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History and interpretation of early soil and organic matter investigations in Deli, Sumatra, Indonesia

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ABSTRACT

This paper provides a history of the investigation of the soils and organic matter of Deli in Sumatra, Indonesia, for growing tobacco in the early 20th century and an interpretation based on current data, knowledge and understanding. We first review some early chemists and agrogeologists' investigations on the soils of Deli to increase tobacco production. Van Bemmelen studied the humus of the soil of Deli in 1890 and formalised an 8-year fallow plantation scheme for growing tobacco. While maintaining organic matter had been established, the complexity of soil distribution in the area was more important in determining the quality of tobacco. It took another 40 years for the soil in Deli area to be properly mapped. Jan Henri Druif in the 1930s mapped and classified the soils of Deli based on their parent material and mineralogical composition. We then describe the rise and demise of the tobacco industry from 1930s-current. We examine the implication of the fallow system and soil distribution with the current understanding of soil carbon processes and recent data. The results are interpreted and discussed considering i) the myth of "poor" tropical soils, ii) nutrient availability after slash and burn, iii) soil organic matter decline after forest conversion and recovery after fallow, and iv) soil mapping and provenance. Based on published studies and observed data coupled with modelling, we attempt to explain early researchers' observations and deductions. We summarise soil organic carbon dynamic conditions in the tropics after 50 years of forest clearance: under fallow rotation, it is possible to maintain, on average, a constant value of 20% organic carbon (OC) decrease from the original level, while continuous cropping can decrease OC levels up to 30–40%. An extreme condition with continuous cultivation and little organic matter input can result in an OC decline of up to 80%. The historical studies enable to appreciate aspects of soil mapping and organic matter that are repeatedly overlooked in present-day research.

"The soil here is excellent; it can produce three tons of dried peanut bunch per hectare. If we hadn't proved it ourselves, maybe people would never have believed it. Good soil. First-class. Profitable. Even the peanut leaves and stems are good for fertiliser and cattle feed" -Pramoedya Ananta Toer, *This Earth of Mankind* (1980)

1. Introduction

The role of soil organic matter (SOM), its spatial and temporal variation and relation with land management has been debated for more than a century. In the mid-nineteenth century, the scientific study of soil had begun (Brevik and Hartemink, 2010; van Baren et al., 2000) but the study of soil in tropical landscape was still scarce. During the period 1890s–1940s, the emerging field of tropical soil science in Indonesia was considered by two main groups of scientists: the agrochemists who studied soils in the laboratory and formulated fertiliser application, and the agrogeologists who studied soils in the field (van Baren et al., 2000).

The study of the soils of the Deli region in Sumatra (Indonesia) garnered much interest among European scientists. In the early years of the Dutch colonization in the Sumatra island (1870s), much of the economic interest was directed towards the exportation of high-value commodities, such as tobacco and rubber. The economic interest urged scientists, in particular, Jakob Marteen van Bemmelen (1830–1911), David Hissink (1874–1956) and Eduard Carl Julius Mohr (1873–1970) to conduct studies on tropical soils, with a particular interest on the local soil conditions. The objectives of these scientists were directed towards the increase of agricultural productivity or seeking favourable soil types for growing profitable crops such as tobacco.

Several of the concepts developed on the soil of Deli are still applied

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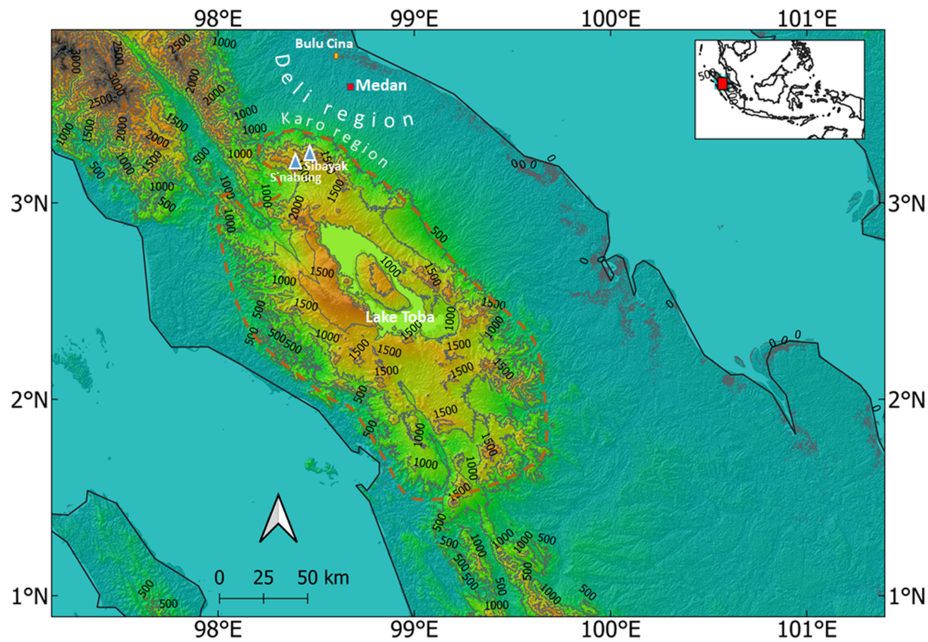

Fig. 1. The Deli region in Sumatra, Indonesia. The orange dashed line is approximately the culmination of Toba known as the Batak Tumor by Rein Van Bemmelen (approximately at an elevation contour line of 500 m). The capital of North Sumatra, Medan and the Bulu Cina tobacco plantation are marked in the map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

today, such as the van Bemmelen conversion factor from soil organic carbon to soil organic matter (Minasny et al., 2020), or the fallow rotation to mitigate soil organic carbon decline after forest clearance (van Bemmelen, 1890b, 1890d). But our understanding of soil organic carbon dynamic and tropical soil science have increased. Some of the early concepts have led to contemporary misconceptions. Similarly, the tools to study the soils and soil organic matter of the Deli area have changed, which requires adaptation and interpretation of early soil knowledge using present-day data and knowledge.

This paper first reviews in Section §2 early studies on the soils of Deli to support the booming tobacco plantation industry (1890s–1930s). We recount the history of the establishment of tobacco in Deli to appreciate the context of soil research done by Dutch scientists in that era. In Section §3 we analyse some contemporary data from Deli with models and current understanding of soil and organic matter research in the tropics. Finally, we attempt to explain the historical observations using the present-day concepts of soil mapping

2. Early studies on the soil of Deli

2.1. Soil organic matter for growing Deli tobacco (1890–1920s)

Deli is a region in East Sumatra, historically controlled by the Sultan of Deli in the 1600s. The Deli region became a protectorate of the Netherlands East Indies in 1861. This area covered the current Deli Serdang and Serdang Bedagai regencies. The plain area in Deli (elevation 2–10 m) faces the Strait of Malacca in the north and rises gradually to rolling hills in the south (up to 50 m), further south is the mountainous area with a sharp rise from 100 m to 1000 m within 20 km where we can find the Sibayak (elevation 1450 m) and Sinabung (elevation 2380 m) mountains and further south again is the remnant of Toba caldera (Fig. 1). The area still has active volcanoes; Sinabung has erupted since 2010 and still produces ash deposits that affect the landscapes (Fiantis et al., 2019).

The tobacco plantation industry in Deli started in 1863 by a Dutch colonial planter, Jacob Nienhuys[1] (1836–1927), who obtained a land concession from the Sultan of Deli. While the initial trial with tobacco was not that successful, subsequent trials proved that the soils of Deli were valuable in producing high-quality, broad, thin yet strong light-coloured leaves for cigar wrap. The first few years of production realised a huge profit, and the high quality of the tobacco leaf attracted international buyers. Deli tobacco fetched a very high price in Europe and the United States.

Emile Mulder, a colonial planter, was commissioned to write a report on "Cultivation of Tobacco in Sumatra" for the USDA (Mulder, 1898). Milton Whitney (1860–1927), the USDA Chief of Division of Soils and an avid cigar smoker (Fanning and Fanning, 2001), wrote a foreword to the report stating that there was so much interest in the Deli tobacco that it was important for the US growers to know all the information concerning the conditions and methods of production. Mulder (1898, p. 11) noted the very high organic matter content in the soils from Deli (between 9 and 26%) and clay mixed with sand as very well adapted to tobacco. See supplementary material S5 on growing of Deli tobacco in the USA.

Early colonial planters believed that soils that were already used by indigenous shifting cultivation and left under *alang alang* grasses (*Imperata cyindrica*) were unsuitable for growing tobacco. Tobacco was only best grown on soil, which had just been cleared of virgin forest. They also believed that the forest soils, once cleared, were only suitable for one tobacco crop (Pelzer, 1978). This belief was because when the soil was grown for several years, the quality of the tobacco declined. Fertiliser dealers offered various products, but they appeared not to be effective. Soil samples were sent to the Netherlands and Germany to be analysed.

Jakob van Bemmelen, the Professor in Chemistry at the University of Leiden in the Netherlands, was asked by the tobacco planters to investigate the reason why the soil of Deli was fertile, and to find out the cause of fertility decline observed in recent years (Van Bemmelen, 1890d). Two soil samples from Deli were provided to van Bemmelen by Jacob Theodoor Cremer[2] (1847–1923), a member of the House of

[1] Nienhuys was narrated as the pioneer of tobacco plantation. He initiated the import of Chinese indentured labour to work on the plantation. Around 1868, Nienhuys was accused of flogging seven coolies to death. The Sultan of Deli ordered Nienhuys to leave the country, and so he left in 1869 and never

(*footnote continued*)
returned.

[2] Cremer became the director of the Deli company in 1870 after Nienhuys left. He was the architect of Coolie Ordinance, legalized in 1880 by the government of the Dutch East Indies, that allowed company to engage indentured workers in a contract that obligated them to work for a number of years. It included

Representatives in the Netherlands, who was the administrator of the Deli tobacco Company prior to the latter position.

