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Conversion Factors for SI and non-SI Units

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 non-SI Unit	To convert Column 2 into Column 1, multiply by
	Length		
0.621	kilometer, km (10^3 m)	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
3.28	meter, m	foot, ft	0.304
1.0	micrometer, μm (10^{-6} m)	micron, μ	1.0
3.94×10^{-2}	millimeter, mm (10^{-3} m)	inch, in	25.4
10	nanometer, nm (10^{-9} m)	Angstrom, Å	0.1
	Area		
2.47	hectare, ha	acre	0.405
247	square kilometer, km^2 (10^3 m)^2	acre	4.05×10^{-3}
0.386	square kilometer, km^2 (10^3 m)^2	square mile, mi^2	2.590
2.47×10^{-4}	square meter, m^2	acre	4.05×10^3
10.76	square meter, m^2	square foot, ft^2	9.29×10^{-2}
1.55×10^{-3}	square millimeter, mm^2 (10^{-3} m)^2	square inch, in^2	645
	Volume		
9.73×10^{-3}	cubic meter, m^3	acre-inch	102.8
35.3	cubic meter, m^3	cubic foot, ft^3	2.83×10^{-2}
6.10×10^4	cubic meter, m^3	cubic inch, in^3	1.64×10^{-5}
2.84×10^{-2}	liter, L (10^{-3} m^3)	bushel, bu	35.24
1.057	liter, L (10^{-3} m^3)	quart (liquid), qt	0.946
3.53×10^{-2}	liter, L (10^{-3} m^3)	cubic foot, ft^3	28.3
0.265	liter, L (10^{-3} m^3)	gallon	3.78
33.78	liter, L (10^{-3} m^3)	ounce (fluid), oz	2.96×10^{-2}
2.11	liter, L (10^{-3} m^3)	pint (fluid), pt	0.473
	Mass		
2.20×10^{-3}	gram, g (10^{-3} kg)	pound, lb	454
3.52×10^{-2}	gram, g (10^{-3} kg)	ounce (avdp), oz	28.4
2.205	kilogram, kg	pound, lb	0.454
0.01	kilogram, kg	quintal (metric), q	100
1.10×10^{-3}	kilogram, kg	ton (2000 lb), ton	907
1.102	megagram, Mg (tonne)	ton (U.S.), ton	0.907
1.102	tonne, t	ton (U.S.), ton	0.907
	Yield and Rate		
0.893	kilogram per hectare, kg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12
7.77×10^{-2}	kilogram per cubic meter, kg m^{-3}	pound per bushel, bu^{-1}	12.87
1.49×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 60 lb	67.19
1.59×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 56 lb	62.71
1.86×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 48 lb	53.75
0.107	liter per hectare, L ha^{-1}	gallon per acre	9.35
893	tonnes per hectare, t ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
893	megagram per hectare, Mg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
0.446	megagram per hectare, Mg ha^{-1}	ton (2000 lb) per acre, ton $acre^{-1}$	2.24
2.24	meter per second, m s^{-1}	mile per hour	0.447
	Specific Surface		
10	square meter per kilogram, m^2 kg^{-1}	square centimeter per gram, cm^2 g^{-1}	0.1
1000	square meter per kilogram, m^2 kg^{-1}	square millimeter per gram, mm^2 g^{-1}	0.001
	Pressure		
9.90	megapascal, MPa (10^6 Pa)	atmosphere	0.101
10	megapascal, MPa (10^6 Pa)	bar	0.1
1.00	megagram per cubic meter, Mg m^{-3}	gram per cubic centimeter, g cm^{-3}	1.00
2.09×10^{-2}	pascal, Pa	pound per square foot, lb ft^{-2}	47.9
1.45×10^{-4}	pascal, Pa	pound per square inch, lb in^{-2}	6.90×10^3

(continued on next page)

Conversion Factors for SI and non-SI Units

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 non-SI Unit	To convert Column 2 into Column 1, multiply by
	Temperature		
1.00 (K − 273)	Kelvin, K	Celsius, °C	1.00 (°C + 273)
(9/5 °C) + 32	Celsius, °C	Fahrenheit, °F	5/9 (°F − 32)
	Energy, Work, Quantity of Heat		
9.52×10^{-4}	joule, J	British thermal unit, Btu	1.05×10^{3}
0.239	joule, J	calorie, cal	4.19
10^{7}	joule, J	erg	10^{-7}
0.735	joule, J	foot-pound	1.36
2.387×10^{-5}	joule per square meter, J m^{-2}	calorie per square centimeter (langley)	4.19×10^{4}
10^{5}	newton, N	dyne	10^{-5}
1.43×10^{-3}	watt per square meter, W m^{-2}	calorie per square centimeter minute (irradiance), cal cm^{-2} min^{-1}	698
	Transpiration and Photosynthesis		
3.60×10^{-2}	milligram per square meter second, mg m^{-2} s^{-1}	gram per square decimeter hour, g dm^{-2} h^{-1}	27.8
5.56×10^{-3}	milligram (H_2O) per square meter second, mg m^{-2} s^{-1}	micromole (H_2O) per square centimeter second, μmol cm^{-2} s^{-1}	180
10^{-4}	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square centimeter second, mg cm^{-2} s^{-1}	10^{4}
35.97	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square decimeter hour, mg dm^{-2} h^{-1}	2.78×10^{-2}
	Plane Angle		
57.3	radian, rad	degrees (angle), °	1.75×10^{-2}
	Electrical Conductivity, Electricity, and Magnetism		
10	siemen per meter, S m^{-1}	millimho per centimeter, mmho cm^{-1}	0.1
10^{4}	tesla, T	gauss, G	10^{-4}
	Water Measurement		
9.73×10^{-3}	cubic meter, m^3	acre-inches, acre-in	102.8
9.81×10^{-3}	cubic meter per hour, m^3 h^{-1}	cubic feet per second, ft^3 s^{-1}	101.9
4.40	cubic meter per hour, m^3 h^{-1}	U.S. gallons per minute, gal min^{-1}	0.227
8.11	hectare-meters, ha-m	acre-feet, acre-ft	0.123
97.28	hectare-meters, ha-m	acre-inches, acre-in	1.03×10^{-2}
8.1×10^{-2}	hectare-centimeters, ha-cm	acre-feet, acre-ft	12.33
	Concentrations		
1	centimole per kilogram, cmol kg^{-1}	milliequivalents per 100 grams, meq 100 g^{-1}	1
0.1	gram per kilogram, g kg^{-1}	percent, %	10
1	milligram per kilogram, mg kg^{-1}	parts per million, ppm	1
	Radioactivity		
2.7×10^{-11}	becquerel, Bq	curie, Ci	3.7×10^{10}
2.7×10^{-2}	becquerel per kilogram, Bq kg^{-1}	picocurie per gram, pCi g^{-1}	37
100	gray, Gy (absorbed dose)	rad, rd	0.01
100	sievert, Sv (equivalent dose)	rem (roentgen equivalent man)	0.01
	Plant Nutrient Conversion		
	Elemental	***Oxide***	
2.29	P	P_2O_5	0.437
1.20	K	K_2O	0.830
1.39	Ca	CaO	0.715
1.66	Mg	MgO	0.602

Suggestions for Contributors to the *Soil Science Society of America Journal*

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For tabular matter, 9 lines of typewritten matter equal 1 column-inch of type. Allow also for rules and spacing. Tables with more than 35 units (including space between words) in a horizontal line can rarely be set 1 page-column wide.

