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Precocious 19th century soil carbon science

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ABSTRACT

Soil organic matter is important for nutrient exchange in the soil environment, carbon sink, and soil fertility. Soil scientists usually estimate the amount of organic matter in a soil from its carbon content using the 1.724 conversion factor. The origin of this conversion factor is conventionally attributed to Jacob Maarten Van Bemmelen, a Dutch chemist. In the early nineteenth century, science academies devoted considerable attention to understanding soil humus to increase agricultural productivity. Van Bemmelen investigated the fertility of soils for growing tobacco in Indonesia. Van Bemmelen's 1890 publication used the 1.724 factor for estimating humus content from elemental analysis of C concentration. A survey of the scientific literature from the same period indicated that Emil Wolff was the first to suggest the factor. This paper draws a brief historical summary of van Bemmelen's research on soil organic matter, and discusses the origin and use of the 1.724 factor using the scientific literature from 1900s to 1930s. The origin of the factor is contextualized with the emerging humus theory of the 19th century. Our study suggests that the factor has been erroneously attributed to van Bemmelen and widely used in English, French, Dutch, and German literature. The 1.724 factor was originally developed for the conversion of carbon to humic substances, which themselves do not have a clear definition. Many regional studies have indicated the inadequacy of the factor.

1. Introduction

The van Bemmelen factor is known in soil science as a conversion factor of 1.724 for estimating soil organic matter (OM) from soil organic carbon content (OC). This factor is frequently and conveniently used (e.g., by Badía and Marti, 2003; de Castro Padilha et al., 2020; Minasny and McBratney, 2018; Rudiyanto et al., 2016), but also repeatedly criticised (Alexander and Byers, 1932; Pribyl, 2010; Heaton et al., 2016). It is one of the earliest so-called pedotransfer functions (Van Looy et al., 2017). This factor is usually attributed to Jakob Maarten van Bemmelen (1830–1911), a Dutch chemist from the University of Leiden. Van Bemmelen's significant major legacy contribution to soil science is on the theory of absorption or adsorption (Van Bemmelen, 1897). He is credited for having derived the first adsorption isotherm (Sposito, 1980) and contributed to the humus study by suggesting that humus is a colloidal complex.

Van Bemmelen's use of the 1.724 factor appeared in an 1889 publication on analysing the chemical components arable soils, using the soil of Deli in Sumatra (Van Bemmelen, 1890b) as an example. In the early nineteenth century, scientists devoted considerable attention to understanding the origin and chemical nature of humus, i.e., the resistant organic black materials in the soil that was thought to be the source of soil fertility. Scientists analysed humus' composition with fractionation and classification, but despite the efforts, the quantification of humus amount remained a difficult task. To solve this problem, humus content (i.e., soil organic matter) was estimated indirectly from its chemical composition (i.e., soil carbon content). Conversion from soil carbon to soil organic matter is one of the earliest pedotransfer functions and was promoted by Wolff (1864) and Warrington and Peake (1880). The current literature almost exclusively, however, attributes the origin of this conversion factor to van Bemmelen.

This paper provides a brief history of van Bemmelen and the origin and use of the 1.724 factor. We narrate his work on soil considering the knowledge on humus from the late 19th century. We consider some contemporary concepts of soil organic matter to explain historical observations. Finally, we discuss the reasons why the 1.724 factor has been misattributed to van Bemmelen.

2. Van Bemmelen and the 1.724 factor

2.1. Jakob Marteen van Bemmelen (1830–1911)

Jakob Maarten van Bemmelen (Fig. 1) was born on 3rd November 1830 in Almelo, the Netherlands. He studied chemistry at the University of Leiden and obtained a doctorate in 1854 on the extraction of chemical compounds from *Cibotium cumingii*, a fern from Sumatra (Praptosuwiryo et al., 2011). He started his career as a chemist in