Van Bemmelen published five papers related to this research in a German publication *Landwirtsch Versuchsstat*, all dated 1st December 1889:

- The first paper (Van Bemmelen, 1890a) is on the composition of soil for growing tobacco, comparing the volcanic soil in Deli (Sumatra), Malang (Java), and the river-clay soil in Rembang (Java).
- The second paper (Van Bemmelen, 1890b) is on the determination of water, humus, sulphur, colloidal silicate, and manganese in arable soil. This paper is often cited as the origin of the van Bemmelen factor which converts soil carbon to organic matter content. This paper is discussed in Minasny et al. (2020).
- The third paper (Van Bemmelen, 1890c) is on the composition of soils comparing the volcanic soil from Deli and soil from Java and other soils from the Netherlands based on methods derived in the second paper.
- The fourth paper (Van Bemmelen, 1890d) is on the fertility of the forest soil of Deli, Sumatra for tobacco production, and the problem of the decrease in its productivity.
- The fifth paper (Van Bemmelen, 1890e) is on the composition of the ash of the tobacco leaves in relation to their quality, especially their flammability. This is not a soil science paper *per se* but is related to the overall Deli tobacco study.

Van Bemmelen (1890a) described his work as follows (p. 257):

> As communicated in more detail in subsequent papers on the soils of Deli in Sumatra, for the past twenty years, an ever-expanding tobacco plantation has produced an excellent product. The plantation took place on virgin soils covered by forests. This forest soil has proved to be extremely fertile.

Van Bemmelen (1890a, p. 258) described the soil from Deli as follows:

> The geology of the soil is unknown. The soil was of volcanic origin and a weathering product of volcanic ash. The layer is said to be quite thick, however little of it is known yet. The region is rising from the coast in a southwestern direction towards the high ridge that has volcanoes. The volcanic clay is heavy and has a light consistency. In the coastal area, it is gray in colour, e.g. B soil in Medan 15–50 m above the sea. This is now highly regarded. In the higher elevation areas (60–150 m), the soil is reddish-brown clay or loam, which is very fertile as well and is considered as the best soil.

The area in Deli had not been well surveyed in that period. The first soil sample called Deli I, a red-brown soil, was obtained about 50 m above sea level and had a humus content of 5.1%. The second soil sample, called Deli II, a gray soil, came from 15 m above sea level and had an organic matter (OM) content of 3.25% (Fig. 2) (van Bemmelen, 1890a).

Van Bemmelen summarised the reason why the Deli soil was very suited to grow tobacco, which is due to the physical aspects of the humus that provide good structure and large water holding capacity (p.391):

> According to the best notices given to me by knowledgeable planters from Java and Sumatra on my inquiries[3], experience establishes that valuable tobacco needs favourable climatic conditions (early rain, etc.) obtained from soils which were used to be overgrown with forest and therefore rich and have loose humus layer in the surface. It is the view of the intelligent tobacco growers, in Java and Deli; that the peculiar, humus forest floor in Deli can be felt as soon as you step on the floor, it is bouncy and deep. The mild (non-acidic) forest humus unite the physical and chemical factors.
> Fresh forest floor, when cultivated with tobacco, carries little weeds. All of this can be observed in the first years on different soils: clay, sand, etc. Without any fertilizer, the best wrapper Tobacco can be obtained. Only such forest soils are considered suitable, the ones with a humus-rich layer of at least 2–4 dm. 1.5 dm is probably the outermost limit; 6 dm is a lot.

Based on the chemical analysis, van Bemmelen mentioned some of the favourable properties of the soil of Deli: (1) a high content of humus and NH_3 soluble humates, (2) a high nitrogen content, (3) a high phosphoric acid content, (4) a good amount of dilute acid-soluble potash, and (5) the potash is not bound to hydrochloric and sulfuric acids, but humic substances and the colloidal silicate; (6) a high content of hydrochloric acid-soluble colloidal silicate, which contains a lot of bound water and is a very basic aluminium silicate (Hissink, 1904a).

While van Bemmelen had never been to Indonesia, he attributed the fertility of the forest soil to the thick humus layer and the peculiar composition of the amorphous humus silicate complex (van Bemmelen, 1890d, p. 392):

> The humus, the loose physical constitution, and the peculiar composition of weathering silicate are undoubtedly very important factors for conserving the right moisture content, and the nutrition of plants through the proliferating roots and fast growth of the leaves (see Fig. 2).

When the planters tried to grow tobacco immediately after the first harvest, they got poor results. And since there were still lots of forests in East Sumatra, the planters just cleared large area of virgin lands.

> "The second and subsequent tobacco harvest," says Fritz Reuter, an administrator of the oldest Deli company, "can't even remotely be compared with her predecessor on the same but wood-covered soil; even repeated and deeper tjankollen[4] with simultaneous application of Guano was unable to compensate it fully."

To solve this problem, van Bemmelen recommended restoring the humus floor. After harvest, if the soil was left bare, it would be instantly occupied by alang-alang (*Imperata cylindrica*), an invasive species that was believed to cause soil degradation. Thus, to restore the forest, fast-growing trees needed to be grown as overgrown shrubs would shade the *Imperata,* which would then die, and then other trees would grow.

The long fallow period means that the whole area can be continually used for tobacco production. A plantation would occupy a large area (about 3000 ha), and each year only about a tenth of the area would be grown. Van Bemmelen, through his analysis and the 19th century concept of humus, realised the importance of maintaining soil organic matter (humus floor), which created well-structured soil.

> If you want this fine variety of tobacco, good quality colour, creamy and flammable, then you need a temporary restoration of the forest in the first place. Just applying chemical fertilizers as attempted by the planters is practically useless.

The long fallow system for growing tobacco had been implemented in Deli since the early 1880s (Deli-Maatschappij, 1884). The paper (van Bemmelen, 1890d) was noted as the first scientific study on the soil of Deli. While van Bemmelen conducted chemical analysis on two soil samples, his conclusion on humus was informed by colonial planters in

(*footnote continued*)
poenalie sanctie *or penal sanction that allowed the company to punish the workers if they didn't comply. Cremer later became the Dutch Minister of Colonies from 1897 to 1901.*

[3] Van Bemmelen acknowledged communication with staff from the Deli company, Hendrik Cornelis van den Honert (administrator), A. Enthoven and J. Rappard.

[4] cangkul (verb) means to hoe.

Fig. 2. Harvesting of tobacco on the plantation in Klumpang – 1903. Image from Royal Netherlands Institute of Southeast Asian and Caribbean Studies and Leiden University Library.

Deli and his paper formalised the fallow system.

Initially, a 10-year rotational period was practised, later an 8-year rotational system became standard practice: 1 year of crops of 45 days of tobacco and a season of rice for plantation workers, and 6 years fallow with a growth of young (secondary) rainforest (van der Poel, 1933). It was also found that the fallow was effective in reducing the occurrence of slime-disease (*Bacterium solanacearum*) (Wiersum, 1983).

Van Bemmelen concluded the report by stating the need to establishing a scientific experimental station in Deli to deepen the knowledge on soil, vegetation, and geology of the area (Van Bemmelen, 1890d). In 1895, with the cooperation of Deli planters association, Melchior Treub (1851–1910), the Director of the Botanic Garden in Buitenzorg (now Bogor), established the 8th Department to conduct scientific studies specifically on Deli tobacco culture. The first researcher assigned to work in Deli was Dr. Jacob van Breda de Haan (1866–1917), who conducted the first research on afforestation called *reboisatie* and recommended the use of *Albizzia moluccana* (Van Breda de Haan, 1898).

2.2. Research into the soils of Deli (1920s-1930s)

Early colonial planters happened to cultivate physically and chemically fertile alluvial soils in the Deli region that were derived from volcanic materials. This success prompted other planters to clear new forests in the proximate areas and discovered that the soils were different and had low fertility. The planters expanded their area further south to Asahan (south east of Deli) and Siak (in the Riau province of Sumatra) only to discover the soils could not produce the same quality of tobacco. Lands appeared to have a similar forest cover, but the soils were completely different. While the fallow system could restore the humus layer, the nature of the mineral soil component proved much more critical.

In the beginning, the colonial planters only recognised three types of soil in Deli (Druif, 1932): grayish white soils of the coastal plain, the red soils on the higher elevation, and some black soils that occurred sporadically.

Initially, chemists were asked to investigate the soil variation in the Deli region. Dr. A. van Bijlert, a chemist from the Botanic garden in Bogor made the first attempt in 1899 by separating the soils into two groups: the residual soils and the fluvial soils which consisted of transported materials (van Bijlert, 1900). The effort was continued by David Jacobus Hissink (1874–1956)[5], a chemist from Amsterdam stationed at the botanic garden in Bogor in 1900. Hissink used data of soil physical and chemical analyses fertiliser trials, made an attempt to classify the soils of Deli based on total nitrogen, phosphorus, potassium content, and loss on ignition (Hissink, 1904b). He recognised five types of soil: clay soil, mixed (sand and clay) soil, sandy soil, red weathered soil, and black sandy soil. A soil map of 1:100,000 was produced but was thought to be unnatural. The classification was also not practical as the analysed soil samples were from fertiliser trials, which ignored their regional pedogenesis. The effort was continued by several other chemists.