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December 1997

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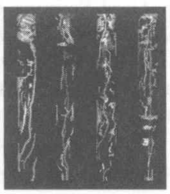

This issue's cover: Three-dimensional reconstruction of macropores in four intact soil cores (800 mm × 77 mm ID). Computer programs were developed to generate these three-dimensional representations on the basis of x-ray CAT scan data. The macropores are displayed as vertical descending structures. An artificial macropore (1-mm ID polyethylene tubing) was placed in the fourth column to verify the ability of the CAT scanner to portray the size and the location of a known pore. It can be observed in the 3-D representation of the macropores of the fourth column. See Johan Perret et al., Three-dimensional quantification of macropore networks in undisturbed soil cores, p. 1530–1543.

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SOIL SCIENCE SOCIETY OF AMERICA
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HISTORY OF SOIL SCIENCE

George Nelson Coffey, Early American Pedologist

Eric C. Brevik*

ABSTRACT

George Nelson Coffey joined the Bureau of Soils in 1900, the second year of its existence, and worked in the program for about 11 years. During those years he worked on soil surveys in many parts of the United States. Those surveys exposed him to a wide variety of soils. Because of his experience and knowledge, he was chosen to supervise soil classification and correlation after five years with the Bureau. During the time that he was in charge of soil classification and correlation, Coffey became acquainted with earlier soil studies, such as those of E.W. Hilgard in Mississippi, T.C. Chamberlain in Wisconsin, and the Dokuchaiev school in Russia. From those sources and his own field experience, Coffey developed and promoted his ideas of soil genesis and classification. Coffey's ideas were in marked contrast to the prevailing idea in this country that soils were simply a function of the underlying rocks. Coffey presented his ideas in journal articles for several years, culminating with the publication of USDA Bureau of Soils Bulletin No. 85 in 1912. Bulletin 85 is now recognized as a classic, but like Coffey's journal articles, it fell on deaf ears in 1912. Coffey left the soil survey program before Bulletin 85 was published and worked at the Ohio Agricultural Station, where he worked on soil mapping, an erosion study, and fertilizer trials. Later, Coffey moved on to the University of Illinois. In 1922 Coffey left soil science as a career but retained his interest in soils and geology. After he left the soil survey program Coffey's publications on soil genesis and classification were largely forgotten. About a decade later a profound change in the concept of soil and in the understanding of soil genesis began in the United States. Championed by Curtis F. Marbut, the change occurred gradually in the 1920s, 1930s, and beyond. A new group of American pedologists emerged who had learned of and from the Dokuchaiev school and had the benefit of the profound changes that had occurred in the United States. Those pedologists rediscovered Bureau of Soils Bulletin No. 85 and earlier publications by Coffey and recognized the advanced nature of Coffey's ideas of soil genesis and classification. Those ideas mark Coffey as one of the first, if not the very first, of the American pedologists.

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THE YEAR 1999 marks the 100th anniversary of the organized national soil survey program in the United States (Buol et al., 1997; Simonson, 1986a). At this time, it seems appropriate to look back at some of the people who have pioneered new ideas in soil science and soil survey in the United States, particularly those associated with the soil survey program. One of those people, and one who is far less known than figures such as Milton Whitney, Curtis F. Marbut, or Charles E. Kellogg, is George Nelson Coffey. The purpose of this paper is to document Coffey's ideas concerning soil genesis and classification and some of the people and factors that influenced him as he developed those ideas. I will do this by exploring Coffey's academic background, his career with the U.S. Department of Agriculture's Bureau of Soils, and his career after leaving the Bureau.

Early Education

George Nelson Coffey was born on 17 Jan. 1875 in Patterson, NC (Fig. 1) (Marquis, 1924). He began his college education at the University of North Carolina (UNC) and received his Bachelor of Philosophy degree cum laude in 1900 (M. Martin, UNC Archivist, written communication, 29 Sept. 1998). The Bachelor of Philosophy degree combined humanities and social science coursework with the physical sciences. Undergraduate degrees at UNC did not list majors at that time, but Coffey's records show that he concentrated on geology and chemistry (Martin, written communication, 29 Sept. 1998). Coffey's first professional position was as an assistant in the UNC geology laboratory from 1899 to 1900 (Marquis, 1924).

Abbreviations: ASA, American Society of Agronomy; GWU, George Washington University; UNC, University of North Carolina.

Fig. 1. George Nelson Coffey, January 1965. Reprinted by permission of the *Wooster Daily Record*, Wooster, OH.

The Bureau of Soils Years

Coffey joined the Bureau of Soils in 1900 (Marquis, 1924), in time for the Bureau's second year of field mapping. At that time it was common for the soil survey to hire geologists to do soil mapping. Geologists were often familiar with soil work, as Coffey (1911) notes:

> The first work upon the soils of this country was conducted principally by geologists. As the soil is composed very largely of mineral matter and has been formed by the breaking down of the rocks, it is but natural that its study, owing to its great economic importance, should have early attracted their attention. Nearly all of the earlier and, in fact, many of the present geological surveys have devoted much of their energies to its study.

Coffey's first job with the Bureau of Soils was as Field Assistant, a position he held from 1900 to 1904 (Marquis, 1924). Coffey coauthored at least 13 soil survey reports for parts of Illinois, Iowa, Kansas, North Carolina, and Ohio during that five-year span (Holman et al., 1939). The speed with which these early surveys were produced is in marked contrast to the eight person years per county standard commonly used today in Iowa (T.E. Fenton, written communication, 12 Nov. 1998) or the six calendar years used to map Grand Forks County, North Dakota in the late 1970s (J.A. Doolittle, written communication, 9 Sept. 1998). The early soil surveys were not nearly as detailed as current surveys, a fact that explains their rapid production.