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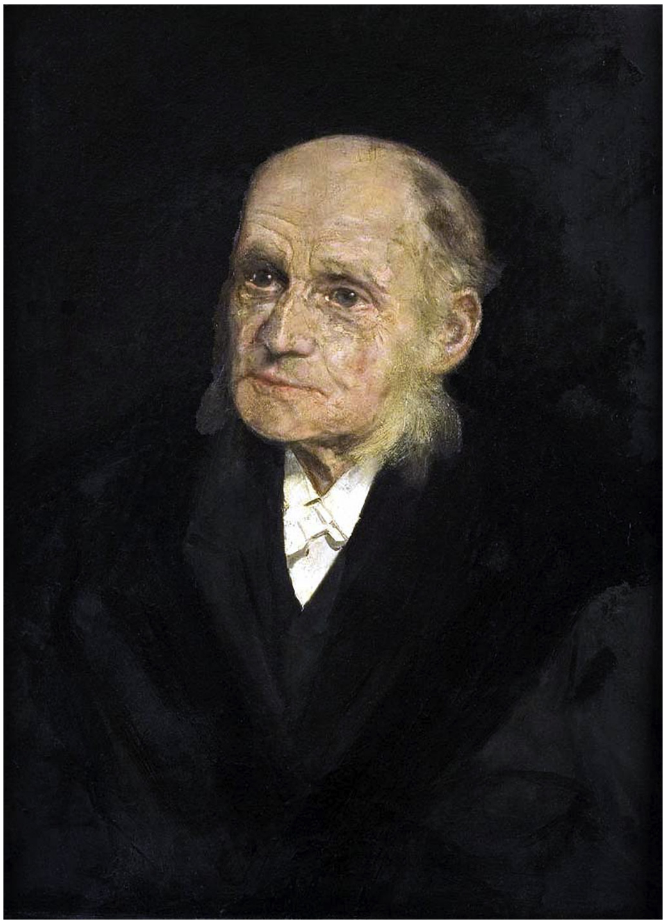

Fig. 1. Jakob Maarten van Bemmelen (1830–1911), from van Kersen & Ekkart (1973).

1852 in the chemical laboratory of the University of Groningen. He became a lecturer in chemistry and physics at the Agriculture School in Groningen in 1854, where he investigated agricultural problems such as cultivating soils with poor fertility. This was where his interest in soil chemistry began (Chardon 2010; Beneke and Lagaly, 2005).

In 1874, van Bemmelen was appointed chair of inorganic chemistry at Leiden University. His laboratory provided agricultural investigations on soil analyses from the government and private companies. He extracted chemical elements from the soil with acids of different strengths to estimate the part available for the plant. He also studied the problem of acid sulphate soils in the reclaimed area in the west of the Netherlands (Chardon 2010).

Around 1889, van Bemmelen conducted studies on soil from Deli for growing tobacco in the then Netherlands East Indies (part of present-day Indonesia). He published five papers in a German publication *Landwirtsch Versuchsstat* (Van Bemmelen, 1890a, 1890b, 1890c, 1890d,). The studies were requested by the tobacco company in Deli, which was concerned about the declining yield of tobacco. As far as we know, these are the only publications by van Bemmelen on soil organic matter in the tropics. In the first paper, he compared volcanic soils from Deli in Sumatra and Malang in Java and an alluvial soil from Rembang (Java) for growing tobacco. Van Bemmelen described the soil of Rembang, which had produced good tobacco crop but later produced low-grade tobacco. The second paper (Van Bemmelen, 1890b) is on the determination of chemical properties in arable soil. This paper is often cited as the origin of the so-called van Bemmelen factor. A full discussion on van Bemmelen's work on the soils of Deli, Sumatra is provided in the companion paper (Minasny et al., 2020).

In 1889, van Bemmelen prestigiously became the Rector of the University of Leiden and in 1910 published the book *Die Absorption*, from which he is known as the founder of the theory of absorption (or adsorption) from the soil solution (Beneke and Lagaly, 2005).

2.2. Van Bemmelen and the Humus theory (19th century)

The 19th century research on soil organic matter or humus focused on fractionating and classifying humus (Kononova, 1961). Soil organic matter was distinguished into undecomposed plant residues and dark-coloured humic substances that were formed by the decomposition of organic matter, called *matière noire* by the French agronomist Louis Grandeau (1834–1911).

De Saussure (1767–1845) in 1804 showed that humus contains more carbon and less hydrogen and oxygen than the original plant residues (Kononova, 1961). Carl Sprengel (1787–1859) in Germany (1826), provided a detailed chemical analysis of humus. He developed the procedure to separate humic acids using alkali extraction. Sprengel recognised different forms of humus as a source of plant nutrients (Stevenson, 1994). Berzellius classified humus based on solubility in alkaline solutions (Kononova, 1961).