In particular, the approach of Vriens and Tijmstra (1910) is worth mentioning, as they proposed to group or catalogue soils solely from their chemical and physical properties in an analytical manner. They described 12 soil physical and chemical properties, e.g., N, P, K, Ca were coded as A, B, C, D. Each property had 3–4 levels of concentration, from low to high, coded as a, b, c, d. From the combination, they obtained 37 sub-properties (e.g. Aa, Ab, Ac, Ad, Ba, …). The combination of 12 properties (at 3–4 levels) resulted in 629,856 soil groups. Inevitably, this complex system was not practical. Although this partition is logical, it does not necessarily partition the variation in the soil universe in an optimal way. This type of soil grouping was later proposed by Leeper (1956) as an analytical method of classification.

An alternative approach seeks groupings of soil based on common substrate and geology. Geological maps and reports of East Sumatra were produced, including a report by Edward Carl Julius Mohr (1873–1970), who was head of the agrogeology and soil research department in Bogor, Java (Mohr, 1919). A geology map of North Sumatra at 1:1000,000 was produced by Józef Zwierzycki (1888–1961) (Zwierzycki, 1919). Although at a regional scale, this geology map distinguished alluvial area near the coast, most area near Toba was liparitic (rhyolitic) materials and the area near Karo was dominated by andesitic materials. Rein van Bemmelen (1904–1983), a geologist and grandson of J.M. Van Bemmelen, at the 5th Netherlands Indies Natural Science Congress in Surabaya in 1928, discussed the agrogeological mapping of Sumatra and pointed out the importance of getting an insight into the genesis of the soil (van Bemmelen, 1928). It is unknown whether an actual map was produced.

[5] Hissink stayed in Deli for 3 years and returned to the Netherlands in 1903. In 1924, he became one of the founders of the International Society of Soil Science (ISSS) in Rome and was appointed Secretary General, a position he held until 1950.

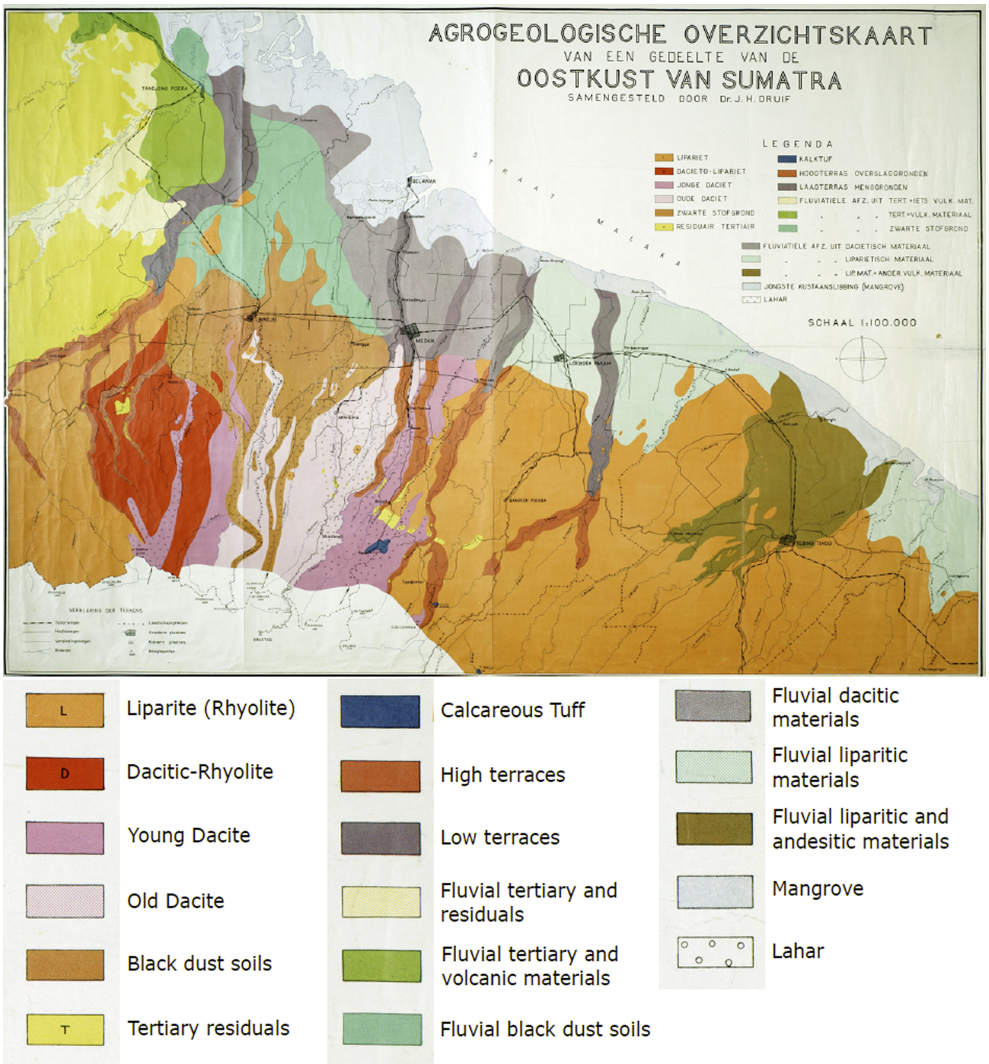

Fig. 3. Agrogeological map of the east coast of Sumatra published at 1:100,000 (Druif, 1938b).

In 1905, Mohr founded the laboratory of agrogeology and soil research (Laboratorium voor Agrogeologie en Grond Onderzoek) in Bogor. Agrogeology was proposed as a science that specialises in studying soil type (van Baren, 1919). Agrogeology is defined as the geology of the upper part of the land surface or geology of the present, that studies the processes that form soil and the properties of soil. The study needs to be conducted in the field with soil profile as an entity. The final result of field-investigation is an agrogeological map, not a geological map with agronomical indications (van Baren, 1921).

In Deli, the tension between chemists and agrogeologists can be palpated from the writing of Druif (1934) (as translated by Salgado, 1959), who wrote:

> When our research station took up the investigation of the soils, work started as usual; mechanical analyses were made by hundreds, chemical analyses at least ten times as many. Then, it was thought that every problem of soil could be solved by pH determination and that physical properties just provided what the soil investigators needed for the finishing touch.
>
> Although in practice, these investigations did not prove to be a complete failure, they make no difference. The baffling problem of the distribution of good and poor lands for growing crops and the question as to where and how their boundaries could be traced remained unsolved.
>
> The chemical analyses ought to have been helpful, but as they were made by chemists and especially concerning the problems of fertilizing and amelioration, nobody realised that the differences found in soil were of pure petrographical nature, not to say geological and therefore needed geological interpretation, which was at that time, however, not imminent.

The failure of the chemists to map the soil led the Deli research station to establish the agrogeological department in 1926 in charge of soil mapping, headed by C.H. Oostingh. Oostingh made the first attempt by recognising residual soils by their volcanic parent materials: rhyolitic, dacitic, and andecitic (Oostingh, 1928). Jan Henri Druif (1893–1970) continued Oostingh's work in 1929. Druif made lots of field observations of outcrops, transects, hand augers, and laboratory mineralogical measurements of rocks and soils (See Supplementary Material S1). Finally, Druif made a breakthrough by recognising the distribution of different parent materials in which the soils formed. Subsequently, he was able to make detailed soil description of Deli and described them in his four-part publication: *De Bodem van Deli* or the Soil of Deli (Druif, 1932, 1934, 1938a, 1939).

The soils in the Deli area had been heavily influenced by volcanic activities. The most important physiographic feature in the area was what Rein Van Bemmelen, called the Batak Tumor (Van Bemmelen, 1939, 1949), an oblong-shaped crustal swell around 150 km length and 275 km wide which culminated at the Toba caldera (Fig. 1).

Druif (1938a) divided the soils of Deli into two groups: the autochthon, those formed by the residual in situ weathering of the tuffs (materials of tephra and lava ejected from a vent during a volcanic eruption) and the allochthon, those shaped by fluvial and marine transport, e.g., tuffs carried and redeposited by the rivers. The autochthon formations were divided into the tertiary and quaternary volcanic parent materials. The oldest soils were derived from sedimentary rocks of the Tertiary formations in the western hill region, which were poor in nutrients, acid, brownish-red and yellow in colour, and deemed not suitable for tobacco. These soils are now allocated to Ultisols. The autochthon volcanic materials came from lava flows of several volcanic activities. The main soils were derived from rhyolite (or previously called *liparite*) tuff, which was from the Youngest Toba Tuff eruption that occurred around 74,000 years ago (Storey et al., 2012). The rhyolitic soils are red, rich in clear quartz crystals, biotite, allanite, and zircon, high in K content but of low fertility because of low pH and nutrient content.

Younger soils were from dacitic tuff from the Karo region with less quartz, high in Mg, and rich in organic matter. There were two types of dacitic deposits, the older and the younger dacitic tuff and lahar. The youngest volcanic materials are the most fertile, they came from lahars and ashes from Mount Sinabung and Sibayak, which were composed of dacite and andesite, high in Ca, Mg and P. These soils were called in Dutch "zwarte gronden", or black dust soils, made up of fine sand and silt ashes that were easily blown by the wind (dusty). These soils contain a large amount of OM, as high as 13 to 17 percent. The black soils are currently allocated to Andisols in the USDA Soil Taxonomy, while soils from other volcanic materials are allocated to Inceptisols.

To differentiate the different parent materials, Druif used optical mineralogy examination. Druif (1938b) completed a 1:100,000 agro-geological map of the Deli area based on a geological-morphological-mineralogical approach (Fig. 3). Lava flows of different ages can be visualised in Druif's soil map radiating from the Sinabung and Sibayak area on the bottom left of the map: the old and young dacitic lava covered by the youngest ash derived materials. The materials broadened when they reached lowlands and were affected by fluvial processes. Soils grouped based on main parent materials are summarised in Table 1.