From 1905 to 1909 Coffey was in charge of soil classification and correlation (Marquis, 1924). He also made a brief return to the University of North Carolina in 1905 as a lecturer on soils (Marquis, 1924). Coffey became aware of the need for a better soil classification system while he was in charge of classification and correlation (Bureau, 1961). Coffey believed that too much emphasis was being put on geology and not enough on the properties of the soil (Coffey, 1909b, 1912; Bureau, 1961), a belief that prompted him to return to school to do graduate work (Bureau, 1961).

Coffey's main duties with the Bureau of Soils appear to have been administrative while he was in charge of soil classification and correlation. He only authored or coauthored three research publications during that interval, and all the work for those publications was done in 1909 (Holman et al., 1939). Two of those publications were reconnaissance surveys, one for eight counties in southern Texas and one for 22 counties in western South Dakota (Holman et al., 1939). The third was a paper titled "Clay Dunes" that was published in the *Journal of Geology* (Coffey, 1909a) and was based on some observations Coffey had made during the reconnaissance survey for southern Texas.

Coffey completed his Master of Science degree at George Washington University (GWU) in Washington, DC in 1907. His major was titled "Principles of Soil Classification" and he received minors in practical meteorology and mineralogy (K. Betts, Executive Director of Alumni Relations, GWU, written communication, 29 Sept. 1998). Review of published portions of his thesis (Coffey, 1911) reveal that Coffey was well schooled in the history of soil science and theories pertaining to it up to that point. Although he reviewed the efforts of dozens of groups and individuals, Coffey (1911) primarily reserved his praise for work done by three parties. The first was E.W. Hilgard, who spent most of his career as a geologist and soil scientist working in Mississippi and California (Buol et al., 1997). Coffey (1911) stated that Hilgard's work in Mississippi had never received the attention it merited. The second was Chamberlain. Coffey (1911) stated that Chamberlain's soil map of Wisconsin (made in 1882) appeared to be the first soil map published in the USA based on the physical properties of the soil and declared Chamberlain's map one of the best general state maps ever issued. Coffey (1911) also noted that both Hilgard and Chamberlain's work had found a close relationship between soils and vegetation. Finally, Coffey (1911) devoted a relatively large portion of the manuscript to and heaped lavish praise on the work of V.V. Dokuchaiev and his students in Russia. Coffey's exposure to the three above influences, along with his extensive field experience, was instrumental in the formation of his personal ideas concerning soil genesis. Coffey would spend a good deal of time between 1908 and 1916 trying to promote his ideas within the American soil science community.

Coffey was involved in the newly formed American Society of Agronomy (ASA), and used the ASA meetings and publications as a platform to introduce his ideas. At the 1908 ASA meeting in Ithaca, NY, Coffey (1909b) argued that climate and drainage could be just as important in soil formation as geologic origin and also noted that differences in native vegetation could lead to soil differences. Coffey (1909b) stated:

> In general, it may be said that where the processes of soil formation are fairly uniform, the character of the soil will follow very closely that of the underlying formations; but where there is a marked variation in these processes, due either to climatic or drainage conditions, then a soil map and geologic map will be very dissimilar.

Coffey (1909b) showed that he did not feel that the system of soil classification being used at the time, which was largely based on geology (Whitney, 1909; Simonson, 1986a), was adequate. For example, Coffey (1909b) stated:

> There is no more fundamental problem before the agronomist today than the proper classification and correlation of soils. . . . . Differences in the character of the soil may be due to a great many causes. Some of these are the result of geological, some of chemical, some of physical, and some of biological factors, all of which are so closely related that it is often impossible to separate them.

By this point in his career Coffey had conducted extensive field work in parts of the USA ranging from the warm humid climate of North Carolina, to the dry cold of South Dakota, to the dry heat of Texas (Holman et al., 1939; Marquis, 1924). His master's work had exposed him to the ideas, both good and bad, of dozens of soils workers from around the globe (Coffey, 1911). Coffey is most noted for his authorship of Bureau of Soils Bulletin No. 85 (Coffey, 1912). Certainly, Bulletin 85 (Coffey, 1912) is commonly cited by authors when they discuss early attempts to incorporate the Dokuchaiev school of soil genesis into American soil science theory (e.g., Simonson, 1997; Buol et al., 1997; Simonson, 1986b; Gennadiyev and Olson, 1998). However, his 1908 presentation (Coffey, 1909b) is clear evidence that Coffey had begun to promote ideas influenced by Dukuchaiev's work well before writing his more noted Bulletin 85. The influence of Hilgard and the Russian school of soils on Coffey's ideas can be seen in another of Coffey's early papers as well (Coffey, 1909c). The influence of the extensive fieldwork Coffey did early in his Bureau of Soils career, fieldwork that exposed him to a wide array of soils and soil-forming conditions, is also seen in these 1909 publications.

At the 1909 ASA meeting in Omaha, NE, Coffey (1909c) argued that soil properties needed to be considered when crop yield tests were conducted. The standard practice was to largely ignore soil properties when conducting plot experiments at that time (Hilgard, 1892; Coffey, 1909c, 1912; Marbut, 1922). At this meeting Coffey also showed that he was a field-oriented pedologist. The common practice among soil scientists at that time was to bring soil samples to the laboratory and use information collected in the laboratory to separate and classify the soils (Coffey, 1909c, 1912; Marbut, 1921). Coffey (1909c) advocated the use of field studies to separate and classify soils and the use of laboratory analysis to answer questions that could not be answered in the field.

> This method of attacking soil problems is rather the reversal of the usual practice, but I believe that the field studies should precede those of the laboratory, because of the great difficulty of duplicating field conditions. The field observations can then be used as a check upon and an aid in the interpretation of results of laboratory investigations. If this method had been followed in the past it might have prevented the publication of erroneous conclusions deduced from laboratory studies alone. (Coffey, 1909c)

The debate over the proper balance between field and laboratory work continues in pedology today. These statements and others made by Coffey (Coffey, 1909c) place him squarely in the camp of those with a strong field orientation.

Coffey served as the second president of ASA and as a member of the ASA publications committee in 1909. Coffey also formed and chaired an ASA committee on soil classification from 1909 to 1914 (Bureau, 1961). His ASA activities were in addition to the Bureau of Soils job and his work toward his Ph.D. at GWU in Washington, DC.

Coffey was put in charge of the Bureau of Soils Great Plains Division in 1909, a post he held until 1911 (Marquis, 1924). Coffey continued to participate in fieldwork on soil surveys while in charge of the Great Plains division, but again at a lesser pace than during his first five years with the Bureau. Coffey published material from his master's thesis in 1911 (Coffey, 1911), work that has been discussed in greater detail above. Again, his thesis (Coffey, 1911) is an example of Coffey's admiration for the ideas of Hilgard, Chamberlain, and Dokuchaiev and shows Coffey incorporating the ideas of these men with his own and and publishing them prior to Bulletin 85 (Coffey, 1912).

