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The Theoretical Potential of Hondsrug Glacial Rock Dust as Soil Remediator in The Netherlands

Niels Christian Olfert

ABSTRACT

Agriculture in the Netherlands is a major source of ammonia (NH3) emissions. Deposited nitrogen levels in the Netherlands reached 2-3 times their critical value at the start of 2020. Excess nitrogen in soil may cause declines in biodiversity and ecosystemic disequilibrium. This may lead to acidic and decalcified soils that are less capable of retaining nutrients. The mineral fines in rock dust are proven agents in soil remediation and remineralization. Glacial moraine deposits are a branded source of rock dust and are contained in the glacial till of the "Hondsrug" area, a boulder clay ridge in the northeastern Netherlands. Formerly, erratic rocks from this boulder clay served various practical purposes. The existing apparent inutility of these erratic rocks motivates us to review their potential as rock dust. Lack of chemical analyses on the *in situ* erratic rocks resorts to an evaluation of their inferred Fennoscandian source rocks which are of igneous and sedimentary lithology. The chemical composition of these inferred source rocks is compared with that of proven rock dust suppliers. It is concluded that even though there are compositional parallels between the rock dust, the Hondsrug area glacial till is comparatively decalcified and mineralogically of limited benefit. Moreover, exceptional magnitudes of erratic rocks are scarcely encountered while at the same time, the bulk is preserved as geological heritage. Despite the adversities, it could be chosen to commence trials with crushing idle erratic rocks in the Hondsrug area whenever this may be assessed as a useful supplement.

Keywords: Crop Nutrition, Glacial Erratic Rocks, Nitrogen, Netherlands Agriculture, Rock Dust, Soil Remineralization.

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I. Introduction

Agriculture in the Netherlands is a major source of ammonia (NH_3) emissions [1]. As a result of increased manure production from Netherlands' livestock, ammonia emissions in 2017 and 2018 exceeded the 128 kt limit agreed to by the European Union [2] (see Fig. 1). Even though the recorded ammonia emissions in 2019 were 123 kt [3], excessive nitrogen emissions have unfavourably affected the subsurface. An example thereof is the sandy soil of the ancient deciduous forest of oak trees hosted by the Veluwe National Park [4].

Since 2015, there have been several experiments to reduce deposited nitrogen that had reached 2-3 times its critical value of 1071 mol per hectare at the start of 2020 [4]. These experiments involved application of Eifelgold® rock dust as "slow-release fertilizer" [5].

De Vries *et al*. [5] reports a significant positive effect of rock dust on soil chemistry. Plant leaves recorded higher nutrient content–especially potassium and magnesium–and the nitrogen content of oak leaves had decreased. Even though a natural solution ideally includes further reducing nitrogen deposition [4], it proves that soil remineralization can partially restore nutrient balance in tested soils within three years after application.

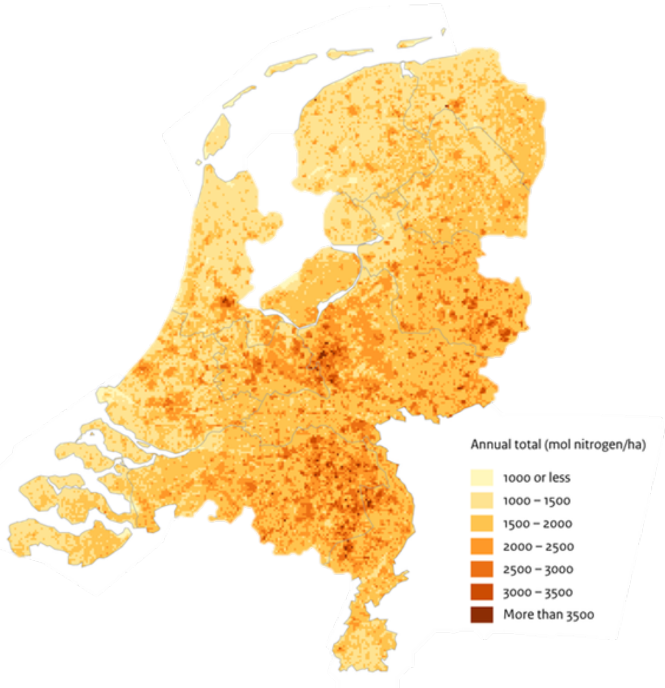

Fig. 1. Average nitrogen deposition in the Netherlands in 2018.

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Soil remineralization relies on mineral fines to restore soil fertility by resupplying nutrients previously removed by agricultural activities or natural forces [6]. The contribution of agricultural intensification to soil degradation remains a recognized phenomenon worldwide as rock dust gains traction amongst academics. In 2022 a team of researchers from the University of Bristol conducted research that involved cultivation of red clover with nitrogen-fixing bacteria on a typical pH~7 silt loam that was treated with glacial rock dust and estimated its nitrogen fixation capacity as a measure of fertility in comparison with two equivalents; an untreated control group and one that was treated with synthetic fertilizer. The team reported that comparatively, rock dust treatments promote nitrogen fixation and mitigate N_2O emissions [7]. Environmental valuables that multinational brewer Carlsberg illustrated a year earlier by increasing their crop yields with 30% after treating a barley field in Denmark with rock dust from Greenland's granite bedrock [8].

II. Soil Remineralization and its Sources

Rock dust is an assemblage of mineral fines with a constitution typically favourable for soil remineralization purposes that derive from crushed or weathered source rock.

