On the Origin of the Theory of Mineral Nutrition of Plants and the Law of the Minimum

R. R. van der Ploeg,* W. Böhm, and M. B. Kirkham

ABSTRACT

Modern treatises on the origin of the theory of mineral nutrition of plants and the Law of the Minimum usually refer to books published by Justus von Liebig in 1840 and 1855. These works are believed to be original reports of Liebig's own research. Occasionally, however, scholars of early agronomic literature have stated that these books by Liebig contain doctrines on mineral plant nutrition and nutrient deficiencies that had been published earlier by Liebig's countryman and colleague Carl Sprengel (1787–1859). To examine such statements, we studied the relevant literature. This study showed that the agronomist and chemist Carl Sprengel conducted pioneering research in agricultural chemistry during the first half of the 19th century. His early articles and books mark the beginning of a new epoch in agronomy. He published in 1826 an article in which the humus theory was refuted, and in 1828 another, extended journal article on soil chemistry and mineral nutrition of plants that contained in essence the Law of the Minimum. Sprengel's doctrines are presented again in the books published by Liebig in 1840 and 1855. To avoid a dispute on priorities and impacts and to recognize and commemorate the achievements of both pioneering scientists, the Association of German Agricultural Experimental and Research Stations has created the Sprengel-Liebig Medal. We propose that the international community of agronomists acts similarly by recognizing Sprengel as a cofounder of agricultural chemistry and that the Law of the Minimum henceforth be called the Sprengel-Liebig Law of the Minimum.

Authors dealing with the history of Soil Science frequently recognize different periods of development. Russell (1952) and Wild (1988), for example, call the period from 1800 to 1860 the Modern Period. For Boulaine (1994), this period ended around 1870. According to these authors, this was the period in which both physiology and agriculture were founded. Major advances of the Modern Period were the refutation of the humus theory and the development of the theory of mineral nutrition of plants. A discussion of the humus theory is given, for example, by Russell (1952) in the introductory chapter of his classic book on soil conditions and plant growth. The Swedish professor of chemistry J.G. Wallerius (1709–1785), from the University of Uppsala, is often quoted as the most prominent founder of the humus theory (Russell, 1952).

The German chemist Justus von Liebig (1803–1873) is generally considered as the most significant scholar of the so-called Modern Period (see, for example, Browne, 1944) and as the founder of modern agriculture. His main publications related to agronomy (Liebig, 1840, 1855) appeared in the second half of this period. Other prominent pioneer agronomists of this era were Boussingault in France and Lawes and Gilbert in England. All these scholars took active parts in the development of the theory of mineral nutrition of plants and in recommending the use of mineral fertilizer in agriculture (Russell, 1952; Wild, 1988; or Boulaine, 1994).

In addition to being considered the founder of the theory of mineral nutrition of plants, Liebig is celebrated because of his formulation of the Law of the Minimum. According to Black (1993), Liebig (1855, p. 23–25) stated his law in three parts as: "1. By the deficiency or absence of one necessary constituent, all others being present, the soil is rendered barren for all those crops to the life of which that one constituent is indispensable. 2. With equal supplies of the atmospheric conditions for the growth of plants, the yields are directly proportional to the mineral nutrients supplied in the manure. 3. In a soil rich in mineral nutrients, the yield of a field cannot be increased by adding more of the same substances."

Scholars of early German literature on agronomy, such as Browne (1944), Wendt (1950), and Böhm (1987), however, have pointed out that the refutation of the humus theory, the development of the theory on mineral nutrition of plants, and the formulation of the Law of the Minimum, in essence, already had been carried out in the 1820s and 1830s by Liebig's countryman and colleague Carl Sprengel. In today's agronomic literature, however, the work of Sprengel is rarely acknowledged (see, for example, Rossiter, 1975; Viets, 1977; Dyke, 1993; or McDonald, 1994). For that reason, our objective in this paper is to draw attention to Sprengel's work, so that present and future generations of agronomists have a chance to recognize fully his achievements.

The Life of Sprengel—A Brief Outline

A first biography (in German) about Carl Sprengel was written by F. Giesecke, but his manuscript [Giesecke, 1945. Philipp Carl Sprengel (1787–1859): Biographical study about the life and work of the important agricultural chemist as a contribution to the history of the natural and agricultural sciences] was never published. This manuscript, as well as much of the material on which it was based, is kept by the Library of the University of Hohenheim at Stuttgart, Germany.

The most thorough study about the life and work of Sprengel seems to have been conducted by Giesecke's student Günter Wendt in the late 1940s. On the basis of this study, Wendt earned his doctorate from the Univer-

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sity of Göttingen. His thesis work also was published (Wendt, 1950). Copies of Wendt's publication may be obtained either from W. Böhm or from the senior author. A more recent biography about Sprengel can be found in Böhm (1987). The Sprengel biographies of Wendt (1950) and Böhm (1987) are based on the unpublished Giesecke manuscript, but include additional material, such as unpublished Sprengel letters, kept by the State Archive of Sprengel's home state Niedersachsen (Lower Saxony) in Wolfenbüttel and the University Archive in Göttingen.