I believe that a telling sign of how Coffey perceived himself professionally is given in his biographical information published in *Who's Who in America*. The first entry for Coffey in this series is in the 1906–1907 edition (Leonard, 1906). From then until the 1910–1911 edition (Marquis, 1910), Coffey listed his occupation as "geologist", despite the fact that he had worked for the Bureau of Soils in various soil science capacities for more than 10 years by 1911. However, from the 1912–1913 edition (Marquis, 1912) until his last entry in the 1940–1941 edipption (Marquis, 1940), Coffey listed his occupation as "soils specialist" or "agriculturalist". This apparent change in occupational attitude came about shortly after Coffey began his attempts to broaden the American concept of soil formation beyond simply geologic weathering (Coffey, 1909b, 1911, 1912). At the 1915 meeting of the American Association for the Advancement of Science, Coffey also made an attempt to introduce the term "soilists" to describe or identify those who research soil issues (Coffey, 1916).

Coffey completed study for his Ph.D. at GWU in 1911. Although his degree was in geology, the title of his dissertation was "A Study of the Soils of the United States" (Betts, written communication, 5 Oct. 1998). Coffey's final significant contribution as a member of the Bureau of Soils was also titled "A Study of the Soils of the United States" and was based on his dissertation (Coffey, 1912). This is Coffey's best-known work and was published as Bureau of Soils Bulletin No. 85. Coffey (1912) proposed that two groups of soil-forming factors lead to observed soil variation, the soil-forming material and the soil-forming agencies. Coffey's (1912) soil-forming material was analogous to the modern concept of parent material. He continued to include moisture and temperature as the most important of the soil-forming agencies (Coffey, 1912), which could be equated to the modern concept of climate as a soil-forming factor. Vegetation and topography were mentioned by Coffey (1912) as less important soil-forming agencies that are related to moisture. Coffey (1912) also stated that age (i.e., time) "should be given due weight in classification" when it led to differences in soil properties. Therefore, it appears that, at least at some level, Coffey was at that time a proponent of the five soil-forming factors commonly recognized today.

Coffey (1912) continued Bulletin 85 with a discussion of the need for soil classification and a review of some of the past systems that had been used for soil classification. The past systems identified by Coffey (1912) included geological, physical, chemical, vegetation, climatic, and those that consisted of some combination of the above. Furthermore, he divided geological classification systems into those based on (i) age, (ii) lithology, and (iii) agency of rock formation and divided physical classification systems into those based on (i) texture, (ii) structure, and (iii) color (Coffey, 1912).

After discussing the various classification systems that had been used in the past, Coffey (1912) described what he viewed as the requirements for an ideal soil classification system. Much of Coffey's (1912) discussion of an ideal classification system is still valid today. In many ways, Coffey's (1912) idea of an ideal system of soil classification came close to describing some of the basic principles on which modern U.S. soil taxonomy is based. Coffey believed that the ideal system would be multicategorical and would recognize differences in the soil as creating the fundamental divisions between soils. In Coffey's (1912) words:

> The ideal classification would be one in which the individual types are grouped in a number of divisions, each larger grouping representing more and more distinct relationships in the soils. Thus in one of the major divisions there would occur no type which closely resembles any of the other divisions.

Coffey's description closely resembles one of the attributes the Soil Survey Staff desired for U.S. soil taxonomy:

> The system should be multicategorical. The hierarchy of the categories should have a rationale that allows for first conceiving all soils into broad categories while providing for more detailed separations in lower categories. (Buol et al., 1997)

Later, Coffey (1912) wrote:

> In making such a classification it would be necessary to recognize inherent differences in the soil itself as the fundamental idea; to consider it as a natural body having a definite genesis and distinct nature of its own and occupying an independent position in the formations constituting the surface of the earth.

The Soil Survey Staff had similar ideas concerning how to separate out the various soils:

> Differentiae should be soil properties that can be observed in the field or quantitatively measured by reliable techniques. (Buol et al., 1997)

Coffey (1912) also stated that there was a need for study of the various constituents of soil formation and their relative influence on soil formation to construct the ideal classification. Many such studies were conducted during the development of U.S. soil taxonomy, the soil-landscape studies in Iowa (Ruhe et al., 1967) and New Mexico (Gile and Grossman, 1979) being two examples. Coffey (1912) noted that the relative importance of a given soil property is not the same in all soils, a fact that is acknowledged in U.S. soil taxonomy. For example, the soil moisture regime is used as a differentiating characteristic at both the suborder and great group levels (Buol et al., 1997).

In 1912 Coffey was beginning to understand and publish some of the attributes that would be needed to create a strong soil classification system. Many of these attributes appeared in *Soil Taxonomy* (Soil Survey Staff, 1975) when it was published 63 years later. This is not an attempt to give Coffey any credit for *Soil Taxonomy*, but to point out how clearly Coffey seems to have seen the problem facing the soil science community in establishing a solid soil classification system. This also is not meant to imply that U.S. soil taxonomy is ideal. Again, in Coffey's words (1912):

> . . . it seems that it will never be possible to construct an ideal system of classification, although it is well to have it in mind and to make our classification correspond as nearly as possible to the ideal one.

It seems that many of the attributes that Coffey had in mind as necessary for an ideal soil classification system were attributes also deemed important by the architects of U.S. soil taxonomy.

After presenting his concept of the ideal soil classification system, Coffey (1912) introduced his own classification system, which he termed a genetic system. Coffey's (1912) system consisted of three levels. At the highest level, Coffey (1912) identified five broad classes: (i) arid or unleached soils low in humus, (ii) dark-colored prairie or semileached soils rich in humus, (iii) light-colored timbered or leached soils low in humus, (iv) dark-colored swamp or leached soils high in organic matter, and (v) organic or muck and peat soils. Coffey (1912) noted that the final two broad classes were created by local factors, and were thus less important than the first three. He then suggested eight subdivisions of his broad classes: (i) soils from crystalline rocks, (ii) soils from sandstones and shales, (iii) soils from limestones, (iv) soils from ice-laid materials, (v) soils from unconsolidated water-laid material, (vi) soils from aeolian material, (vii) soils from gravity-laid material, and (viii) alluvial soils (Coffey, 1912). Coffey (1912) believed these subdivisions were relevant for the first three broad classes, but not for the last two. The final level of Coffey's (1912) system was the series. The classification system proposed by Coffey (1912) was an incomplete one, a fact that Coffey readily acknowledged. The only level of this classification system that seemed firm was the set of five broad classes. The eight subdivisions seemed to be a tentative suggestion rather than a firm proposal, and how the series were meant to fit into the entire system was not well defined. Coffey (1912) was not able to divide some of his broad classes into the proposed subdivisions and in a number of cases was not able to divide his broad classes down to the series level. Coffey (1912) attributed the problems encountered to an insufficient understanding of the properties and characteristics of the soil.