For soil remineralization, Hamaker and Weaver [9] recommended mineral fines from rock gravels, glacial moraine deposits, and hard silicate rock types, such as slower-weathering granites. All these examples are exhibited in the glacial tills commonly constituting the shallow subsurface of the "Hondsrug" area (see Fig. 2), a boulder clay ridge in north-eastern Netherlands roughly 60 km in length, formed as a consequence of massive glacial retreat from the present-day Fennoscandian Peninsula in the Pleistocene epoch [10]. It constitutes a geological complex that is characterized by marked NNW-SSE oriented linear features which were shaped by ice streams during the Saalian glaciation, approximately 150 kya [10].

The Hondsrug glacial till hosts numerous erratic rocks and boulders of varying dimensions. In the past, there was economic potential in mining erratic rocks and boulders due to their application as building material for roads and reinforcement purposes [11]. However, presently, these rocks and boulders prove rather problematic for farmers as they cause damage to farm equipment during the harvesting season. This "idle potential" is the primary motivation for writing this article.

Academic research (e.g. [12]-[14]) persistently suggests that silicate rock dust has the potential to enhance plant health that is–in turn–contingent on a familiar basis of fourteen elements essential for plant growth–nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), chlorine (Cl), boron (B), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), nickel (Ni) and molybdenum (Mo)–based on studies (e.g. [15]-[17]).

The main goal of this article is to practically assess the potential and feasibility of the geologically distinct boulder clay found in the Hondsrug area as a source for rock dust.

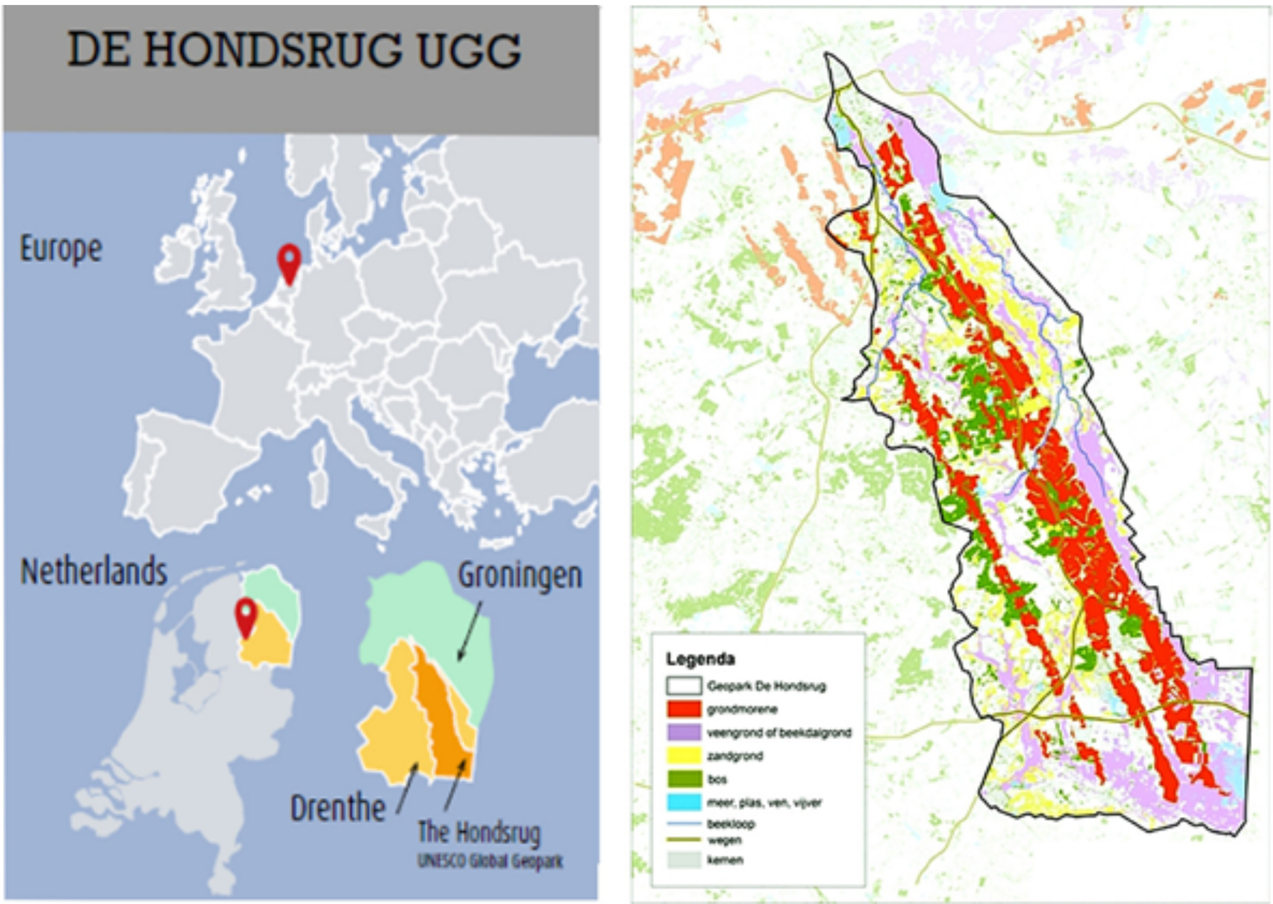

Fig. 2. Location and outline of the Hondsrug area in the province of Drenthe and relative to the province of Groningen, within the scope of Europe-Netherlands.

