil organic matter, decomposition, mineral dissolution and other principals. Most pedogenetic models have considered the chemical reactions and physical processes in the soil at a single location in a landscape or at a horizon or a pedon scale.

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199
Huggett [5] presented a model with the view point of soil-landscape system as staring, transforming and transmitting "power plants". He has treated soil as a three-dimensional body of a soil-landscape system. Slater et al., [6, 7] presented a framework for integrating soil-landscape and pedogenetic models in a three-dimensional context. Also, special attempts have been made to formulate mechanistic models for profile development at a particular location in the landscape [7]. This profile model is then coupled with a slope evaluation processes forming an integrated model. Heimsath et al. [8] integrated a soil production function into their landscape evaluation model. They were able to simulate soil evaluation across a landscape and verify it with field data obtained from Tennessee valley. Follain et al. [9] presented a basic mechanistic model that considered soil formation spatially at the catena to landscape scale. They have presented a numerical study and showed numerical application of the model.

In this study, the correlation between pedogenetic and landscape with soil changes process with respect to time were considered. The purpose of present study was to introduce a simple mechanistic model for soil production at the catena scale in the landscape of Qazvin area in Northwest of Iran and then to illustrate the application of the model in quantifying pedogenesis.

**MATERIAL AND METHODS**

**Theory:** The present model has considered a landscape with surface elevation \( z \), soil thickness \( h \) and soil-bedrock interface \( e \) along a horizontal \( x \)- and \( y \)- axes (Figure 1).

Changes in soil thickness with respect to time duration depends on the processes of formation of soil from weathering of bedrock, the loss of materials by chemical weathering and the transport of soil by erosion. The changes in simple mathematical form is shown as follows:

- Change in soil thickness = weathering + in flow – out flow

The soil formation model in the landscape is based on the studies carried out by Minasny and Mc Bratney [10, 11]. The model was based on mass balance, where the changes in soil thickness with respect to time duration depends on the processes of:

- Physical weathering of bedrock
- The loss of materials by chemical weathering and
- The transport of soil by erosion.

Soil formation depends on the rate of breakdown or weathering of the underlying parent materials under physical, chemical and biological processes. The changes in soil elevation included in changes of soil thickness, bedrock weathering and soil weathering with respect to time duration. The parameters involved in soil elevation is defined in the following equation:

\[
\frac{\partial h}{\partial t} + \frac{\rho_e}{\rho_s} \frac{\partial e}{\partial t} = -\nabla q \tag{1}
\]

Where \( h \) is the thickness of soil, \( \frac{\partial e}{\partial t} \) is the rate of bedrock weathering, \( v = \left( \frac{\partial}{\partial x}, \frac{\partial}{\partial y} \right) \) is Del operator" a partial derivative vector of transport of soil material, \( q \) is the flux.

![Fig. 1: Model for soil formation in Qazvin landscape](image)
density, \( \rho_s \) is the density of soil and \( \rho_r \) is the density of rock. Heimsath et al., [12] have suggested that the rate of physical weathering of bedrock has an exponential decline with soil thickness:

\[
\frac{\partial e}{\partial t} = -\rho_o \exp(-kh)
\]  

(2)

Where \( P_o \) [m year\(^{-1}\)] is the potential (or maximum) weathering rate of bedrock and \( k \) [m\(^{-1}\)] is an empirical constant. The reduction of weathering rate with thickening of soil is related to the exponential decrease of temperature amplitude with increasing depth below the soil surface and also the exponential decrease in average water penetration for freely-drained soils. The function of diffusivity and slope of the curvature are included in the following equation:

\[
\frac{\partial h}{\partial t} = -\frac{P_o \frac{\partial e}{\partial t}}{\rho_s} + D \frac{\partial^2 z}{\partial x^2}
\]  

(3)

The above equation shows that regolith production (for the larger \( h \) which is indicating thicker cover) depends on the weathering rate (for the lowering of the rock weathering front of \( e \)) and removed material. The last term of the above model as function of diffusivity \( (D) \) and second derivative which represents the of slope of curvature \( \frac{\partial^2 z}{\partial x^2} \). Ahnert [13] described the critical thickness model as a piecewise function of either:

For \( h < h_c \), \( \frac{\partial e}{\partial t} = P_o (1+k h/h_c - h/h_c^2) \)  

(4)

or

For \( h > h_c \), \( \frac{\partial e}{\partial t} = P_o k_1 \exp (h - h_c) \)  

(5)

Where \( h_c \) is the critical thickness, \( k_1 \) is the weathering constant which determines the relative magnitude of weathering when greater than \( h_c \) compared to bare rock. As an alternative, \( h_c \) presents a continuous function which describes the weathering process:

\[
\frac{\partial e}{\partial t} = -(P_o \exp(-k_1 h) - \exp(-k_2 h)) + P_o
\]  

(6)

Where \( k_j \) is the weathering rate constant when \( h \leq h_j \) and \( k_j \) is the rate when \( h = h_j \) and \( P_o \) is the weathering rate at steady-state condition [m year\(^{-1}\)] for the condition \( k_j < k_j \).

The critical thickness where weathering is optimized; as stated as follows:

\[
h_c = \frac{\ln(k_2/k_1)}{k_2 - k_1}
\]  

(7)

**Methods:** Field investigation and geographic location of 1000 sampling points were recorded by GPS. Thereafter, by integration of the soil, geologic and topographic maps, have resulted in 50 topography units in the study area. Topographic maps were digitized using AutoCAD Civil 3D, 2010 and Arcview GIS software (Figure 2).