Three of the five broad classes as described by Coffey (1912) compare favorably, though not exactly, to definitions used for soil orders in *Soil Taxonomy* (Soil Survey Staff, 1975). Coffey's arid soils description was close to the definition used for the present day Aridisols, his dark-colored prairie soils had a similar relation to the Mollisols, and his organic soils description is similar to the definition of Histosols. It is impressive that Coffey was able to arrive at soil groupings that would be independently "rediscovered" by the authors of *Soil Taxonomy* more than 50 years later. Coffey's (1912) light-colored timbered soils do not have an equivalent in the modern U.S. soil taxonomy. Coffey's (1912) black swamp soils were described as forming a transition from the light-colored timbered soils to the organic soils, and again, do not have an equivalent in U.S. soil taxonomy.

The soil map of the United States produced as part of Bulletin 85 bore some resemblance to one published three years earlier by Whitney (1909), a map based primarily on geology. However, Coffey's map showed some recognition of the influence of moisture, temperature, and vegetation on soil formation, as he discussed it in the text by including arid soils in the west and splitting the east into several areas of prairie and timber soils (Coffey, 1912; Simonson, 1986b).

Whitney sent Coffey's manuscript for Bulletin 85 to the government printing office with a disclaimer in his letter of transmittal that stated:

> I recommend that it be published as Bulletin No. 85 of the series of this bureau. In publishing it, however, the Bureau of Soils does so for the purpose of offering it to the scientific world as a contribution to the subject, without indorsing the scheme of classification proposed and without accepting all the conclusions drawn from the facts cited. (Coffey, 1912).

It seems strange that Whitney would recommend publication of a work he did not agree with. However, Simonson (1986b) discovered that in 1903 Whitney rejected three manuscripts submitted for publication by F.H. King, leading to King's resignation from the Bureau of Soils and publication of the manuscripts elsewhere. Simonson (1986b) concluded that Whitney must have decided to recommend publication of Coffey's work with the disclaimer rather than risk a repeat of King's private publication. Publication of Coffey's (1912) work was quickly followed by Bulletin 96 (Marbut et al., 1913), which among other things seemed to assert that the Bureau of Soil's concept of soil and soil classification remained unaffected by the ideas presented the previous year by Coffey (Simonson, 1986b).

I have only found one reference to Bulletin 85 (Coffey, 1912) among the publications I have reviewed that were written between 1912 and the 1930s. It was in a soils book by Wolfanger (1930). However, Wolfanger (1930) stated that Coffey (1912) subscribed to the theory that soil properties were primarily controlled by the properties of the underlying rock and further implied that the theories of soil genesis offered by Coffey (1912) were similar to those offered by Marbut et al. (1913). While it is true that the soil genesis ideas published by Coffey (1912) did still show some influence from the earlier ideas of soil being a product of rock weathering (i.e., a geologic bias), they were advanced far beyond the ideas of Marbut et al. (1913). Compare, for example, the following excerpts from the soil genesis sections of these bulletins. Coffey (1912) wrote:

> All of these differences (referring to the variation of properties observed in soils), however, may be traced to two sets of factors: First, the character of the rock or material from which the soil has been derived; and second, the processes or agencies by means of which this material has been changed from mere rock or rock debris into a medium suitable for the growth of plants. The former has to do with soil-forming material, the latter with soil-forming agencies. To these two groups of factors are to be attributed the numerous variations in soil conditions found over various parts of the earth.

On the same topic, Marbut et al. (1913) wrote:

> It is of vast importance, therefore, in the classification of soils to recognize not only the character of the rock from which the material has been derived but also the agencies which have acted in the transportation and deposition of the soil material and the changes which have taken place since its deposition. The character of the parent rock material, with the influences of general physiography dependant upon this, the transportation and redeposition of such material or its sedentary character are the factors on which the soil province is based.

Study of these sections in their respective bulletins shows a vast difference in the described theories of soil formation. When he referred to "soil-forming agencies", Coffey (1912) was stating that factors other than just geology, such as temperature, moisture, vegetation, and topography, play important roles in determining the properties of a soil. Marbut et al. (1913) allowed that many soils form in sediments that have been transported from their source area, often mixed with sediments from other source areas and then redeposited, when they referred to "agencies". Marbut et al. (1913) ended by concluding that it is the nature of these deposits and the properties given them by their various source areas that eventually determine the properties of the soil formed in them. Ultimately, Marbut et al. (1913) were still stating that the properties of the geologic material controlled the properties of the soil formed in that material. They were not allowing for the influence of other soil-forming factors such as climate and vegetation.

Despite my inability to locate many references to Bulletin 85 in most of the 1910s to 1930s literature that I reviewed, there must have been a fair number of researchers who at least reviewed Bulletin 85 at some point in time. Additional copies of Bulletin 85 were printed after the supply from the original printing was exhausted, something that Coffey was quite proud of (Bureau, 1961). It appears that Bulletin 85 was probably widely read but not widely accepted within the American soil science community.

Coffey stated that he had written reports on soils in several states, including North Dakota and Pennsylvania (Marquis, 1924). In a personal interview, he also told Bureau (1961) that he had worked in Louisiana. I have been unable to find soil surveys or other publications for any of these states with Coffey's name on them. It is possible that Coffey provided assistance in those areas while with the Bureau of Soils but did not do enough to warrant authorship. Upon review of some of the early surveys, it also appears that it was common to list the authors of a survey as the party leader(s) and party (e.g., Coffey, Rice, and party, 1915). Coffey may have worked in these states and fell under the "party" heading. Alternatively, it is possible that he conducted research in these states at a later time and I have been unable to locate the relevant articles.

The Post-Bureau Years

Coffey left the Bureau of Soils in 1911 to pursue work at the Ohio Agricultural Station at Wooster (Marquis, 1924). It appears that Coffey was hired to conduct soil surveys for the state of Ohio. In his report for the year ending 30 June 1911, Ohio Experiment Station director Charles E. Thorne wrote:

> . . . the work is now to be supplemented by a reconnaissance survey of the soil types of the state, made by an expert of broad experience in this field of work. (Thorne, 1911)

I believe the expert referred to by Thorne is Coffey. Although others also worked on the reconnaissance survey, Coffey had just been hired and was an expert at soil survey who had done such work in a number of states. Also, when the statewide reconnaissance survey was completed and more detailed county scale surveys begun, the responsibility for the soil survey program was moved from the Cooperation Department to the Soils Department (Thorne, 1913). Coffey was moved from the Cooperation Department to the Soils Department at the same time (Thorne, 1913). The Ohio reconnaissance survey was eventually published by the Bureau of Soils (Coffey et al., 1915).