Short descriptions, in German, about Sprengel's life and work, are further given by Giesecke (1929), Schroeder (1987), and, in particular, by Böhm (1993, 1997). An excellent treatment in English on the history of agricultural chemistry that includes a discussion of the life and work of Sprengel was provided by Browne (1944). Some biographical information about Sprengel can be found also in Poggendorff (1863) in the American Philosophical Society Library at Philadelphia, PA. From the cited publications, especially from Wendt (1950) and Böhm (1987), the following brief outline about the life of Sprengel was prepared.

Philipp Carl Sprengel was born on 29 March 1787, on a combined post station and farm house in rural Schillerslage near Hannover, Germany. From his childhood on, he showed a strong interest in farming. As a boy of only 15 yr, he started an apprenticeship at the agricultural academy of Albrecht Daniel Thaer in nearby Celle (Fig. 1). Around 1800, Thaer was one of the most renowned agronomists in Germany and an avid supporter of the humus theory for plant nutrition. In 1804, Sprengel moved with Thaer to Möglin northeast of Berlin on the banks of the Oder River, where he worked as Thaer's assistant until 1808. From 1808 to 1817, Sprengel was an agronomic adviser and manager on large estates in Saxony, Silesia, and Thuringia. During that period, he lived occasionally in Dresden in the wintertime, where among other subjects, he studied chemistry. In the following years, he traveled extensively in his home country as well as in Switzerland, France, Belgium, and the Netherlands to broaden his views on farming. In these years of vocational wandering, he became convinced that for any progress in farming, agriculture needed the sound foundation of basic science.

In search for principles and methods from basic science, Sprengel registered in 1821, at the age of 34, as a student of natural sciences at the University of Göttingen (Fig. 1). After earning his doctorate in 1823, he worked eight more years at this University. His work included both research and teaching. In 1831, Sprengel moved to Braunschweig (Fig. 1) to become a college professor of agronomy and forestry (at the Collegium Carolinum), and to head a new research and experiment station. However, the research and experiment station never was established, which caused Sprengel to leave Braunschweig in 1839 with disappointment.

In that year, he accepted a position in the state of Prussia, where in 1842 in Regenwalde (Pommern) he founded his private academy. Here he was able to demonstrate on a field scale the applicability of his theory of mineral plant nutrition in a crop rotation system. Also

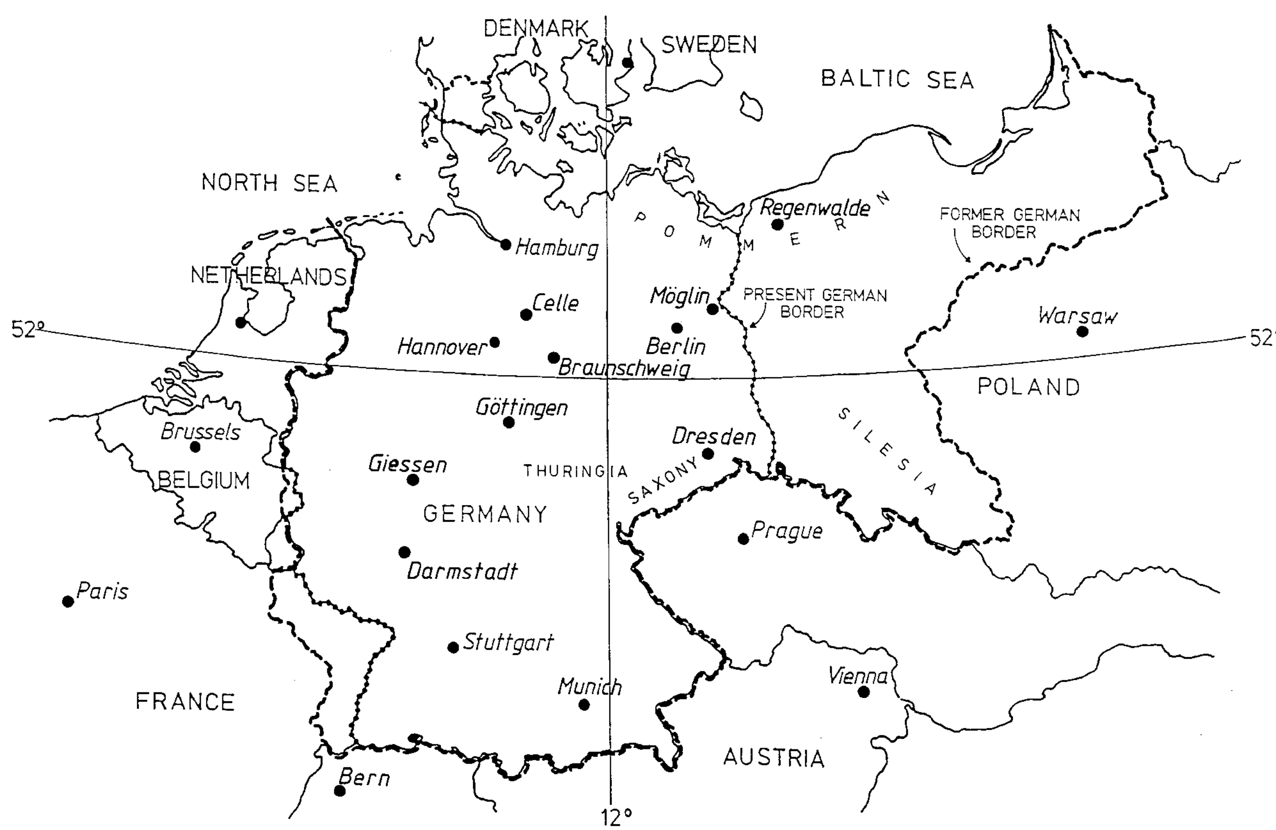


Fig. 1. Map of Germany in its former and present borders, with some of the main stations in the life of Carl Sprengel.

in Regenwalde, he met Ernestine Juliane Amalie von Wulffen, whom he married in 1841 at the age of 54. Juliane was only 19 yr old at the time of their marriage. Carl Sprengel and his wife had two children, a girl and a boy. His many activities in Regenwalde included the successful foundation of a factory that produced agricultural machinery. Sprengel's undated picture is shown in Fig. 2. He died of heart failure on 19 April 1859, at Regenwalde, now Resko, Poland.

The Work of Sprengel

The year 1787, in which Sprengel was born, fell at the end of a period in the development of soil science and plant nutrition that Russell (1952) and Wild (1988) call the Phlogistic Period. It was the period in which the nutrition of plants commonly was explained with the so-called humus theory. This theory stated that plants lived on humus-derived extracts (in German *Extraktivstoff*) containing simple water-soluble compounds of C, H, O, and N from which they were able to rebuild more complex plant tissue. Plants also were thought to be able, by means of an internal vital force (in German *Lebenskraft*, in Latin *vis vitalis*), to generate from these four elements other vital constituents such as Si and K (Wendt, 1950; Russell, 1952; Wild, 1988). Some fertilizer substances like salts and lime were considered useful for plant growth, but only because they promoted the decomposition of humus and the dissolution of organic matter in the soil solution. Albrecht Thaer (1752–1828), Sprengel's mentor, was one of the most well-known advocates of the humus theory (Wendt, 1950). His often quoted book of four volumes (Thaer, 1809–1812) was translated into English as late as 1844 (Russell, 1952), showing that the humus theory even in the Modern Period (1800–1860) still received acceptance.

Fig. 2. Carl Sprengel (1787–1859), as shown on an undated picture kept by the Main Library of the University of Göttingen (Germany).

Russell (1952) and Wild (1988), however, also point out that during the Phlogistic Period, new methods for studying plant nutrition were developed such as pot experiments and plant analyses. The end of the Phlogistic Period and the beginning of the Modern Period are marked by the work of de Saussure (1804) in Switzerland. de Saussure did pioneering work on gas exchange of plants and the nature and origin of salts in plants. He showed that plant roots were able to take up salts from the soil. For example, he demonstrated that N was taken up by roots, but was not assimilated from the air. Initially, however, the work of de Saussure did not receive much attention (Russell, 1952).

During the time when de Saussure carried out his experiments in Switzerland, Sprengel started his career in agronomy as a student at Thaer's academy at Celle (1802–1804). From this time until 1821, when he registered as a student at the University of Göttingen, he obtained invaluable practical experience in agronomy at a variety of locations in Germany as well as in adjacent countries. He became familiar with agronomy under different climatic conditions; on different soils from different parent materials; with different crops; and with different organic and mineral fertilizers such as marl, gypsum, and lime. Without doubt, he was in 1821 one of the most experienced and knowledgeable agronomists in Germany (Wendt, 1950).

As a student of natural sciences, Sprengel took courses in chemistry (as he had done in Dresden), physics, botany, mineralogy, geology, and mathematics. By 1823, he had earned his doctorate in chemistry and economics. Sprengel stayed at the University of Göttingen, conducted research in agricultural chemistry, and became a lecturer (docent) in 1826. From 1827 on, he taught a course in agricultural chemistry (in the winter semester of 1827-1828 5 h a week), which was the first time in Germany that such a course was offered (Böhm, 1987). Sprengel also taught a course in general agriculture. At this time he began to publish results of the research he had been conducting at Göttingen since 1824. His research dealt mainly with the analysis of plants (cultivated as well as wild plants) and the soils on which they grew. He must have made innumerable analyses, but unfortunately much of his original data were lost, possibly in a fire that destroyed his academy at Regenwalde in 1859.

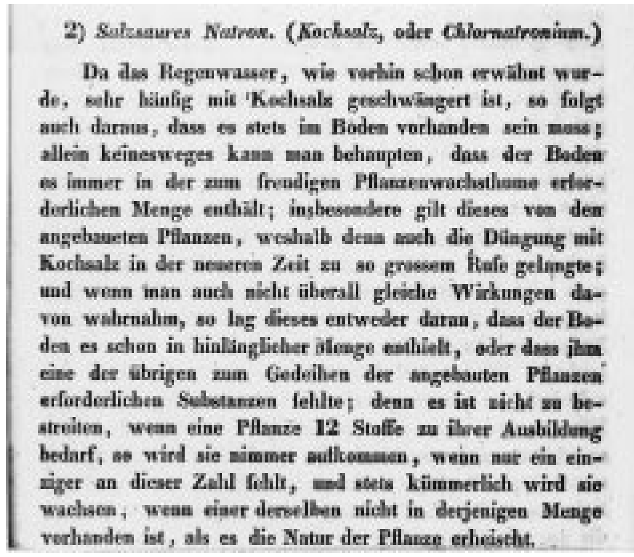
His first publications dealt with the humus theory and the role of soil organic matter as the only source of plant nutrients. Sprengel (1826) analyzed water-soluble constituents in the humus extract (*Extraktivstoff*) of a number of soils. In contradiction with the then current humus theory, Sprengel found in the extracts a variety of salts such as alkali nitrates, sulfates, chlorides, and phosphates.

In view of the salts he had determined previously in the ash of plants, and the work of de Saussure about salt uptake by plant roots and CO_2 assimilation from the air, Sprengel concluded that these soluble salts in the humus extract were the real plant nutrients. Hence, in this publication Sprengel essentially disproved the humus theory. It is of interest that Sprengel's article of 1826 was published in the *Archiv für die Gesammte Naturlehre*. The editor of this journal was the chemist Karl Wilhelm Gottlieb Kastner from the University of Erlangen, under whose guidance Justus von Liebig earned his doctorate in 1823, the same year in which Sprengel was awarded his degree at Göttingen. Initially, Liebig also published occasionally his work in this journal, for example, in no. 9 of the 1826 volume.

After completing his work on soil organic matter, Sprengel went one step further and analyzed the entire rooting zone of a large number of soils. In a following publication, Sprengel (1828) considered the various soil inorganic compounds he had determined in the topsoil as well as in the subsoil. He discussed in detail their relevance as plant nutrients for various crops, their use as possible fertilizers, and the methods of analysis. In some cases, for example with NH_3, he discussed the possibility of producing such fertilizers. Simultaneously, he described his theory on mineral nutrition of plants more precisely than in his first publication (Sprengel, 1826). In total, he listed 20 elements that he considered as plant nutrients, including N, P, K, S, Mg, and Ca (Sprengel, 1828, p. 432). In this article (p. 93), he in essence also formulated the *Law of the Minimum*. In a discussion about the use of salt (NaCl) as a fertilizer, Sprengel stated:

> Because, as mentioned before, rainwater often contains salt, it follows that this is always present in the soil; however, this does not mean that the soil always contains it in sufficiently large amounts to allow luxurious plant growth; this is especially true for cultivated plants, and, for this reason, fertilization with salt has recently gained much recognition; and if the same beneficial results were not always seen, this was either because the soil already had enough salt in it, or one of the other substances necessary for crop growth was missing; because it is indisputable, that, when a plant needs 12 substances to develop, it will not grow if any one of these is missing, and it will always grow poorly, when one of these is not available in a sufficiently large amount as required by the nature of the plant.

The original text, as part of p. 93 from Sprengel (1828), is shown here as Fig. 3. In other publications (e.g., Sprengel, 1831, p. 635; Sprengel, 1839, p. 52), he repeated this law in slightly different words. We can assume that contemporary scholars, at least in Germany, had knowledge of this law as formulated by Sprengel. His article of 1828 was published in the *Journal für Technische und Ökonomische Chemie* (edited by Otto Linné Erdmann), where Sprengel published more than 20 articles between 1828 to 1833, some of which consisted of numerous parts. A list of Sprengel's publications in this journal for the six years mentioned is shown in Table 1. The *Journal für Technische und Ökonomische Chemie* in this period was a reputed outlet in which work of such scholars as Liebig, Gay-Lussac, and Berzelius was also occasionally published.


2) *Salzsaures Natron. (Kochsalz, oder Chlornatronium.)*

Da das Regenwasser, wie vorhin schon erwähnt wurde, sehr häufig mit Kochsalz geschwängert ist, so folgt auch daraus, dass es stets im Boden vorhanden sein muss; allein keinesweges kann man behaupten, dass der Boden es immer in der zum freudigen Pflanzenwachsthume erforderlichen Menge enthält; insbesondere gilt dieses von den angebaueten Pflanzen, weshalb denn auch die Düngung mit Kochsalz in der neueren Zeit zu so grossem Rufe gelangte; und wenn man auch nicht überall gleiche Wirkungen davon wahrnahm, so lag dieses entweder daran, dass der Boden es schon in hinlänglicher Menge enthielt, oder dass ihm eine der übrigen zum Gedeihen der angebauten Pflanzen erforderlichen Substanzen fehlte; denn es ist nicht zu bestreiten, wenn eine Pflanze 12 Stoffe zu ihrer Ausbildung bedarf, so wird sie nimmer aufkommen, wenn nur ein einziger an dieser Zahl fehlt, und stets kümmerlich wird sie wachsen, wenn einer derselben nicht in derjenigen Menge vorhanden ist, als es die Natur der Pflanze erheischt.

Fig. 3. Excerpt from page 93 of Sprengel (1828) with Sprengel's first formulation of the Law of the Minimum; the English translation is given in the text.

Sprengel stayed at the University of Göttingen until 1831. On the basis of the courses he was teaching, Sprengel wrote a book of two volumes on agricultural chemistry. The first volume (Sprengel, 1831) dealt with inorganic aspects of soil chemistry, and the second one (Sprengel, 1832) with organic aspects. In both works, Sprengel's theory of mineral nutrition of plants and his Law of the Minimum are treated in detail.

In 1831, Sprengel moved from Göttingen to Braunschweig. Although he continued to do research, Sprengel now spent much time on administration. In Braunschweig, he conducted his first field trials. He also wrote review articles about the use of ammonia, lime, and gypsum as fertilizers. In the journal that he was editing (*Land- und Forstwirthschaftliche Zeitschrift für Nord-Deutschland*), he published a number of other articles (see Wendt, 1950). During his stay at Braunschweig, Sprengel authored three books: one on soil science (Sprengel, 1837), one on soil amelioration (Sprengel, 1838), and one on fertilizer use (Sprengel, 1839). His book on soil science is one of the first comprehensive works on this subject matter (see Joffe, 1949; or Schroeder, 1987). Sprengel left Braunschweig and moved to Regenwalde in 1839 to become secretary-general of the semi-governmental society of (rural) economy in Pommern (see Fig. 1). His main duty was to foster agronomy in research and teaching as well as in extension. In particular, he was hired to teach his theory of plant nutrition and to demonstrate, on a field scale, use of mineral fertilizers.

In his new position, Sprengel developed a large number of activities. Among others, he founded an agronomy journal (*Allgemeine Landwirthschaftliche Monatsschrift*) that he also edited and a soil testing laboratory. His principal achievement in this period of his life, however, was the foundation of an agricultural academy and experiment station at Regenwalde in 1842, initially named Landwirthschaftliche Lehranstalt zu Regenwalde. Sprengel

Table 1. List of publications of C. Sprengel in the *Journal für Technische und Ökonomische Chemie* (Journal of Technical and Economical Chemistry) in the period 1828 to 1833; notice that some of his publications (all are in German) consisted of more than one part.

Year	Title	Vol. (no.)	Pages
1828	Von den Substanzen der Ackerkrume und des Untergrundes, insbesondere, wie solche durch die chemische Analyse entdeckt und von einander geschieden werden können; in welchen Fällen sie dem Pflanzenwachsthume förderlich oder hinderlich sind und welche Zersetzungen sie im Boden erleiden {On the substances in the topsoil and subsoil, especially, how they can be detected by chemical analysis and how they can be separated from each other; in which cases they are stimulating or hindering plant growth, and how they decompose in the soil}.	2(4)	423–474
		3(1)	42–99
		3(3)	313–351
		3(4)	397–421
1829	Von der Lage, den physischen Eigenschaften, den chemischen Bestandtheilen und der Vegetation einiger im Königreich Hannover vorkommenden sehr fruchtbaren und sehr unfruchtbaren Bodenarten {About the location, the physical properties, the chemical constituents and the vegetation of some very fertile and very infertile soils that are found in the Kingdom of Hannover}.	4(1)	1–38
1829	Zur Agriculturchemie {About agricultural chemistry}.	4(3)	344–362
1829	Einige Bemerkungen über wildwachsende, des Anbaues Würdige Pflanzen, nebst Mittheilung der Resultate ihrer chemischen Analyse {Some remarks about wild, but worth cultivating, plants and a report about the results of their chemical analysis}.	5(1)	41–75
		5(2)	114–147
		5(3)	284–299
		6(1)	84–100
		6(3)	321–333
1830		8(4)	355–374
		9(1)	1–20
1831		10(1)	34–69
1829	Von den Ursachen der Unfruchtbarkeit mancher Bodenarten, die über dem Muschelkalke ruhen und den Mitteln sie ertragsfähiger zu machen {On the causes of unfertility of some soils, that rest on Muschelkalk [a local limestone] and how they can be made more fertile}.	5(3)	300–327
1829	Auf welche Weise in den Oekonomien, ohne grosse Mühe und Kosten, eine beträchtliche Menge Ammoniaksalze gewonnen werden können {How considerable amounts of ammonia salts can be produced in agriculture without large efforts and costs}.	6(1)	63–71
1829	Von den chemischen Bestandtheilen der von den Landwirthen benutzten Stroharten und dem Werthe welchen sie hiernach als Viehfutter und Streumaterial haben {On the chemical constituents of different types of straw used by farmers and their value as fodder and litter}.	6(3)	312–320
		6(4)	392–406
1830	Ueber Rindviehharn {About cattle urine}.	7(1)	1–34
		7(2)	171–195
		8(4)	375–382
1830	Unterricht in Oeconomie und Agriculturchemie betreffend {Teaching farm management with respect to agricultural chemistry}.	7(1)	128–132
1830	Ueber die Benutzung des Baumlaubes als Viehfutter und die chemischen Bestandtheile mehrerer Laubarten {On the use of tree leaves as fodder and the constituents of various kinds of foliage}.	7(3)	261–281
		8(1)	11–19
1830	Ueber die chemischen Bestandtheile der Ackerkrume eines Feldes auf welchem Herr B.C.R. Prof. Lampadius mehrere Versuche mit gebranntem Thon anstellte (vergl. Band 5. S.33 und Band 6. S.347 dies. Journ) so wie über die düngenden Wirkungen des gebrannten Thons überhaupt {On the chemical constituents of the topsoil of a field on which Mr. B.C.R. Prof. Lampadius conducted a number of experiments with burned clay (compare vol. 5, p. 33 and vol. 6, p. 347 of this Journal) as well as on the fertilizing effect of burned clay in general}.	8(2)	208–219
1830	Ueber Pottasche- und Alaun-Gewinnung aus Granit, Gneis und anderen kieselsaures Kali enthaltenden Gebirgsarten {On the production of potash and alum from granite, gneiss, and other rocks that contain potassium silicates}.	8(2)	220–221
1830	Ueber die chemischen Bestandtheile der gebräuchlichsten Streumaterialien {On the chemical constituents of the most common litter materials}.	8(3)	269–286
1830	Ein untrügliches und wohlfeiles Mittel, um augenblicklich die grauen Ackerschnecken zu vertilgen {An infallible and cheap means to exterminate instantaneously the gray field slug}.	9(1)	125–131
1830	Vom Lichte (aus Dr. Carl Sprengels nächstens bei Vandenhoeck und Ruprecht in Göttingen erscheinender *Chemie für Landwirthe, Forstmänner und Cameralisten*) {About light (from Dr. Carl Sprengel's soon-to-appear book *Chemistry for agronomists, foresters, and agricultural economists*, [published by] Vandenhoeck and Ruprecht in Göttingen)}.	9(2)	172–186
1830	Von der Wärme {About heat}.	9(3,4)	275–303
1830	Chemische Untersuchung einiger zur Verfertigung von Töpferwaaren und Ziegeln dienenden Thonarten {Chemical examination of some clays that are used for the production of pottery and bricks}.	9(3,4)	307–315
1831	Giebt es Humussäure und humussaure Salze der Urzeit {Are there archaic humic acids and salts of humic acids?}.	10(1)	118–120
1831	Ueber die feuerfesten Bestandtheile unserer gewöhnlichen Getreidekörnerarten {On the incombustible constituents of our common cereal grains}.	10(3)	344–351
1831	Zur landwirthschaftlichen Chemie. Auszüge und kurze Bemerkungen aus Dr. Sprengels nächstens erscheinender *Chemie für Landwirthe* {About agricultural chemistry. Extracts and short remarks from Dr. Sprengel's soon-to-appear book *Chemistry for agronomist*, [foresters, and agricultural economists]}.	11(2)	152–206
1832	Chemische Untersuchung der cultivirten Holzarten auf ihre feuerfesten Bestandtheile {Chemical analysis of the incombustible constituents of the cultivated tree species}.	13(3)	382–388
1832	Chemische Untersuchung der Blätter und Stengel des grossen Negerkorns (Holcus sorghum) {Chemical analysis of the leaves and stalks of large African corn (Holcus sorghum)}.	13(3)	389–391
1832	Chemische Untersuchung der Erdäpfelblätter (Helianthus tuberosus) {Chemical analysis of potato leaves (Helianthus tuberosus)}.	13(3)	392–394
1832	Chemische Untersuchung der Felddistel (Serratula arvensis, Cnicus arvensis) {Chemical analysis of the field thistle (Serratula arvensis, Cnicus arvensis)}.	13(3)	395–396
1832	Chemische Untersuchung der Brachgewächse und ihrer Blätter, hinsichtlich der in ihnen befindlichen feuerfesten und nährenden Bestandtheile {Chemical analysis of the fallow herbs and their leaves, regarding their incombustible and nutritional constituents}.	13(4)	474–487
1833	Zur landwirthschaftlichen Chemie. Auszüge und kurze Bemerkungen aus Sprengel's Chemie für Landwirthe. 2.BD. {On agricultural chemistry. Extracts and short remarks from Sprengel's *Chemistry for agronomists*, [*foresters, and agricultural economists*], *Volume 2*}.	17(2)	184–214

carried the main teaching load of the academy and simultaneously he managed the experiment station. From 1846 on, his state-supported academy was called the Academy of Agriculture in Regenwalde. Sprengel also founded a factory for agricultural machinery at Regenwalde and a dairy factory (see Wendt, 1950). Although state supported, both the academy and the industry were privately owned and managed by Sprengel. In many aspects, Sprengel's activities at Regenwalde thus resemble those of Lawes at Rothamsted (see Dyke, 1993).

In spite of his many tasks, he revised in the 1840s his earlier books (i.e., Sprengel, 1837, 1838, 1839), and he wrote a new book of three volumes on crop production (Sprengel, 1847–1852). According to Böhm (1987), this book is still among the best published in Germany on this subject matter. Sprengel was active until shortly before he died in 1859 at the age of 72.

Sprengel and Liebig

A discussion and an evaluation of the work Sprengel (1787–1859) are not possible without a reference to Liebig (1803–1873) and his contribution to agricultural chemistry. Therefore, a brief survey of the life and work of Liebig is given here; more detailed biographical and bibliographical information is provided by Browne (1944), Paoloni (1968), and Böhm (1997).

Justus von Liebig was born in 1803 at Darmstadt (Fig. 1), where his father owned a drugstore. The products sold included paints and varnishes that he produced himself. The young Liebig gained his first chemical experience in his father's laboratory. Although Liebig did not finish high school, he registered at the age of only 16 as a university student, first at Bonn and later at Erlangen.

Fig. 4. Justus von Liebig (1803–1873), in 1840 a propagandist and promulgator of truths already announced by others, rather than a discoverer of new knowledge.

His exceptional abilities were recognized soon and by 1823 Liebig had earned, under the supervision of the previously mentioned K.W.G. Kastner, his doctorate (interestingly enough in medicine and philosophy) from the University of Erlangen. As mentioned before, in the same year Sprengel was awarded his doctorate from the University of Göttingen. In the next year, at the age of only 21, Liebig accepted a professorship at the University of Giessen (Fig. 1), and in 1825 he became a full professor of chemistry at the same University. From 1822 on, Liebig published extensively, at first mainly on topics of inorganic chemistry, and after 1830, increasingly on organic chemistry and pharmacy. By the end of the 1830s, Liebig was a distinguished and world-renowned scientist, with nearly 300, much regarded, high-impact publications in the leading journals of chemistry and pharmacy (see Paoloni, 1968).

In 1837, Liebig was asked by the British Association for the Advancement of Science to give a report on the state of organic chemistry and organic analysis (see Browne, 1944). The first part of this report (on agriculture and physiology) was published 3 yr later (Liebig, 1840). It is most noteworthy that Liebig did not publish about topics in agricultural chemistry until 1840. Occasionally, however, he published in the journal that he was editing (*Annalen der Pharmacie*) contributions by others related to agricultural chemistry, such as one by Sprengel in 1835 about mineral constituents of wood. In this regard, one of the papers at the symposium organized by the American Association for the Advancement of Science in 1940, in commemoration of the hundredth anniversary of the publication of Liebig's *Organic Chemistry in its Applications to Agriculture and Physiology*, noted that "Liebig's great prominence as an organic chemist did not qualify him in 1840 to become an authority on agricultural chemistry" (Browne, 1942a). The same article further remarked that Liebig "ignored the fact that long before the appearance of his book (Liebig, 1840) Carl Sprengel had announced opinions with regard to humus and mineral fertilizers that were almost identical with those which Liebig himself afterwards proclaimed." At the same symposium, Waksman (1942) and Browne (1942b), in treatises about the humus theory and the Law of the Minimum, respectively, noted "that the fact that plants obtain their minerals directly from the soil was already clearly outlined by Sprengel (1838) two years before the publication of Liebig's book, and that a formulation of the Law of the Minimum can be found in Sprengel (1837)." Accordingly, Browne (1944), in the preface to his book on the history of agricultural chemistry, wrote "that in his *Organic Chemistry in its Applications to Agriculture and Physiology* Liebig was more a promulgator and defender of truths that had already been announced than a discoverer of new knowledge." More recent views on Liebig's work in agricultural chemistry can be found in Finlay (1991), Munday (1991), and Schling-Brodersen (1992). Figure 4 shows an undated picture of Liebig around 1860.

As mentioned earlier, the most thorough study about the life and the work of Sprengel was conducted by Günter Wendt in Germany in the late 1940s. Wendt (1950) discusses in detail the early publications of Sprengel (1826, 1828) that may not have been available to either

Browne (1942b) or Waksman (1942) at the time of the Liebig Symposium in 1940. Wendt (1950) also gives a careful account of Sprengel's long dispute with Liebig about parts in Liebig's book that were taken from his work without proper acknowledgment. However, Liebig insolently ignored Sprengel's complaints and continued to pass off the theory of mineral nutrition of plants as his own. In view of the historical developments, both Wendt (1950) and Böhm (1987) therefore concluded that Carl Sprengel must be considered as the true founder of the doctrine of mineral nutrition of plants and Justus von Liebig as the indefatigable contender in the struggle for its acceptance.

The question has been raised as to why the work of Liebig (1840) was accepted so widely, whereas the work of others, such as Sprengel, received only moderate attention. The answer seems to be that Liebig's book was very timely, because of a general concern, in the Old World as well as in the New World, about worn-out soils, growing populations, and threatening famines (see Wendt, 1950 or Rossiter, 1975). Additionally, in contrast to other scholars who had been publishing on agricultural chemistry, Liebig was a world-renowned and celebrated scientist. However, because Liebig was only moderately familiar with the subject matter, his views and statements were not in every aspect correct. Hence, his book was controversial and provocative, and, therefore, drew much attention. However, with his fame, passion for the subject, and polemic style, Liebig achieved wide acceptance for the theory of mineral nutrition of plants. By 1848, his book had passed through more than 20 editions and reprints: six in Germany; five in England; three in the USA; two in France; two in Italy; and one each in Denmark, Holland, Poland, and Russia (see Browne, 1944; Paoloni, 1968; and Böhm, 1997). In the first edition of his book (Liebig, 1840) and also in the several following ones, Liebig did not discuss specifically the Law of the Minimum. This law is discussed specifically in Liebig (1855, 1st ed., p. 23–25, or 2nd ed., appendix, p. 121–122), where the term *minimo* is used for the first time. Not until the seventh edition of his first book in 1862, Vol. 2, p. 223 (more than three decades later than Sprengel), did Liebig clearly formulate the Law of the Minimum.

Initially, the work of Wendt (1950) caused some controversy in Germany. However, in 1955 the Association of German Agricultural Experimental and Research Stations (VDLUFA) decided to take proper action. It created the Sprengel-Liebig Medal, with which persons are acknowledged regularly for outstanding achievements in, or services to, agriculture. By doing so, a dispute about priorities and impacts was avoided, and both pioneering scientists, Sprengel and Liebig, are recognized and commemorated equally. In view of the evidence provided by the early German literature on agriculture, the VDLUFA action appears to have been most appropriate.

Conclusions

Our study of early agronomic literature revealed that the German agronomist Carl Sprengel (1787–1859) conducted basic and high-impact research on soil fertility and plant nutrition during the first part of the so-called Modern Period of soil science and plant nutrition. His pioneering research can be considered as the start of agricultural chemistry. In the 1820s and 1830s, he disproved the humus theory; postulated the theory of mineral nutrition of plants, which states that plants require mineral elements to develop; and he formulated the Law of the Minimum. He wrote fundamental text books on agricultural chemistry, soil science, soil amelioration, plant nutrition and fertilizers, and crop production. He founded his own academy of agriculture, edited two agronomy journals, and established the first soil testing laboratory in Germany. He taught the first university course on agricultural chemistry in Germany. He also was the founder of a successful factory of agricultural machinery. His manifold outstanding contributions make him a pioneer of agricultural chemistry as much as Boussingault, Lawes and Gilbert, or Liebig. Sprengel deserves to be recognized as one of the founders of agricultural chemistry. Furthermore, in view of the historical developments, it seems to be appropriate to call the Law of the Minimum henceforth the Sprengel-Liebig Law of the Minimum.

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