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III. The Hondsrug Glacial Till Chemically Decomposed

The Hondsrug glacial till is classified based on composition and class orientations and can be subdivided into six types [6]. Three of these subtypes are still calcified at present, whereas the other three are calcium depleted.

The erratic rocks and boulders of the till are predominantly of granite, gneiss and sandstone lithology. These lithologies typically yield silica and potassium feldspar, which produce secondary clay-sized minerals upon weathering.

Haldorsen *et al*. [18] conducted a study on the composition and source of the clay-sized fractions illite, kaolinite and smectite–amongst others–of the applicable Saalian glacial till in the Netherlands. Five of 23 samples analysed coincide with the Hondsrug area. These were collected from the Emmerschans and Erica localities. Results suggest that weight percentages of illite are relatively high compared to other localities in the Netherlands, whereas those of kaolinite are relatively low. The representation of smectite appears indistinct: overall it is relatively underrepresented in the Hondsrug samples. An exception however forms one sample that contains the highest relative proportion of smectite over the complete sample set, which is believed to have volcanic over pedogenic origin [18]. Both illite and kaolinite are composed of silicon and aluminum. In addition, illite contains potassium, magnesium and iron in a range of possible proportions. Beidellite is considered a common soil-smectite, which has an ideal chemical formula consisting of silicon and aluminum, in addition to interchangeable calcium and magnesium [19].

IV. Is Hondsrug Glacial Till a Serious Candidate for Rock Dust?

Given the limited sample size and its inconsistencies, early deductions about the potential of Hondsrug glacial till as rock dust should be treated with caution. With that said, there are two observations from Haldorsen *et al*. [18] that provide a favourable contribution to this potential. Firstly, the comparatively abundant illite, which is one of the principal mineral sources of potassium in many soils [20] that is, in turn, a prime constituent for commercial NPK fertilizers. Secondly, the recorded substantial proportion of smectite. Smectite is considered particularly important in temperate region soils due to the fact that it has a high cation exchange capacity (CEC) and therefore many plant nutrients can be retained in its mineral structure [19], [21]. Due to its expansive nature and negative charge, smectite is highly reactive in soils. Therefore, it readily exchanges K^+, Ca^{2+}, Mg^{2+}, Na^+, in addition to other cations required for plant growth [21].

Despite these encouraging observations, Wim de Vries from Wageningen University & Research (WUR) argues that employment of rock dust should be–as a matter of course–dependent on prior assessment of a soil's fertility [22]. Soil fertility concerns nutrient availability and its usage within plants [23]. Not all soils are equally fertile and retain their nutrients equally effectively (e.g. [24]). This is particularly true for the deeply leached southern hemisphere oxisols [25].

Although European soils are generally considered fertile [26] in 2019, the European Commission estimated that Europe loses 9 million metric tons of it per year [27]. The Nutrient Management Action Plan seeks to reduce nutrient loss by at least 50% [28], [29] and managing nitrogen better throughout its lifecycle constitutes one of its actions.

V. How is the Hondsrug Soil actually Doing?

The complications of excessive nitrogen emissions with respect to soil quality are multifaceted [30]. Primarily, excess nitrogen in soil may cause declines in biodiversity and ecosystemic disequilibrium and–in turn–yields acidic and decalcified soils that are less capable of retaining nutrients.

The critical deposition value (CDV) for nitrogen measures the effects of excessive nitrogen emissions and is defined as "the limit, beyond which the risk cannot be excluded that the quality of the habitat type is significantly affected as a result of the acidifying and/or fertilizing influence of the atmospheric nitrogen deposition" [31]. According to WUR, an average deposition value of 1000 mol/ha/yr would bring a significant part of the natural areas in the Netherlands near the CDV. It must be noted that the value of the CDV is dependent upon habitat type and may thus vary from one area to the other based on nitrogen toleration.

The provincial government of Drenthe–the domain that includes the Hondsrug area–issued a course of action in 2021 to reduce nitrogen deposition and foster nature while ensuring economic advancement. The document that ensued emphasizes current and expected nitrogen deposition for several protected nature areas, among which a ~351 ha stream valley on the western Hondsrug flank called Elperstroomgebied that has low nitrogen toleration [32].

In 2018, nitrogen deposition in Elperstroomgebied ranged between 1017-1733 mol/ha/yr. In that year, 57% of the area stayed within limits of the CDV for nitrogen. Nitrogen deposition in Elperstroomgebied is expected to decrease to 860-1477 mol/ha/yr by 2030 [33]. It should be noted that most of the deposited nitrogen in the area (~65%) sources from externally–other provinces and abroad–and the emphasized area poses a case that requires special attention [34].

The agricultural importance of periglacial sediments has been widely demonstrated (e.g. [35]) and therefore it is inconceivable that geological exploitation of rocks for improved fertility in the Hondsrug area requires the same urgent necessity and attains similar measurable effectiveness as for developing countries with lower quality soils that spend much on chemical fertilizer (e.g. [36]).

Since October 2013 [25] Brazilian federal law sanctions and regulates the usage of crushed silicate rock remineralizers for crop nutrition in their readily leachable soils – an approach that may ensue a model for reduced long-term dependency on imported chemical fertilizers for the developing world [25] whose own mineral sources are often exploited by multinational mining companies [37].

There establishes greater recognition for 'Development Minerals' to alleviate poverty and sustain food production and rock dust could play a key role in this emergent field [37]-[38]. Not every rock however must also roll.

VI. An Analytical Approach

Ramezanian *et al*. [39] treated two wheat cultivars on three different soil types with volcanic rock dust under controlled conditions for a three-year period and reported no demonstrable ecological or agricultural benefit. In contrast, Bakken, Gautneb and Myhr [40] and Bakken *et al*. [41] used crushed rock including the mineral nepheline–a potassium source–as a fertilizer to positive effect [25] and others have since explored its potential (i.e. [42]). Granite, along with other igneous rocks, is multifarious. Its complex geological history determines its exact elemental composition. Therefore, reliable assessments of its potential as agricultural supplement demand accurate analysis of its constituents. Once chemical comparison with equivalents of proven rock dust yields demonstrable parallels, positive inferences could be drawn regarding its potential as rock dust.

Unfortunately, Haldorsen *et al*. [18] does not publish the glacial till's elemental constituents. The chemical composition of granite dust applied by Faraone and Hillier [12] is protected intellectual property of Heritage Memorials Ltd. Disclosure of its potential is thus subject to future comparative investigations. Outside of examining the *in situ* erratic rocks and boulders of the Hondsrug glacial till, it can be focused on investigating its source rock prior to glacial advance. Haldorsen *et al*. [18] show the main source of Baltic crystalline indicators based on the information given in De Waard [43] and Zandstra [44]-[45]. On the basis thereof, the five Hondsrug area samples originally derive from the eastern Baltic, from generally Precambrian and Paleozoic source bedrock. Schuddebeurs [11] already indicated that the bulk of the observed indicator boulders in the Hondsrug area comprise (aplite-)granites from Åland, SW Finland and Småland, S Sweden. Eklund, Fröjdö and Lindberg [46] present a statistical approach for the fascinating history concerning the generation of the various magmas that rendered different types of Åland granites, including those that are termed rapakivis. Their research suggests a mixed origin of the typically encountered rocks, the inferred chemical composition of which is presented subsequently:

SiO_2: 62.55%; Al_2O_3: 13.99%; FeO: 8.83%; CaO: 4.47%; Na_2O: 3.18%; K_2O: 3.27%; MgO: 1.79%; TiO_2: 1.39%; with trace amounts of MnO and P_2O_5.

The volcanically derived smectite is thought to have originated from reworked, lithified tertiary sediments that accumulated in the North Sea during and after the opening of the Atlantic Ocean [18]. These sedimentary rocks are encountered in the Scania province of southern Sweden [47]. Erlström and Guy-Ohlson [48] presented their investigation of the Upper Triassic Norian Kågeröd Formation in Scania which is dominated by clays and mudstones alternating with sandstones. The clays and mudstones are dominated by kaolinite, but also provide a source of smectite and illite. Even though it is challenging to determine the exact locality of the Tertiary sedimentary rocks from the literature, and it remains speculative to attribute absolute uniformity between the rocks, there appear characteristic analogies. Inductively Coupled Plasma-Atomic Emission Spectroscopic (ICP-AES) analysis of a clay sample yielded the following distribution of oxides:

SiO_2: 50.1%; Al_2O_3: 23.1%; Fe_2O_3; 13.8%, with trace amounts of CaO, Na_2O, MnO, TiO_2, K_2O, MgO and P_2O_5.

Even though the above-presented distribution of elements could be considered effectively varied, Bolland and Baker [49] demonstrated that low potassium, phosphorus and nitrogen content in powdered granite limited its effectiveness when applied.

VII. Let's See if Those Erratic Rocks can pull Their Weight

Fig. 3 represents a stockpile of erratic rocks excavated by a Hondsrug area farmer during harvesting which is exhibited at heritage museum Hunebedcentrum, connected to Hondsrug UNESCO Global Geopark.

An informed approximation supposes a volume of 25 cubic metres (Olfert, personal communication, 2022). Based on recent application of rock dust for soil remediation purposes on sandy soil in southern Netherlands, 10 t/ha rock dust is a proposed requirement [50]. In calculating the mass (m) of erratic granite or gneiss, a specific weight of 2.7 kg/m^3 is proposed and a constant 0.6 is introduced to account for irregular shape [51].

$$m = V \cdot 0.6 \cdot 2.7 \quad (1)$$

From (1), it follows that the supposed volume (V) of 25 cubic metres weighs 40.5 t. Due to uncertainties with regards to stockpiled volume and the omit of pore spaces–which, despite the added irregularity constant, is expected to yield greater mass–an educated range of plausible masses of 35-45 t is proposed for the stockpiled erratics. It should be noted that the stockpile in the above image is considered an exceptional excavation in terms of the magnitude of erratics (Wolters, personal communication, 2022). It can be inferred that for remediation of the ~351 ha Elperstroomgebied, as much as ~100 equivalent stockpiles may be required presuming its effectiveness as a soil remediator.

Fig. 3. Stockpile of Hondsrug area erratic rocks exhibited at a heritage museum connected to Hondsrug UNESCO Global Geopark shown for estimation purposes.

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VIII. Is It All Practical and Realistic?

Table I represents the chemical composition from proven rock dust producers SIBELCO and Eifelgold® compared with the above-presented distribution of elements in the hypothetical Hondsrug area source rocks to infer its effectiveness.