Druif could only distinguish different volcanic materials based on the soils' mineralogical composition and produced this unique lithological soil classification. Mohr (1944) further noted the strong relationship between the local soil type and quality of the tobacco, akin to the French *terroir* concept for vineyards. This soil provenance determined the price, tobacco from dacitic and andesitic soils fetched the highest price while tobacco on rhyolitic soils attracted a much lower price (Jochems and Ten Cate, 1932) (Table 1).

2.3. Soil classification of Deli (1938)

In addition to producing a map, Druif (1938) also made an attempt to classify the soils of Deli. The soils were first divided into 3 groups: the autochthon, allochthon, and allochthon on autochthon. Each group was then divided into mineral and organic soils. For the autochthon (residual) soils, each soil parent material class was subdivided based on soil colour. For the allochthon (fluvial or marine transported) soils, the subdivision was made based on soil texture. For the allochthon on autochthon (colluvial) soils, the soils were first divided by the position in the landscape (slopes, low, middle and high terraces, and peats). They were then subdivided based on parent materials. A summary is presented in Fig. 4. This is an example of an early soil classification system where soils were first divided based on their parent materials, and subdivided by colour and properties. This kind of classification based on subdivision of parent materials, geomorphology, and soil properties had been suggested, such as by Elmer Fippin as early as 1911 (Figure 11 in Miller and Schaetzl, 2016), but never realised.

During that period, Mohr and other Dutch scientists had created several classification systems for soils in Indonesia (van Baren, 1933;

Table 1
Soil in Deli based on its parent material according to Druif (1938a), arranged from the youngest to oldest. The soil characteristics and average price of tobacco grown on them are from Druif (1938a) and Gibbs (1940).

Soil type	Colour and texture	Dominant primary minerals	Soil pH	Price guilder per pound*	USD per pound*
River alluvia and mangrove soils	Sands-clays		5.4–6.5	not used for tobacco	
Alluvial soil derived from dacitic-andesitic tuff	clays to clay loams that are light to dark yellowish browns, and brown sandy soils	Amphibole, a lack of biotite	5.3–5.2	1.90	0.95
Alluvial soil derived from liparitic tuff	varies from clays to sands that are quite similar in colour to above; deficient in plant nutrients	Quartz, K feldspar, biotite	5.3–5.8	1.10	0.58
Andesitic or black dust soil	grey when dry and black when wet sandy with much silt, high OM	K feldspar, andesine, hypersthene, oligoclase, magnetite, ilmenite, biotite	5.5	1.70	0.85
Young Dacitic	dark brownish-red sandy loam	Quartz, K feldspar, magnetite, ilmenite, amphibole, hyperstene	top: 5.5 sub: 5	2.00	1.00
Old Dacitic	a dark reddish-brown loam	Amphibole, oligoclase, magnetite, ilmenite, biotite	6.2–6.7	1.30	0.65
Dacite Liparitic	reddish brown-yellow loam	Quartz, K feldspar, magnetite, ilmenite, biotite, green amphibole, zircon	top: 5.9 sub: 5.2	1.50	0.75
Liparitic	red clay loam	Quartz, K feldspar, biotite, zircon, allanite.	top: 6 sub: 4.5	0.90	0.45
Soil derived from old sedimentary rocks	Red-yellow clay, highly leached		4–5	0.20	0.10

* Average tobacco price received at Amsterdam from 1893 to 1930, based on the conversion of 1 USD = 0.4 guilder (Gibbs, 1940).

AUTOCHTONE GRONDEN.
(Ontstaan uit geologisch oudste en middelmatige oude vormingen).

ANORGANISCH (Minerogene, semi-humogene en humogene gronden) — LIXIVIUM-BODEMS (VIRIEL-SENIEL). ‖ ORGANISCH (Organogene gronden)

GEOLOGISCH JONGER (QUARTAIR) (Vulkanisch) ‖ GEOLOGISCH OUDER (TERTIAIR) (Marien)

	Primair „Roode" gronden (Tuf)	Primair „Roode" gronden (Lahar, Tuf en Asch)			Primair „Zwarte" gronden (L, T en A) ')				„Roode" gronden (n. vulkanisch) ")			„Zwarte" gronden (ged. vulkanisch) ''')		Donkergekl. gronden
	LIPARITISCH	D.LIPARITISCH	O.DACITISCH	J.DACITISCH	A.DACITISCH		KALKSINTERTUF		SEUROELA		KEUTAPANG	GRENSKLEI		VEEN
	a, b.	a, b, c, d.	a, b, c, d.	a, b, c, d.	a, b, c, d.		e, f. **)		g. h. **)		g. k. **)			g. h, i, k. ***)
				Bruinviolet (22)										
Bruin	(1)	(8)	(15)	(23)	Zwart	(30) (30A)****)	Zwart	(37)				Bruinviolet	(51)	
Rood	(2)	(9)	(16)	(24)	Bruin	(31) (31A)	Bruin	(38)	Rood	(40)	(46)	Zwart	(52)	(55)
Geelrood	(3)	(10)	(17)	(25)	Geelbruin	(32) (32A)			Geelrood	(41)	(47)	Bruin	(53)	
Geel	(4)	(11)	(18)	(26)	Geel	(33) (33A)			Geel	(42)	((48))	Geelbruin	(54)	
Geelwit	(5)	(12)	(19)	(27)	Geelwit	(34)			Geelwit	(43)	((49))			
Wit	(6)	(13)	(20)	(28)	Wit	(35)	Wit	(39)	Wit	(44)				
Grijs	(7)	(14)	(21)	(29)	Grijs	(36)			Gevlekt	(45)	Gr. Grijs (50)			

Toelichtingen :

') L. T en A : Lahar, Tuf en Asch, vulkanisch "), niet vulkanisch, ''') gedeeltelijk vulkanisch.
*) a. b. c. d. : Grof, Fijn, Laharrand en Laharmidden.
**) e, f. : Zandig, Steenrijk.
***) g. h. i. k. : Zandig, Kleiig, Leemig en Steenhoudend.
****) „Verplaatste" zwarte stofgrond.

ALLOCHTONE GRONDEN
(Ontstaan op de geologisch jongere en allerjongste sedimenten in de kustvlakte)

ANORGANISCH (Minerogene, semi-humogene en humogene gronden) SKELET-BODEMS (JUVENIEL) ‖ ORGANISCH (Organogene gronden)

GEOLOGISCH ZEER JONGE VORMINGEN (QUARTAIR) (Fluviatiel) (Vlakteafzettingen en oeverwallen, pematangs) (Donkerbruine, bruine, gele, bruingele, geelwitte, grijze, witte gr.) ‖ GEOLOGISCH ALLERJONGSTE VORMINGEN ") (QUARTAIR) (Marien) (Strandwallen, pematangs, en kustaanslibbingen) (Bruingele, gele, geelwitte, grijze, witte gr.) | Donkergekleurde gronden

	LIPARITISCH	G.LIP.	DACITISCH	A.DAC.	GEM. TERT.-VULK. MAT. ONDER GROEP	met WAMPOE	LIPARITISCH	G.LIP.	DACITISCH	A.DAC.	GEM.T.-V. MAT.	VEEN (PAJA'S) a, b, c. *)
ZAND ')	(89)	(98)	(107)	(116)	(125)	(125A)	((134)	(143)	(152)	(161)	(170)	L. (83 A)
L. ZAND	(90)	(99)	(108)	(117)	(126)	(126A)	(135)	(144)	(153)	(162)	(171)	GL. (179)
K. ZAND	(91)	(100)	(109)	(118)	(127)	(127A)	(136)	(145)	(154)	(163)	(172)	DAC. (180)
LEEM	(92)	(101)	(110)	(119)	(128)	(128A)	(137)	(146)	(155)	(164)	(173)	A. DAC. (87 A)
Z. LEEM	(93)	(102)	(111)	(120)	(129)	(129A)	(138)	(147)	(156)	(165)	(174)	GEM. T-V MAT. (182)
K. LEEM	(94)	(103)	(112)	(121)	(130)	(130A)	(139)	(148)	(157)	(166)	(175)	(182 A)
KLEI	(95)	(104)	(113)	(122)	(131)	(131A)	(140)	(149)	(158)	(167)	(176)	
Z. KLEI	(96)	(105)	(114)	(123)	(132)	(132A)	(141)	(150)	(159)	(168)	(177)	
L. KLEI	(97)	(106)	(115)	(124)	(133)	(133A)	(142)	(151)	(160)	(169)	(178))	

Toelichtingen :

1) De onderstreepte soorten treden het meest op.
') Deze categorie moet nader gescheiden worden volgens korrelgroote etc. (Zeer grof, grof, medium, fijn, witzwartszand e.a.) De overige groepen worden nader onderscheiden in kleuren.
") Hier moet feitelijk nog een algemeen tweedeeling worden doorgevoerd op grond van al of niet aanwezig zijn van zout.
*) a, b, c. : zandig, leemig, kleiig veen.
Lip. Veen heeft een parallel nummer, evenzoo A.dac. veen, omdat verschil met de andere nummers feitelijk neerkomt op een verschil in ligging van een paar km t.o.z. van de kustlijn en eigenlijk van geen belang is. (Verg. 2e deel der tabel).
G. Lip = gemengd liparitisch materiaal, A.dac. = andesito-dacitisch materiaal. Gem. T.-V. Mat. = gemengd tertiair-vulkanisch materiaal.

Fig. 4. Classification of the soils of Deli according to Druif (1938a). Soils were divided into residuals (autochthon), transported (allochthon), and transported on residuals (not shown). The autochthon soils were first divided based on their age and parent materials: younger mineral soils, virile-senile soils, and organic soils. The younger mineral soils were further divided based on their volcanic materials. And for each volcanic material, the soil is divided based on their colour. The allochthonous soils were divided based on mineral and organic soils. The mineral soils are younger (juvenile) soils which were then divided into fluvial or marine formations. Each formation is distinguished by its volcanic materials, and each volcanic material is divided based on texture class.

Sukarman et al., 2013) and mostly based on a geological approach, i.e., the soil was grouped by its parent materials. The American zonal system had just been proposed by Marbut (1928) and was probably not well known nor readily applicable for tropical areas. In the absence of any relevant system, Druif created his own classification based on the subdivision of properties (texture and colour). It may be logical, but in practice could end up with lots of impossible combinations. Druif himself recognised that not every combination of colour and texture might exist. Druif made an inventory and reckoned that about 200 soil types could exist. He made a soil catalogue with the list of soil numbers that occurred in the 71 plantation estates in Deli. This classification was used in soil mapping at a scale of 1:10,000 and for 50 large estates. Detailed 1:5000 maps were produced on 2500 plantation divisions so planters could decide which area to use for producing the best quality tobacco (Druif, 1938a). The soil maps were described as a way of mitigating financial investment risk (Druif, 1938a):

> If on the strength of the maps produced, only 1% of the total area is excluded permanently, the total amount of money spent in 10 years of this work, will be repaid through cutting down avoidable losses.

Although the soil classes based on parent materials proved to be useful (Table 1), the detailed classification proved to be too complicated and was abandoned in subsequent studies (Tan and Van Schuylenborgh, 1961).

2.4. Soil and society in Deli (1930s–1950s)

The Dutch colonial tobacco industry drove many soil studies in the Deli area (Fig. 5). The initial work at the Deli Research Station was on laboratory analysis (Edelman, 1947). Research on soil types, mineralogy, and geology dominated the thematic soil research from 1900 to the 1940s. Mohr wrote the book *De Bodem der Tropen in het Algemeen, en die van Nederlandsch-Indie in het Bijzonder* in 1933–38, translated into English by Robert Pendleton and published in 1944 with the English title *The Soils of Equatorial Regions, with special reference to the Netherlands East Indies* (Mohr, 1944). The book dedicated three pages discussing the Deli tobacco industry and soil.

Fertiliser trials started in the early 1900s, with a large number of experiments establishing fertiliser recommendations for different soil types. Rates of fertiliser application before planting were designed based on soil types to improve quality, not to increase yield (van der Poel, 1933). Organic materials in the form of green manures were also recommended for disease suppression and increasing soil fertility. Edelman (1947) provided a summary of soil research conducted on Deli tobacco during the Dutch colonial period.

The boom of the plantations in the 1920s is considered as the golden age of Dutch colonialism, however, with much human suffering. Colonial plantations practised land grabs, labour exploitation, and mistreatments (Van den Brand, 1902). Mohr (1944) noted:

> How distinct is the soil from Deli that it could only produce such a fine product? While soil is the most important factor, the distributed

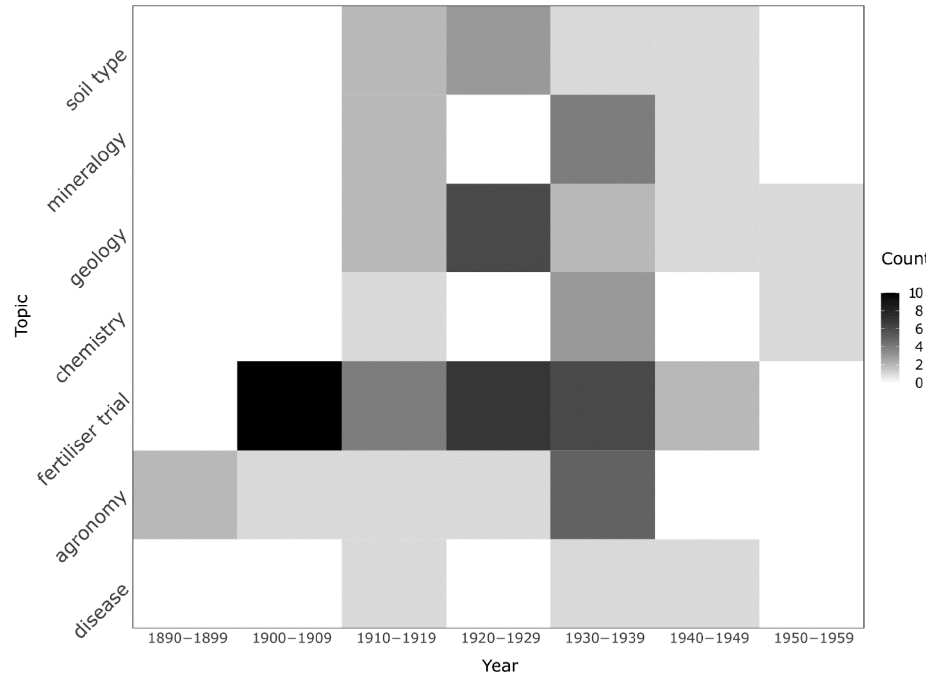

Fig. 5. The number of papers on Deli tobacco on various topics for the period 1890–1960. The data are from the bibliography provided in Tam (1993).

rainfall and humidity were also favourable for tobacco. In addition, the human factor was important: a good supply of "capable oriental labour" and highly technical occidental supervisors.

The colonial planters imported a large number of so-called coolies or indentured labour from Java, China, and India to work on the plantations, creating a massive human migration into Indonesia. It was estimated at around 100,000 labourers were transported in 1910 and grew to more than 300,000 in 1930 in East Sumatra (Houben and Lindblad, 1999). Hissink (1914a) noted the poor treatment of the indentured labours bound under the inhumane coolie ordinance. Writer Pramoedya Ananta Toer wrote in *Footsteps*:

> Dutch lawyer J. van der Brand who worked in Deli wrote "De Millionen uit Deli" (The Millionaires from Deli) exposed exploitative practices of tobacco plantation in Sumatra. The Dutch government felt obliged to send an investigator, Judge J.L.T. Rhemrev, to check on the veracity of Brand's allegations. The results of Rhemrev's report- the tobacco plantation workers' plight was even worse than Brand had reported… I recalled the report in the Sumatra Post of the cruelty of the European plantation owners, who never ceased in their search for fertile land.

The history of Deli tobacco from a colonial planter's view is described in Pelzer (1978). The human exploitation in the Deli tobacco industry was expounded in Breman (1989).

2.5. The demise of the Deli tobacco industry (1950s-Current)

The Deli tobacco industry, which started in 1864, rapidly expanded to 49 plantations by 1880 and reached its peak in 1890 with 270 plantations and an estimated area of around 500,000 ha. A 1927 film showed the immensity of the industry (see Mullens, 1927). Druif's soil mapping success did not last long. The Deli tobacco demand declined in the 1930s because of the global economic crisis. Cigarette addiction took over. Other plantation crops such as tea, rubber, and oil palm were more easily grown and fetched better prices. In 1942, Japan invaded Indonesia, and the production of Deli tobacco was halted. Areas growing tobacco were used to grow food crops. In 1945, Indonesia declared its independence, and tobacco production continued until the 1950s. In 1958 the Indonesian government nationalised all foreign-owned plantations. From 1996 until today, the Deli tobacco plantations have been under the management of PTPN II (*PT Perkebunan Nusantara II*). *Deli Proefstation* became *Balai Penetitian Tembakau Deli* or Research Station of Deli Tobacco, which existed until as late as 2019.

The Deli tobacco plantation area shrunk because squatters occupied the land. The original concession land of 260,000 ha area in 1870 became half in the late 1950s, and in 1965 became 59,000 ha, 46,000 ha in 1984, and 43,000 ha in the 1990s. The decrease in tobacco demand for health reasons further contracted the industry. In 1935–1939, the harvest area was about 12,500 ha, in 1950s became 4000 ha (Metcalf, 1952), and currently it is only 5 ha.

The 8-year fallow practice has not been practicable since the 1970s. It was not possible to maintain the long fallow period because of squatters who would claim "idle" fallow land. In the early 1980s, a sugar factory was established in Sei Semayang in the Deli region. The PTP IX introduced tobacco with sugar cane in a 5–6 year rotation: tobacco (1 year), 3 years of sugar cane (2 ratoons), and 1 year of fallow with legumes (*Mimosa invisa*). As currently understood, the main reason for this rotation is for disease control, not OM restoration.

In Klambir Lima and Klumpang (andesitic-dacitic alluvial), soil organic carbon (SOC) content measurements were taken yearly since 1975 on the same plot (Fig. 6a). The observations show that both plots had similar values of organic carbon (OC) around 1.5% in 1975, and the values had been declining because of the continuous rotation of tobacco and sugar cane with only a short fallow. Soil OM inputs were reduced as most plant materials were harvested and input of OM was very low. As a consequence, the reported yield productivity of tobacco also decreased (Fig. 6b). The productivity in Deli's best area was previously reported from 1 to 1.5 ton per hectare, while the current yield is reported to be only around 0.2 ton/ha.

Indonesia's first soil classification system was created in 1957 by Rudi Dudal and M. Soepraptohardjo based on the great soil group FAO and US system (Dudal and Soepraptohardjo, 1957). In the 1980s, Indonesian soil scientists adopted the USDA soil classification system (Sukarman et al., 2013), and most of the weathered volcanic soils were allocated to Inceptisols of the Udepts suborder. Such a classification is not very useful in the Deli area as it does not distinguish materials that were derived from different volcanic activities and alluviation. Several

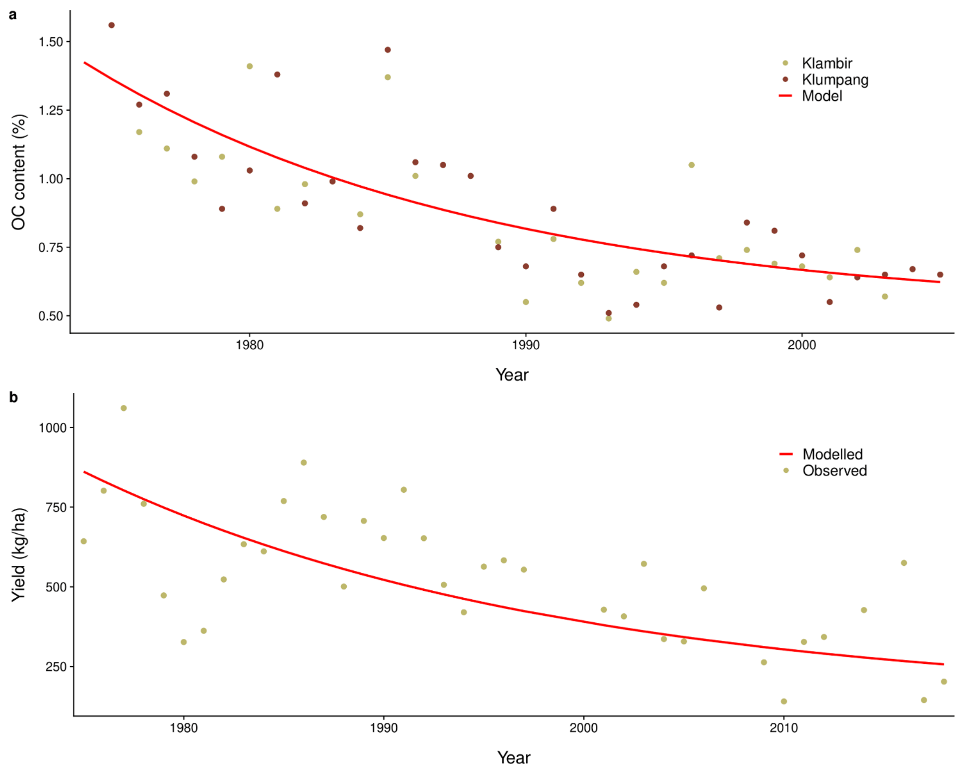

Fig. 6. Soil OC content from topsoil in Klambir and Klumpang with continuous tobacco and sugar cane (a) and yield of tobacco in Deli from 1975 to 2015 (b).

mapping projects been conducted in the north Sumatra area, notably the Land Resources Evaluation and Planning Project (LREP) in 1986–1990. A 1: 250,000 soil map across the Sumatra Island was mapped by the Center for Soil and Agro-climate Research. The mapping uses land units system approach, which was built based on the elements of the landform, primary parent material, topography, and soil type (Balsem et al., 1990). Topography maps and Landsat imageries were used in the interpretation. Druif's map is no longer used because it is deemed unsuitable. Land unit is classified according to USDA Soil Taxonomy at the Great Group level. Land suitability maps were produced for supporting food crops.

In 2014, the Indonesian National Soil Classification was established based on a morphogenetic approach (Subardja et al., 2016) (See also Supplementary Figure S4 for a contemporary soil map of Deli). An attempt was made to differentiate soils derived from volcanic materials into Andosol, Kambisol (more weathered but with high base saturation), Latosol (more weathered soil with low base saturation), or others.

3. Soil in the tropics from a contemporary perspective

3.1. The myth of "poor" tropical soils

Early researchers believed that in humid and hot equatorial regions, the warm temperature (average annual temperature of 25 °C or more) does not allow humus to accumulate as decomposition is faster than production (Senstius, 1930). Some have suggested that tropical soils have low organic matter content, aged, highly weathered, have a high content of Fe and Al oxides, depleted in nutrients (Grau et al., 2017; Sanchez, 2019; Soong et al., 2018). This is contradictory to the rich humus of tropical forests, as observed by van Bemmelen. Thus, some suggested a paradox to explain why luxurious rainforest can grow in this depleted soil. An unfounded theory was widely accepted that nutrients were only stored in plant tissues, and once the biomass was removed, the soil is unable to support other plants (Dalling et al., 2016). It was believed that most of the nutrients were conserved in the forest floor, as organic material decayed, the nutrients were recycled in plants and none of them went in the soil (Jordan and Herrera, 1981).

This idea was reflected by Loew (1900, p.7) in Physiological studies of Connecticut leaf tobacco who reasoned "the fact that some tobacco soils of Sumatra contain less of nutrients than tobacco soils in northern countries and still produce excellent crops" was because:

> A tropical temperature might favour the development of the root in humus soil to such an extent that relatively less of mineral nutrient for the unit of soil will suffice for a normal plant development.

Such a simplistic view of nutrient cycling based on a generalisation of poor tropical soils (Grau et al., 2017) is difficult to justify. Tropical regions cover a large land area, and there is a large variety of tropical soils (Vitousek and Sanford Jr, 1986) with almost the whole range of lithologies. Nutrient cycling on different soils and vegetation has adapted to such conditions. Soils from the tropics can support a continuous production of annual crops with proper management (Sanchez et al., 1982). Yet, it is still common to read the counterfactual both in educational materials (SSSA, n.d.; University of Michigan, n.d.; Khan Academy, n.d) and popular science articles (Hartl, 2019).

3.2. SOM and nutrients after forest clearance

Van Bemmelen noted the rapid decomposition of the organic matter once the forest was cleared. The high temperature in Deli (mean annual temperature of 27 °C with a minimum and maximum of 21–33 °C) rapidly oxidised the soil organic matter. However, it was not established whether the decline in productivity was solely because of SOM. While SOM decline was rapid after forest clearing, most studies show that the topsoil OC content decreased by 20–30% 1–2 years after clearing (Powers et al., 2011).

The OM content of forest soils in Deli, according to Mohr (1944), was between 13 and 17% (SOC = 8–10%). The report by Mulder (1926) showed OM content of the topsoils of Deli varied between 9 and 26%, with a mean of 14%, and even the subsoil had OM values of 7–8%. These are the Andisols (Tan, 2008). Edelman (1947) noted that despite tobacco having been cultivated on this soil for a long time, the OM content of the black dust soil was still in the order of 12%, which he called a stable humus form. We now know that the short-range-ordered clay minerals (allophane, imogolite, and ferrihydrite) made this soil stores lots of carbon via metal-humus complex (Al/Fe and OM complexes) forming stable carbon along with physical protection (Fiantis et al., 2019; van Noordwijk et al., 1997).

For Inceptisols, van Noordwijk et al. (1997) analysed data from Sumatra collected in 1987–1990 period found a mean OC content in the primary forest was 3.59% and 3.33, 3.22, 2.92% for secondary forest, perennial crops and shrubs, respectively. Those values are similar to values reported by Hardon (1936) for soils in the lowlands of South Sumatra with OC: 3.38, 3.83, 3.34, and 2.98% for primary forest, secondary forest, shrubland, and cropland, respectively.

Mohr (1944) added that while it was true that the SOM needed to be replaced after a year of cultivation, however, humus as determined by the laboratory analysis, was not merely the single factor for crop quality. He postulated that the cause of quality decline could be microflora (microbes) in the soil and soil physical quality (structure and permeability). Mohr dedicated three pages in his book discussing humus in the tropical forest. He postulated that some trace elements might play an important role in tobacco quality. As some plants could accumulate these trace elements effectively from the soil, the humus derived from these dead plants might able to make those elements more readily available. It is unknown whether the hypothesis is true.

There is now an extensive literature on slash-and-burn agriculture (Nye and Greenland, 1964; Palm et al., 1996). It is established that after forest clearance and burning, ash reduces soil acidity, increases soil nutrient availability (in particular N, P, K, Ca, Mg), decreases exchangeable acidity and Al concentration and enhances microbial activity (Sanchez et al., 1983; Brady, 1996; Juo and Manu, 1996; Ketterings and Bigham, 2000). Following rainfall, nutrients from the ash leached into the soil, which promoted crop growth and yield. However, the effects were only in the top few centimetres of the soil (2–5 cm, Thomaz et al. (2014)) and were short-lived as some nutrients were easily leached, and there was a risk of soil erosion if the soil was left bare.

Sanchez et al. (1983) studied Ultisols in Peru and found that six months after burning, the levels of available N and K were reduced, along with sporadic S, Cu, and B deficiencies. Topsoil organic C and total N decreased at an annual rate of 25% during the first year but approached an equilibrium afterward. Ketterings and Bigham (2000) found that in Oxisols in Jambi, Sumatra, 12 weeks after burning, exchangeable Ca decreased to pre-burn levels, and Al saturation increased markedly. However, the rate of soil degradation depends on the texture and mineralogy of the soil.

As early tobacco cultivation applied little to no fertiliser, the burning of the humus or organic layer created a favourable condition for tobacco in supplying nutrients. The increased pH values could increase the availability of some micronutrients.

Several studies have evaluated the decline in topsoil OC after forest clearance in the tropics (e.g., van Straaten et al., 2015). The relative decrease of topsoil OC compared to the forest condition usually follows a first-order kinetic form (Fig. 7):

$$\Delta C = \frac{[OCcrop - OCforest]}{OCforest} = a * exp(-kyear) + b, \tag{1}$$

where ΔC is the relative change in soil OC content, *OCcrop* is the OC under cropping and *OCforest* is OC content under forest, a + b are empirical constants representing maximum ΔC, and k is the rate constant (in year^{-1}) . Van Straaten et al. (2015) showed that 20 years after forests been converted to tree plantation, resulting in an average 30% decrease of topsoil OC (0–10 cm, $k = 0.15$ year^{-1}). Analysing data from Powers et al. (2011) who evaluated topsoil OC change from forest to cropping in the tropics, indicated 40 years after forest conversion to cropping and plantation resulted in an OC decrease of 37% (data from various depths: 0–5 to 0–40 cm, a median of 0–10 cm, $k = 0.047$). A meta-analysis by Luo et al. (2010) on topsoils in Australia showed that 40 years of cultivation for cropping has led to 46% OC loss (0–10 cm, $k = 0.067$). The rate of decrease from global data *meta*-analyses indicated around 30% OC decrease after 40 years of deforestation, for example, Murty et al. (2002) reported $k = 0.41$ year^{-1} (various depths 0–80 cm), and Deng et al. (2016) indicated $k = 0.04$ year^{-1} (various depths 0–100 cm, median 0–20 cm) (Fig. 7).

3.3. SOM after fallow

The 8-year rotation (7 years of fallow, 1 year of cropping) to allow the restoration of soil organic matter and nutrients, as suggested by van Bemmelen, had been in effect practised in traditional shifting cultivation, with short cultivation and a long fallow period. The land was cleared and used for 2–3 years and then abandoned for 10–20 years (Bautista-Cruz and Del Castillo, 2005; Brady, 1996). Kipp (1990) even suggested that the tobacco fallow scheme in Deli was inspired by shifting cultivation practised by the local Karo farmers. Van Bemmelen (1890d) established the need for a long fallow as he believed the source of soil fertility was the humus layer. Mohr (1944) noted that the very long fallow period was possible was because of the high price of the tobacco.

The fallow period allowed the accumulation of biomass and the restoration of SOM and nutrients. The rate of SOM accumulation following afforestation depends on previous land use, forest type, climate, soil texture, pH, and mineralogy. A mathematical model by Greenland and Nye (1959) indicated that a fallow:crop ratio of 3:1 would maintain the OM at 75% of the equilibrium level. Another review reported an average 10% soil OC increase after afforestation for soils in the tropical region with stronger OC accumulation in clay soils (Laganière et al., 2010).

Bautista-Cruz and Del Castillo (2005) studied afforested soils following agricultural fields abandonment in a tropical montane cloud forest in southern Mexico. The thickness of O horizon increased to about 5 cm after 15 years and up to 30 cm after 100 years. Soil C stock increased in the first 15 years with a very high rate of 4.29 Mg C/ha/year in the top 20 cm. In tropical Queensland in Australia, 8 to 33 years after reforestation did not show a significant increase in soil C stock relative to the agricultural baseline (Lewis et al., 2019). They attributed most C accumulation in living woody plant biomass. These studies indicated that the OM and nutrient restoration rate depends on soil type, climate, and vegetation factors.

3.4. Modelling contemporary SOM decline in Deli

To understand the SOM dynamics in Deli and also the effect of fallow, we simulate it using a simple first order kinetic reaction model. As shown in Fig. 6, SOM in Deli was declining for the period 1980–2010. We fitted a first-order decay model (Eq. (1)) to the data and found a rate constant k of 0.069 year^{-1}. By assuming that the original OC content is 3%, similar to the Deli I soil of van Bemmelen (also the average OC content of Inceptisols in Sumatra reported by van Noordwijk et al., 1997), we extrapolated the OC value back in time and estimated that the soil would be at its original OC level around 1960. Based on the assumption of 3% OC content, we calculate the relative change of OC decline after continuous use as follows:

$$\Delta C = 0.8 * exp(-0.069\text{year}) - 0.83 \tag{2}$$

Reported rate constants in the literature (e.g., van Straaten et al., 2015; Powers et al., 2011) (Fig. 7) indicated that cropping after forest clearance reach an equilibrium after about 40 years with an average 30% decline. Our analysis of the Deli soil showed the lowest decline of 78% from its original C content after 40 years because of continuous cultivation and little OM return.

We simulated soil OC dynamics under the practised rotational

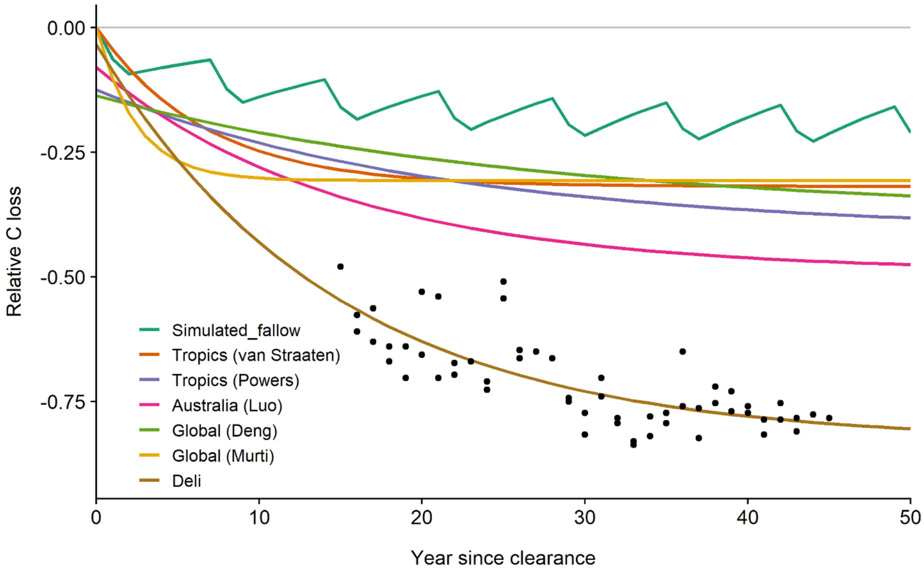

Fig. 7. Relative soil OC decline following forest clearance based on several publications (lines) and field observation in Deli (dots). Also showing a simulated fallow condition (green line). The grey line with constant value at 0 represents the original C content. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fallow system (1 year of cultivation, 6 years of forest, and 1 year of bare fallow) based on a simple 2 compartment model (Hénin and Dupuis, 1945):

$$\frac{dC}{dt} = hA - kC\# \tag{3}$$

where dC/dt is the rate of C change over time, which depends on input A, humification factor h, and the decomposition of C at a rate constant of k. We set a constant h and k of 0.069 $year^{-1}$. C input A during the fallow period set at the steady-state condition value with no change, $dC/dt = 0$, and during cultivation set at 0.1 A and 0.5 A during the second year. Fig. 7 shows the various OC dynamic conditions after 50 years of forest clearance: under the 8-year fallow system, we can avoid huge loss and maintain an average 20% decrease from its original level. When the soil is recovered after 6 years of forest, the OC is at 85% of its original level. Continuous cropping can decrease OC levels to 30–50%.

Soil under little OM input, as observed in the current Deli data (Fig. 7), resulted in an OC decrease of up to 80%. When the soil is under this chronic loss of OC, there is evidence to show that we can reverse the OC decline. The soil carbon transition curve (Van Noordwijk et al., 2015) describes a rapid decline of soil carbon due to human clearing of natural vegetation for cropping, followed by a critical phase of diminished soil fertility, and it can be recovered by improving agricultural practices. In the case of the Deli fields, efforts had been made to incorporate sugar cane and other crop residues to increase soil OC and yield. Nyak Akoeb (2008) found that an application of compost from crop residues at a rate of 5 ton/ha can increase SOC in the depleted soil from 0.8 to 1.1%. Agroforestry (Albrecht and Kandji, 2003) is another potential way to increase soil C sequestration in the tropics. Understanding the interaction of organic matter, soil mineralogy, soil physical and chemical properties are more meaningful than focussing on nutrients with the assumption that all tropical soils are poor.

3.5. Contemporary geology research and soil provenance

Druif differentiated various lava flows and ages based on geological principles and mineralogical studies. Contemporary research using radioactive dating has identified that the Toba mountain had at least four major explosive eruptions (Chesner, 1998). The oldest was the Haranggaol Dacite Tuff (HDT, ejected volume 35 km^3) about 1.2 million years (Ma) ago. This was followed by the Old Toba Tuff (OTT), which erupted about 0.79 Ma (1,000 km^3), the Middle Toba Tuff (MTT) erupted 0.5 Ma (60 km^3). The Youngest Toba Tuff (YTT) produced a super eruption around 74,000 years ago with the most recent estimate of 73,880 years, with an uncertainty of 640 years (Storey et al., 2012). The eruption ejected around 2800 km^3 of pyroclastic materials) caused global cooling for six to ten years (Budd et al., 2017).

After the YTT eruption of rhyolitic tuffs, volcanic activity continued, eruptions continued episodically for another 6 to 24,000 years, progressing westward across the caldera (Mucek et al., 2017). One of the characteristics of the YTT is the mineral allanite, called orthite by Druif (1938a), which was rare or absent in most acid volcanic rocks, but abundant in Toba. Van der Marel (1948) noted that allanite and zircon are the two main heavy minerals of soils from Toba.

The YTT events influenced the Karo plateau to the north of the caldera, with Sinabung and Sibayak mountains. There is geological evidence that Mt Sinabung shows 'strong geochemical kinship' with the Toba Caldera (Mucek et al., 2017). Sinabung has been erupting since 2010 and it is still uncertain the age of the previous Sibayak and Sinabung eruptions. Analysis on the zircon of Sinabung lava and recent pyroclastic flows indicated a mean age of 32,000 ± 14,000 years, with the youngest around 10,000 years (Mucek et al., 2017).

Druif (1934) can only recognised different volcanic materials based on optical mineralogy. At the time, nalysing elemental concentration of soil and its parent materials was still too expensive. Fig. 8 shows a contemporary elemental analysis of volcanic materials that affected the soil of Deli from the acidic rhyolite from Toba to dacite, andesite, and basaltic andesite from the Karo region (See Supplementary Material S2). Fig. 9 shows the principal component analysis of the elemental composition of volcanic materials in north Sumatra based on data from recent publications (Chesner, 1998; Harahap, 2011; Mucek et al., 2017). These materials contribute to the variety of soils found in Deli. It can be seen that the elemental concentration (which was difficult to measure during Druif's period) could be used to differentiate different parent materials.

