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Ronald Amundson
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1

Introduction to Soils

> Certainly no clear line of demarcation has as yet been drawn between species and sub-species . . . or again between sub-species and well-marked varieties, or between lesser varieties and individual species. These differences blend into each other in an insensible series; and a series impresses the mind with the idea of an actual passage.[1]
>
> Charles Darwin, *Origin of Species*

1.1 Introduction

The soils that blanket most of the Earth's land surface are a membrane through which water, solids, and gases pass or with which they interact. These processes impact global climate, regional and global hydrology, and water chemistry, and the soils themselves are stores of largely unknown biological diversity that are only now being examined in an exploratory manner. Their importance to the functioning of the planet, and to human outcomes, makes it an exciting time to study them and their processes.

Pedology[2] is a natural science that concerns itself to a great extent with the biogeochemical processes that form and distribute soils across the globe. The word, and the science, originated during the scientific expansion of the nineteenth century,[3] a period of intellectual innovation that resulted in the development of geology and other branches of the natural sciences. Of course, soil had been examined by farmers, early scientists, and philosophers for thousands of years prior to the 1800s but primarily as a medium for plant growth and other agricultural or industrial uses. It was the epiphany of Russian and American scientists[4] that soil is a three-dimensional component of the Earth's surface, and that it is predictably distributed in relation to certain environmental and geological factors, that elevated the study of soil into a bona fide branch of science.

Soil is the object of study in pedology. While the science of pedology has a broadly accepted definition, there is no precise definition for soil as a three-dimensional object, nor is there likely ever to be one. The reason for this paradox is that soil is part of a continuum of materials at the Earth's surface.[5] At a soil's base, the exact line of demarcation between "soil" and "nonsoil" will continue to elude general agreement because the chemical and physical changes induced by pedogenesis disappear gradually, commonly over great vertical distances. Similarly, an identical problem confronts anyone attempting to delineate the boundary between one soil "type" and another. Soil properties, such as horizons, commonly change gradually and continuously in a horizontal direction, which leads to a

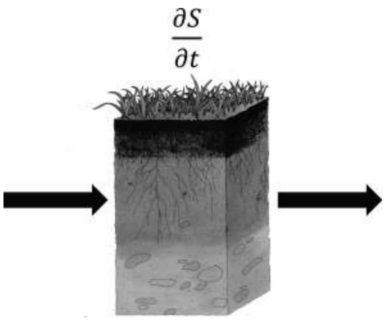

Figure 1.1 Schematic view of a soil, an open chemical system. Mass and energy enter and exit, causing changes to the state of the system over time.

view that the Earth possesses an infinite variety of soils.[6] A science with a “poorly” defined object of study is not peculiar to pedology. As Charles Darwin recognized in the *Origin of Species*,[7] an exact definition of a species, or a living being,[8] may elude a biologist, yet this has in no way hindered profound advances in our understanding of life.

To contend with the soil continuum, scientists partition it, albeit arbitrarily, into systems that suit the need of the investigator. Systems are human constructs that confine our focus and allow us to develop quantitative tools to evaluate a portion of the soil continuum. These systems are open to their surroundings and allow the passage and transfer of energy and matter (Figure 1.1). The properties inside a physical system vary in response to certain sets of factors: the initial state, the surrounding environment, and time.[9] The formulation of soil systems, and their dependence on sets of factors, constitutes the paradigm of pedology that was first formulated in general terms by the visionary Russian scientist V. V. Dochuchaev[10] and later cast into a more formal theoretical framework by the American Hans Jenny.[11] These concepts about soils also have a direct bearing on our understanding of ecosystems (because soil is a key part of terrestrial ecosystems). This theory ultimately provides a definition of soil that, while not precise in identifying its boundaries, is consistent with this theoretical framework: *“*soil is those portions of the earth’s crust whose properties vary with soil forming factors.*”*[12]

This definition of soil recognizes it as a natural component of nature. At a finer scale (i.e. the nature of what is within the system), soils have been described as “multicomponent, multiphase, open systems that sustain a myriad of interconnected chemical reactions, including those involving the soil biota.”[13] Later, the chemical and mineralogical makeup of the solid phase will be examined. Likewise, the enormous importance of biota for soils will be discussed under several topics, particularly in terms of their effect on the C cycle. Finally, the interaction between the inorganic and organic components will be examined through the process of weathering, and its chemical and physical implications for soil characteristics will be evaluated. Throughout, however, the focus will be on properties and processes observable *in situ* in nature, and thus, some of the microscopic and molecular details will be bypassed in order to begin to appreciate the more macroscopic spatial patterns found in nature.