TABLE I: Chemical Composition by Percentage of Oxides

	SIBELCO	Eifelgold®	Åland	Norian Kågeröd Fm
SiO_2	46	42-44	62.55	50.1
Al_2O_3	18	13-15	13.99	23.1
FeO	-	-	8.83	-
Fe_2O_3	11	10-12	-	13.8
CaO	8	11-13	4.47	t.a.
Na_2O	5	2-4	3.18	t.a.
K_2O	5	3-4	3.27	t.a.
TiO_2	3	2-3	1.39	t.a.
MgO	4	8-10	1.79	t.a.
MnO	-	t.a.	t.a.	t.a.
P_2O_5	-	t.a.	t.a.	t.a.

t.a. signifies trace amounts. A single dash (-) signifies absence of relevant oxide.

It must be urgently noted that the afore-presented concerns one single example, per presumed source rock, and that documentation of additional chemically analysed samples from other localities within Åland, Småland and Scania is found to be sparse. The chemical constitution of erratic rocks and boulders compared to the original source rock might have significantly altered due to geological processes. Therefore, effective research should invariably encompass thorough chemical analysis of the *in situ* erratic rocks and boulders constituting the glacial till, in favour of theoretical correlation with its inferred source.

Even though the values in table I correspond to certain extent, it is evident that CaO is underrepresented in the two hypothetical Hondsrug area source rocks. The importance of calcium as a regulator of plant growth and development is widely testified (e.g. [52]). The fact that the current Hondsrug glacial till is presumably abundantly decalcified proves unfavourable.

On that same token, from Chiwona *et al*. [42] it may be implied that dissolution rates–hence–nutrient release from potassium feldspar in granite is too slow to meet the required standards set by nepheline which–in turn–only forms in silica-poor rocks which are underrepresented in the Hondsrug glacial till. Priyono and Gilkes [53] however, concluded that potassium feldspar may be used as effective K fertilizer. In spite thereof, glasshouse experiments carried out by Priyono and Gilkes [54] to further constrain the agronomic effectiveness of potassium feldspar versus a reference fertilizer (K_2SO_4) in K-deficient soils supported the limited benefit of the former in lieu of the latter. Irrespectively, Lim *et al*. [55] recommends feldspathic adsorbents for groundwater remediation, and evaluations by Ciceri and Allanore [56] and Manning [20] suggest that the primary weathering of feldspar yields significantly higher weathering and dissolution rates than previously proposed–a component that might be correlated with plant and soil microbiological processes and invariably substantiates the increased energy rate of rock milling to reduce particle size [57].

Regardless of academic variance, the concept of the Hondsrug glacial till as a source of rock dust meets public resistance. Harry Huisman–the curator of geology tied to the Hondsrug UNESCO Global Geopark–shed light on a number of these adverse considerations. Firstly, the amounts of erratic rocks and boulders that are currently uncovered during harvesting are limited in size and quantity. Exceptional magnitudes of erratics–such as presented above–are scarcely harvested. Furthermore, local farmers themselves consider the glacial soils unproductive (Huisman, personal communication, 2022) and excavation of glacial till and its erratic rocks and boulders is considered economically unviable. It is confirmed the glacial till found in the Hondsrug area is abundantly decalcified (Huisman, personal communication, 2022). Most importantly, Hondsrug UNESCO Global Geopark strives to preserve these erratic rocks and boulders as geological heritage (Huisman, personal communication, 2022).

Wim de Vries from Wageningen University & Research (WUR) moreover notifies about the hazards of incorrect utilization of rock dust. Some of these hazards include excessive soil mineralization, decreased availability of phosphorus and potential alterations to soil fauna [22], all of which have bad effects on soil fertility. Swoboda [57] furthermore states that nutrient imbalances may arise from excessive rock dust application. Maaike Weijters from B-Ware–a research institute whose scientific focus lies on chemistry and ecology–argues that more research is needed to ascertain the long-term effects of rock dust on organic soils [22].

IX. Conclusions And Recommendations

The high NH_3 emissions, adversely affecting soils, show that there is potential need for remineralization in the Netherlands. Mineral fines in rock dust have the potential to remediate soil by restoring its nutrient balance. There are ongoing practical experiments with the application of rock dust in the Netherlands to reduce deposited nitrogen, to satisfying effect. The hypothetical source rock from the Hondsrug glacial till shows chemical parallels with proven rock dust SIBELCO and Eifelgold®.

Despite the similarities, there are substantial reasons to abandon the Hondsrug glacial till as a source of rock dust. Essentially, these include the fact that the current Hondsrug glacial till is abundantly decalcified and dissolution rates for potassium are deemed too slow, that exceptional magnitudes of erratics are scarcely harvested, and that Hondsrug UNESCO Global Geopark strives to preserve erratics as geological heritage.

It is recommended to proceed with rock dust experiments in soil remediation to ascertain its long-term effects on soil and ecosystem and advocate for the necessary resources toward that end.

Since the chemical composition of the *in situ* erratics remains undisclosed, as a subject of further research, it may be proposed to carry out chemical analysis of these rocks. In case analysis certifies *in situ* erratics as effective soil remediator, there ensues a humble selection of propositions as follows:

Even though Hondsrug UNESCO Global Geopark strives to preserve erratics as geological heritage, and excavation of glacial till is considered economically unviable, it could be chosen to commence trials with crushing stockpiled *idle* erratics whenever this may be assessed as a useful supplement for local purposes. To this end, it could be considered to provide local farmers cost-effective means to crush small-scale erratic in the future.

It is not proposed to use regional rock dust from more remote sources to remediate protected nature areas such as Elperstroomgebied. Given its expected limited contribution as a remediator and the foreseeable logistical complications, this is not deemed to present a sustainable solution.

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Conflict of Interest

Authors declare that they do not have any conflict of interest.

References

[1] Velthof GL, Van Bruggen C, Groenestein CM, De Haan BJ, Hoogeveen MW, Huijsmans JF. A model for inventory of ammonia emissions from agriculture in the Netherlands. *Atmospheric environment*. 2012 Jan 1;46:248-55. https://doi.org/10.1016/j.atmosenv.2011.09.075.

[2] Jimmink BA, Coenen PW, Dellaert SN, Geilenkirchen GP, Hammingh P, Leekstra AJ, *et al*. Informative Inventory Report 2017: Emissions of transboundary air pollutants in the Netherlands 1990-2015. https://doi.org/10.21945/RIVM2017-0002.

[3] Wever D, Coenen PW, Dröge R, Geilenkirchen GP, t Hoen M, Honig E, *et al*. Informative Inventory Report 2021. Emissions of transboundary air pollutants in the Netherlands 1990–2019. DOI: 10.21945/RIVM-2021-0005.

[4] Drok W. Redt steenmeel het oude eikenbos op de Veluwe? *Nature Today*, 2020 15 February [Accessed 3rd Mar 2022]. Dutch.

[5] De Vries W, Weijters M, de Jong A, van Delft B, Bloem J, van den Burg A, *et al*. Verzuring van loofbossen op droge zandgronden en herstelmogelijkheden door steenmeeltoediening. In: *Vereniging van Bos- en Natuurterreineigenaren (VBNE)*. Available via Alterra, WUR, 2019 [Accessed 3rd Mar 2022].

[6] Barker AV, O'Brien TA, Campe J. Soil Remineralization for sustainable crop production. In: *Beneficial Co-Utilization of Agricultural, Municipal and Industrial by-Products*. 1998 (pp. 405-413). Springer, Dordrecht. https://doi.org/10.1007/978-94-011-5068-2_35.

[7] Sgouridis F, Forrester H, Tingey S, Wadham J. Glacial Rock Flour as soil fertility amendment increases N fixation activity in red clover and enhances soil N2O reduction. *EGU General Assembly 2022*, Vienna, Austria, 23–27 May 2022, EGU22-5489. https://doi.org/10.5194/egusphere-egu22-5489.

[8] Gronholt-Pedersen J. Climate-friendly farming: Greenland's melting glaciers offer an answer. *Reuters*, 2021 18 November [Accessed 1st Dec 2022].

[9] Hamaker JD, Weaver DA. *Survival of Civilization*. Seymour, MI, USA: Hamaker-Weaver Publishers; 1982 Jun.

[10] Bregman EP, Smit FW. Genesis of the Hondsrug: A Saalian megaflute, Drenthe, the Netherlands. Steering Group aspiring EUROPEAN GEOPARK de Hondsrug. 2012.

[11] Schuddebeurs AP. Zwerfsteentellingen in Noord-Nederland. *Mededelingen van de Werkgroep voor Tertiaire en Kwartaire Geologie*. 1982 Jan 1;19(3):81-108. Dutch.

[12] Faraone N, Hillier NK. Preliminary evaluation of a granite rock dust product for pest herbivore management in field conditions. *Insects*. 2020 Dec 11;11(12):877. https://doi.org/10.3390/insects11120877.

[13] Ramos CG, Hower JC, Blanco E, Oliveira ML, Theodoro SH. Possibilities of using silicate rock powder: An overview. *Geoscience Frontiers*. 2022 Jan 1;13(1):101185. https://doi.org/10.1016/j.gsf.2021.101185.

[14] Swoboda P, Döring TF, Hamer M. Remineralizing soils? The agricultural usage of silicate rock powders: A review. *Science of The Total Environment*. 2022 Feb 10;807:150976. https://doi.org/10.1016/j.scitotenv.2021.150976.

[15] Brady NC, Weil RR, Weil RR. *The nature and properties of soils*. Upper Saddle River, NJ: Prentice Hall; 2008 Jan.

[16] Tucker MR. Essential plant nutrients: their presence in North Carolina soils and role in plant nutrition. In: *North Carolina State Documents Collection*. State Library of North Carolina Department of Agriculture and Consumer Services, Agronomic Division; 1999. Available via NC State University [Accessed 3rd Mar 2022]. https://sampson.ces.ncsu.edu/wpcontent/uploads/2021/07/2-Essential-Plant-Nutrients.pdf?fwd=no.

[17] White PJ, Brown P. Plant nutrition for sustainable development and global health. *Annals of botany*. 2010 Jun 1;105(7):1073-80. https://doi.org/10.1093/aob/mcq085.

[18] Haldorsen S, Jørgensen P, Rappol M, Riezebos PA Composition and source of the clay-sized fraction of Saalian till in The Netherlands. *Boreas*. 1989 Jun;18(2):89-97. https://doi.org/10.1111/j.1502-3885.1989.tb00377.x.

[19] Schulze DG. Clay Minerals. In: *Encyclopedia of Soils in the Environment*, vol. 1, Hillel D, Ed. Boston: Elsevier / Academic Press, 2005, pp. 246-254.

[20] Manning DA. Mineral sources of potassium for plant nutrition. In: *Sustainable Agriculture*, vol. 2, 2011, pp. 187-203. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-0394-0_11.

[21] Borchardt G. Smectites. In: *Minerals in soil environments*. Dixon JB and Weed SB, Madison, Soil Science Society of America, 1989, pp 675-727. https://doi.org/10.2136/sssabookser1.2ed.c14.

[22] Van Duinhoven G. Steenmeel toedienen mag soms/ nooit/ wel/ misschien/ nog niet. In: *Vakblad natuur bos landschap. Stichting Vakblad Natuur Bos Landschap*. Available via Alterra, WUR; 2021 [Accessed 30 Jul 2022]. Dutch. https://edepot.wur.nl/547395.

[23] Foth HD, Ellis BG. *Soil fertility*, Lewis CRC Press LLC. USA 290p. 1997.

[24] Vitousek PM, Naylor R, Crews T, David MB, Drinkwater LE, Holland E, *et al*. Nutrient imbalances in agricultural development. *Science*. 2009 Jun 19;324(5934):1519-20. https://doi.org/10.1126/science.1170261.

[25] Manning DA, Theodoro SH. Enabling food security through use of local rocks and minerals. *The Extractive Industries and Society*. 2020 Apr 1;7(2):480-7. https://doi.org/10.1016/j.exis.2018.11.002.

[26] Helmholtz Association of German Research Centres. *Mapping the most fertile soils in Europe*. [Internet] 2007 [updated 2007 Nov 16; cited 2022 Dec 1]; Available from: https://www.sciencedaily.com/releases/2007/11/071115113328.htm.

[27] Politico.eu. *Mud and guts: Europe's forgotten environmental crisis* [Internet]. 2019 [updated 2019 Apr 3; cited 2022 Dec 1]. Available from: https://www.politico.eu/article/europe-forgotten-environmental-crisis-soil/.

[28] Remineralize The Earth. *Rock Dust as a Sustainable Amendment in Northwestern European Agriculture* [Internet] 2022. [updated 2022 May 1; cited 2022 Dec 1]. Available from: https://www.remineralize.org/2022/05/rock-dust-as-a-sustainable-amendment-in-northwestern-european-agriculture/#:~:text=Silicon%20in%20rock%20dust%20may,usage%20and%20sequestering%20CO2.

[29] Schilthuis G. Perspectives for nutrient management in Europe Under the Farm to Fork Strategy and the Common Agricultural Policy. *PHOS4YOU Final Conference*, 2021 Sep 23; Essen, Germany.

[30] Clark CM, Bai Y, Bowman WD, Cowles JM, Fenn ME, Gilliam FS, *et al*. Nitrogen deposition and terrestrial biodiversity. In: *Encyclopedia of Biodiversity*, 2nd ed, vol. 5, Levin SA, Ed. Waltham, MA: Academic Press. pp. 519-536. 2013;5:519-36. https://doi.org/10.1016/b978-0-12-384719-5.00366-x.

[31] Van Dobben HF, Van Hinsberg A. Overzicht van kritische depostiewaarden voor stikstof, toegepast op habitattypen en Natura 2000-gebieden. In: *Alterra-rapport 2397*. Available via Alterra, WUR; 2008 [Accessed 30th Jul 2022]. Dutch. https://library.wur.nl/WebQuery/wurpubs/434041.

[32] Provincie Drenthe. *Drentse Aanpak Stikstof: Gebiedsverkenning Elperstroom*. [Internet] 2021 [updated 2021 Nov 23; cited 2022 Jul 30]. Dutch. Available from: https://www.provincie.drenthe.nl/publish/pages/133091/lg-w2111_181-drentse_aanpak_stikstof-gebiedsverkenningen-elperstroom.pdf.

[33] Gies E, Kros H, Voogd JC. Inzichten stikstofdepositie op natuur: Memo. Wageningen Environmental Research; 2019. Dutch.
[34] Natuur en Milieufederatie Drenthe. *Van crisis naar oplossingen: Bouwstenen voor een Drents stikstofprogramma* [Internet] 2019 [updated 2019 Dec 3; cited 2022 Jul 30]. Dutch. Available from: https://www.drentsparlement.nl/Vergaderingen/Statencommissie-Omgevingsbeleid-OGB/2019/06-december/15:00/OGB061219-B1-NMF-Drenthe-03-12-2019-Bouwstenen-Drents-Stikstofprogramma-COMPL.pdf.
[35] Catt JA. The agricultural importance of loess. *Earth-Science Reviews*. 2001 Jun 1;54(1-3):213-29. https://doi.org/10.1016/S0012-8252(01)00049-6.
[36] Jenkins S. How the Russia-Ukraine War Helped Fuel Record Fertilizer Prices. *Federal Reserve Bank Of St. Louis*, 2022 4 October [Accessed 9th Jan 2023]. Available from: https://www.stlouisfed.org/publications/regional-economist/2022/oct/russia-ukraine-war-record-fertilizer-prices.
[37] Hilson G, Hilson A, McQuilken J. Ethical minerals: Fairer trade for whom? Resources policy. 2016 Sep 1;49:232-47. https://doi.org/10.1016/j.resourpol.2016.05.002.
[38] Franks DM. Reconsidering the Role of Minerals and Matter in International Development. *IUGS Resourcing Future Generations*, Bryan Lovell Meeting 2017: Mining for the Future
[39] Ramezanian A, Dahlin AS, Campbell CD, Hillier S, Mannerstedt-Fogelfors B, Öborn I. Addition of a volcanic rockdust to soils has no observable effects on plant yield and nutrient status or on soil microbial activity. *Plant and soil*. 2013 Jun;367(1):419-36. https://doi.org/10.1007/s11104-012-1474-2.
[40] Bakken AK, Gautneb H, Myhr K. The potential of crushed rocks and mine tailings as slow-releasing K fertilizers assessed by intensive cropping with Italian ryegrass in different soil types. *Nutrient Cycling in Agroecosystems*. 1996 Feb;47(1):41-8. https://doi.org/10.1007/BF01985717.
[41] Bakken AK, Gautneb H, Sveistrup T, Myhr K. Crushed rocks and mine tailings applied as K fertilizers on grassland. *Nutrient Cycling in Agroecosystems*. 2000 Jan;56(1):53-7. https://doi.org/10.1023/A:1009709914578.
[42] Chiwona AG, Cortés JA, Gaulton RG, Manning DA. Petrology and geochemistry of selected nepheline syenites from Malawi and their potential as alternative potash sources. *Journal of African Earth Sciences*. 2020 Apr 1;164:103769. https://doi.org/10.1016/j.jafrearsci.2020.103769.
[43] De Waard D. Glacigeen Pleistoceen, een geologisch detailonderzoek in Urkerland, Noordoostpolder. *Verhandelingen Geologisch en Mijnbouwkundig Genootschap*. 1949;15:70-246. Dutch.
[44] Zandstra JG. A new subdivision of crystalline Fennoscandian erratic pebble assemblages (Saalian) in the central Netherlands. *Geologie en Mijnbouw*. 1983;62(3):455-69.
[45] Zandstra JG. Explanation to the map 'Fennoscandian crystalline erratic of Saalian age in The Netherlands'. In: *Tills and Glaciotectonics*. Van der Meer JJM. Ed. Rotterdam: Balkema, 1987, pp 127-134.
[46] Eklund O, Fröjdö S, Lindberg B. Magma mixing, the petrogenetic link between anorthositic suites and rapakivi granites, Åland, SW Finland. *Mineralogy and Petrology*. 1994 Mar;50(1):3-19. https://doi.org/10.1007/BF01160135.
[47] Tullborg EL, Larsson SA, Björklund L, Stigh J, Samuelsson L. Thermal evidence of Caledonide foreland, molasse sedimentation in Fennoscandia. *Swedish Nuclear Fuel and Waste Management Co*.; 1995.
[48] Erlström M, Guy-Ohlson D. An Upper Triassic, Norian–Rhaetian, outlier in Skåne, southern Sweden. *Bulletin of the geological Society of Denmark*. 1999;45:89-97.
[49] Bolland MD, Baker MJ. Powdered granite is not an effective fertilizer for clover and wheat in sandy soils from Western Australia. *Nutrient Cycling in Agroecosystems*. 2000 Jan;56(1):59-68. https://doi.org/10.1023/A:1009757525421.
[50] Bosgroepen.nl. *Steenmeel helpt bij duurzaam herstellen van 520 hectare bodem en natuur* [Internet] 2021 [updated 2021 Nov 8; cited 2022 Jul 30]. Dutch. Available from: https://bosgroepen.nl/bosgroep-zuid-nederland/steenmeel-helpt-bij-duurzaam-herstel-bodem-en-natuur/.
[51] Lemmers N. Hoe groot en zwaar is een hunebedsteen? En hoe weten we dit? *Hunebed Nieuwscafe*, 2017 [Accessed 30th Jul 2022]. Dutch. Available from: https://www.hunebednieuwscafe.nl/2017/09/hoe-zwaar-groot-is-hunebedsteen/.
[52] Hepler PK. Calcium: a central regulator of plant growth and development. *The Plant Cell*. 2005 Aug;17(8):2142-55. https://doi.org/10.1105/tpc.105.032508.
[53] Priyono J, Gilkes RJ. Dissolution of milled-silicate rock fertilisers in the soil. *Soil Research*. 2004;42(4):441-8. https://doi.org/10.1071/SR03138.
[54] Priyono J, Gilkes RJ. High-energy milling improves the effectiveness of silicate rock fertilizers: a glasshouse assessment. *Communications in soil science and plant analysis*. 2008 Feb 1;39(3-4):358-69. https://doi.org/10.1080/00103620701826498
[55] Lim WR, Kim SW, Lee CH, Choi EK, Oh MH, Seo SN, *et al*. Performance of composite mineral adsorbents for removing Cu, Cd, and Pb ions from polluted water. *Scientific reports*. 2019 Sep 19;9(1):1-0.
[56] Ciceri D, Allanore A. Microfluidic leaching of soil minerals: release of K+ from K feldspar. *PloS one*. 2015 Oct 20;10(10):e0139979. https://doi.org/10.1371/journal.pone.0139979.
[57] Swoboda P. Rock dust as agricultural soil amendment: a review. M.Sc. Thesis. University of Bonn; 2016.

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