In France, Grandeau (1878) developed a method to extract this *matière noire* with an acid pre-treatment (HCl) to dissolve carbonates, followed by an alkaline reagent (NH_4OH). The solution was dried, and the ash mineral and organic matter content were measured (Boulaine and Feller, 1985).

Within this context, van Bemmelen studied the adsorption of metals by organic matter (Van Bemmelen, 1888). He found that humic materials were not homogeneous substances but amorphous and colloidal (Van Bemmelen, 1888). He proposed humus as a colloid that formed a complex of humate and colloid silicate (*colloïdalen Komplex von Humat und Silikat*) (Van Bemmelen, 1890c). Alkali bases were adsorbed to the humic substances, and these adsorbed bases contribute to soil fertility. The acidity of humus was not due to free humic acids, but due to the reaction of humus with mineral salts; the bases were adsorbed from the salts, liberating the mineral acids.

He criticised Grandeau's method (Van Bemmelen, 1890c, p. 351):

> The determination of humus in soil, which is dissolved by dilute alkalis (before or after treating the earth with a dilute acid), and the mineral components that dissolve at the same time, can teach us little. Such simple means are completely insufficient to assess the value of humus and to decide how much alkaline bases, phosphoric acid that is absorbed by the humus substances.

He believed that the alkali bases found in the ash of the *matière noire* were not chemically combined to carbon in the organic matter but were adsorbed by the humic materials.

The role of humus for supplying plant nutrients was debated. Liebig first rejected the idea that humus is a direct source of plant nutrients, rather it is a mere product of photosynthesis (Kononova, 1961). Grandeau asserted that humus does not nourish the plant but makes digestible mineral nutrients (Boulaine and Feller, 1985) . Humus increases the solubilization of mineral nutrients and, thus their bioavailability to plants, a vehicle for mineral food. This new concept was appreciated by Liebig, who sent Grandeau a congratulatory letter in 1872 (Manlay et al., 2007).

The 19th century scientists understood humus to be a biological product of microorganisms, rather than a chemically synthesised product. Humus is a product of decomposition and a source of nutrients. The availability of nutrients depends on the stage of decomposition. Ewald Wollny (1846–1901) from Munich is notable for his work on the role of humus on soil physical properties. Wollny (1897) outlined the role of humus in improving soil tilth, and the formation of soil aggregates, creating pore spaces for air and water, and reducing soil temperature extremes. Humus is recognised as an important factor of soil-forming processes. Russian scientist Vasily Dokuchaev (1846–1903) wrote *The Russian Chernozems* in 1883 and provided a supplemental map of the humus content in the soils of European Russia (Dokuchaev, 1883; Hartemink et al., 2013). Russian scientists showed that continuous cultivation of cereals on chernozem resulted in decreased soil fertility and increased susceptibility to drought (Kononova, 1961).

2.3. Van Bemmelen and the 1.724 factor (1890)

Van Bemmelen's publication, commonly cited as the origin of the 1.724 factor (Van Bemmelen, 1890b) described methods of soil analysis *On the determination of (hygroscopic) water, humus, sulphur, silicic acid bound in colloidal silicates, and manganese in arable soils*.

For the analysis of humus, he wrote (van Bemmelen, 1890b, p. 280):

> Humus is obtained by multiplying the carbon content by the factor of Wolff: 1.724. Carbon, water, and of the loss on ignition is conducted in combustion tubes in a current of oxygen. Nitrogen was measured according to the method of Dumas.

The methods described in van Bemmelen's paper were summarised in English in a publication *Principles and Practice of Agricultural Analysis* by Harvey Washington Wiley (1844–1930), an American chemist.

Van Bemmelen (1890b) also derived a method to calculate the strongly bound water, which was called the method of Von Bemmelén (sic) by Wiley (1894, p.320). Van Bemmelen posited that soil contains colloidal humus and colloidal silicate, which made the determination water content challenging. Water content obtained from drying soil at 100 °C has no significant meaning as it was determined by the soil's initial condition, temperature, and humidity, and doesn't reflect the amount of water held by the colloid. Van Bemmelen was more interested in determining the water after the soil had been equilibrated at certain liquid vapour at a certain temperature. In other words, the osmotic potential. He set a condition at which the soil was dried over sulphuric acid, the point at which the tension of the water vapour in the soil, at a temperature about 15 °C, approached zero. The water in the soil under this condition he called strongly bound water. It is unclear what would be the corresponding osmotic potential. A publication by Alexander and Haring (1936) indicated that equilibrating the soil with a 3.3% (by mass) sulphuric acid solution was used to estimate the quantity of colloid present in a soil. The water held under this condition was equivalent to 99% relative humidity at 20 °C or −1.4 MPa.