Here, the initial soil thickness with a uniform thin soil cover of 10 cm was assumed, since information on the initial soil condition was not available. Therefore, an initial thickness that corresponds to liner function of slope or curvature was a good start. It is a fact that there is a relationship between topography and soil thickness that should be considered. Thus, starting with a uniform soil thickness, bear the weakness of our assumption. Parameters of the model used for calculation and implemented to this simulation are summarized in Table 1.

![Fig. 2: Digital elevation model of the landscape of Qazvin plain, Northwest of Iran](image-url)
Table 1: Parameters of the model used in the present study

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (m² year⁻¹)</td>
<td>0.0003</td>
</tr>
<tr>
<td>P₀ (mm year⁻¹)</td>
<td>0.25</td>
</tr>
<tr>
<td>P₅ (mm year⁻¹)</td>
<td>0.05</td>
</tr>
<tr>
<td>k (m⁻¹)</td>
<td>4</td>
</tr>
<tr>
<td>k' (m⁻¹)</td>
<td>6</td>
</tr>
<tr>
<td>ρ₁ (kg m⁻³)</td>
<td>2600</td>
</tr>
<tr>
<td>ρ₂ (kg m⁻³)</td>
<td>1300</td>
</tr>
</tbody>
</table>

It is assumed that the density of rock and soil (ρ₁, ρ₂) and diffusivity (D) are stable from the view point of time and space. The values of these parameters are based on field survey investigation of the study area and experimental result of laboratory finding of the collected samples. It is also obtained from literature that were available and trials to the model to take realistic values. The simulation assumed to be a closed system, where materials cannot be moved outside of the system. This ensures a mass balance. The simulation also considered the area has a uniform parent material, climate and influence of organisms. The most important variable factors were topography and time.

RESULTS AND DISCUSSION

The obtained results of present study showed that environmental factors such as climate and geology had sensible influence on soil production in the study area. Result showed that soil accumulation in the valleys and soil erosion on the ridges has occurred. Soils from the upper slope are transported down-slope by erosion processes and fill the gullies. The soil appears to be thicker in the gullies than along the valleys. This is caused by the assumption of uniform diffusive transport across the landscape. The soil thickness is strongly correlated with curvature. The effect of climate, rock type and land management is illustrated by different combinations of weathering rate and erosive diffusivity. The model also exhibits the characteristics of a nonlinear dynamic system (Figure 3).

This figure obtained by using equation 6 with $P_o = 0.25 \text{ mm year}^{-1}$, $k = 6 \text{ m}$ and $P_5 = 0.05 \text{ mm year}^{-1}$ with critical thickness $h$ at 20 cm. The weathering of bedrock was fastest under an intermediate thickness of soil and slower under exposed bedrock or under thick mantled soil. This was because of weathering required the presence of water and under thin soil or exposed bed rocks water cannot penetrate and there by tends to run off and hence reducing the chance of the chemical weathering of the bed rocks. Figure 4 shows the evolution of soil thickness in the landscape after 1000, 5000, 10000, 20000, 30000 years of simulation. Starting from an initial uniform soil thickness, the landscape evolves into areas with high variation of soil thickness. The model was tested to simulate 30,000 years using the parameter value listed in Table 1. The simulation assumed a close system to ensure a mass balance.

Figure 5 depicts the soil thickness with respect to time for five selected points along a transect lines. Soil at points A and B remained relatively thick with respect to time duration as they are located in concave relatively flat areas, whereas at points D and E with steep slopes, the soils are relatively thin.

![Fig. 3: A model for the soil weathering function](image)
Fig. 4: Evolution of soil thickness in the landscape after 1000, 5000, 10000, 20000, 30000 years of simulation.

Fig. 5: Soil thickness as a function of time for the selected points in the landscape

The mean value of the soil thickness for the whole area shows a slow increase in the soil thickness at initial stage, due to weathering model which requires a critical thickness around 20 cm. After 20,000 years, the rate of soil formation starts to decrease proportionally. The simulation assumed the area had a uniform parent material, climate and influence of organisms. The most important stated factors are topography and time. Topography drives the soil redistribution in this landscape.
CONCLUSION

The rudimentary mechanistic model for soil formation in a Qazvin landscape has been presented and the possibility of nonlinear dynamic system investigated. In this study, application and the results from the projected model are illustrated. It was assumed that the material diffusivity coefficient (D) was always constant in landscape from the viewpoint of time and place and it was independent of slope and curvature. However, according to the obtained results, there was one nonlinear relationship between curvature and soil depth and a dependency of D on the gradient that was clearly affected by the curvature. Nonlinear diffusivity was found and a nonlinear relationship between sediment flux and gradient were observed. As the soil develops, the gradient and curvature will also change and consequently D (which is assumed to be constant) can change. In spite of the assumptions and limitations, the results were promising in terms of quantitative modeling of pedogenesis. Application of the model can include a prediction of the affect of land management on soil development and the suggestions of management practices in a landscape. However, to use and validate the model in the landscape more field and laboratory work is required to collect data to estimate the exact parameters of the model. For further researches, model needs to be developed and improved for combination of the other major pedogenetic processes and take into the account nonlinear, soil system.

REFERENCES