1.2 Factors Defining the Soil System

The soil system, and the factors that define it, will now be elucidated to understand how soils form and how they can be quantitatively examined. Hans Jenny applied principles from the physical sciences to the study of soil systems and soil formation. Briefly, Jenny recognized that soil systems (or if the above-ground flora and fauna are also considered, ecosystems[14]) exchange mass and energy with their surroundings and that their properties can be defined by a limited set of independent variables. Based on comparisons with the physical sciences, Jenny's state factor model of soil formation states that:

$$\underbrace{Soil/Ecosystems}_{\substack{dependent\\variables}} = f(\underbrace{initial\ state\ of\ system, surrounding\ environment, elapsed\ time}_{\substack{independent\\variables}}) \tag{1.1}$$

where the terms on the right-hand side of the equation constitute independent variables, which, when combined with the indeterminate function *f*, define the state of the system. The somewhat generic variables can be further refined, in the case of soil systems, as a result of innovations by Dokuchaev and others. Their work identified a set of more specific environmental factors that encompass the generic factors listed earlier:

$$\mathrm{Soils(S)/Ecosystems(E)} = f(\underbrace{climate(cl), organisms(o)}_{\substack{surrounding\\environment}}, \underbrace{topography(r), parent\ material(p)}_{\substack{initial\ state\\of\ soil}}, time(t), \ldots) \tag{1.2}$$

The variables on the right side of Eq. (1.2), the so-called "soil-forming factors,"[15] have these important characteristics: (1) they are independent of the system being studied[16] and (2) in many parts of the Earth, the state factors vary independently of each other (though, of course, not always). As a result, through judicious site (system) selection, the influence of a single factor can be observed and quantified in nature.

Based on the characteristics of the factors discussed earlier, Jenny cast Eq. (1.2) into differential form, opening some important conceptual and quantitative avenues:

$$dS = \frac{\partial S}{\partial cl}dcl + \frac{\partial S}{\partial o}do + \frac{\partial S}{\partial r}dr + \frac{\partial S}{\partial p}dp + \frac{\partial S}{\partial t}dt \tag{1.3}$$

where the quotients on the right side are the partial derivatives of the functions relating any soil property to that independent variable (e.g. $\frac{\partial S}{\partial factor} = f'(\mathrm{factor})$).

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The goal of many biogeochemical studies of soil is to empirically determine the form of the function *f*(factor), since these functions, as Jenny pointed out, cannot be reliably determined on strictly theoretical grounds. In order to determine the nature of these functions in the field, a series of sites must be selected in which only the variable of interest is allowed to change, and other variables are held constant. Equation (1.3) provides two ways in which other variables may be "held constant." First, the absolute range in a factor (∂ factor) can be held at 0, eliminating confounding impacts from this variable (e.g. a series of sites, all the same age but in different climates, could be used to examine the effect of climate on a soil property). Second, a variable may be "held constant" in a field study if its partial derivative $(\frac{\partial S}{\partial factor}) \cong 0$. For example, in the case of soil C, C is strongly dependent on time, but it reaches steady state in approximately 10^3 to 10^4 years. Thus, if the effect of another factor is of interest (e.g. climate), a series of sites in differing climates and of differing ages (as long as the sites are at steady state) may be used to examine the effect of climate.

A second aspect of the differential form of the state factor equation (Eq. (1.3)) is that it is observationally possible (though certainly a considerable effort) to determine the relative importance of individual factors for a given soil property through a series of single-variable studies, so that the absolute and relative importance of $(\frac{\partial S}{\partial factor})$ for all state factors on a soil property may be determined. To date, this has been only partially achieved, but with growing data sets obtained using a state factor concept (combined with multivariate statistical analyses and emerging advances in data science), it may be possible to begin to conduct and construct such comparisons if the data have been properly collected. The current "Critical Zone" research program of the National Science Foundation consists of a series of field sites specifically selected to examine the effect of an array of the state factor variables (Figure 1.2).

One criticism of Eq. (1.3) that has been raised by a few is that it has never been solved. This apparently springs from the fact that there is indeed no single numerical

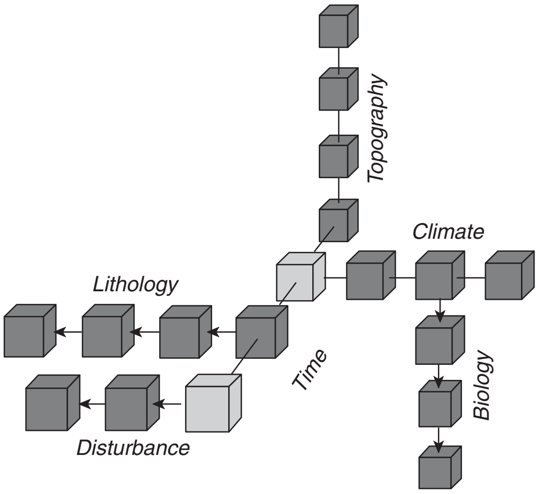

Figure 1.2 Conceptual design of the Critical Zone Observatory network. A number of sites, in varying state factor space, will allow the development of quantitative functions. From S. L. Brantley et al., *Frontiers in Exploration of the Critical Zone*. Report of a workshop sponsored by the National Science Foundation, October 24–26 (2005), Newark, DE, 30p.

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Table 1.1 The major factors of soil and ecosystem formation, and a brief outline of their characteristics

State Factor	Definition and Characteristics	Common Parameterization
Climate	Regional climate	Mean annual temperature (^{0}C), mean annual precipitation (mm)
Organisms	Potential biotic flux into system	Very few studies
Topography	Slope, aspect, and landscape configuration	slope (%), curvature (L^{-1})
Parent Material	Chemical and physical characteristics of soil system at t = 0	Chemical/mineralogical content
Time	Elapsed time since system was formed or rejuvenated	yr^{-1} or Ky^{-1}
Humans	A special biotic factor due to magnitude of human alteration of earth and humans' possession of variable cultural practices and attitudes that alter landscapes	Very few studies

model to describe the effect of all factors on any given soil property, or an entire soil, for the whole of the planet. Such a goal still is, and will likely remain, elusive. However, this view does not account for the growing number of solutions for specific locations and for specific properties – especially for climatically and societally important soil properties such as carbon and nitrogen. A goal of this book is to illuminate how one can analyze and use data effectively, and the following text will include some examples of solutions to Eq. (1.3) and what they mean for understanding soils in global processes.

Table 1.1 provides a brief definition of the state factors of soil formation and some ways in which they have been numerically or qualitatively represented. A field study designed to observe the influence of one state factor on soil properties or processes is referred to as a sequence: for example, a series of sites that have similar state factor values except climate is referred to as a climosequence. Similar sequences can be, and have been, established to examine the effect of other state factors on soils. A review of soil state factor studies was presented by Birkeland.[17] A set of papers discussing the impact of Jenny's state factor model on advances in pedology, geology, ecology, and related sciences is presented in Amundson et al.[18]

The state factor approach to studying soil formation is an effective quantitative means of linking soil properties to important variables[19] and is a way of designing experiments. There is a large and growing assemblage of soil data for the USA and the globe. As data acquisition and analytical tools improve, these data are being more widely examined for insights into factorial relationships. A challenge to uncovering clear principles, such as dependence of a property on climate, is that data sets may also have enormous ranges of lithologies, topographic positions, soil ages, land use, etc. that obscure the signal of, for example, climate.

One of the most commonly investigated state factors is climate. Climate has a first-order control on many of the processes that will be examined in this book, particularly C cycling, chemical weathering, and hillslope soil processes. In a number of instances, using large data

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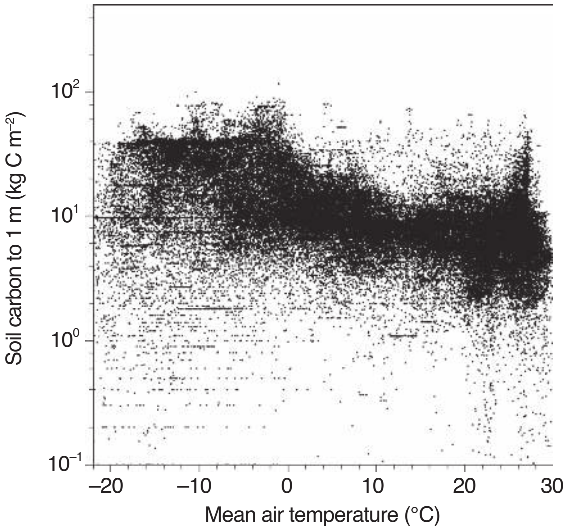

Figure 1.3 Scatterplot of soil C as a function of mean annual temperature, as compiled from large global soil data sets. C. D. Koven et al., Higher climatological temperature sensitivity of soil carbon in cold than warm climates, *Nature Climate Change*, doi: 10.1038/NCLIMATE3421 (2017).

sets spanning significant climate gradients, where other variables were not held constant, the climate impact still emerges, though with more variation due to the secondary impacts of the remaining state factors. For example, recently Koven et al.[20] used two large global soil databases to explore the temperature sensitivity of soil C storage to temperature (Figure 1.3). The plot shows that as temperature increases, soil C decreases, because, as will be discussed later, decomposition rates correspondingly increase. The results are statistically significant, but the "noise" in the trends reflects variations in rainfall, slope position, etc. By carefully designing a study to control for variations in other state factors, one can more clearly observe the effect of the variable of interest.

An ideal location to design natural experiments is the midcontinent of North America. There, rainfall and temperature vary systematically with latitude (T) and longitude (P). Additionally, large areas have similar parent materials and ages, so that the effect of climate on specific soil properties of interest can be determined. Jenny[21] recognized this during his first visit to the area as part of the International Congress of Soil Science field tour in 1927, and immediately upon his appointment as assistant professor at the University of Missouri, he began assembling climate data and previously published soil N data for the USA and Canada to test the hypothesis (and the relations) between climate and N in soils. Jenny's research, and that of others who followed, illustrates two important ideas emphasized throughout this book: (1) the power of state factor gradients to understand patterns and rates of soil processes, and (2) the fact that data to address many questions already exist in libraries and now, of course, more frequently at one's fingertips on the Web. Jenny's award-winning original research was done with climate data and soil analyses that had been published at the time, but now the amount of information completely dwarfs that which was available 100 years ago.

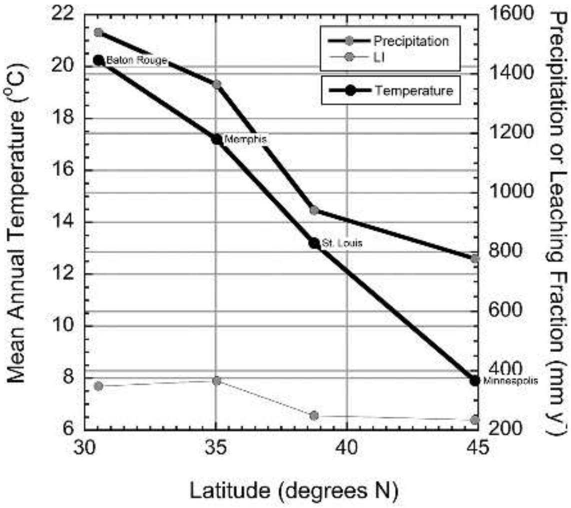

Figure 1.4 Annual temperature, precipitation, and calculated water balance vs. latitude along the Mississippi River corridor. Data from NOAA and WorldClimate.org.

One of the gradients that Jenny explored is a N–S transect from Wisconsin to Mississippi (which he called "humid prairie soils – silt loam"). Subsequent research, which we will begin to discuss here and return to later in the book, has followed to focus on the chemical weathering in soils along this same transect. The soil transect follows the loess-covered uplands just east of the Mississippi River corridor, loosely traced along its entirety by US Highway 61.[22] Climatically, temperature declines to the north, as does precipitation. Jenny recognized that the water balance (he used a "humidity index" = precipitation/saturation deficit of air) was largely similar along the gradient, and thus, the climatically driving variable can be considered to be temperature. Since Jenny's work, other metrics for water balance have been developed, and in Figure 1.4, the *leaching index*, or the total of monthly precipitation that exceeds evapotranspiration (using the Thornthwaite model), is shown for four major cities along the transect, confirming that available soil water for leaching is very similar, but the temperatures vary greatly.

Figure 1.5 shows Jenny's soil N data, for the upper 15 cm, for uncultivated sites from Wisconsin to Mississippi. The results show that N (or if one multiplies by approximately 10 (C/N ratio), the C%) increases with decreasing temperature. Later, we will see that this is a balance of N and C inputs and losses controlled by climate. In the midcontinent, transects can also be developed along a roughly E–W direction, where temperature is constant and rainfall changes. Finally, by taking somewhat NW to SE transects in some locations, precipitation can be held constant while temperature changes.[23] Jenny and others have used these opportunities to disentangle the effects of temperature and precipitation on soil C storage.[24]

More recently, geoscientists have quantified the total soil chemical changes along the Mississippi corridor gradient.[25] As we will learn, most of the mass of soils consists of primary silicate minerals, which undergo slow rates of chemical alteration to release biogeochemically

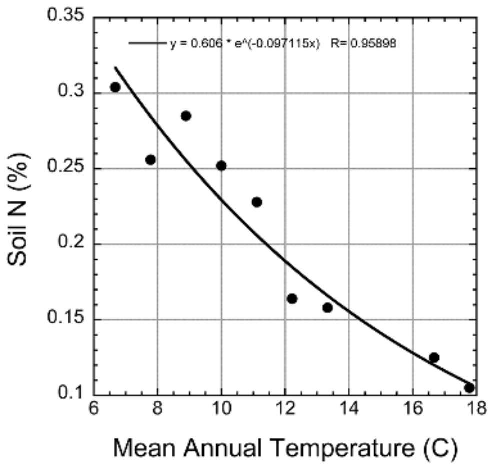

Figure 1.5 Soil N (upper 30 cm) vs. mean annual temperature. Data from H. Jenny, A study of the influence of climate upon the nitrogen and organic matter content of the soil, Missouri Agricultural Experiment Station Bulletin, 152 (1930).

important elements, such as Ca, which are an important part of many biochemical mechanisms. Also, it will be shown that it is more accurate to compare the concentration of an element that can be chemically released and removed with that of an element that is insensitive to removal (Ti). The authors calculated the CaO/TiO_2 ratio for the entire soil profile at 22 sites along this gradient (Figure 1.6). The results show that from the northernmost to the southernmost site, the ratios of CaO to TiO_2 declined from 1.7 to 0.4. As discussed, the amount of precipitation that falls and moves through the soils each year is roughly the same at all sites, due to higher evapotranspiration rates with increasing temperatures. However, the temperature, duration of warm seasons, and associated biological activity increase greatly with increasing temperatures. These changes all facilitate chemical weathering, which is reliant on (1) temperature and (2) acidity, in addition to water flux. While it might be tempting to compare how both N and Ca/Ti change with temperature by examining the first derivative of the exponential models' fit through the data, this is not an accurate analysis, in that the soil N is roughly at steady state (a constant value), while the Ca/Ti ratios continue to change (albeit slowly) with time. The original climate sequence that Jenny exploited continues to be used for other environmentally relevant questions that are important today.

1.3 Summary

Pedology is a science that is commonly observational (e.g. field-based observations of long-term "natural experiments") rather than experimental in nature, concerned with the origin and functioning of soils in place on the landscape. While experimentation, and concepts from experimental sciences, informs our understanding of soils, the vast expanse of time

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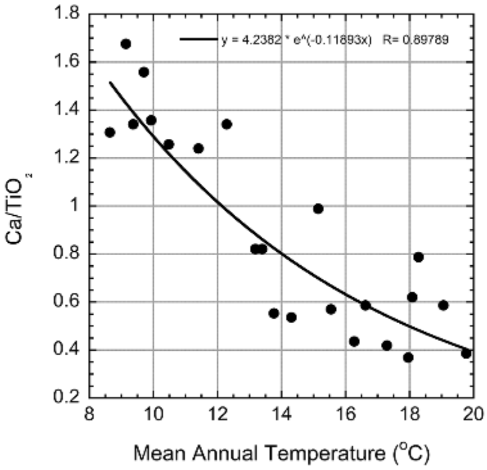

Figure 1.6 The Ca to Ti ratios of soil profiles along a latitude gradient along the Mississippi River. Data from D. R. Muhs et al., Impact of climate and parent material on chemical weathering in loess-derived soils of the Mississippi River Valley, Soil Science Society of America Journal, 65, 1761–1777 (2001).

required to form soils requires pedologists to develop tools, concepts, and modes of scientific enquiry for problems not always confronted in the lab.

Pedology, like soil itself, is part of an intellectual continuum. There is no clear demarcation between pedology and related branches of the natural sciences, particularly geology and ecology. In many ways, pedology has as much in common with these sister sciences as with the "traditional" branches of the soil sciences such as physics, chemistry, etc., which are primarily experimentally driven.

The conceptualization of soil as a physical system, controlled by an array of factors that are independent of the system itself, is a powerful tool that allows one to develop and explore the mathematical relationships between these factors and soil properties of interest. These relations can then be useful, alone or with other relations, in ultimately understanding how soils function and are distributed.

1.4 Activities

1.4.1 Soil in Current Events

To appreciate the enormous importance of soil to society, conduct a web search of "soil in the news." For example, the *New York Times* presently maintains a compilation of recent soil-related articles under the heading "Soil." Pick three news items, read them, and provide a paragraph discussion of how the state factor theory may be relevant to the issues. In 2020, the following three issues are chosen as examples of "soil in the news."

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China's Rover Finds Layers of Surprise Under Moon's Far Side

This article reports on the results of ground-penetrating radar analysis of the *regolith* in a crater on the far side of the moon (look up, and define, the concept of regolith). The researchers found over 40 m of regolith, or soil, over bedrock. This soil has been formed over the eons by meteor impact and subsequent degradation of the moon's surface.

What are the values of common factors of soil formation for the moon, and, most importantly, what *additional* state factors might be important be in this unique planetary setting?

"Earthworm Dilemma" Has Climate Scientists Racing to Keep Up

This news article addresses the impact of European earthworms that have been introduced to the northern latitudes of North America. Some of these species facilitate the degradation of litter layers, release C to the atmosphere, and impact biodiversity.

From a state factor perspective, what factor has been impacted by the introduction of worms, and how can the state factor model be used to design observational experiments to study and quantify the changes over time?

To Combat Climate Change, Start From the Ground Up (With Dirt)

In this graphic essay, the author repeats many statements and sentiments made about soil, and our management of soil, as a means of mitigating and adapting to climate change. These heartfelt essays, by nonscientists, may sometimes misstate or overplay certain issues. For example, do some online research to determine the accuracy or basis of the following statements:

1. Soil stores 20× its weight in water (search topics like soil water-holding capacity)
2. It keeps carbon out of the atmosphere (search topics such as natural negative carbon emissions)
3. "Dirt is dead, soil is alive" (how does this compare with our definition of soil?)

1.4.2 Solving the State Factor Equation

In this chapter, the generic state factor model and equation were introduced. The real excitement, as a scientist, is to uncover quantitative relationships, insert them into the equation, and create models of practical significance. Here, we explore this, solving the same equation that Jenny first solved nearly a century ago.[26]

Soil scientists had long recognized that soil organic matter (which also contains most of the soil nitrogen) tends to decrease with increasing temperature and increase with increasing rainfall. However, no mathematical relationships had been derived. Jenny assembled hundreds of published, and new, soil analyses (N% in the surface horizon) and assembled the associated climatic information. Jenny recognized that the climate factor has at least two major components: temperature and moisture. In several papers between 1928 and 1930, Jenny pointed out that characterizing the temperature of a location is a complex function of season and other factors. He settled on using the parameter *mean annual temperature* largely because it was the most readily available metric for most weather stations. Many