Observations made by Coffey on the Ohio reconnaissance survey exposed him to a problem he felt to be particularly unique to Ohio, the changes in drainage brought about by the multiple glaciations that had occurred there. Those observations led to a lifelong passion as Coffey attempted to work out the drainage changes. Coffey published a series of papers on this subject (Coffey, 1914a, 1930, 1958, 1961), the last when he was 86 years old.

Aside from his survey work at Wooster, Coffey made at least four significant contributions to soil science during his time in Ohio. The most recognized is his participation as chair of the committee formed by ASA five years earlier to develop a new soil classification system for the USA and Canada. The culmination of the committee's efforts was reported in Coffey (1914b). Coffey's work on that committee seems to be something he was quite proud of (Marquis, 1924). However, many members of the committee seem to have been dissatisfied with the results of its work (Coffey, 1914b). Coffey himself felt that too much emphasis was placed on genetic factors and not enough on soil differences, thought there should have been a division emphasizing the difference between black prairie soils and lighter-colored timber soils at a high level, disagreed with some of the nomenclature, and felt that soil color should have been given more weight (Coffey, 1914b). It appears that there was a particular difference of opinion between Coffey and C.F. Marbut over whether or not to set the black prairie soils and lighter-colored timber soils apart at a high level (Simonson, 1986c). The classification system proposed by the ASA committee never seems to have progressed any farther than that recorded in the 1914 report, and it was never adopted (Simonson, 1986b).

The Missouri Agricultural Experiment Station is generally given credit for making the first measurements of soil erosion by water (Miller, 1946; Browning, 1977; Meyer and Moldenhauer, 1985). These experiments began in 1915 (Miller, 1946). However, while at Wooster, Coffey (1913a) worked on what he believed to be the first experiment to quantitatively determine the amount of sediment removed from fields by erosion during rainfall events. Coffey (1913a) described how the Wooster Experiment Station had set up a plot for an erosion study and what treatments the station planned to use in the course of the study. Coffey (1913a) did not give any results as the study was set up but had not yet been conducted. Further, Meyer and Moldenhauer (1985) found that any results from the Wooster erosion study were apparently never published, therefore explaining how the Missouri studies came to be recognized as the earliest. Many other states began similar erosion studies shortly after Missouri (Meyer and Moldenhauer, 1985), but Congress did not allocate funds to the Bureau of Chemistry and Soils for the study of soil erosion until 1929 (Meyer and Moldenhauer, 1985; Bennett, 1964). Major efforts in soil erosion research did not begin in the United States until the 1930s (Meyer and Moldenhauer, 1985), nearly 20 years after Coffey (1913a) published his notes on the need to study soil erosion by water and how to conduct such a study. This shows again that Coffey was ahead of his time in many of his ideas.

Coffey was also involved in fertilizer trials while at the Wooster Experiment Station (Coffey, 1913b). The trials were unique because they attempted to document differences in yield taking into account the effect of different soils as well as the effect of the fertilizer (Coffey, 1913b). Many such trials at that time neglected to account for soil differences and thus would yield contradictory results that could not be explained (Hilgard, 1892; Coffey, 1912; Marbut, 1922). In 1914 Coffey assisted the Ontario Agricultural College in beginning their soil survey of Ontario (Marquis, 1924; Simonson, 1986b). Also in 1914, Coffey married Clara Kean of Wooster (Bureau, 1961).

In 1915 Coffey left the Ohio Experiment Station to take a position at the University of Illinois as the Assistant State Leader for County Farm Advisors (Marquis, 1924), an organization comparable to the present-day Extension Service (Bureau, 1961). Coffey's final article in the *Journal of the American Society of Agronomy* (Coffey, 1916) was published during this time, but it was really only a brief summary of past attempts at soil classification with a note as to the current trends. Although the "Soil Survey of Trumbull County, Ohio" (Coffey et al., 1919) was published by the Bureau of Soils in 1919, the field work for that survey was completed in 1914. Therefore, I consider the ASA article (Coffey, 1916) to be Coffey's last published contribution to soil science, at least so far as I have been able to determine. A listing of Coffey's publications is given in the appendix.

Coffey was not involved in the Illinois state soil survey program, which at that time was run by the Soil Fertility division at the University of Illinois Agricultural Station (Davenport, 1923). Another individual of note, Coffey's friend C.G. Hopkins, was in charge of the Illinois soil survey program until his death in 1919 (Davenport, 1921).

A son was born to the Coffeys in 1921, and in 1922 Coffey left the University of Illinois and returned to Wooster, OH, where he obtained a controlling interest in the Wayne County Abstract Company (Bureau, 1961). Coffey made the move away from agriculture because he desired to spend more time with his family (Bureau, 1961). In addition to running his abstract business, Coffey took extension courses in law from LaSalle University and received his law degree in 1932 (Bureau, 1961). Coffey seems to have lost touch with ASA after leaving the University of Illinois, as I have not been able to find any references to him in the general indexes of the *Journal of the American Society of Agronomy* from 1917 through 1948. American Society of Agronomy records show that Coffey was never made a fellow of ASA, but do not show when he ceased being an active member (C. Tindall, ASA Membership Registrar, written communication, 20 Nov. 1998). Coffey also listed membership in the American Title Association and the Ohio Title Association as his involvement in professional organizations (Marquis, 1924), but ASA was noticeably absent from that list.

Although Coffey left soil science as a career, he never lost interest in soil classification or in geology. His continued interest in geology is evident in the professional papers he published long after leaving the sciences for his abstract career (Coffey, 1930, 1958, 1961). In addition, Coffey reviewed the *7th Approximation* with considerable interest (Bureau, 1961). The last date I have been able to establish for Coffey is January 1965, when the *Wooster Daily Record* reported on Coffey's 90th birthday (F. Beeson, *Wooster Daily Record* General Manager, written communication, 17 Nov. 1998). At that time, Coffey was living at the Glendora Nursing Home in Wooster (Beeson, written communication, 17 Nov. 1998). The *Wooster Daily Record* does not have a copy of Coffey's obituary (Beeson, written communication, 17 Nov. 1998).