The work by Druif in mapping soil parent material based on primary mineralogical composition and linking the price of tobacco to soil type represents early work on soil provenance. A term such as *geographical indication* links agricultural produce to a specific geographical origin and possess qualities of that origin (Coggins et al., 2019). Rather than measuring soil primary mineralogical components, we can now measure geochemical characteristics of the soil rapidly using proximal sensors such as the portable x-ray fluorescent spectrometer (Stockmann et al., 2016) or FTIR (mid-infrared) spectrometer (Ng et al., 2019). The ability to distinguish soil types (Fig. 6) from geochemical composition allows us to identify the origin of a product. Druif demonstrated almost 90 years ago that producing maps of soil types, particularly recognising

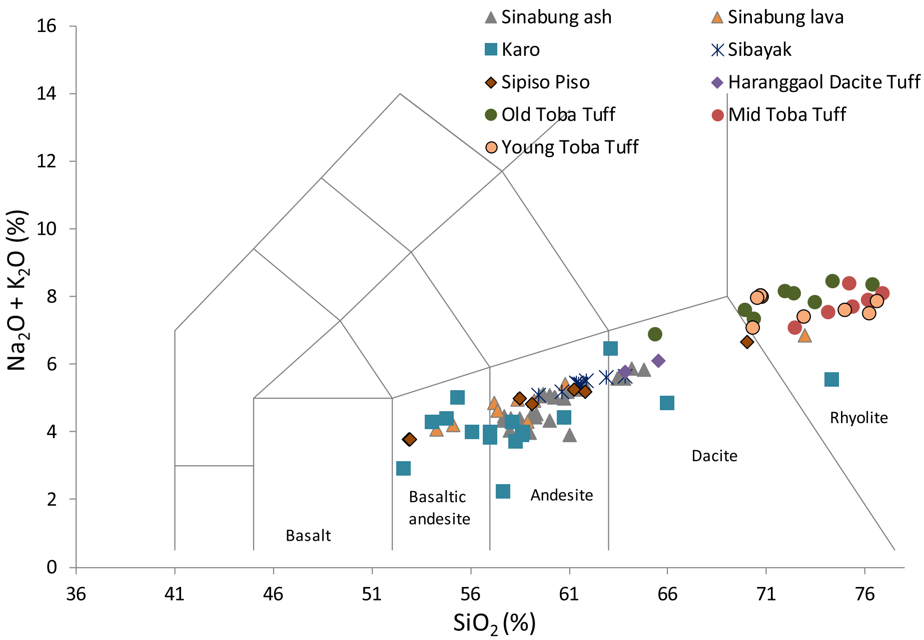

Fig. 8. Geochemistry of different volcanic materials that influence soil from Deli plotted on total alkalis vs. SiO2 volcanic rock classification of Le Bas et al. (1986). Toba tuffs and Haranggaol data from Chesner (1998), Sinabung ash from Primulyana et al. (2019), Sinabung lava, Sibayak, and Sipiso Piso from Mucek et al. (2017), Karo (include Sibayak, Singkut, Sipiosopiso, and Haranggaol) from Harahap (2011).

lithology and consequent mineralogy, allows product differentiation. Certainly, this is an area we should focus on linking digital soil mapping to soil provenance (Malone et al., 2014).

3.6. Soil mapping

If we were to map the soil of Deli today, we would start with collecting spatial covariates, designing a sampling scheme, collecting soil samples, and probably perform mapping using some machine-learning algorithms (Padarian et al., 2019). In the absence of environmental

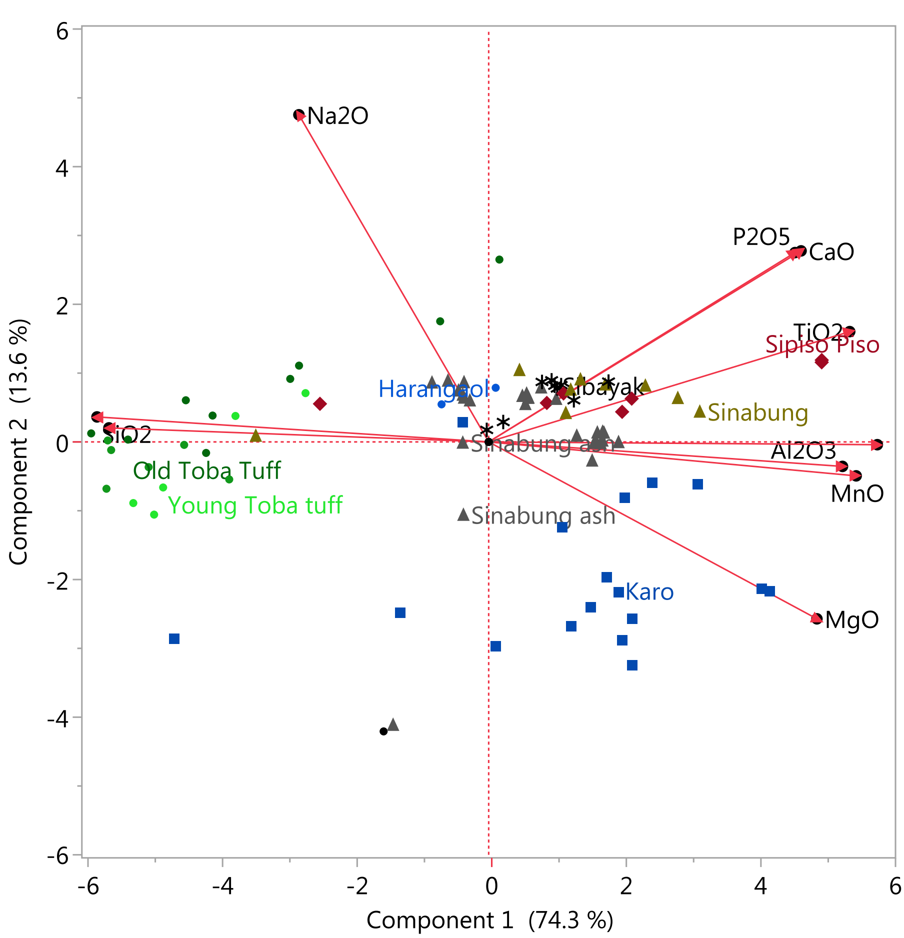

Fig. 9. Biplot of geochemical elemental concentration of volcanic materials that influence soil from Deli. The x-axis shows the first principal component and the y-axis the second principal component of geochemical concentrations of volcanic materials from North Sumatra. The lines in the plot represent the loadings of the chemical elements, and the dots are the samples. Source of data is quoted in Fig. 8.

information, Druif decided first to investigate the soil parent materials, which allowed him to differentiate soil types. As there was no *de facto* soil classification system, he created his own system that suited the local conditions, even though several broad-scale classification systems of soils the Netherlands East Indies existed at that time. That work highlighted the importance of recognising parent materials in any mapping exercises. While there have been several digital mapping of soil parent material studies (Lacoste et al., 2011), most current soil mapping works only used the available covariates. Most studies would allocate the soil observations using the *de facto* classification system and then map the occurrence of the soil class. As we described, in the case of Deli, mapping based on a top-down classification system would produce less meaningful classes as most soils would be allocated to a broad class, e.g. Typic Hapludepts under the USDA system. Building soil classes using bottom-up approach based on local data (e.g., Odgers et al., 2011) would create more meaningful soil classes and map. The effective merging of bottom-up and top-down approaches has always been the challenge of useful soil classification – Butler's (1980) taxonomic hiatus (the discrepancy between conceptual taxonomy class and actual soil in the field).

4. Conclusions

We can summarise the brief history and present-day interpretation of the soils of Deli story as follows:

- Early studies on the soils of Deli have shown that soils in the humid tropics are diverse, and that the soil type and composition are more crucial than the organic matter in determining quality of crops. As most of the soils from Deli are derived from young volcanic materials, relatively high concentrations of elements are still contained in primary minerals.
- The long fallow period was established in the 1880s–1930s on the preconceived idea of rich humus layer and heavily leached tropical soil rather than evidence. We now have more understanding of the underlying mechanisms of OM decline: the clearance of forest and the burning of biomass neutralise acidity and release nutrients that are readily taken up by the first crop. Only after the first crop, OM and nutrients decline rapidly.
- Early soil classification scheme adapted to Deli's soils by Druif recognised the important of parent materials in distinguishing between soil types. Parent material information should be used for soil mapping in complex areas.
- Early 20th century research by Druif in mapping soil parent material based on primary mineralogical composition and linking the price of tobacco to soil type is similar to present-day concepts of soil provenance. In agriculture, this is now often referred to as the term *geographical indication* which links agricultural produce to a specific geographical origin.
- Past experience in long-term cropping and soil management in Deli coupled with modelling have shown that continuous exploitation of soil results in a steady decrease in soil OM. However, with soil-specific management, it is possible to slow down the decline.

The colonial planters started deforestation for large-scale plantations in Indonesia. Much foreign research in Indonesia still focuses on OC loss as a result of deforestation (van Straaten et al., 2015). There should be more effort in understanding how to increase soil OC in these soils, i.e., how soil OC interacts with mineral components, and how they can nourish microbes and be physically and chemically protected and stabilised. Management of soil to increase its OC stock should be the way to offset this land-use change effect. Composting, green manuring, and application of plant residues have been trialled in Deli to restore the soil's OM content. The effort to increase soil organic matter can be framed in the 4 per 1000 initiative and puts soil carbon and agriculture on the global agenda. There will be challenges in regions with small landholders, such as in Indonesia. A concentrated action towards soil OC sequestration will restore soil condition that is currently in an acute state, advance food and nutritional security, and improve the environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.104909.

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