Van Bemmelen further made the calculation for estimating the amount of tightly bound water, for soils with no carbonates, where the loss on ignition can be regarded as the sum of the humus and water content. Thus, the estimation of humus is important. Van Bemmelen gave an example with the volcanic soil of Deli, which had the following elementary analysis: Carbon: 2.94%, Water: 14.78%, Nitrogen: 0.28%, and the Loss on ignition was 17.54%. The humus content was: $2.94 * 1.724 = 5\%$. Thus, the strongly bound water was estimated as the difference between loss on ignition and humus = 12.47%.

He further assumed that the humus contained 5% H, and thus 0.25% of H in humus, which corresponded to 2.28% water held by humus. Thus, the hygroscopic water of soil and humus was: $12.47 + 2.28 = 14.75\%$. The value was comparable to the analysis (using sulphuric acid drying) of 14.79%.

This analysis of strongly bound water is akin to what is referred to as lattice water, water bound in mineral lattices, and on organic matter surfaces, which was determined as the amount of water lost between 100 and 1000 °C (Zreda et al., 2012).

2.4. The history of the 1.724 factor (1820s–1930s)

Clearly, van Bemmelen did not derive the 1.724 factor, he himself referred to it as the Wolff factor. Emil Theodor von Wolff (1818–1896) from Hohenheim Agricultural Academy in Germany developed a method for measuring soil OC. His method was based on organic matter oxidation with sulphuric acid and potassium bichromate, and measuring the evolved carbonic acid (Wolff, 1864, p 221):

> In order to calculate the amount of humus substance from the carbon content of the soil, at least roughly calculated, I take that humus has an average of 58 percent Carbon; one only has to multiply the carbon by 1.724 or the carbonic acid with 0.471.[1]

But Wolff did not provide any data to show how the factor was derived. Several researchers prior to Wolff had published an estimate of carbon in organic matter or humus. The earliest reference was from Carl Sprengel's (1787–1859) publications (Sprengel, 1826; Sprengel, 1827) in which he found that the *Humussäure* (humic acid) was composed of 0.580 carbon, 0.399 oxygen, and 0.021 hydrogen. As noted by Alexander and Byers (1932), this is probably where the 1.724 factor originated.

Nevertheless, the work by Sprengel (1826) was criticised by Berzelius (1828) as inaccurate. However, it was Wolff (1864) that first proposed the use of the 1.724 factor despite supporting evidence. Warrington and Peake (1880) from Rothamsted Experimental Station attributed the factor to Schulze, Wolff, and Fresenius. Schulze (1849) calculated that humus was 58% C, based on the assumption that ¼ of the soil organic matter was undecomposed plant remains with a carbon content of 52%, whereas the remaining ¾ was humified material with a carbon content of 60%. Fresenius recommended the chromic acid method for determining soil carbon, which was adopted by Warrington and Peake (1880). Another early adopter was Loges (1883), who quoted the use of the Wolff factor to estimate the humus substance of soils.

Wiley's (1894) publication is probably the first English publication that attributed van Bemmelen. Wiley (1894, p. 332) called it the humus method of van Bemmelén (sic):

> Van Bemmelén obtained the content of humus by the multiplication of the content of carbon in the soil by the factor of Wolff.

Following on, the literature generally has attributed this factor to van Bemmelen, as noted in Cameron and Breazeale (1904, p. 31):

> On the authority of Wolf, van Bemmelen and Wollny, the most popular usage is to multiply the amount of carbon dioxide found by the factor 0.471. This factor seems to be based on the assumption made as a result of Wollny's well-known investigations that the percentage of carbon in the organic matter, or rather humus of the soil, varies but little from 56 percent.

Cameron and Breazeale (1904) measured organic matter from 19 typical agricultural soils from the US and showed that the C content in soil OM varied from 33.3 to 49.22%, with an average of 41.77%. But they explained (Cameron and Breazeale, 1904, p. 44):

> Furthermore, this organic matter, not extracted by the ammonia, is made up largely of cellulose, or cellulose-like substances in which the percentage of carbon approaches closely the figure given by Van Bemmelen.

Alexander and Byers (1932) said that Cameron and Breazeale mistakenly attributed van Bemmelen for the carbon content of cellulose, which was found to be 44.44% C.

Despite controversy on the origin and veracity of the factor, it started to be widely adopted at the beginning or the 20th century, particularly in the USA. The factor appeared without attribution in the 1916 edition of the book *Soils: Their Management and Properties* by Lyon et al., 1915 p. 114):

[1] The 0.471 factor is due to the conversion of CO_2 to C: $12/44 \times 1.724$.

> Multiplying the carbon by 1.724 is considered as giving an approximate figure for the organic matter.

However, a subsequent edition of the book *The Nature and Properties of Soils* by Lyon and Buckman (1922, p.312) added:

> 1.724, was the most reliable indication of the organic content of a soil.

Selman Waksman (1888–1973) and his team from Rutgers University in the USA repeatedly used the factor in publications from 1920s to 30s. In the paper *On method of determining humus in the soil*, Waksman (1926) wrote: "The determination of total carbon in the soil; the quantity thus obtained is multiplied by 1.74 [*sic*] to give the soil organic matter". Waksman and Stevens (1930) further wrote "the most reliable method available at present for determining quantitatively the soil organic matter is based upon the determination of organic carbon, which is multiplied by 1.724 to give total soil organic matter."

Various authors in the period of 1920s–1930s criticised the factor, including Read and Ridgell (1922), Robinson et al. (1929), and Lunt (1931) who found that the C content of soil organic matter varied considerably and the factor was generally underestimated.

Some authors used this factor without attribution, including, Sievers (1923), and Russel and McRuer (1927), and Robinson et al. (1929). Some attributed Schulze, Wolff, van Bemmelen (Read and Ridgell, 1922; Lunt, 1931). Leigty and Shorey (1930) attributed it to van Bemmelen, while Isaac and Adamson (1935) attributed it to Van Bemmelen and Wollny. Slater and Carleton (1939) described it the conventional Wolff factor.

The German literature attributed van Bemmelen for the factor, notably by Springer (1928, p. 320) who noted that:

> Wolff, van Bemmelen and Wollny, gave the average content of "humic matter" of the soil as 58%. … Carbon content is multiplied by 1.724 to get the "humus content" (or more correctly, the organic matter) of the soil.

The factor appeared in the French literature in Demolon and Leroux (1933), where they wrote:

> The best method for measuring soil organic matter is to determine the organic carbon concentration and multiply it by 1.724 (Waksman, 1930).

The Dutch literature used the factor extensivelyfor the estimation of humus content (e.g., Hissink and Spithost, 1932). Kortleven (1950), estimated stabile humus content using the factor and argued that "this factor was already mentioned by Schulze in 1849 and therefore is not the van Bemmelen factor".

The term van Bemmelen factor was widely quoted and used by soil scientists as a convenient factor to calculate the abundance of organic matter. Alexander and Byers (1932) and Waksman (1936) attributed the appellation because of its extensive use by van Bemmelen. But we can't verify that statement from van Bemmelen's publications and there is no indication that he promoted it. The attribution appeared to be widely used after his death (1911). It seems that the citation by several researchers, subsequent approval by Waksman, and the mention in several methods of soil analysis books (Wiley, 1894, 1926; Robinson, 1939; Piper, 1942; Allison, 1965) supported van Bemmelen as the originator of the factor – although this is clearly misleading.

3. Discussion

3.1. Humus concept

Humus is commonly used as an indicator of soil fertility (Zanella et al., 2018). Van Bemmelen (1890d) noted that early colonial planters in Deli described a good quality soil as "excellent humus soil". Humus and SOM are commonly used to refer to decayed organic material. Classical views such as that of Stevenson (1994) differentiated between soil organic matter and humus, where OM is the light fraction, and humus refers to humic substances and products resynthesised by microorganisms that have stabilised as an integral part of the soil. The concept of humic substances and humification process is now strongly debated (Lehmann and Kleber, 2015). Nevertheless, (outdated) humus concepts from the 19th century are still being used (Tan, 2014).

The contemporary view is that humic substances (e.g., humic and fulvic acids and humins) are artificial products of strong alkaline solution extraction that do not occur in natural soil (Kleber and Lehmann, 2019). It was demonstrated that alkaline extraction is unable to clearly separate humic from non-humic substances. The extraction also cannot separate materials created by secondary synthesis from other, ionizable organic compounds. The classical humus theory hypothesised that humic acid comprises large, complex macromolecules forming a stable or recalcitrant SOM fraction. However, it was shown that humic substances are only a small fraction of SOM with smaller and simpler molecular structures (Stockmann et al., 2013). Another important recent finding is that the molecular structure of organic matter does not determine the stability of soil carbon, but stability is a function of soil properties and the environment (Schmidt et al., 2011). Microbial activity is the main agent for SOM stabilization. Nevertheless, the humic proponents believed that natural humic substances and the humification process could be observed in natural conditions, such as composting materials (Olk et al., 2019). There is also another view that humic substances are natural products that should be regarded as supramolecular associations of self-assembled heterogeneous and relatively small molecules derived from the decomposition of organic materials (Piccolo, 2002).

SOM is now regarded as a continuum of progressively decomposing organic compounds. It is commonly differentiated as particulate organic matter, mineral-associated OM, and resistant OC (Cotrufo et al., 2019; Stockmann et al., 2013). Nevertheless, humus and humic materials are still more popular than soil organic carbon or organic matter in books and scientific papers (See Supplementary material S1).

3.2. The 1.724 factor and concept misattribution in soil science

The van Bemmelen or 1.724 factor is an average compositional factor, which is by no means a constant. The factor was derived from an 1827 study based on the composition of humic acid. It was used to estimate humus content, although some considered it the same as organic matter. Furthermore, many studies derived conversion factors based on organic matter measured from loss on ignition and carbon content derived from the Walkley and Black method (e.g., Brogan, 1966). Both methods are known to be inaccurate, adding more uncertainty to the correction of the factor. Since OM in mineral soil cannot be quantified accurately, it would be more reliable to measure and report soil OC, rather than relying on the factor.

Pribyl (2010) found the factor ranged between 1.4 and 2.5 with a median value of 1.9 from various studies and suggested that a factor of 2, would be more accurate than 1.724. Various regional studies show that the factor is not applicable in various soils and is affected by the methods of analysis (Jolivet et al., 1998; Paramananthan et al., 2018; Jensen et al., 2018; Ouyang and Lee, 2020).

Pribyl (2010) noted that convenience, authority, and tradition rather than the strength of evidence are responsible for the widespread use of this factor. This indicates that once a concept is established in the literature, scientists tend to use it, no matter how many times it has proven to be imprecise. Ironically the paper by Pribyl (2010), which criticised the use of this factor, is often cited as the source of the factor (e.g., Shangguan et al., 2014).

In soil science, misattribution, while not common, is not limited to the van Bemmelen factor. For example, the mineral theory of plant nutrition, commonly attributed to Justus von Liebig, had been published earlier by Carl Sprengel (van der Ploeg et al., 1999). Jenny's soil forming factors equation published in 1941 had been formulated by Russian scientist Sergey Zakharov in 1927 (Florinsky, 2012). The water flow in unsaturated soil equation commonly attributed to L.A. Richards (1931) had already been derived by Lewis Fry Richardson in 1922 (Raats and Knight, 2018). Selman Waksman is attributed to the discovery of streptomycin, while it was actually discovered by his student Albert Schatz (Wainwright, 1991). We often attribute a subsequent person, and not the actual discoverer, as the originator of new phenomena; most scientific discovery is a community effort. And as demonstrated in this paper, almost nothing is new under the sun, a lot of ideas had already been discussed previously. We should recognise the contribution of all those who have furthered knowledge of soil science.

4. Conclusions

We can summarise the brief history of the 1.724 factor and how it relates to the development of soil science

- The factor is widely used to 3 decimal places, but it is only an approximation. A distributed PTF (with median 1.9) could possibly be used for modelling purposes. It would be more accurate to report organic carbon.
- Once a simple concept is established in the literature, scientists tend to hang on to it, no matter how many times it has proven to be imprecise or unsuitable. This may have held back more studies and a better understanding of soil organic material.
- Concept or discovery misattribution, although uncommon, has happened in soil science (and other sciences and all through history). We often strive to promote a single discoverer of a phenomenon or concept, while it is mostly a community effort and most ideas or phenomena have been discussed or studied antecedently.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.geodrs.2020.e00306. These data include the Google map of the most important areas described in this article.

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