CONCLUSIONS

From the available literature it cannot be said that Coffey had an influence on the many changes that began to occur in the prevalent thoughts and theories of American soil scientists between 1900 and the 1930s. However, the literature does document that Coffey was one of the first American soil scientists to give serious consideration to many of those ideas and theories, even though they were not accepted at the time that Coffey was promoting them. Coffey is commonly given credit for the forward thinking he displayed in his ideas of soil genesis and classification as outlined in Bulletin 85 (Coffey, 1912). However, he was promoting many of those ideas before Bulletin 85 was published (Coffey, 1909b, 1911). If the American soil science community had heeded Coffey, the changes in soil theory eventually championed by Marbut (e.g., Marbut, 1921, 1922) may have begun more than a decade earlier. Coffey was also an early pioneer in studies of soil erosion by water (Coffey, 1913a) and worked on fertilizer trials (Coffey, 1913b). Coffey was involved in the earliest days of the organized Soil Survey in the United States and held some of the highest positions in that organization. As stated by Cline (1977), Coffey has not been given enough credit by many soil scientists for his great foresight. George Coffey can certainly be considered one of the first true American pedologists.

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APPENDIX

This is a listing of soil science and geology publications authored or coauthored by George Coffey that I have located in my research. It is highly doubtful that this listing is complete. I welcome the input of anyone that has knowledge of or comes across a publication not listed here.

Burgess, J.L., and G.N. Coffey. 1905. Soil survey of the Garden City

Area, Kansas. p. 895–924. *In* Field operations of the Bureau of Soils, 1904. U.S. Gov. Print. Office, Washington, DC.

Coffey, G.N. 1909. Clay dunes. J. Geol. 17:754–755.

Coffey, G.N. 1909. Physical principles of soil classification. Proc. Am. Soc. Agron. 1:175–185.

Coffey, G.N. 1909. Value of the field study of soils. Proc. Am. Soc. Agron. 1:168–175.

Coffey, G.N. 1911. The development of soil survey work in the United States with a brief reference to foreign countries. Proc. Am. Soc. Agron. 3:115–129.

Coffey, G.N. 1912. A study of the soils of the United States. USDA Bureau of Soils Bull. 85. U.S. Gov. Print. Office, Washington, DC.

Coffey, G.N. 1913. An erosion study. J. Am. Soc. Agron. 5:230–232.

Coffey, G.N. 1913. The purpose and interpretation of fertilizer experiments. J. Am. Soc. Agron. 5:222–230.

Coffey, G.N. 1914. Changes of drainage in Ohio. Science 40(1034): 607–609.

Coffey, G.N. (chair). 1914. Progress report of the Committee on Soil Classification and Mapping. J. Am. Soc. Agron. 6:284–288.

Coffey, G.N. 1916. The present status and future development of soil classification. J. Am. Soc. Agron. 8:239–243.

Coffey, G.N. 1930. Preglacial, Interglacial, and postglacial changes of drainage in Northeastern Ohio with special reference to the Upper Muskingum Drainage Basin. Ohio J. Sci. 30(6):373–384.

Coffey, G.N. 1958. Major glacial drainage changes in Ohio. Ohio J. Sci. 58(1):43–49.

Coffey, G.N. 1961. Major preglacial, Nebraskan, and Kansan glacial drainages in Ohio, Indiana, and Illinois. Ohio J. Sci. 61(5):295–313.

Coffey, G.N., C.W. Ely, R.C. Lloyd, C. Willis, A.F. Kidder, and G.A. Crosthwaite. 1904. Soil survey of Johnson County, Illinois. p. 721–736. *In* Field operations of the Bureau of Soils, 1903. U.S. Gov. Print. Office, Washington, DC.

Coffey, G.N., C.W. Ely, C.J. Mann, R.C. Lloyd, C. Willis, A.F. Kidder, G.A. Crosthwaite, and G.H. Eidman. 1904. Soil survey of McLean County, Illinois. p. 777–794. *In* Field operations of the Bureau of Soils, 1903. U.S. Gov. Print. Office, Washington, DC.

Coffey, G.N., C.W. Ely, C.J. Mann, J.G. Mosier, R.C. Lloyd, C. Willis, and A.F. Kidder. 1904. Soil survey of Winnebago County, Illinois. p. 753–776. *In* Field operations of the Bureau of Soils, 1903. U.S. Gov. Print. Office, Washington, DC.

Coffey, G.N., C.W. Ely, C.J. Mann, J.G. Mosier, C. Willis, and A.F. Kidder. 1904. Soil survey of Knox County, Illinois. p. 737–752. *In* Field operations of the Bureau of Soils, 1903. U.S. Gov. Print. Office, Washington, DC.

Coffey, G.N., C.W. Ely, J.G. Mosier, and A.F. Kidder. 1904. Soil survey of Sangamon County, Illinois. p. 703–720. *In* Field operations of the Bureau of Soils, 1903. U.S. Gov. Print. Office, Washington, DC.

Coffey, G.N., and W.E. Hearn. 1902. Soil survey of Alamance County, North Carolina. p. 297–310. *In* Field operations of the Bureau of Soils, 1901. U.S. Gov. Print. Office, Washington, DC.

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DIVISION S-1—SOIL PHYSICS

Numerical Analysis of the Effect of the Lower Boundary Condition on Solute Transport in Lysimeters

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ABSTRACT

Field lysimeters are often used to assess environmental behavior of agrochemicals. Most lysimeters used to date have a free-draining lower boundary where leaching out of the lysimeter occurs by gravity alone. In this case, the lower boundary of a lysimeter is open to the atmosphere, and consequently, leachate is collected only if the bottom of the lysimeter becomes water saturated. In a field soil, such local water saturation does not occur. The objective of this study was to evaluate the effect of the lower boundary condition on chemical leaching. Numerical simulations were used to compare solute transport in field soils and in lysimeters. Simulations were carried out in homogeneous sandy and loamy soils under steady-state, unsaturated water flow conditions. Water flow was described by the Richards equation and solute transport by the advection–dispersion equation. The effect of linear and nonlinear and instantaneous and kinetic sorption was investigated. The results showed that for a conservative solute the differences between field soil and lysimeter increase as the coarseness of the soil increases. Decreasing water flux increases the difference between field soil and lysimeter. In general, solute transport in the lysimeter is characterized by a slower mean velocity, a larger spreading, and smaller concentration values. For solutes subject to linear equilibrium sorption, the sorption mechanism compensates for the effects of the lower boundary condition. The larger the sorption coefficient, the less the difference between lysimeter and field soil. However, large differences are found in the case of strongly convex nonlinear sorption isotherms.

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LYSIMETERS ARE OFTEN USED to assess the leaching behavior of pesticides under field conditions. A lysimeter is a large soil block surrounded by a casing, with the lower boundary shaved off from the parent soil and usually exposed to atmospheric pressure (Bergström, 1990). This exposure results in a hydraulic barrier for water flow. The soil at the lower boundary has to be saturated with water before drainage outflow can occur. To overcome the problem of water saturation, at the bottom of the lysimeter a suction can be applied with porous ceramic plates, pipes, or fiberglass wicks (Bergström, 1990; Nordmeyer and Aderhold, 1994; Young et al., 1996). However, for lysimeters with a large surface area, the use of suction devices is impractical and often problematic (Bergström, 1990). Consequently, most large lysimeters have a drainage system open to atmospheric pressure. We will limit our discussion to this type of lysimeter.

Lysimeters are intended to represent field conditions much better than laboratory columns and have been widely used to investigate fate and behavior of chemicals in soils (Bergström, 1990; Hance and Führ, 1992; Winton and Weber, 1996). Assuming that there is an undisturbed soil block in the lysimeter, the only difference between the lysimeter and the field soil is the lower boundary condition. It is unclear to what extent water and solute transport are affected by this difference in boundary conditions.

Several comparative studies between field soils and lysimeters have been reported in the literature. The comparisons included the temporal variation of temperature (Kubiak et al., 1988; Pütz et al., 1992; Nordmeyer and Aderhold, 1994), water content (Kubiak et al., 1988; Pütz et al., 1992), P fluxes (Magid et al., 1992), and pesticide concentrations in soil (Kubiak et al., 1988; Weber and Keller, 1994; Jene et al., 1998). Colman (1946) and Dowdell and Webster (1980) compared gravity-drained lysimeters with suction-controlled lysimeters. Colman (1946) used porous fired clay plates at the bottom to apply suction, and reported considerable differences in drainage rate, drainage quantity, water content, and water potential between the two types of lysimeters. Dowdell and Webster (1980) applied the suction with porous ceramic candles installed at the bottom of the lysimeter. They found no significant differences in amount of drainage water and NO_3 concentrations, but the suction-controlled lysimeter showed continuous water outflow for longer periods of time. Recently, major experimental efforts have been made to compare field soils and lysimeters in respect to pesticide leaching. Jene et al. (1998) studied Br and benazolin (4-chloro-2-oxobenzothiazolin-3-ylacetic acid) movement in a field soil instrumented with a dense grid of suction cup samplers, and compared the results with those obtained from lysimeters. The lysimeters were located 20 km away from the field site, but had otherwise the same soil characteristics. The suction applied to the suction cups in the field soil was adjusted to the potential measured with tensiometers installed adjacent to the suction cups. Cumulative outflow of water and bromide was larger in the lysimeters than in the field soil, but Jene et al. (1998) attributed this result to differences in evapotranspiration between the sites. In contrast to water and Br^-, the authors did not find great differences in pesticide leaching between field soil and lysimeters. A comprehensive experimental comparison between field soils and lysimeters is currently ongoing (Pütz et al., 1998), but no experimental results are available at present. The experimental evidence as to whether, and to what degree, a suction-free lysimeter adequately represents field conditions is not conclusive to date.

The purpose of our study was to evaluate the effect of the lower boundary condition on solute transport by using numerical simulations to compare solute transport in field soils and lysimeters. The field soils were characterized by a unit-gradient lower boundary condition, and the lysimeters by a seepage boundary condition. Simulations were performed under steady-state, unsaturated water flow with two textural classes of soils, a sand and a loam. Solutes with different sorption properties were used. The reaction processes considered were linear and nonlinear and instantaneous and kinetic sorption. Effects of different distribution coefficients, nonlinearity factors, and sorption rate coefficients were investigated.

THEORY

Transport Equations

We confine the discussion to a homogeneous soil, and assume that water transport can be described by the one-dimensional Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \quad [1]$$

where θ is the volumetric water content ($L^3\ L^{-3}$), h is the matric potential (L), $K(h)$ is the unsaturated hydraulic conductivity ($L\ T^{-1}$), t is time (T), and z (L) is the vertical coordinate, taken positively upward. The water retention characteristic $\theta(h)$ and the unsaturated hydraulic conductivity function $K(h)$ are given by the Mualem–van Genuchten parametrization (van Genuchten, 1980):

$$\theta(h) = \begin{cases} \theta_r + (\theta_s - \theta_r)\,[1 + |\alpha h|^{1/(1-m)}]^{-m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad [2]$$

and

$$K(h) = \begin{cases} K_s S_e^{1/2}\,[1 - (1 - S_e^{1/m})^m]^2 & h < 0 \\ K_s & h \geq 0 \end{cases} \quad [3]$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad [4]$$

where θ_r and θ_s are the residual and saturated water contents ($L^3\ L^{-3}$), respectively, K_s is the saturated hydraulic conductivity ($L\ T^{-1}$), and α (L^{-1}) and m are parameters.

The solute transport is described by the advection–dispersion equation:

$$\frac{\partial \theta C}{\partial t} + \rho\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left(\theta D\frac{\partial C}{\partial z}\right) - \frac{\partial J_w C}{\partial z} \quad [5]$$

where C is the solute concentration in solution ($M\ L^{-3}$), S is the sorbed solute concentration ($M\ M^{-1}$), ρ is the soil bulk density ($M\ L^{-3}$), D is the dispersion coefficient ($L^2\ T^{-1}$), and J_w is the volumetric water flux ($L\ T^{-1}$). The dispersion coefficient is given as (Bear, 1972):

$$\theta D = \lambda |J_w| + \theta \tau D_m \quad [6]$$

where λ is the dispersivity [L], D_m is the aqueous molecular diffusion coefficient of the solute in water [$L^2\ T^{-1}$], and τ is the tortuosity factor. The tortuosity factor is calculated from the volumetric water content θ and the saturated water content θ_s according to Millington and Quirk (1961) as $\tau = \theta^{7/3}/\theta_s^2$. Solute sorption is assumed to be governed by first-order kinetics with a nonlinear Freundlich isotherm:

$$\frac{\partial S}{\partial t} = \beta(K\,C^n - S) \quad [7]$$

where K is the sorption coefficient ($L^3\ M^{-1}$), n is a dimensionless nonlinearity factor (−), and β is the rate coefficient (T^{-1}).

Initial and Boundary Conditions

We consider steady-state, unsaturated water flow with a specified flux q at the soil surface. The initial condition for the matric potential h_0 is the steady-state matric potential at the specified water flux. These initial potentials were obtained by simulating the water flow until steady-state was reached. Solutes are collected at a given depth L. We assume that the water table in the field soil is well below the observation depth. The conditions at the lower boundary ($z = -L$) correspond to a unit-gradient condition for the field soil (McCord, 1991) and to a seepage or zero-potential condition for the lysimeter. For the field soil, we consider a semi-infinite system with boundary conditions imposed at $z = -\infty$. The initial and upper boundary conditions for the water flow are then given as: