A Renaissance of Pseudosands:

On Improving the Understanding of Soil Architecture in Deeply Weathered Soils

by

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“La tierra no tiene dueño, es de todos.”

(“The land has no owner, it is everyone’s.”)

- Tránsito Amaguaña -

(1909–2009)

To all women in science

THESIS COMPONENTS AND AUTHOR CONTRIBUTIONS

This dissertation includes three chapters (Chapter 2 to 4), that have either been already published, submitted to peer-reviewed scientific journals or are ready for submission. For the inclusion into this thesis, the formatting required by the journals has been removed, spelling mistakes were corrected and all sections, figures and tables were re-numbered to fit in a common layout. References of each chapter were combined in a single list of references at the end of this dissertation.

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The authors contribution to the respective publication is detailed below.

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Chapter 4

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ABSTRACT

Soil texture, the most widely used soil property to describe single grain size distribution, is different from soil structure. Setting them equal neglects the impact of actual particle arrangements under natural conditions. Particularly in deeply weathered soils, the mismatch between soil texture and structure has widely been described. It is therefore not surprising, that biogeochemical models built on texture-based assumptions systematically diverge from field observations, for example, often overestimating nitrous oxide emission rates. Water-stable aggregates like pseudosands, often described for deeply weathered soils, might be responsible for this mismatch. In the field they are perceived as sand, but in laboratory analysis for texture determination measured as clay and silt.

This thesis develops pseudosands as a tractable entry point into studying aggregate stability and pore space as complementary aspects of soil structure. An initial literature review revealed a persistent lack of consistent classification for pseudosands, hindering comparison across studies. However, when looking for water-stable aggregation in literature, dynamic water balances emerge as the most determining pattern for their global distribution. Within this *Goldilocks zone,* spanning humid to perhumid climates in tropical to cold temperate latitudes, drying-wetting cycles act as stabilizing and selective forces through chemical weathering and physical comminuting. Although pseudosands have been described (at least) since the 1960s, this thesis further establishes them as a distinct textural class in their own right, as, unlike sand, they display mechanical stability largely independent of size. Modeling pseudosands as sand holds only moderately for hydrological purposes and fails for biogeochemical processes such as nitrous oxide emission rates for deeply weathered soils. Actually, pseudosands show distinct water retention and porosity, while their quantity alone does not predict functional hydraulic impact. Pseudosands are therefore not sand but neither the plain sum of their clay- and silt-sized units.

While most aggregates remain volatile across time and space, constantly forming, dissolving, and transforming, pseudosands stand out as an exemplarily stable aggregate. If such stability is indeed a function of pedogenic age, it stands to reason that all sufficiently aged soils could eventually develop water-stable aggregates of this kind. As a rare anchor point within an otherwise highly diverse and opaque soil system, they offer remarkable potential for study.

ZUSAMMENFASSUNG

Die Bodentextur, die am häufigsten verwendete Bodeneigenschaft zur Beschreibung der Einzelkorngrößenverteilung, unterscheidet sich von der Bodenstruktur. Ihre Gleichsetzung vernachlässigt den Einfluss der tatsächlichen Partikelanordnung unter natürlichen Bedingungen. Besonders in tiefgründig verwitterten Böden ist die Diskrepanz zwischen Bodentextur und -struktur vielfach beschrieben worden. Es überrascht daher nicht, dass biogeochemische Modelle, die auf texturbasierten Annahmen beruhen, systematisch von Feldbeobachtungen abweichen und beispielsweise häufig Lachgas-Emissionsraten überschätzen. Wasserstabile Aggregate wie Pseudosande, die häufig für tiefgründig verwitterte Böden beschrieben werden, könnten für diese Diskrepanz verantwortlich sein. Im Feld werden sie als Sand wahrgenommen, in der Labor-Texturbestimmung jedoch als Ton und Schluff gemessen.

Die vorliegende Arbeit entwickelt Pseudosande als greifbaren Einstiegspunkt, um Aggregatstabilität und Porenraum als komplementäre Aspekte der Bodenstruktur zu untersuchen. Eine erste Literaturübersicht zeigte einen anhaltenden Mangel an einheitlicher Klassifikation für Pseudosande, was Vergleiche zwischen Studien erschwert. Jedoch, bei der Betrachtung wasserstabiler Aggregation in der Literatur erwiesen sich dynamische Wasserhaushalte als das bestimmende Muster für ihre globale Verbreitung. Innerhalb dieser *Goldlöckchen-Zone*, die von humiden bis perhumiden in tropischen bis kaltgemäßigte Klimazonen reicht, wirken Trocken-Nass-Zyklen sowohl stabilisierend als auch selektierend, durch chemische Verwitterung und physikalische Zerkleinerung. Obwohl Pseudosande (mindestens) seit den 1960er Jahren beschrieben wurden, etabliert diese Arbeit sie weiterführend als eigenständige Textur-Klasse, da sie, im Gegensatz zu Sand, eine mechanische Stabilität aufweisen, die weitgehend größenunabhängig ist. Die Modellierung von Pseudosanden als Sand zeigt nur bedingte Verbesserungen für hydrologische Fragestellungen und versagt für biogeochemische Prozesse wie Lachgas-Emissionsraten. Tatsächlich zeigen Pseudosande eigene Wasserretentions- und Porositätseigenschaften, wobei ihre Menge nicht allein mit ihrer funktionalen hydraulischen Wirkung gleichzusetzen ist. Pseudosande sind daher kein Sand, aber offenbar auch nicht die Summe ihrer ton- und schluffgroßen Partikel.

Während die meisten Aggregate über Zeit und Raum volatil bleiben und sich ständig bilden, auflösen und umwandeln, heben sich Pseudosande als exemplarisch stabiles Aggregat hervor. Sollte diese Stabilität tatsächlich eine Funktion der pedogenetischen Zeit sein, liegt es nahe,

dass alle hinreichend gealterten Böden im Laufe der Zeit derartige wasserstabile Aggregate entwickeln könnten. Als seltener Ankerpunkt innerhalb eines ansonsten hochgradig diversen und undurchsichtigen Bodensystems bieten sie bemerkenswertes Potenzial für weitere Forschung.

RESUMEN

La textura del suelo, la propiedad del suelo más utilizada para describir la distribución del tamaño de grano individual, difiere de la estructura del suelo. Equipararlas pasa por alto el impacto de la organización las partículas bajo condiciones naturales. Particularmente en suelos profundamente meteorizados, el desajuste entre textura y estructura del suelo ha sido ampliamente descrito en textos científicos. Por lo tanto, no sorprende que los modelos biogeoquímicos basados en premisas de textura diverjan sistemáticamente de las observaciones de campo, por ejemplo, sobreestimando a menudo las emisiones de óxido nitroso. Los agregados estables al agua, como las pseudoarenas (*pseudosands*), frecuentemente descritas en suelos profundamente meteorizados, podrían ser responsables de este desajuste. En el campo se perciben como arena, pero en el análisis de laboratorio para la determinación de textura se miden como arcilla y limo.

Esta tesis desarrolla las pseudoarenas como un punto de entrada abordable para estudiar la estabilidad de los agregados y el espacio poroso como aspectos complementarios de la estructura del suelo. Una revisión bibliográfica inicial reveló una persistente falta de clasificación consistente para las pseudoarenas, lo que dificulta la comparación entre estudios. Sin embargo, al examinar la agregación estable al agua en la literatura, los balances hídricos dinámicos emergen como el patrón más determinante para su distribución global. Dentro de esta *zona de Goldilocks*, que abarca climas húmedos a perhúmedos desde los trópicos hasta zonas frías-templadas, los ciclos de secado-humedecimiento actúan como fuerzas tanto estabilizadoras como selectivas, mediante meteorización química y fragmentación física. Aunque las pseudoarenas han sido descritas (al menos) desde la década de 1960, esta tesis las establece además como una clase textural distintiva, ya que, a diferencia de la arena, presentan una estabilidad mecánica en gran medida independiente del tamaño. Modelar las pseudoarenas como arena resulta solo moderadamente válido para fines hidrológicos y falla para procesos biogeoquímicos, como las tasas de emisión de óxido nitroso en suelos profundamente meteorizados. De hecho, las pseudoarenas muestran una retención de agua y una porosidad distintivas, mientras que su cantidad por sí sola no predice su impacto hidráulico funcional. Las pseudoarenas no son, por lo tanto, arena, pero tampoco son la simple suma de sus unidades del tamaño de arcilla y limo.

Mientras que la mayoría de los agregados permanecen volátiles en el tiempo y el espacio, formándose, disolviéndose y transformándose constantemente, las pseudoarenas destacan como

un agregado ejemplarmente estable. Si esta estabilidad es en efecto una función del tiempo, cabría esperar que todos los suelos eventualmente desarrollen agregados estables. Como un punto de anclaje dentro de un sistema por lo demás altamente diverso y opaco cómo lo son suelos en general, ofrecen un notable potencial para su estudio.

TABLE OF CONTENT

THESIS COMPONENTS AND AUTHOR CONTRIBUTIONS..... I
ABSTRACT III
ZUSAMMENFASSUNG V
RESUMEN VII

CHAPTER 1 | General introduction 1
1.1 | Bridging soil fertility and soil structure 1
1.2 | On soil aggregation 3
1.3 | An opportunity within the complexity 4
1.4 | Pseudosand holds its ground 6
1.5 | Thesis outline 7

CHAPTER 2 | A soil scientist's guide to pseudosands 9
Abstract 10
2.1 | Introduction 11
2.2 | Material and methods 14
2.3 | Results 18
2.4 | Discussion 24
2.5 | Conclusion 34
Acknowledgments 35
Declaration of generative AI use 35

CHAPTER 3 | The "extra pinch" of pseudosand to enhance tropical biogeochemical processes understanding 37
Abstract 38
3.1 | Introduction 39
3.2 | Approaches 42
3.3 | Effects of pseudosands on hydrological and biogeochemical modeling 47
3.4 | Conclusions and outlook 50
Acknowledgments 51

CHAPTER 4 | Pseudosands do not simply mimic sand 53
Abstract 54
4.1 | Introduction 54
4.2 | Material and methods 56
4.3 | Results 59
4.4 | Discussion 62
4.5 | Conclusions 67
Acknowledgments 68

CHAPTER 5 | Conclusion 69
5.1 | Pseudosands as a blueprint for aggregation 69
5.2 | Research outlook 70
5.3 | On the transdisciplinary melting pot 71

BIBLIOGRAPHY 73
SUPPLEMENTARY MATERIAL 89
For Chapter 2 89
For Chapter 3 99
For Chapter 4 102

DECLARATION 107
DECLARATION ON THE USE OF AI 108
ACKNOWLEDGMENTS 109
CURRICULUM VITAE 111

CHAPTER 1 | General introduction

Civilizations rise from the soil (McNeill & Winiwarter, 2004) and every society that has fed itself and settled has done so on the basis of a few decimeters of structured soil (Brevik et al., 2018; Cunfer, 2021; Kopittke et al., 2024). What makes soils function depends largely on structures no greater than the size of sand grains (Garland et al., 2024). Together, they shape the architecture that defines processes at different spatial and temporal scales (Vogel et al., 2022) when interacting in a three-dimensional space with solids, liquids and gases.

The challenges on researching soil and soil structure today mirrors, in many ways, the broader pattern of human inquiry: a challenge is encountered, questions are formulated in response, and, subsequently, means to answer them are developed (Richter, 2007). Many relevant questions have been shaped by human needs, ranging from maintaining fertility and crop production to preventing degradation, and increasingly, to regulating water, carbon, nutrients, and greenhouse gas emissions. Ultimately, the goal is to understand how soil functioning emerges from interactions across these different scales, from the individual aggregate to the landscape. Currently, we are losing this basis for life on Earth (Silver et al., 2021), and its faster than we manage to understand how this system acts and reacts (Prăvălie, 2021).

1.1 | Bridging soil fertility and soil structure

The study of soils and their structure was initially driven by urgent practical pressures. For much of soil sciences' history, the primary concern has been how to sustain agricultural productivity and food security (Cunfer, 2021; Güldner et al., 2021). Soil productivity was not simply a given characteristic of land, but something that could be enhanced, maintained, or lost through human management. In the early 20th century, Emil Truog (1938) captured this practical orientation in his publication entitled "Putting Soil Science To Work", by emphasizing that land productivity had to be understood through accumulated knowledge and observation by farmers, agronomists, and naturalists. The need for such knowledge became increasingly evident as intensive cultivation, deforestation, and continuous cropping led to compacted and eroded soils that lost their capacity to sustain yields (Lal, 2008; Vanwalleghem et al., 2017). These were not isolated failures but systemic consequences of land use practices that had long outpaced the contemporary scientific understanding of soils in general.

The consequences of intensive land use have repeatedly shown that productivity is not only dependent on the nutritional status of soils and their (micro-)biology, but cannot be separated

from the physical properties of soils and the combined interactions among them. Across human history, continuous cultivation and nutrient depletion contributed to long-term loss of land fertility, while erosion removed the very soil upon which production depended. Examples from the Mediterranean and North Africa illustrate how intensive grain production contributed to soil degradation and the decline of once-productive lands in times of the Roman Empire (Fuchs, 2007; Gomiero, 2016). Industrial Revolution accelerated these processes (Brunt, 2004) as mechanization enabled cultivation at unprecedented spatial scale and temporal rate, mainly increasing profits in the agricultural sector. In the 1930s, events like the Dust Bowl in North-America or later on the Virgin Lands Campaign in the Soviet Union were triggered by the combination of mechanically unstable topsoil, large-scale removal of vegetation, and extreme climatic conditions (Bischoff et al., 2017; Prăvălie, 2021). Already in 1892, soil scientist Dokuchaev had explored the causes of famine under drought in his Special Expedition to the Russian Steppes, recommending remedial actions to counteract structural degradation and avoid further severe erosion. However, this warning went largely unheeded then and in the years that followed (Moon, 2005).

The cumulative weight of these crises increased the interest on soil structure and soil stability. Since then, it has become impossible to consider crop productivity without accounting for erosion and soil degradation (Bartoli et al., 2016). What had initially been approached primarily as applied science aimed at maintaining fertility increasingly became a fundamental scientific question. The focus shifted from managing soil for productivity to understanding the underlying soil functioning and processes. As the discipline matured, it drew attention from a diverse range of disciplines, each bringing distinct perspectives and methodologies on how to study aggregations. This process has been particularly facilitated by advances in analytical technologies within the last decades (Amelung et al., 2024). The aim was no longer solely to intervene, but to understand the processes and mechanisms governing aggregate formation, stabilization, and breakdown (Abayneh et al., 2006; Huang et al., 2016; Thomaz et al., 2022). The shift also sought to advance spatio-temporal upscaling from molecules to the Earth system, and to translate understanding of the past, into manage practices in the present and planning for the future (Garland et al., 2024).

Soil physicists approached aggregation through the lens of mechanics and hydrology, seeking to understand pore structure and water retention (Lipiec et al., 2007; Menon et al., 2020), as well as the compressive strength of aggregates, moving beyond stability indices toward measurable physical properties (Felde et al., 2020). Soil chemists and, later, microbiologists

identified the binding agents responsible for aggregation, such as organic polymers, fungal hyphae, and microbial biofilms (Rabot et al., 2018; Totsche et al., 2018). Mineralogists examined soil profiles and parent material through micromorphological analysis, as well as the inorganic constituents of aggregates (Bremer & Sander, 2011; Cooper et al., 2005). Further, environmental scientists broadened the scope by linking aggregate stability to carbon sequestration (Bronick & Lal, 2005), reduction of greenhouse gas emissions (Blagodatsky & Smith, 2012; Mangalassery et al., 2013), or mitigation of land degradation or erosion (Barthès & Roose, 2002; Ding & Zhang, 2016). Each discipline effectively incorporated a different perspective and the soil scientists today are left with the challenge of integrating this accumulated but fragmented knowledge to address contemporary challenges, whilst new knowledge is being generated as a result of technological advances.

While these diverse perspectives greatly expanded our understanding of soils, they also introduced a new problem: soil structure came to be described through multiple structural entities, scales, and disciplinary languages. Soil structure thus became not a single object of study, but a collection of overlapping perspectives (Roosch, 2024). The challenge today, therefore, is not to create and accumulate further new measurements, but to understand how these descriptions relate to one another.

1.2 | On soil aggregation

An aggregate is a group of primary particles that cohere more strongly with one another than with surrounding soil particles (Kemper & Rosenau, 1986), representing a locally ordered structure that runs counter to the entropic tendency toward disorder and dispersion. Yet the apparent simplicity of this definition conceals considerable complexity. Aggregates are not static objects. They continuously form, stabilize, reorganize, and break apart as forces acting within the soil are highly variable and in continuous shift. Moreover, while roots and fungal hyphae, inorganic cementation, and organic binding promote aggregation, factors such as tillage, raindrop impact, slaking, and clay dispersion act in the opposite direction (Díaz-Zorita, 2002; Thomaz et al., 2022). Aggregation is therefore rather a dynamic equilibrium and not a permanent structural state.

The arrangement of primary particles within aggregates has consequences extending far beyond the solid states. Particle arrangement determines how pores are created and connected. It influences the spatial distribution of water and nutrients and provides habitats for microorganisms (Totsche et al., 2018; Wilpiszeski et al., 2019). If aggregates describe how

solid particles are organized into discrete units, pores describe the void space generated by that organization. Rather than representing two competing perspectives and mutually exclusive explanations of soil structure, contemporary discussions increasingly recognize aggregates and pores as complementary aspects of it (Roosch, 2024; Vogel et al., 2022).

This becomes particularly important when considering the scale at which soil structure is studied. While aggregates themselves contain smaller structural units, surfaces and pores, they are simultaneously embedded within larger-scale soil arrangements. The classical hierarchical model of Oades & Waters (1991) and Tisdall & Oades (1982), for example, conceptualized soil structure as a hierarchy in which macroaggregates contain microaggregates that ultimately dissociate into primary particles. Such a model provides an intuitive connection between structural organization across scales. However, its applicability is not universal. It was developed largely from observations of temperate soils in which organic matter plays an important role in structural stabilization, whereas strongly weathered tropical soils have been found to not follow the same stepwise hierarchy (Pessoa et al., 2022; Vrdoljak & Sposito, 2002).

Thus, the aggregate is a moving target in more than one sense. Its physical state changes continuously, its internal architecture can vary, and the conceptual meaning assigned to it differs among soils and scientific disciplines. Most fundamentally, however, the aggregate is difficult to study because its boundaries are neither always visible nor necessarily independent of the method used to define them.

1.3 | An opportunity within the complexity

Studying, quantifying, and translating soil aggregation across scales remains remarkably difficult due to the inherent complexity of soil systems. The first challenge is soil's natural opacity (Kravchenko et al., 2019): the soil matrix is a dense, heterogeneous, and largely impenetrable medium that resists direct observation, meaning that the architecture of soils and aggregates, their boundaries, pore networks, and surfaces must be inferred from indirect measurements or destructive sampling rather than observed in situ and in their natural state. Or, as once Van Schuylenborgh (1947) summarized it: "*Soil structure can only be observed when the soil is in an undisturbed state; [but] only in the laboratory structure may be defined in distinct characteristics* ".

The second, and perhaps more fundamental problem is that the delimitation of aggregates remains vague (Kravchenko et al., 2019). The boundaries of aggregates are not always unambiguous, and, more critically, biased on how aggregates have been isolated and

characterized as a consequence of the energy selected to separate them from their surrounding soil matrix (Díaz-Zorita, 2002). What we call an aggregate is therefore partly a function of methodology rather than of their intrinsic properties. This poses a profound challenge for analysis: properties characterized at the nanoscale must be reconciled with the much larger scales, where many processes interact in variable ways. In theory, nanoscale measurements of stability and porosity could be upscaled to field or landscape scales, and ultimately to global models of carbon storage, erosion, and water cycling. However, in practice, each transition between scales introduces assumptions, averaging, and loss of structural information.

A pivotal moment in studying soil structure was the work of Yoder (1936), who developed practical field techniques to assess soil stability under the mechanical stress of water (Amézketa, 1999; Rieke et al., 2022). This work established a method still widely used today: wet-sieving soil samples to determine the fraction that disperses under water and in contrast the fraction stable to slaking. Despite numerous subsequent modifications and their universal use, the method has never been free of controversy. Soil scientists challenged it early on for producing inconsistent results and, more fundamentally, for potentially measuring something other than true aggregate stability (Rogowski, 1964).

Part of this conceptual impasse is inseparable from a persistent and very practical problem: the absence of a standardized measurement protocol that would allow results to be meaningfully compared across studies, soils, and disciplines. This is not a new observation: researchers have recognized the inconsistency of aggregate stability measurements since (at least) the mid-twentieth century, and numerous protocols have been proposed over the decades (Almajmaie et al., 2017), including modifications of Yoder's wet-sieving technique to ultrasonic energy approaches, rainfall simulation, and, more recently, imaging-based methods (Rabbi et al., 2016).

Yet, no scientific consensus has emerged on which method best captures the fundamental nature and function of soil aggregates, partly because the mechanisms and processes governing aggregate formation and transformation remain unclear. This adds on the lack of a shared vocabulary within this field: methods differ in the way of isolating aggregates, the size ranges variably between classification systems and the energy inputs differ, resulting in low comparability across studies. the result is a field that remains, after more than a century of active research, fragmented not only across disciplines but within them. Therefore, while it is a research area rich in data, it too often cannot speak by itself.

This lack of standardization is a particularly acute problem in soil science, because soil is among the most spatially and temporally heterogeneous natural systems on Earth, and aggregates are variably volatile. Unlike branches of science where standardization emerged comparatively early, like water quality monitoring, soil science has historically developed across a wide range of national research traditions, agronomic contexts, and disciplinary frameworks, each evolving its own measurement convention. The consequence is that decades of aggregate stability data in scientific literature are often not directly comparable. Agreeing on standardized protocols would not resolve this once and for all, such standards will inevitably need to be revisited and refined as new insights challenge existing methods, establishing a shared baseline is a necessary first step. It is also an urgent one: addressing food security, climate change mitigation, and ecosystem restoration through science-based policy requires a field that can, at minimum, understand a common language about the structures it studies.

This leaves soil science with an unusual situation: a large and continuously expanding body of observations about aggregates, but no framework through which all of these observations can readily be connected. While the same structural object can be approached through its stability, pore system, mineralogy, chemical bonding, or biological components, the measured properties relate to defined spatio-temporal settings. Aggregates consequently remain a moving target for each discipline, shaped by the properties that are prioritized, the spatial scales selected and the methods regarded as appropriate. Within this methodological and conceptual uncertainty, a particular class of soil structural units presents an unusual opportunity: pseudosands!

1.4 | Pseudosand holds its ground

Pseudosands, compared to other aggregates, occupy an unusual position within this broader impasse. Most aggregates are very volatile and disintegrate under the very energy required to isolate and study them, leaving often researchers to infer their structure indirectly, or not at all. Pseudosands on the contrary are defined precisely by their resistance to such disruption (Martinez & Souza, 2020). Their stability under strong mechanical and hydraulic stress means they can be handled, measured, and compared in ways that most soil aggregates cannot, offering a rare opportunity to study aggregate properties directly rather than inferring them from indirect proxies. Yet this same stability, and the fact that pseudosands are tactilely similar to sand grains, is also the reason why they are often misidentified in the field, only to be reclassified in classic laboratory analyses as finer fractions (Lilienfein et al., 1999).

This distinction challenges the assumption that particle size alone provides an adequate description of soil material. Two objects of the same external size may have fundamentally different internal architectures, as here the sand being a primary particle and pseudosands an aggregate composed of smaller particles. In the latter case, the arrangement of constituent particles creates an internal pore system and surface area that cannot be inferred from external particle size alone. Their occurrence therefore raises questions not only about how aggregates are stabilized, but also about how aggregation should be conceptualized across soils and scales. Historically recognized for their distinct behavior, but subsequently obscured by conventional texture analysis, they offer an opportunity to reconsider aggregation from a structural rather than purely operational perspective. In this sense, pseudosands may warrant a renaissance: not simply because they represent an overlooked soil fraction, but because they provide an unusually accessible window into the structure and functioning of aggregates themselves.

1.5 | Thesis outline

This thesis comprises three chapters of publications or manuscripts that delve deeper into pseudosands, from their potential distribution range and an explanation for it (Chapter 2), to their historical framing and a comparison of their structural and mechanical differences from sand (Chapter 3), up to a first characterization of their hydrological properties (Chapter 4).

In Chapter 2, I address where pseudosands are likely to occur and why. Yet, due to a lack in consistent terminology, I expanded the literature search to include water-stable aggregation via wet sieving. Through a multi-lingual literature review, the relationship between soil-forming factors and the global occurrence of water-stable aggregates is synthesized, narrowing down some geographic and pedogenic conditions under which pseudosands form. Additionally, this review proposes a standardized framework for identifying and classifying water-stable aggregation and pseudosands based on mechanical stability.

Chapter 3 develops the conceptual case that treating pseudosands as sand constitutes a significant and under-recognized source of uncertainty in tropical soil process understanding, and argues that pseudosands warrant formal recognition as a distinct soil texture class.

Finally, **Chapter 4** applies this understanding to soil hydrology: it derives the hydrological properties of pseudosands and provides empirical evidence for the central claims of Chapters 2 and 3, that is that treating pseudosands have own key soil functions that are not well represented by sand alone.

CHAPTER 2 |
A soil scientist's guide to pseudosands

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KEYWORDS soil structure, micro-aggregates, water-stable aggregates, soil forming factors, global distribution, Holdridge Life Zones, weathering and comminuting

HIGHLIGHTS

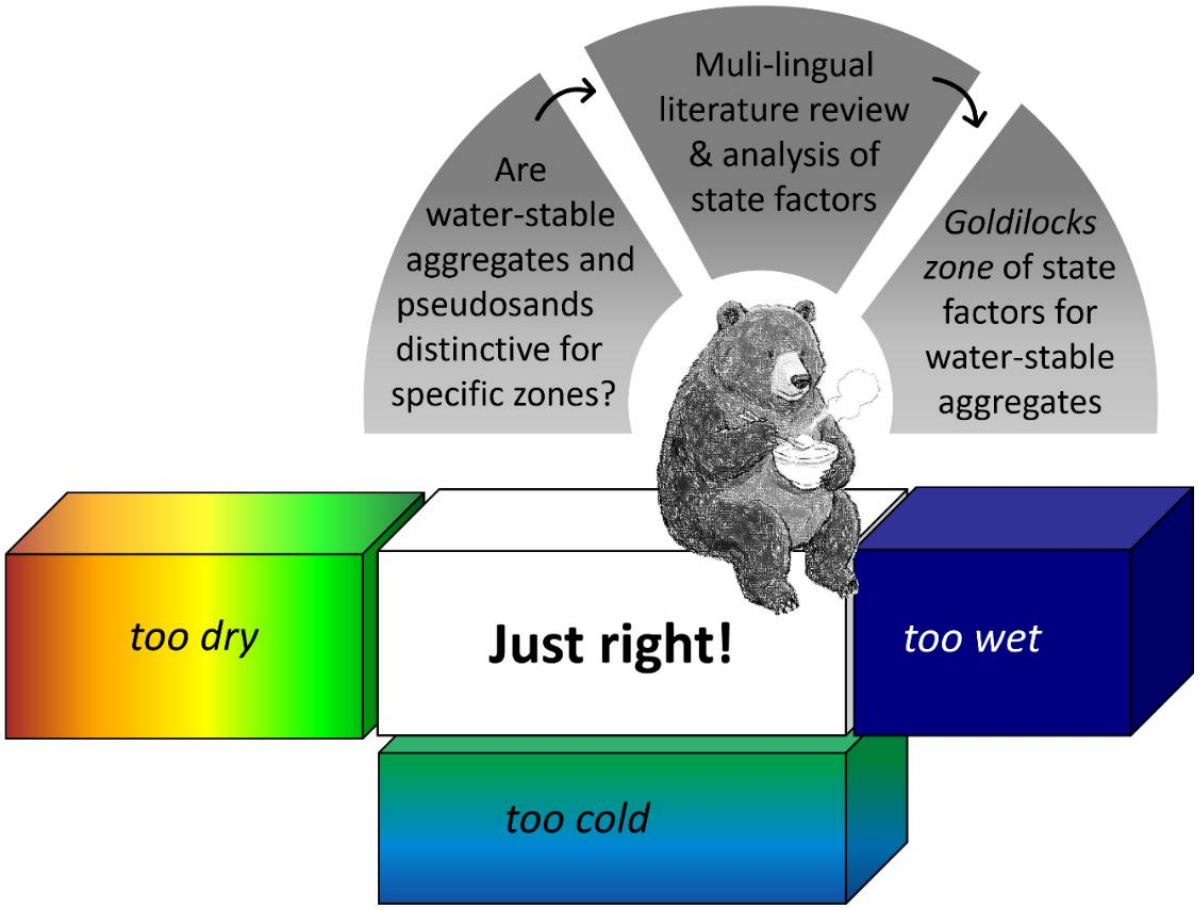
- Pseudosands lack systematic study due to inconsistent classification
- Goldilocks zone in (per-)humid tropical to cold temperate regions was identified
- Ferralsols and soils with clay-translocated horizons dominate body of literature
- Proposal for standardized protocol based on mechanical force and binding agents

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ABSTRACT

Pseudosands are extremely stable aggregates in soils known to science for at least since the mid-20th century. However, aside from being considered a tropical phenomenon, pseudosands remain inadequately described, classified and studied. Different names and diverging definitions led to an inconsistent terminology. This shortcoming must be addressed, as soil structure has a decisive influence on soil energy and elemental cycles and is largely determined by soil aggregates and single particles. A framework on how to identify and distinguish pseudosands from other water-stable aggregates (WSAs) is needed to enhance studying their properties in detail. Here, we synthesized the relation of state factors of soil formation to the global presence of WSAs through a literature review. The multi-lingual and multi-database approach resulted in largely distinct sets of publications with only minor overlap, complementing one another to build a more complete picture. Because mechanical stability is used as a proxy for identifying pseudosands, this review focused on studies that used wet sieving to separate soil aggregates. We identified a Goldilocks zone in humid and perhumid provinces, ranging from tropical to cold temperate zones, where almost all samples were located. Bedrock is a particularly relevant decisive factor for pseudosands development in weakly developed soils. In deeply weathered tropical soils, however, bedrock's influence on soil composition diminishes after geologically long periods of chemical weathering and physical comminuting. Ferralsols dominate the body of literature, additional to soils with clay-rich subsurface horizons formed through accumulation or translocation (like Acrisols, Lixisols, Luvisols, Nitisols). Additionally, we propose a framework to develop a standardized protocol for WSAs based on resistance to mechanical forces, to be able to standardize the determination of pseudosands and later be able to determine their specific internal and external properties. Different resistances will most likely be also related to binding and glueing agents. A thorough understanding of pseudosands will enhance our knowledge on critical soil processes and ultimately serve as a basis for studying less ephemeral structures in soils and to model the Earth system.

GRAPHICAL ABSTRACT



2.1 | INTRODUCTION

Soil science has always sought to better understand the structure of soils, i.e., the three-dimensional arrangement of soil particles into aggregates and the associated pore network (Garland et al., 2024; Schuylenborgh, 1947). Soil structure defines the architecture that controls the exchange of water, gases, and nutrients between the pedosphere and the rest of Earth systems (Vogel et al., 2022), as it determines whether a raindrop runs off, seeps into the ground, evaporates or if plants and other living organisms take that water up (Letey, 1991). Thus, soil structure - more so than soil texture - determines where and when oxidative, facultative, or anaerobic biogeochemical processes occur in the soil (Wunderling et al., 2024). However, very specific arrangements of particles, namely aggregates, are highly dynamic in space and time, making them difficult to study in disturbed soil samples. A single rain splash or re-arrange after a season of plant growth could be enough to break soil aggregates apart (Zhu et al., 2022). The

emergent properties of aggregates are not linearly reducible from particle level properties (Letey, 1991), which remains a big challenge for the upscaling of properties at the nano-scale to landscape processes at large-scales.

Due to the volatile nature and the opacity of soils, it has always been hard to account for the complex structure and heterogeneity of aggregates (Pereira et al., 2021). Therefore, to be characterized, soils are still disintegrated into their single, discrete textural units (sand, silt, and clay) according to standard laboratory protocols. Even if laboratory protocols would be changed to avoid the use of dispersing agents or mechanical destruction, still, most aggregates will simply disintegrate when exposed to much lower energy levels (Amézketa, 1999). Even quick exposure to water or root growth can disrupt most aggregates, making it difficult to conduct research on soil aggregates internal and external surfaces. Pseudosands are a notable exception: their unusually high stability allows them to withstand handling and analysis that would destroy most other aggregates, offering an opportunity to examine surface properties that standard laboratory protocols would otherwise obscure or destroy (Legout et al., 2005).

Pseudosands are aggregates in soils, which are uniquely and extremely persistent to water dispersion (Bremer & Sander, 2011; Lilienfein et al., 1999; Oades & Waters, 1991). This makes them less transient in nature and physically resilient enough to perform measurement without losing its core structural integrity (Kilian Salas et al., 2024). The perceived similarity to sand in the field has led to the name of pseudosand and to the pragmatic approach of assuming sand-like properties (Stoops & Buol, 1985; Vrdoljak & Sposito, 2002). For practical purposes, they are mostly totally disintegrated along with all other soil aggregates to determine soil texture, and the sand content is then empirically corrected for biogeochemical or hydrological soil modelling (Six et al., 2000). However, their actual physico-chemical properties differ substantially from those of “regular” sands (Kilian Salas et al., 2024), and adapting the sand content is not sufficient to really portrait their traits for hydrological and biological processes in soils (Nitzsche et al., 2008). Highly stable aggregates are ideal to start a deeper dive into specific internal and surface properties, as well as associated processes of soil aggregation. We propose the research on pseudosands as a first tool to start assessing the effects of aggregation across spatio-temporal scales and as a further blueprint for less stable aggregates, because pseudosands maintain their structural integrity under strong external forces beyond intense precipitation events for much longer than other kind of aggregates (Martinez & Souza, 2020). This is at the core of the ongoing debate on soil aggregation and the nature of soil structure,

seeking to understand soil architecture as a mediator of physical, chemical, and biological processes (Amelung et al., 2024; Vogel et al., 2022).

Pseudosands and water-stable aggregates (WSAs) are composed of smaller-sized particles cemented or glued together by a range of agents, forming sand-sized aggregates (Martinez & Souza, 2020; Totsche et al., 2018). Gluing agents comprise organic macromolecules of biotic origin, like proteins, polysaccharides, and extracellular polymeric substances (EPS), while cementing agents are inorganic mineral phases such as iron (Fe) or aluminum (Al) (hydr-) oxides, carbonates, and silicates (Totsche et al., 2018). Gluing and cementing agents can, in principle, confer high mechanical stability, which makes the distinction between pseudosands and other highly stable WSAs complex. Pseudosands typically fall within the group of WSAs, which are defined by their resistance to water-induced dispersion under varying energy inputs (Beare & Bruce, 1993). As the most stable class of WSAs, pseudosands are therefore also defined as opposing to water dispersible clay (Bartoli et al., 1991), which is determined by shaking soil samples in water for 16 h (Martinez & Souza, 2020). Pseudosands distinctive characteristics still need to be fully determined, both in terms of their internal and external structure, to unravel their contributions to ecosystem functioning and to enable upscaling (Kilian Salas et al., 2024). Reasons for missing concerted studies and many still-unknown properties are the lack of clear functional or methodological definitions and approaches to pseudosands and water-stable aggregation, together with a growing number of overlapping terms for pseudosands. This situation might also reflect a broader trend in (soil) science, where different disciplines often approach a similar phenomenon or process mostly through their own methodological and conceptual lenses, leading to fragmented terminology and limited comparability across studies and disciplines. In the context of studying water-stable aggregation, soil physics, soil chemistry, soil microbiology, soil (micro-)morphology, as well as hydrology, biogeochemistry, agronomy and geomorphology converge, yet, also result in a fragmented understanding of pseudosands as the most WSA.

WSAs form through interactions between particles and binding agents under dynamic chemical, biological, and physical conditions; all governed at varying intensities by climate, vegetation, time, parent material, and topography. Beyond standardizing pseudosand nomenclature, a clear classification of WSAs is urgently needed to examine variability within the spectrum of mechanical stability, and to assess whether all extremely stable WSA can be considered pseudosands based on their internal and external properties. However, given the lack of clear nomenclature, we focused on WSAs reported in the literature, interpreting their distribution

patterns through soil-forming factors to ultimately guide towards a clear classification system for WSAs, including pseudosands. Thus, our specific hypotheses are that (I) WSAs are a global phenomenon; and that (II) patterns in state factors of the soil locations reflect conditions and processes leading to the formation of water stable aggregates and pseudosands. To test these hypotheses, we performed a literature search considering publications that used wet sieving to separate aggregates from the soil matrix, focusing on the mechanical stability as an indicator of water-stable aggregation, as well as those explicitly named pseudosands. Finding all relevant literature posed challenges: lack of defined nomenclature for pseudosands has led to numerous undefined synonyms. To minimize language bias, we searched databases and articles in multiple languages in addition to English. This was particularly important because many descriptions of pseudosands and related features originate from research with still limited visibility in major international bibliographic databases, despite substantial local expertise and long-standing research institutions. We coupled a comprehensive literature review analyzing the relationship between soil-forming factors and the documentation of WSAs. Based on that, we propose a framework to design a stepwise protocol to study WSAs more rigorously and to help clarify terminology with respect to their stability, size, and/or binding agents.

2.2 | MATERIAL AND METHODS

2.2.1 | Literature search

For the literature scanning, we followed a predefined protocol for reviewing studies in multiple databases (Table 1). Relatively few contemporary studies explicitly differentiate pseudosands within WSAs, which complicates systematic review efforts. To address this limitation, we expanded our search parameters to include "soil microaggregates" as a general framing and "wet sieving" as the methodological descriptor for pseudosands in all selected databases. We included publications in multiple languages such as Spanish, Portuguese, and French additionally to English, to minimize language bias, expand the scope of available data and ensure a more comprehensive review (Becerril-García & Aguado-López, 2020). We also included publications that we had previously identified manually to capture specific studies missed by standard searches and to account for widely used synonyms of key terms (e.g. *microped*, *nodular structure, granular structure, pseudo-particle,* and even *pseudosand),* when it was not found in the protocol-derived searches, which are the manually-curated data points.

Table 1. *Search terms and databases used for this review. See S2-1 for more detailed information and Zenodo repository linked in the supplementary section and Table S2-1.*

Nr.	Review approach	Database	Search terms	Number of publications
A	Protocol-derived	SCOPUS	pseudo-sand* or pseudosand*	27
B			soil microaggregate and wet sieving	72
C		Web of Science - All Databases	pseudo-sand* or pseudosand*	19
D			soil microaggregate (all fields) and wet sieving (all fields)	69
E	Cross-lingual	SCIELO	pseudosand, pseudoareia	2
F			microagregados solo and in:("scl")	31
G		REDALYC	pseudo-arena OR pseudoarena OR pseudoareia OR pseudo-areia OR pseudosand OR pseudo-sand	9
H			microagregado + "suelo" + "tamizado húmedo" NOT hongos	10
I		African Journals Online (AJOL)	pseudosand	1
J			"water-stable aggregate" AND soil	20
K	Manually-curated	diverse	granular structures, nodular structures, pseudo-particles, pseudosand, (micro-)aggregate, …	30

The literature search was last revisited in July 2025. Publications were sorted and filtered with the following steps: (1) exclusion due to inaccessibility, either because publications were behind paywalls, or because much older publications could not be accessed; (2) exclusion of overlapping publications between databases to avoid repetitions (see Table 1, priority from top to bottom); (3) exclusion of papers related to civil engineering, basic geology, basic (organic) chemistry, and politics, to solely focus on publications that were in their nature related to soil science, based on reviewing the keywords indexed in the publications; (4) exclusion of publications without extractable geoinformation on sampling sites; and (5) ensuring spatial independence among studies that report from the same locations. For this last step, a buffer of 3-minutes at the equator was applied for all points, which is equivalent of 5.565 km, and in cases of overlap, only the sampling point with precisely reported coordinates (as opposed to

loosely described locations) was retained to account for minor coordinate discrepancies, where multiple such points existed of similar geoinformation quality, the one from the earliest publication was selected for further analysis. Coordinate extraction was facilitated by artificial intelligence (AI) to enhance the extraction of geographical information where needed (Wadoux, 2025), as most sampling sites before the 2000s lack precise geolocation (Figure S2-1B). ChatGPT was the selected AI tool, where coordinate approximation was enhanced when further details were missing or inferred when it was only broadly described (see further details in Supplementary Material). All the above-mentioned limitations, filters, and details have been made traceable within the metadata in the Zenodo repository linked in the supplementary section.

2.2.2 | Data analysis

Even if information on state factors was available in the publications, the different reporting methods and classification systems challenges a uniform classification. Therefore, open-access data sources were used to get information on state factors of soil formation (Table 2). For climate, which has the strongest impact on soil formation at the global scale (Certini & Scalenghe, 2023), we used the Holdridge Life Zones (HLZ) classification system rather than current climatic data, because soil formation occurs over extended periods and HLZ has also been shown to reflect soil-climate interactions well (Jungkunst et al., 2022). The HLZ is a global bioclimatic classification system that categorizes terrestrial ecosystems based on three climate variables: mean annual biotemperature, annual precipitation, and the ratio of potential evapotranspiration to precipitation. The database used classifies 38 HLZ in 8 tropical, 7 subtropical, 7 warm temperate, 6 cold temperate, 5 boreal, 4 subpolar, and 1 polar zone(s). Information on parent material was derived primarily from the Global Lithological Map (Hartmann & Moosdorf, 2012). Soil age is determinant (Huggett, 1998) but difficult to measure directly at the global scale, thus time was represented by depth to bedrock as a proxy for soil formation intensity over time, knowing that particularly climate is a covariate in the development of soil depth. Additionally, we used the extension of the Last Glacial Maximum (LGM) from approximately 18000 years before present (Ehlers et al., 2011), to identify soils that would have been reset or significantly disturbed by glacial processes. These processes within the glaciated area can be the interruption in pedogenic development due to ice cover, or soil rejuvenation resulting from the expansion phase of the glaciers. Vegetation type is highly correlated with climate globally. Land use, however, is too dynamic to be defined in detail (Amézketa, 1999), and was therefore omitted for this review. For topography, slope

determination proved to be impractical, as many papers before the 2000s lacked precise geolocation data necessary to distinguish landscape positions. However, the general positioning in the landscape could be derived from simple elevation data. We incorporated soil type to partially compensate for the fact that we did not include all soil-forming factors directly into our analysis, which represents the integrated outcome of the interaction of all state factors. For soil type, the FAO's Harmonized World Soil Database (HWSD, version 1.2) from 2006 was used (Fischer et al. 2008). This database is primarily based on the FAO-UNESCO Soil Map of the World and the FAO Revised Legend (FAO-90), with soil units subsequently harmonized into WRB Reference Soil Groups through cross-referencing (Fischer et al., 2008). To avoid potential overestimation of anthropogenically modified soils, HWSD version 1.2 was preferred over version 2.0 as it provides a more stable representation of baseline soil conditions, better aligned with long-term pedological characteristics rather than recent land-use alterations.

Table 2. *Databases and layers used to access spatial data on soil-forming-factors on a global scale, if not described in the reviewed literature.*

State factor	**Parameter**	**Layers**	**Resolution**	**Source**
Climate	Holdridge Life Zones	38 classes of HLZ	0.01° x 0.01° (degree)	Jungkunst et al. (2022)
Parent material	Bedrock	GLiM – Global Lithological Map	30" x 30" (seconds)	Hartmann & Moosdorf (2012)
Time	Depth to bedrock as proxy	SoilGrids by ISRIC	250 m	Hengl et al. (2017)
	Extent of Last Glacial Maximum (LGM)	Hall (2022)		Ehlers et al. (2011)
Topography	Elevation	Digital Elevation Models (DEM)	30" x 30" (seconds)	Fischer et al. (2008)
Soil type	WRB soil classification	FAO's Harmonized World Soil Database (HWSD), version 1.2	30" x 30" (seconds)	Fischer et al. (2008)

All data was analyzed using R/RStudio and QGIS, version 3.40 (Bratislava version, Tisler), running on Windows 10. All statistical analysis and plotting were done in R version 4.4.0 (64-bit), and RStudio, version 2024.09.1 (Cranberry Hibiscus Release). Geographical data handling and spatial data analysis was done using the packages *sf* (Pebesma, 2016), *raster* (Hijmans, 2010), *terra* (Hijmans et al., 2020), and *tidyverse* (Wickham, 2016) for data analysis. All visualizations and figures were done with *ggplot2* (Wickham et al., 2007).

2.3 | RESULTS

Distinct geographic clusters emerged for the cross-lingual approach for determined regions. Spanish, Portuguese, and French sources concentrated in the regions where each language dominates scientific writing: French in Francophone countries, Portuguese in Brazil, and Spanish across Latin America more broadly. In the protocol-derived approach, regions such as Southern Asia and Central Africa as well as islands like Madagascar, Hawaii, or Cuba were underrepresented. However, this underrepresentation was balanced out by the manually-curated literature search which yielded data points in those regions as well. All review approaches together resulted in a more extensive and complete compilation of data points, that yielded also clear patterns in some state factors.

2.3.1 | Climate

The literature search strategy revealed that WSAs including pseudosands occurred across distinctive climatic zones that go beyond the (sub-)tropics, but not colder than the (cold) temperate zone (Figure 1). Most sampling sites, across all search approaches, were reported from subtropical and tropical regions (Figure 2A). Subtropical regions account for 24.2% of global terrestrial area, but roughly twice as much, 148 out of 289 data points (51.2%) studies originating from these regions. Similarly, 21.8% of data points (63 out of 289) stemmed from tropical regions but they cover only 12.3% of terrestrial surfaces. Together, warm and cold temperate regions cover approximately 23.4% of global surfaces and accounted for 26.0% of data points (75 out of 289), a proportion close to their global distribution.

Regarding humidity provinces, the dataset was strongly skewed towards humid and perhumid conditions: 273 out of 289 data points (94.5%) were reported from perhumid and humid humidity provinces spanning tropical to cold temperate regions (Figure 2B), which collectivelycover only 34.5% of global terrestrial surfaces (Table S2-2). Within subtropical regions, the perhumid province was the most dominant, representing 87.2% of subtropical data

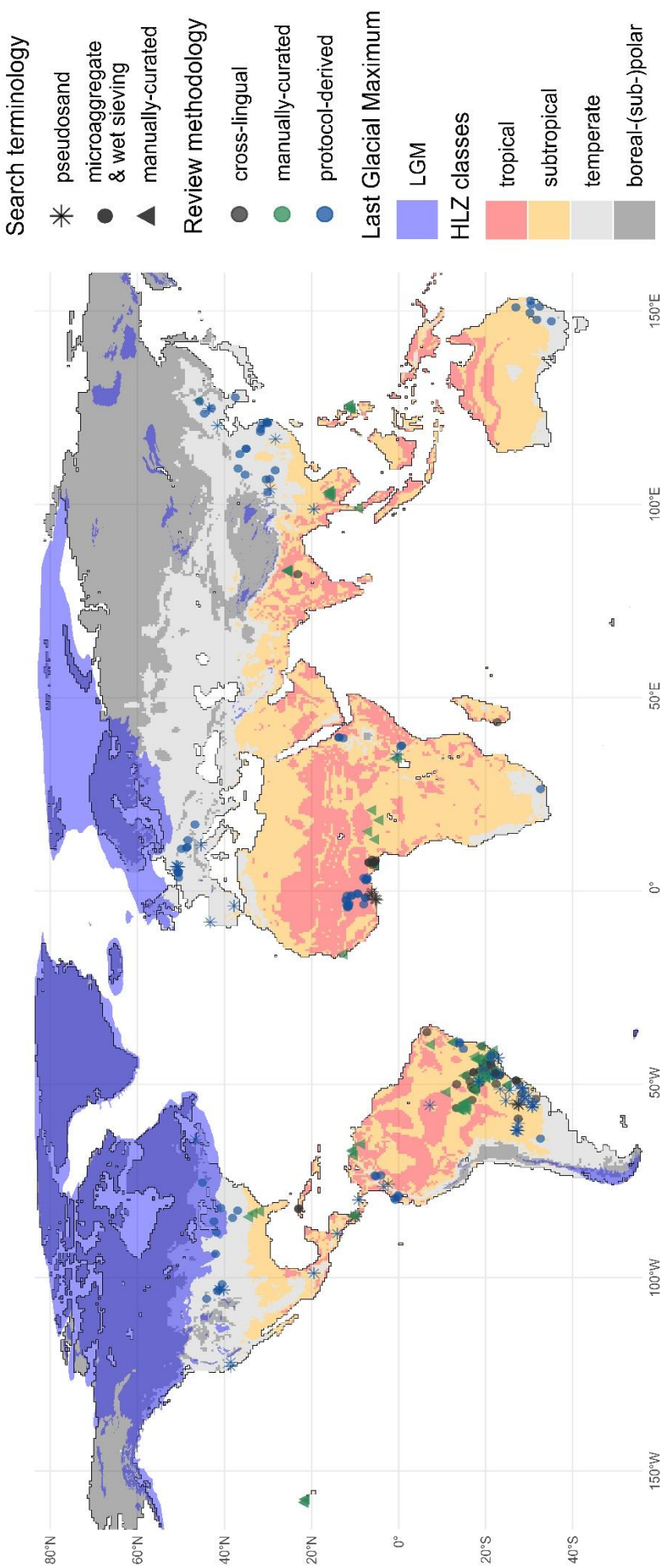


Figure 1. *Distribution of the 289 data points, extracted from the reviewed literature across review approaches for WSAs and pseudosands for different databases. Background data was extracted from Jungkunst et al. (2022) for HLZ latitudinal classes and Hall (2022) for extent of LGM from the Pleistocene (in blue).*

points (129 out of 148) despite covering only 33.8% of subtropical surfaces, and the humid province accounted for a further 8.8% of data points (13 out of 148), corresponding to 18.7% of subtropical surfaces (Figure S2-2 C,D). Within tropical regions, only perhumid and humid provinces were represented. The humid province dominated, accounting for 73.0% of tropical data points (46 out of 63), despite covering only 28.7% of tropical surfaces. The perhumid province accounted for the remaining 27.0% of tropical data points, corresponding to 22.4% of tropical surfaces. In temperate regions, the perhumid province was again the most dominant. For warm temperate regions, the perhumid province accounted for 59.5% of data points (22 out of 37) while covering 24.7% of warm temperate surfaces. For cold temperate regions, the perhumid province accounted for 68.4% of data points (26 out of 38), corresponding to 38.4% of cold temperate surfaces. Humid provinces followed in both temperate regions, representing 27.0% of warm temperate data points (10 out of 37; 29.0% of global surfaces) and 23.7% of cold temperate data points (9 out of 38; 33.5% of global surfaces).

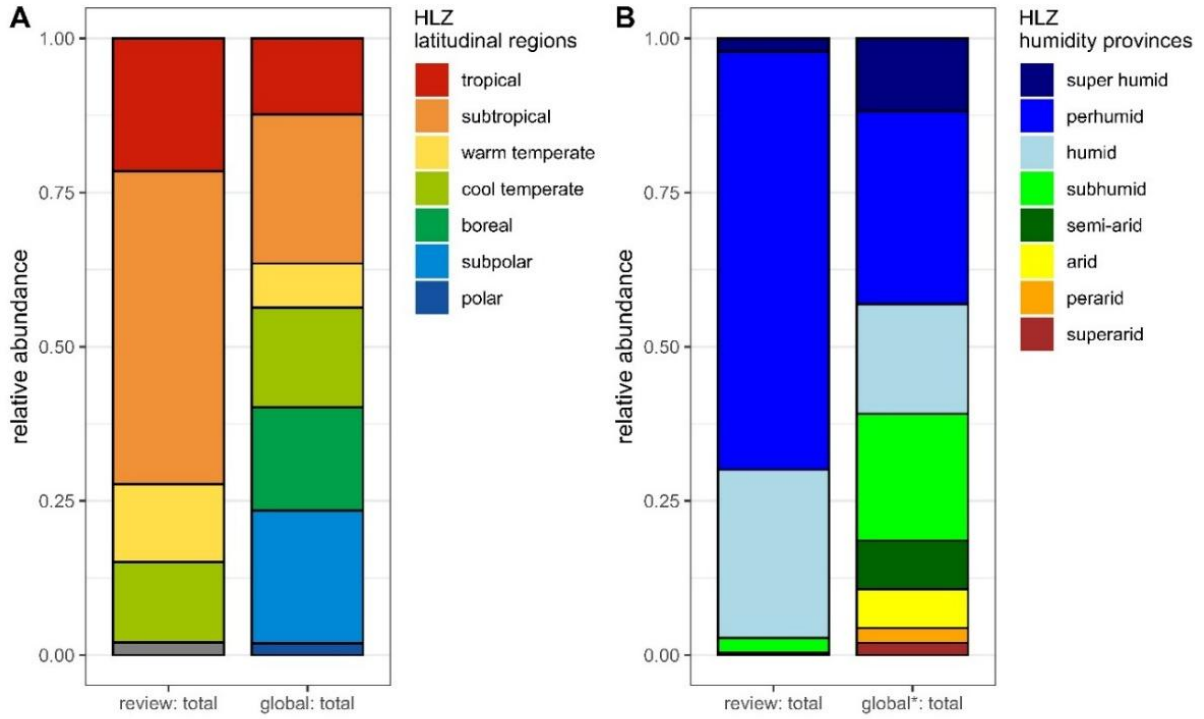


Figure 2. *Relative abundance of data points from the reviewed literature compared to their global distribution within (A) HLZ latitudinal categories and (B) across humidity provinces. Global area that only includes data from latitudinal ranges from tropical to cold temperate are marked with star (*).*

2.3.2 | Bedrock

Parent material analysis revealed that 236 out of 289 data points (81.7%) were located on either sedimentary bedrock or metamorphic rocks: while sedimentary bedrock accounted for 59.8% of data points (173 out of 289), compared to a global surface extent of 69.3%, metamorphic rocks accounted for 21.8 % of data points (63 out of 289), slightly above their global extent of 33.5% (Figure 3, Table S2-3). Within sedimentary bedrock, unconsolidated sediments were the most prevalent parent material type, accounting for 41.6% of sedimentary data points (72 out of 173) and 23.6% of global sedimentary bedrock surfaces. Siliciclastic sedimentary rocks made the second greatest group in sedimentary bedrock with 35.8% of data points (62 out of 173), and 27.0% of global surfaces within sedimentary bedrocks (Figure S2-3 C, Figure S2-3 D,E). In contrast, mixed sedimentary rocks, which cover a comparable global surface area of 27.2%, were notably underrepresented, accounting for only 15.0% of sedimentary rock data points (26 out of 173). Carbonate sedimentary rocks were the smallest subgroup, contributing 7.5% of sedimentary data points (13 out of 173) against a global extent of 11.8% within sedimentary bedrock. Magmatic vulcanite and plutonite rocks each cover around 8% of global surfaces, yet differed substantially in their representation: magmatic vulcanite rocks accounted for 13.1% of total data points (38 out of 289), while magmatic plutonite rocks accounted for only 3.6% (10 out of 289). Within magmatic vulcanite rocks, basic volcanic rocks were by far the dominant parent material type, comprising 57.9% of vulcanite data points (22 out of 38), consistent with their dominant surface share of 52.3% within this group. However, surprisingly, pyroclastic rocks represented an important minor subgroup, covering only 7.95% of vulcanite surfaces yet accounting for 18% of data points (7 out of 38) within magmatic vulcanite rocks. Intermediate volcanic rocks similarly contributed 18% of data points (7 out of 38), while covering a considerably larger relative surface area of 25.8% within magmatic vulcanite rocks. Within magmatic plutonite rocks, all recorded data points fell exclusively on acidic plutonite rocks, which are also the largest subgroup within this parent material class, accounting for 82.0% of plutonite surfaces. Finally, four data points corresponded to locations classified as having no bedrock data in the source maps, three from the manually-curated approach and one from the cross-lingual approach (Figure S2-3 A, B).

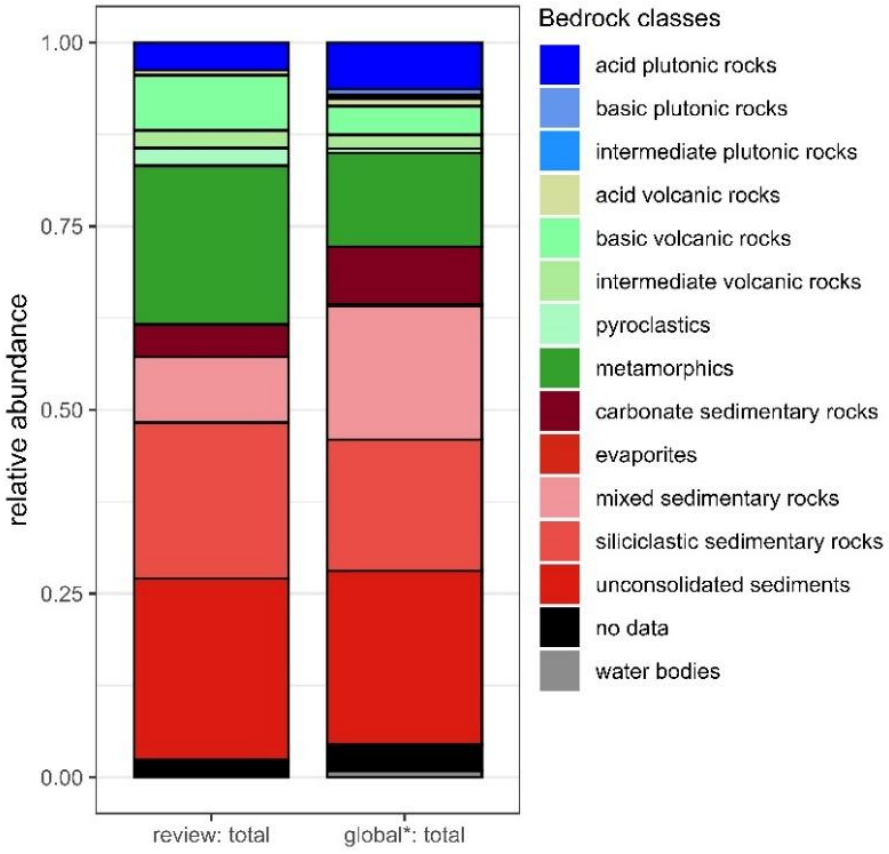


Figure 3. *Relative abundance of data points from the reviewed literature compared to their global distribution for HLZ latitudinal ranges from tropical to cold temperate (marked with star *). Source is the Global Lithological Map (GLiM) by Hartmann & Moosdorf (2012). Some surfaces are too small to be visible in the global barplot, but they are present.*

2.3.3 | Proxies for time and topography

Time is the representation of the duration over which pedogenic processes have been acting and is inherently difficult to determine directly. Therefore, we used the depth to bedrock as a proxy for weathering intensity over time. To facilitate analysis, depths were grouped into ranges. The resulting distribution of depth-to-bedrock ranges was broadly similar between data points and the global analysis, with depths between 10 and 50 m being the most common in both cases (Figure S2-4 A, B). Analysis of the extent of the Last Glacial Maximum (LGM) ice shield indicated that the vast majority of sampling points were located outside the formerly glaciated area, suggesting soil weathering since before the LGM. Only 6 data points fell within the glacial extent, all of which recorded having either carbonate or siliciclastic sedimentary rocks as bedrock.

For topography, elevation above sea level (a.s.l.) was used as a proxy for landscape position and potential for lateral water movement and erosional processes. Data points located between 500 and 1000 m a.s.l. were more frequent in the review relative to their global distribution, while data points between 1500 and 4000 m a.s.l. were sparsely represented (Figure S2-4 C, D).

2.3.4 | WRB soil types

WSAs were reported for 24 out of 36 major WRB soil types (Figure 4). Ferralsols exhibited the highest prevalence of water-stable aggregation across all databases, representing nearly 30% of sampled sites (88 out of 289 points, Figure S2-5 A,B), despite comprising only approximately 4.4% of the global terrestrial surface. The second-most prevalent group were soils with subsurface clay accumulation (argic horizons), representing 26.0% of total data points (75 out of 289 points). These soils with argic horizons are composed of Acrisols (27 out of 75), Lixisols (19 out of 75), Luvisols (16 out of 75), Nitisols (9 out of 75), and Alisols (4 out of 75), which together represented around 12.3% of terrestrial surfaces (Table S2-4). Cambisols comprised 7.5% of terrestrial surfaces and 12.4 % of the data points, and were especially prominent among soil types within the protocol-derived approach (22 out of 35 data points). Despite comprising approximately 27.3% of the global terrestrial surfaces, only 10.0% of data points were derived from soils of an early developmental stages (29 out of 289 data points), which included Leptosols (18 out of 29 points), Arenosols (7 out of 29 points), Vertisols (3 out of 29 points), and Regosols (1 out of 29 points). The remaining 85 out of 289 data points distribute across 12 soil types. Some have very little global surfaces like Plinthosols with 0.7%, Andosols with 0.7%, Planosols with 0.6% and Anthrosols with 0.4%, with 3 to 5 data points each. Contrary, Gleysols and Podzols have greater global presence with around 6.2 to 6.6%, yet, only 7 and 2 data points were found here, respectively. Additional hydromorphic soil types are Fluvisols with a global distribution of 2.7% and 2.8% of data points (8 out of 289). Other soil types had relatively greater global distribution with greater number of data points, like Phaeozems with 2.0% global distributions and 6.2% of data points (18 out of 289 data points) and Kastanozems with 2.7% global distributions and 1.7% of data points (5 out of 289 data points) (Table S2-4).

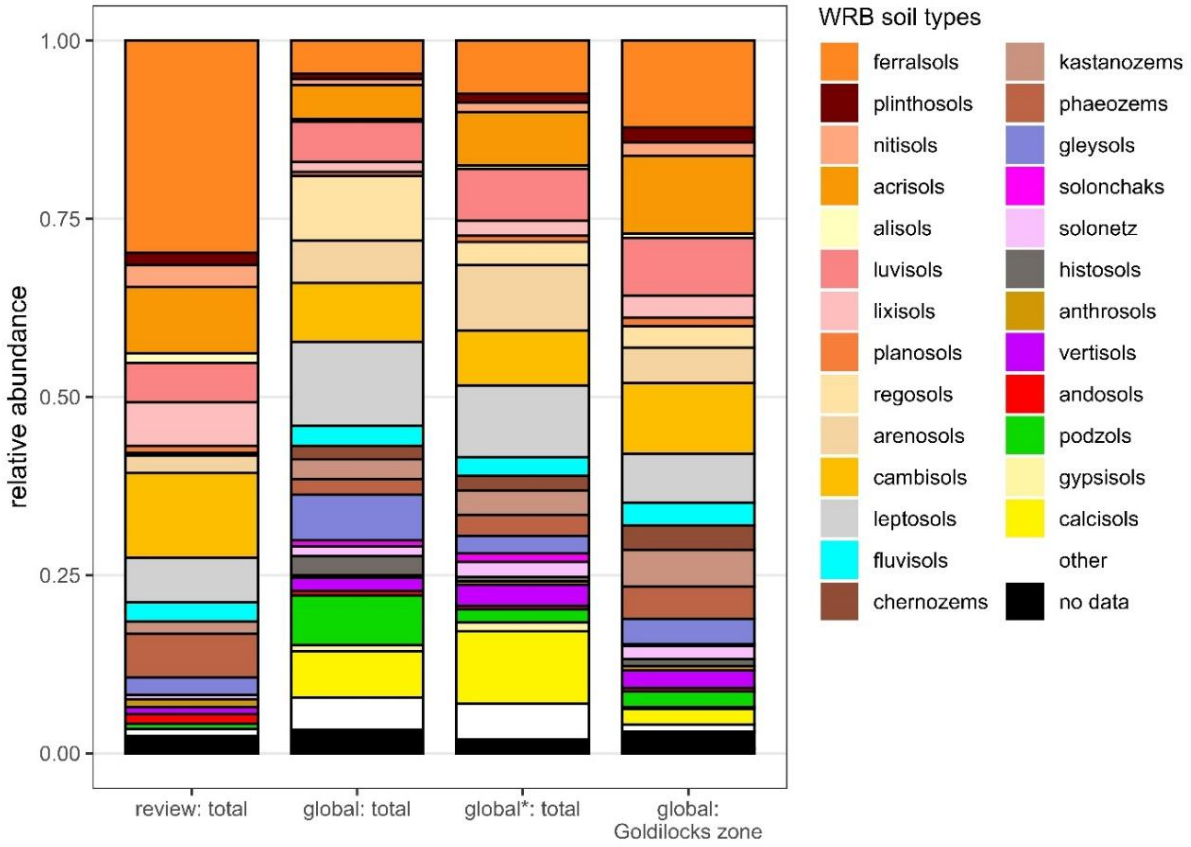


Figure 4. *Relative abundance of WRB soil types from this review compared to global distribution, as well as soil types in relation to their HLZ latitudinal region from tropical to cool temperate (marked with star*), and the Goldilocks zone identified in this review in section 3.1: humid and perhumid provinces within tropical to cool temperate latitudes.*

2.4 | DISCUSSION

Pseudosands are the most stable form of WSAs, yet no consensus exists on how to define, identify, or classify them. An accepted definition is nevertheless urgently needed to target their internal and external properties within the soil matrix, to deepen the understanding of aggregation processes that appear to be gaining dynamic relevance, and to upscale their effects from the landscape to the Earth system (Ebrahimi & Or, 2018; Garland et al., 2024). This review sets out to identify the state factors governing the formation of WSAs in order to draw inferences on the formation of pseudosands, and to trace their expression across major WRB soil classes. The patterns found guided our proposal for a protocol approach to determining WSAs and pseudosands therein.

2.4.1 | The rise of aggregation linked to state factors

What emerged was a coherent picture: WSAs are spread across a broad range of latitudes but remain absent in climates colder than the temperate zone. Apparently, their occurrence is governed more by moisture regime than by temperature. Neither persistently (too) wet nor persistently (too) dry conditions appear sufficient, but perhumid to humid conditions spanning from the tropics to the temperate zone could be a Goldilocks zone for WSAs (*sensu* Kasting et al., 1993). Therefore, the Goldilocks zone that is *just right* for WSA is characterized by a recurring alternation between wetting and drying with a tendency towards more hydration. This climatic condition appears to set a boundary condition for the formation of WSAs. Cementing agents are likely central to this stability (Alekseeva et al., 2009; Jozefaciuk & Czachor, 2014), and the evidence here suggests that aggregate stabilization increases with weathering time and intensity, yet, their precise identity remains unresolved and represents the logical next step for future work.

2.4.2 | Climate

By definition, WSAs must exhibit a certain degree of resistance to dispersion in water (de Oliveira et al., 2005). The fact that WSAs were almost exclusively found in humid and perhumid provinces reinforces our assumption that global geographical patterns will eventually pave the road to a widely acceptable protocol on how to differentiate pseudosands within WSAs. Under dry conditions, WSAs may only hardly form or, in return, aggregates are just not resistant to water. Under too wet conditions, resistance may be futile or the lack of changing conditions that are needed for the initial formation of aggregates and availability of cementing agents, leads to an absence of these humidity provinces in our review. Fluctuating redox conditions, imposed by fluctuating water conditions, are known to solve and resolve Fe, manganese (Mn), cobalt (Co), nickel (Ni), and copper (Cu), all of which can act as cementing agents for aggregates (Totsche et al., 2018).

As soils dry and aerate, oxidizing conditions prevail: exemplarily, Fe^{2+} is oxidized to Fe^{3+} and precipitates initially as ferrihydrite, and with increasing time and crystallization to goethite or hematite (Cudennec & Lecerf, 2006). As soils rewet, anaerobic conditions develop and Fe^{3+} is reduced to its soluble form Fe^{2+}, dissolving Fe oxyhydroxide cements and leaving aggregates weakened and susceptible to dispersion (Ginn et al., 2017). Under prolonged and intense weathering, progressive desilication depletes the profile of Si, and Al (oxy-)hydroxides become the dominant residual phase, in forms of gibbsite (Kirsten et al., 2021). Critically, these more

weathered minerals are not merely passive weathering products - they are active cementing agents (Lockhart et al., 2024): with advancing weathering, minerals develop higher specific surface areas (Fisher et al., 2023), increased surface roughness (Anbeek, 1993), and decline in permanent charge (Chorover et al., 2004). The shift from 2:1 phyllosilicates toward 1:1 clay minerals and oxyhydroxides additionally raises the point of zero charge of clay minerals (Konta, 2009), increasing electrostatic complementarity between positively charged oxyhydroxide surfaces and negatively charged clay particles and organic matter. Compared to less weathered phyllosilicates, whose reactivity is dominated by permanent charge, this shift towards variable, pH-dependent charge increases the strength of these bonding mechanisms (Kleber et al., 2007), which include ligand exchange capacity and inner-sphere complex formation. Unlike swelling 2:1 clay minerals (e.g. smectite or vermiculite), these more weathered minerals are additionally non-expansive and resistant to deformation upon wetting, resulting in inherently less unstable aggregate bonds (Dixon, 1991; Madsen & Müller-Vonmoos, 1989). However, this stabilization is also inherently dynamic and redox-dependent: In permanently waterlogged soils, continuously reducing conditions even prevent metal oxides from ever reprecipitating, leaving soils depleted of these redoximorphic cementing agents (Dorau et al., 2020). Under wetter condition like the superhumid sites these dryer periods may be missing or generally too short so single particles are not cemented during drying conditions – at least apparently it can be both too wet and too dry for WSAs to form. Thus, under continuously wet or dry conditions, aggregate formation may be slow to absent, the resulting aggregates may not be resistant to dispersion in water and fast destruction of very volatile aggregates.

The fundamental requirement for chemical weathering and aggregation processes is the presence of water, which keeps reactants in solution and enables both physical and chemical processes to happen. During drying periods dissolved reactants can precipitate around and between single soil grains which eventually also leads to physical aggregation. Through dissolution processes, chemical rock and mineral weathering are attributed to drying-wetting cycles, and also biological processes like mineralization of organic matter (Rabbi et al., 2020). Furthermore, drying and rewetting within a given chemical environment (e.g., Fe-rich or calcareous parent rock) impact composition, availability and properties of cementing agents and physical reaggregation of single particles within the soil matrix (Bartoli et al., 1992). Retreating water menisci in pores guide the redistribution of particles toward points of contact, pulling them closer together and creating bonds between particles that aggregate them (Dexter, 1988; Seiphoori et al., 2020). Simultaneously, compression of air in pore space during wetting

events causes physical fragmentation (Korenkova & Urik, 2018; Zaher et al., 2005). Beside the presence of dry-wet cycles, also the duration of these appear to have great effect on the intensity of the aggregate breakdown or aggregate stabilization (Liu et al., 2024; Nsabimana et al., 2026), which range from daily variable water balances to seasonal extremes. Therefore, over many repeated cycles, this selective process acts as a natural filter: less stable aggregates are progressively dismantled, while the most resistant ones are maintained and further reinforced (Hamza et al., 2025; C.-S. Tang et al., 2023).

Most data points were recorded for the subtopics and tropics, followed by a smaller number of data points from warm and cold temperate zones. Boreal, subpolar, and polar regions were entirely absent from the dataset. In warm and cold temperate soils, aggregation has been best described by the highly cited hierarchical aggregate model of Oades & Waters (1991). This model postulates that different glueing agents act sequentially at different scales of aggregation according to the organic binding agents involved and together with sand-, silt-, and clay-sized particles form macroaggregates (Rabbi et al., 2020; Totsche et al., 2018). As organic residues within these macroaggregates are gradually decomposed by microorganisms (Wilpiszeski et al., 2019), the decomposing material becomes increasingly encapsulated by minerals and microbial polysaccharides, forming microaggregates within macroaggregates (Fernández-Ugalde et al., 2013). Upon disruption of the macroaggregate, driven by the degradation of root exudates and fungal hyphae, these newly formed microaggregates are released and persist as more stable units. Water-stable aggregation in temperate soils is therefore dependent on the continuous input and turnover of organic matter, and interact with cycles of drying-rewetting and/or thawing-freezing (Denef et al., 2001). Because organic matter is potentially soluble, subject to microbial decomposition, and exhibits faster turnover rates than mineral cements, aggregate formation and breakdown in these systems is inherently more dynamic. Stability is consequently more transient than in mineralogically cemented tropical and subtropical soils (Kirsten et al., 2021), and is closely coupled to vegetation cover and the activity of the soil microbiome. This sensitivity to organic matter inputs and, in turn, the stabilization of organic matter by occlusion within aggregates explains why a substantial body of research in temperate soils has focused on the effects of fertilizer and organic amendment applications on aggregate formation and stability (e.g. Al-Kaisi et al., 2014; Ponyane et al., 2025; Sonsri & Watanabe, 2023). The agronomic relevance of this relationship has prompted the development of dedicated composite metrics, like the Aggregate-size Stability distribution Index (SAI, Márquez et al., 2004), the Aggregate Stability Index (ASI, Niewczas & Witkowska-Walczak, 2005), the Whole

Soil Stability Index (WSSI, Nichols & Toro, 2011), or the Normalized Stability Index (NSI, Huisz et al., 2009), designed to quantify the capacity of a soil to form and retain more stable aggregates in contrast to very volatile aggregates, and to track responses to management-induced changes in organic matter inputs affecting soil structure. In boreal and subpolar regions, research on aggregate formation is not absent (e.g. Digernes et al., 2025), yet our search approach yielded no results for these climate zones. This may reflect potentially counteracting effects of freeze-thaw cycles (Wang et al., 2012) and organic matter interactions on aggregate formation and their general stability (Gajewski, 2025). Their absence from the presented review therefore likely reflects not only sampling bias but may also point to a biogeographic boundary in the occurrence of water-stable aggregation: a transition from aggregates whose stability is governed by mineralogical comminuted and weathered due to exposure to drying-wetting cycles, to those whose stability is determined primarily by dynamics in organic matter.

2.4.3 | Bedrock and time

Parent material exerts a comparatively stronger control on soil chemical composition and mineralogy in younger, less intensely weathered soils, where the bedrock remains closer to the soil surface (Zhang et al., 2024). Primary minerals, as well as early secondary phases such as expanding 2:1 phyllosilicates, still persist here and play a proportionally greater role in exerting bonding or fracturing energy affecting soil architecture than stronger and longer weathered soils (Babechuk et al., 2014; Nesbitt & Wilson, 1992). In many temperate and high-latitude regions, glacial activity has repeatedly rejuvenated soils by exposing fresh parent material, sustaining this mineralogical influence across pedogenic timescales (Temme et al., 2016). Soils are similarly rejuvenated through the deposition of aeolian sediments (e.g., loess) or via solifluction. In some young volcanic soils, parent material such as ashes and pyroclastic rocks may also give rise to short-range-order (SRO) minerals such as allophane and imogolite, whose high specific surface area, variable surface charge, and strong affinity for organic matter promote aggregate stabilization through organo-mineral associations (Chittamart et al., 2024; Fujii et al., 2025). Pyroclastic substrates are typically young and would not be expected to have undergone extensive weathering, but they have high content of Fe (hydr)oxides, which is consistent with current understanding of aggregate formation through dynamic redox conditions (Abayneh et al., 2006). It is still notable that pyroclastic rocks were the only bedrock type among four with less than 1% global land cover, alongside evaporites, basic plutonic rocks, and intermediate plutonic rocks, for which data points could be derived in this study, suggesting that their unique mineralogical properties may be reflected in measurable aggregate stability

signals despite their limited global extent and geologically relatively young age. For soils developed from carbonate-rich sedimentary deposits or unconsolidated aeolian materials such as loess, inherited carbonates contribute to aggregate stabilization by promoting particle flocculation and acting as cementing agents between mineral particles and organic matter (Pihlap et al., 2021).

As weathering advances, the mineralogical and geochemical signature of the bedrock becomes progressively diluted, reducing the direct influence of parent material on soil architecture (Zehetner et al., 2024) and on the formation of WSAs (Aehnelt & Totsche, 2025). Consequently, bedrock has no or only little influence on WSA in regions with intense and prolonged weathering like the tropics and subtropics - here other mechanisms are leading to the formation of WSAs. As the final stage of these prolonged and intense weathering, deeply weathered tropical and subtropical soils accumulate Fe and Al (hydr-)oxides (e.g., goethite ($FeO(OH)$), hematite (Fe_2O_3), gibbsite ($Al(OH)_3$)), alongside low-activity 1:1 clays such as kaolinite and halloysite (Pessoa et al., 2024; West et al., 2004; Huang et al., 2016; Kirsten et al., 2021)), which together constitute the dominant mineral binding agents responsible for the aggregate stability characteristic of highly weathered tropical soils (Bartoli et al., 1992; Pessoa & Libardi, 2022; Schaefer et al., 2008; Vrdoljak & Sposito, 2002).

But we need to acknowledge that it is a simplification to differentiate (sub-)tropical soil from temperate soils by saying the latter are much younger. Soils that devolved beyond the direct or indirect (e.g. aeolian deposition of loess) influence of glaciation during the Pleistocene had time to develop undisturbed on the landscape, and pedogenic structures from that period found today have proven to be sufficiently resistant to resist also present-day alterations (Da Costa et al., 2015; Van Wambeke, 1992). Even soils that developed on recently formed or sedimented parent material were rejuvenated and, in many cases, repeatedly, like in the vicinity of volcano eruptions. However, for non-volcanic and non-fluviatile soils of the (sub-)tropics contemporary soil characteristics cannot be fully understood without considering their long pedogenic history (Mohr et al., 1972).

2.4.4 | Erosivity and topography

Besides the small-scale comminuting and weathering of aggregates, WSAs have also been discussed at the landscape-level of being the result of erosivity and sediment accumulation processes (Barthès & Roose, 2002; Ding & Zhang, 2016; Nciizah & Wakindiki, 2015). The erosive potential of rainfall is governed by the physical properties of precipitation, like

including raindrop size, number of drops per unit time, and fall velocity — which together determine the kinetic energy delivered to the soil surface (Farres, 1987; Fedor, 1992). Slope and elevation further modulate this energy by controlling the velocity and volume of surface runoff and influencing precipitation patterns (Bryan, 2000). Consequently, only those aggregates that withstand erosivity due to precipitation or transportation, are aggregates that can be accounted for (Fedor, 1992). Notably, the present dataset shows that most samples were in the 500–1000 m altitude range, whilst mountain regions above 1500 m a.s.l. were underrepresented. Assessing erosivity and accumulation effects on WSAs, however, requires precise knowledge of a sample's position within the landscape. To improve geolocation coverage across the included publications, we used AI-assisted approximation where coordinates were not explicitly reported in the reviewed publications. This approach necessarily trades off precision: it improves spatial coverage but limits our ability to pinpoint exact sampling locations within the landscape. We therefore refrain from drawing firm conclusions about erosivity patterns based on these approximated coordinates. It must also be noted that vegetation cover plays a critical role in mediating these erosive processes (Tang et al., 2021): vegetation intercepts and attenuates the kinetic energy of heavy precipitation events before they reach the soil surface, thereby protecting aggregate structure from disruption. Erosion and sediment accumulation processes are therefore closely linked to vegetation cover, and are likely enhanced where deforestation or loss of plant cover exposes bare soil to direct rainfall impact (Flores et al., 2020). Taken together, these factors mean that any inference about erosivity drawn from our dataset remains necessarily limited.

2.4.5 | Soil Type

All of the state factors discussed above ultimately converge in the single pedon development that can be classified in soil types as the cumulative expression of all state factors. In this sense, soil classification represents not merely a taxonomic reference but a proxy for the integrated pedogenic history of a site. The majority of data points in the present review derive from old and deeply weathered soils, like Ferralsols, reflecting the prominence of these soil types across regions with long history of intense weathering within the Goldilocks zone. Additionally, also Acrisols were predominant, which also reflect a long weathering history and a mineralogy dominated by stable Fe and Al oxides, further distinguished by a well-developed clay accumulation horizon. Given the illuvial translocation of clay into the B horizon, it is therefore less surprising that pseudosands have been proposed as a characteristic feature of A and/or B horizons (Holthusen et al., 2017; Martinez & Souza, 2020; Schaefer, 2001), rather than of the

underlying, largely unweathered C horizon (Aehnelt & Totsche, 2025). This pattern is corroborated more broadly by the second-most prevalent group in the dataset: soils with argic horizons, which despite their mineralogical and geographic diversity share the defining feature of subsurface clay enrichment. That such soils are disproportionately associated with WSA occurrence suggests that clay illuviation and aggregate stability are not coincidental, but may reflect a common underlying mechanism under high variability in water balances. This interpretation is, however, constrained by a critical limitation in sampling depth (Yost & Hartemink, 2020): the vast majority of studies sample only surface horizons, with little representation of deeper soil layers, which are precisely those in which clay accumulation, mineral cementation, and aggregate preservation are expected to be most pronounced. Deeper sampling strategies will therefore be essential to fully resolve the relationship between subsoil pedogenesis and pseudosands.

Pseudosands are subject to all sorts of physical and chemical energy during soils formation across the globe. Therefore, they better are resistant to these forces, otherwise they would be comminuted or weathered over geological time scales. In a perpetual cycle, the more resistant aggregates will accumulate, less resistant aggregates will break apart, and new ones will form. The likelihood that more resistant aggregates evolve therefore increases with progress of time and intensity of weathering, which would mean that after the deconstruction of the parent material at the onset of soil formation, the soil reorganizes in much more mature stages partially in WSAs.

2.4.6 | Biases to overcome

None of the review methods revealed a complete picture but they proved to be complementary rather than leading to similar results. This suggests that our current understanding of where WSAs occur and what characterizes them, remains incomplete. Each search approach contributed with complementary information rather than duplicating existing findings, verifying our hypothesis and mechanisms leading to WSA. In temperate (both warm and cold) regions, sampling sites were detected almost exclusively using the protocol-derived approach. Overall, this approach overrepresented warm temperate regions relative to their global distribution, reflecting a greater persisting structural bias: the greater availability of research funding, infrastructure accessibility, and English-language scientific output within temperate regions and the Global North (Turba et al., 2026). In many countries of the Global South, English is not the primary language of scientific communication and great effort has to be made

to overcome language hurdles as well as paywalls to be able to publish in scientific journals. As a result, scientific writing and much of the available documentation are still predominantly produced in Spanish, Portuguese, and French across many tropical and subtropical nations, besides English. Therefore, while we attempted to mitigate language bias, this approach may have introduced a geographical bias too. Yet, the extent remains difficult to fully quantify or offset.

The multi-database, multi-language approach revealed that WSAs have been documented across diverse climatic zones. Our findings challenge the prevailing assumption that pseudosands are predominantly or exclusively a tropical phenomenon of deeply weathered soils (Lilienfein et al., 1999; Martinez & Souza, 2020), instead, they are the result of dynamic water balances in soils. However, advancing our understanding faces a fundamental obstacle: the absence of a standardized nomenclature and classification system for WSAs, into which pseudosands are included as the most stable ones. The bewildering array of terms so far used interchangeably or with subtle, unstated distinctions across research disciplines actively hampers comparative studies and difficult mechanistic insights on the pathways to formation and processes leading to their extreme stability. This terminological fragmentation is compounded by a dual, partially contradicting, problem in data coverage. First, despite deliberately incorporating regional databases and non-English literature, tropical regions are potentially under-sampled relative to their pedological diversity (Cherubin et al., 2025; Powers et al., 2011). This gap reflects logistical and infrastructural challenges: many tropical field sites are difficult to access due to limited road networks or remote locations, as well as general research costs (Murrins Misiukas et al., 2021). Second, and paradoxically, non-tropical regions are potentially underrepresented, but for a different reason: Pseudosands were first reported for the tropics (Martinez & Souza, 2020), where they are expected to be most prevalent. Thus, restricting attention to these regions is likely too narrow and researchers rarely investigate in depth their presence and characteristics outside of these expected regions. The absence of data from non-tropical areas does not necessarily reflect the absence of aggregates but rather the absence of research attention. Together, these dual coverage problems mean that our current understanding of WSA distribution is incomplete across the entire spectrum of state factors but was a clear improvement in data coverage.

2.4.7 | Grounding a framework to design a protocol

A recurring challenge in aggregate research is the absence of standardized definitions and measurement protocols, which fundamentally limits the comparability of findings across studies. As Bartoli et al. (2016) noted, researchers continue to adopt a wide range of approaches, making it difficult to draw meaningful comparisons between results. This is not a recent problem, soil scientists have long recognized the need for such a method, however, it remains open to reach a collective agreement on one approach or method. Le Bissonnais (1996) identified the core difficulties that persist to this day, which is that aggregate breakdown and stability remain mechanistically poorly understood, and consensus methods for determining both stability and the internal and external properties of aggregates are still lacking. His framework, which proposes treatments under varying wetting energies to systematically assess aggregate resistance to disintegration, drew on a body of literature stretching back to the late 1930s and is based on a history of unresolved methodological debates that, three decades later, remains unresolved. That the same challenges identified in 1996 by Le Bissonnais (and before by other soil scientists) are still being raised in 2026 does not reflects a lack of effort, but the genuine complexity of the problem, which is the result of many interacting factors at different scales. In recent years, contemporary attempts have been made to better delimit and characterize water-stable aggregation, both conceptually (Poeplau et al., 2024; Totsche et al., 2018) and methodologically (Felde et al., 2020; Roosch et al., 2024), including high-throughput 2D- and 3D-image analysis. Valuable research remains non-comparable due to divergent methodologies, inconsistent size class definitions, and varying aggregate delimitations, which in turn could explain why upscaling aggregate properties to larger spatial or functional scales is difficult (Baveye, 2020). Jozefaciuk & Czachor (2014) proposed measuring disaggregation kinetics as a more objective and informative alternative to conventional stability indices, with the added advantage of allowing the individual contributions of specific binding agents to be examined systematically. This direction is promising, yet disaggregation kinetics alone remain insufficient as a universal descriptor, as again it only describes the energy needed to destroy an aggregate, but says little to nothing about the genesis and stabilization processes, as well as internal and external properties. Wet sieving, the most widely used approach, instead captures a composite response to hydraulic stress that conflates slaking, swelling, and mechanical breakdown. A truly integrative protocol would need to link measured stability parameters explicitly to the underlying binding agents, whilst accounting for aggregate sizes.

Methods that more precisely isolate mechanical stability may offer greater diagnostic power (Felde et al., 2020), but only if accompanied by clear classification criteria and explicit

differentiation between water-mediated breakdown mechanisms (e.g., slaking, splash erosion) and stability under purely mechanical stress. At minimum, the type and magnitude of energy applied should be analyzed more deeply and systematically, considering: i) the specific method used to apply stress, exemplarily gradual wetting, shaking duration, ultrasonic dispersion, the use of dispersing agents that prevent reflocculation (such as hexametaphosphate), or the choice between distilled and tap water; ii) the size classes under consideration, distinguishing for instance between pseudosilt and fine sand fractions; and iii) the binding agents responsible for structural integrity. As a next step, we propose applying systematically varying levels of energy (from gradual wetting to mechanical crushing) to assess whether and how the nature of the binding agent affects the mechanical stability of WSAs dependent of their size and where pseudosands differentiate from other WSA. Since these agents span a spectrum from organic to inorganic materials (Totsche et al., 2018), it is reasonable to expect that mechanical stability varies accordingly, even if aggregates retain their defining property of structural integrity. Rather than classifying pseudosands as texture alone, a combination of physical behavior under defined energy inputs, chemical and mineralogical composition, and inferred glueing or cementing agents may offer a more robust and transferable framework - one that identifies pseudosands at one extreme end of WSAs in a range of stability to water dispersion.

2.5 | CONCLUSION

Pseudosands can be examined as discrete units, differentiated from the surrounding matrix, and as such represent a remarkable entry point for uncovering intra-aggregate and surface properties relevant to hydrology, biogeochemistry, and ultimately to modelling at different scales. Yet, a definition and classification of pseudosands remains open, also in distinction to WSAs. We found that WSAs are a soil property that has been studied predominantly for perhumid and humid provinces from tropical to cold temperate zones. Varying water balances leading to chemical weathering and physical comminuting of soil aggregates over long developing time determine the presence of WSAs. If WSAs are not sufficiently stable, they will progressively be disintegrated, while those that resist these processes have the potential to become increasingly stable over time. These most stable WSAs are pseudosands, and while not all WSAs are classifiable as pseudosands, all pseudosands are WSAs. In this context, a clear and operational definition remains urgently needed to distinguish pseudosands within the continuum of WSAs, one that integrates information on binding agents, defined mechanical stability steps in function of the binding energy and relations to particle sizes.

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DECLARATION OF GENERATIVE AI USE

During the preparation of this work, the authors used generative AI tools (Claude AI) to improve the language and readability of the manuscript. All content generated or modified with AI assistance was subsequently reviewed and edited by the authors, who take full responsibility for the accuracy and integrity of the final text. Additionally, the authors used Raphael AI to generate the bear from the graphical abstract and modified with Windows.

AI assistance was used to facilitate the extraction of geographical coordinate information where needed: ChatGPT (OpenAI, version GPT-4o, last accessed November 2024) was used to approximate or infer coordinates in cases where site locations were only broadly described in the original source material or where precise coordinate data were missing. All AI-derived coordinates were subsequently verified by the authors against available source information to ensure accuracy, and assumptions made by the AI were made traceable within the metadata provided in the associated Zenodo repository.

CHAPTER 3 |
The “extra pinch” of pseudosand to enhance tropical biogeochemical processes understanding

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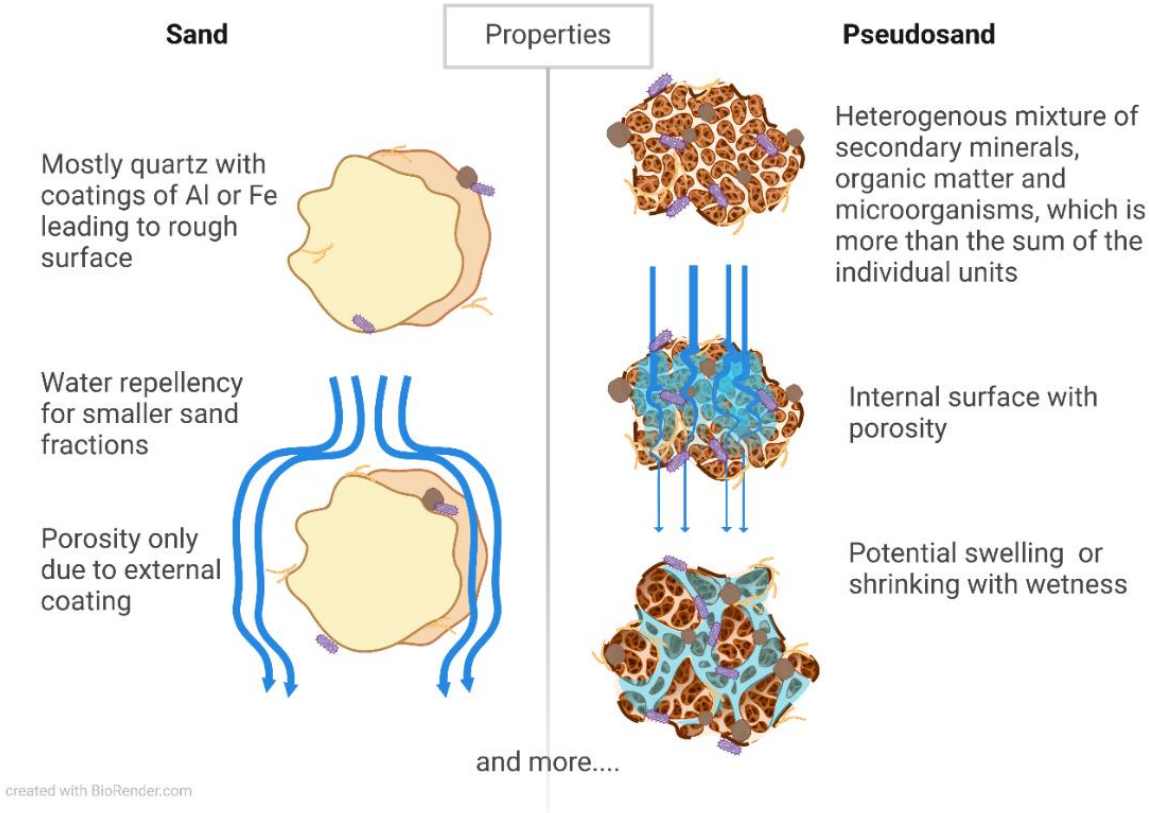
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ABSTRACT

Despite knowing better, water-stable aggregates like pseudosands are still disintegrated into their clay- and silt-sized bits and pieces to serve standardization in texture determination. Lacking yet a viable alternative, this deliberately committed mistake seems the contemporary best practice for modelling purposes, which is far from being ideal. Here, we propose this misconception to be a major cause for flawed process understanding of tropical soils, leading to substantial uncertainties in model development. There is enough evidence as to why pseudosands are neither sand nor the plain sum of its clay- and silt-sized units and should therefore better be defined as an additional soil texture class for which properties have yet to examined across the tropics.

GRAPHICAL ABSTRACT



3.1 | INTRODUCTION

Famed soil scientist Kubiëna, in 1938, correctly stated that *a crushed or pulverized soil is related to the soil formed by nature like a pile of debris to a demolished building* (Letey, 1991). Like any other system, soils are not simply the sum of their units—very Aristotelian. To uncover this gap and increase our understanding of soil biogeochemistry, acknowledging soil structure defined by aggregates is a contemporary goal that recently caused controversy to resurface among soil scientists (Baveye, 2021; Garland et al., 2024; Kravchenko et al., 2019; Rabot et al., 2018; Totsche et al., 2024; Vogel et al., 2022; Wang et al., 2019; Yudina & Kuzyakov, 2019, 2023). Despite all uncertainties, aggregates are widely recognized as a distinct structural level of soil architecture within different spatial and temporal scales (Totsche et al., 2024), even though their significance and effect on energy and matter fluxes are disputed (Garland et al., 2024). The concept of soil aggregation has proven to be useful when linking soil and atmosphere (Jiang et al., 2021; Mangalassery et al., 2013), hydrosphere (Connolly, 1998), and biosphere (Totsche et al., 2018) thus needed for addressing the challenges of upscaling processes involving movement of water, nutrients, and gases from molecules to pores to watersheds and, ultimately, the Earth. Nonetheless, large uncertainties still do exist regarding soil aggregate size, development, and delimitation (Amelung et al., 2024; Garland et al., 2024; Yudina & Kuzyakov, 2019). The reason for the low-key handling of aggregates is the wide variety of processes leading to their formation and destruction, and the dynamic interactions with miscellaneous gluing (e.g., different forms of organic materials) and cementing substances (inorganic materials, e.g., carbonates, Fe-, Mn-, and Al-oxides) (Totsche et al., 2018). Consequently, it is not surprising that the approach to identify and characterize aggregates and their sizes could appear vague or not very systematic (Baveye, 2021; Letey, 1991; Young et al., 2001). But even if an exact determination of where or when aggregates originate and how they evolve or stabilize between snapshots is not feasible, we can still identify the mechanisms and processes that lead to (dis)aggregation (e.g., Bucka et al., 2024; Martin et al., 1955; Roosch et al., 2024) and derive the impact of aggregates on fluxes of energy and matter.

Although modern nondestructive methods allow actual insights into undisturbed soil (Koestel et al., 2021; Peth et al., 2010), it remains a snapshot in time and space and does only partially overcome soils greatest challenge: its opacity. The rise and the fall of aggregates—be it fast or slow—are unstoppable because soils are constantly readjusting to their ever-changing environment (Nikiforoff, 1941). Depending on the amount, availability, and variety of gluing and cementing agents, aggregates can be unstable and highly dynamic regarding their shape

and location, or even be very stable. For the sake of standardization, comparison, and reproducibility, soil aggregates are rarely accounted for in soil characterization as laboratory protocols addressing them are highly diverse and no standardization exists (Almajmaie et al., 2017).

By definition, all kinds of gluing and cementing agents are chemically and mechanically destroyed to only determine the single-grain size distribution (Carter & Gregorich, 2008; Gee & Bauder, 1986), which then is used for site characterization, the derivation of biogeochemical processes, and modeling. For example, gluing organic material is digested with hydrogen peroxide (H_2O_2) (Day, 1965). If present, carbonates and salts are dissolved by an acidic solution and distilled water, respectively (Gee & Bauder, 1986), and cementing Fe- and Mn-oxides are removed by strong reducing agents like sodium dithionite ($Na_2S_2O_4$) (Mehra & Jackson, 2013). Chemical dispersing agents added (e.g., sodium polyphosphate) to maintain repulsive forces, avoid (re)flocculation, and achieve complete chemical dispersion of soils' discrete mineral particles (Gee &Or, 2002).

Within the natural continuum of fragile to stable aggregates, the most persistent ones occur in strongly weathered soils. Due to their high stability, the structural unity is preserved even after events of great fluxes of energy and mass, like heavy rainfall: These so-called pseudosands have already been described several decades ago (Bui et al., 1989; Neufeldt et al., 1999; Santos et al., 1989; Sharma & Uehara, 1968). Nowadays, pseudosands are often referred to by many other non-explicit names like "(clay) micro-/macroaggregates", "granular (micro-/macro-)structure", "(micro/macro) nodular structures", "pseudo-particles" and others (e.g., Cooper et al., 2005; Neufeldt et al., 1999; Pessoa et al., 2022; Rabbi et al., 2015; Radulovich et al., 1992; Volland-Tuduri et al., 2005). Confusion is predictable when no unique name and no clear definition are provided, as it is the case for the term "aggregate" (Baveye, 2021; Letey, 1991; Totsche et al., 2018; Vogel et al., 2022). Since the 1970s, pseudosands were described as *micropeds* in francophone literature in studies about strongly weathered soils (Beaudou, 1972; Chauvel et al., 1978; Muller, 1977; Pedro et al., 1976), highlighting their unique micromorphology (Bui et al., 1989; Santos et al., 1989; Stoops & Buol, 1985), genesis (Embrechts & Sys, 1988), and their effects on hydraulic properties (Curmi et al., 1993). Colloquially, they have also been described as *pó-de-café* or coffee powder for Brazilian Ferralsols, as they apparently resemble it in their shape and size (Azevedo & Bonumá, 2004). Their relevance, regarding hydrological parameters such as water retention and hydraulic conductivity, has empirically been highlighted ever since for tropical soils in, for example,

Brazil (Bui et al., 1989; Martinez & Souza, 2020; Pessoa & Libardi, 2022; Silva et al., 2022), Hawaii (Sharma & Uehara, 1968), Nigeria (Lal, 1978; Opara, 2009), DR Congo (Botula et al., 2012), Thailand (Tawornpruek et al., 2005), and the tropics in general (e.g., van den Berg et al., 1997).

Pseudosands are water-stable (micro-)aggregates and anything but labile. In the field, they feel sandy between our fingers, possibly the feature that led to the name (Beaudou, 1972). It refers to their characteristic of mimicking a sandier texture in the field as later determined through standard laboratory procedures (Radulovich et al., 1992). Similar applies to pseudosilt, which we will not name each time for simplicity. If pseudosands would simply act as sand particles, no further biogeochemical consideration would be necessary. A texture determination without chemical and mechanical destruction would be sufficient. This proxy could be effective when looking into water movement in soils through pedotransfer functions, which also has been done so far by highly regionalizing models and pedotransfer functions (e.g., Rosseti et al., 2022). Thus, it was mostly assumed that pseudosands would have similar characteristics to sand and that higher sand values would represent the conditions found in the field with regard to hydrology. However, these highly site-specific pedotransfer functions based on empirical values have not transcended to actually include pseudosands into the physical and hydrological understanding of tropical soils. Going further, for biogeochemical processes and fluxes, these stable aggregates have not yet been included at all. Hereby, the open question rarely addressed is if stable structures like pseudosands are more relevant for fluxes than the dispersed clay particles determined by classical texture analysis. At the same time, soil biogeochemical models that could answer this question are, however, not yet well-adjusted for the tropics and therefore perform less well than for temperate regions (Albanito et al., 2017; Richards et al., 2016).

Beyond acknowledgment of the existence of pseudosands, some morphological descriptions, and its effect on soil water movements, pseudosands are not accounted for in our process understanding, especially for intensively weathered soils. In the light of this classical recognition of pseudosands, it is surprising that they are not yet integrated into process understanding of intensively weathered soils, given that they are a well-known characteristic for the tropics. Regardless of the reason, we claim that it is time to address this oversight of addressing the specific properties of pseudosand in soil science. We consider pseudosand as a key factor for tropical soil development that so far has widely been ignored. In our opinion, pseudosand cannot be simply treated as sand, as their true nature and function are far more diverse than currently thought with a major implication for hydrological and biogeochemical

modeling. The motivation for writing this data-based opinion article is to promote research efforts and encourage studies unraveling the mysteries surrounding pseudosand worldwide. We suggest that pseudosands should be treated as an additional soil texture class that reflects its internal and external properties and, hereby, helps us to better understand and predict the behavior of tropical soil systems.

3.2 | APPROACHES

We performed a combined measurement and modeling approach on a selected set of samples and data to underpin our opinion targeting to improve the process understanding of tropical soils. Even though there is a widespread recognition that pseudosands are an integral part of intensively weathered soils, there is insufficient incorporation into our process understanding of tropical soils. We want to prompt with this opinion and show why considering pseudosands unique characteristics matter and need to be further integrated in measurements and modeling.

Soil samples originated from Ferralsols of Pará (Brazil) from pastures of different ages and natural vegetation. The challenge was to separate pseudosand from sand, which, in turn, was separated from finer soil particles by wet sieving. We used a threshold of 16 h shaking in water to separate mechanically dispersible clay from water-stable aggregates (Oades & Waters, 1991), which would resemble a heavy precipitation event. However, to determine the proportion pseudosand had on the sand-sized fraction, pseudosands had to be destroyed according to the standard lab protocols. Sand and pseudosand sizes were defined following the classification of the World Reference Base for Soil Resources, with the lower border for fine sand (FS), at 63 μm, following 0.2–0.63 mm for medium sand (MS), and 0.63–2 mm for coarse sand (CS). After shaking and wet sieving, all water-stable particles at sand-sized fractions (further called PS-mixture) were mixed at equal contents for all sampling depths (0–10, 10–30, 30–60, and 60–100 cm) and four sites for further analysis (Table S1).

To differentiate pseudosands from sands, binocular microscopy was applied (Leica S9i, Leica Microsystems), which served as basis for isolating individual pseudosand particles for subsequent examination. In addition to angular particles resembling crystalline characteristics, we observed spherical particles in all sand-sized fractions. We identified these more rounded particles as pseudosands (Figure 5). However, external properties could not be derived from the visual identification alone. Therefore, to obtain a more comprehensive understanding of the pseudosand characteristics, we measured the following properties: quantity, mechanical stability, elemental composition, and water repellency.

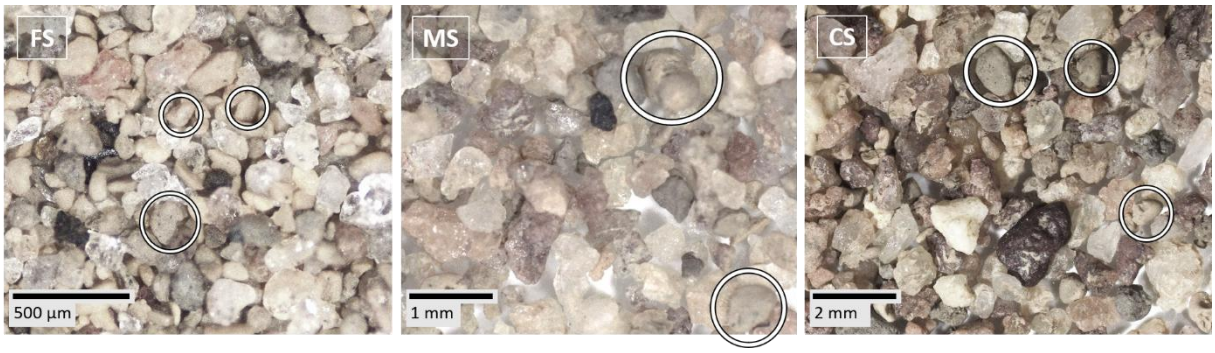


Figure 5. *Water-stable sand-sized particles under the optical microscope in the size fraction of fine sand (FS, 0.063 – 0.2 mm, medium sand (MS, 0.2 - 0.63 mm), and coarse sand (CS, 0.63 – 2 mm) of Brazilian Ferralsols. Circles pointing to particles potentially identified as pseudosands.*

3.2.1 | Sand-sized particle determination for Ferralsols (Pará, Brazil)

Pseudosands were present in all of the tested soil samples. Pseudosands added 16.3% ± 6.2% to the fraction of sand-sized particles (Figure 6A), compared to the concentration of sand via classical texture determination (Supplementary material in Strey et al., 2016) after Gee and Bauder (1986), changing significantly the sand concentration. Higher pseudosand shares were found in the FS fraction, with this proportion decreasing as particle size increases from MS to CS (Figure 6B).

3.2.2 | Mechanical stability

Mechanical stability was measured for handpicked particles from the CS fraction to demonstrate that the optically identified rounded particles (assumed pseudosands) are actually different in their properties from other sand particles. Even when most of the pseudosands were found in the FS fraction, these were too small to handle properly. Single particles of pseudosand (PS-single) and sand (S-single) were crushed using a high-resolution loading frame for material testing (Zwick Roell Allround Line, Zwick Roell). The method is similar to the one described by Skidmore and Powers (1982) and then used in Felde et al. (2020) (more details in Supplement II and Figure S3-1). About 75 single particles were selected, from which 45were optically identified as pseudosands. Independent of size, pseudosands were crushable at similar mechanical energy. In contrast, all other sand-sized particles needed much higher mechanical energies to be crushed and were showing a higher variability (Figure 7). We propose that mechanical stabilities clearly demonstrate that pseudosands have distinct physical characteristics, when compared to single mineral sand particles, and therefore could create

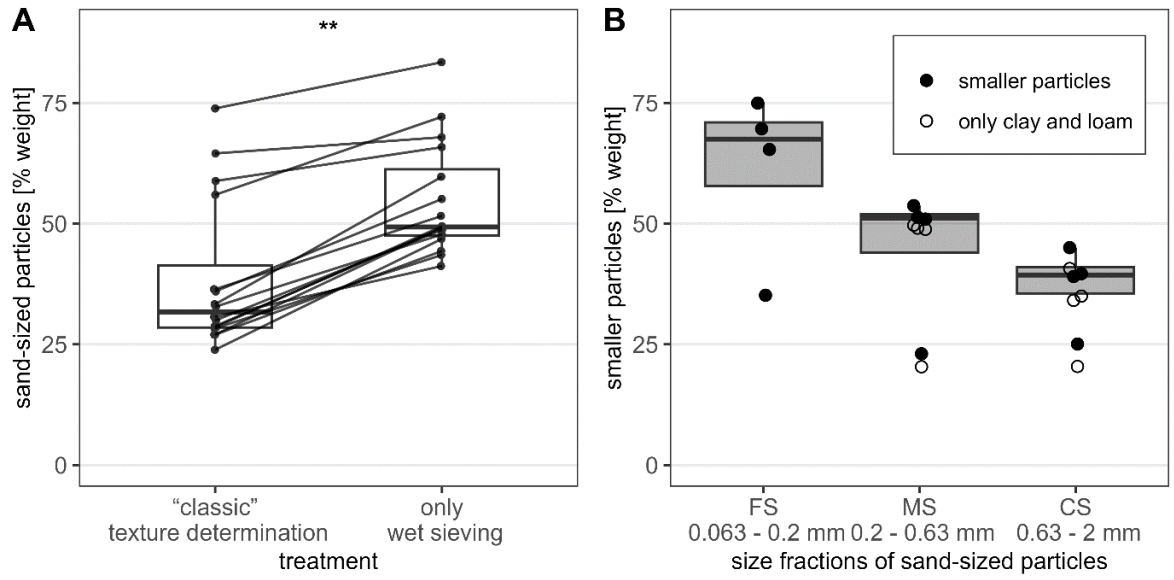


Figure 6. (A) *Proportion of sand-sized particles [% weight] by a classic texture determination following standard laboratory procedures dictated by the treatment with reducing and dispersing substances have significant lower sand-sized particles than via wet sieving (ANOVA, p= 0.020) for all sites and samples from Pará, Brazil, and (B) share from PS-mixture that dissolves into a smaller fraction in comparison to the clay and loam fraction after chemical dispersion by treatment with reducing and dispersing substances.*

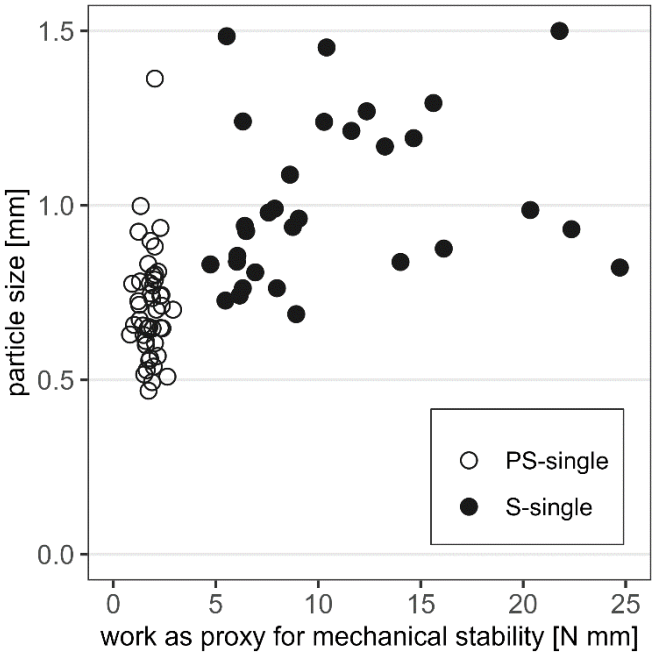
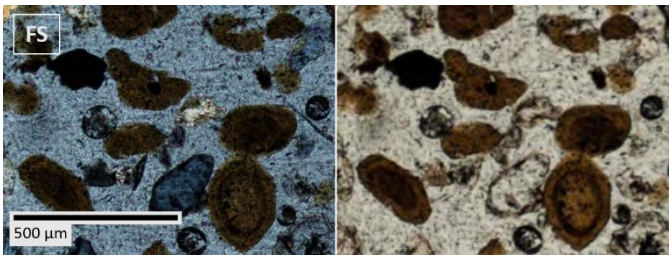


Figure 7. *The work, which equals to the area of the load–displacement curves, is used as proxy for mechanical stability. PS-single are hand-picked pseudosands after optical identification. S-single are all other particles that are water-stable and not pseudosands.*

substantial uncertainties when modeling processes related to water movement or biogeochemical fluxes. Parameters, such as water retention or infiltration, are directly linked to pore stability which, in turn, relies on the solid and liquid phases of soils, with aggregates contributing to all these phases in soils.

3.2.3 Elemental composition

Optical thin sections and energy-dispersive spectrometry (EDS) were performed to derive potentially diverging biogeochemical properties of pseudosand from sand. For the thin sections, grain mounts from PS-mixture were based on epoxy resin and cut into 30 µm thick sections, followed by a quality polishing and an optical microscope using plane and polarized light using a petrographic microscope. EDS mapping (more details in Supplement II) was performed on thin sections with special focus on the determination of silicon (Si) in quartz and aluminum (Al) in gibbsite and kaolinite. Thin sections of pseudosands in all fraction sizes displayed “Liesegang”-like rinds and rings (Figure 8 A,B), possibly concentrating Fe- and Al-rich phases closer to the surface. “Liesegang”-like rings or patterns refer to the periodic bands or rings of precipitates appearing in, for example, porous medium, as a result of the interplay among diffusion, reaction kinetics, and the medium’s physical properties in chemical reactions (Withers, 2010). EDS mapping showed that the particles could be differentiated in those that are composed by silicon (Si) and other of Al which could refer to quartz and gibbsite or kaolinite, respectively, for the elemental composition of water-stable aggregates within the sand fraction (Figure 9 A–C).

A 

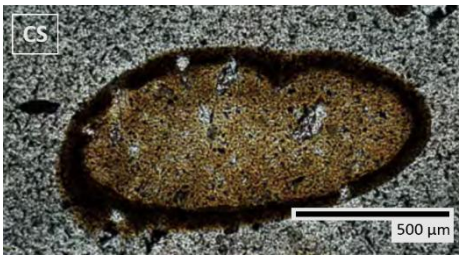
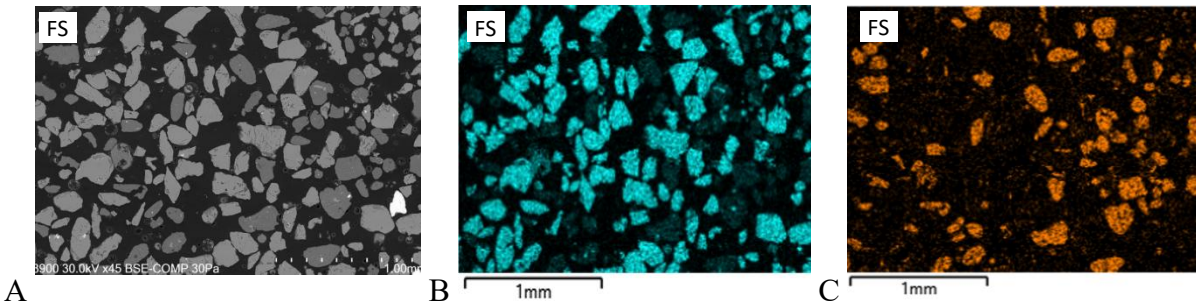
B 

Figure 8. *Optical thin-sections of the PS-mixture in the (A) FS fraction with cross polarized light (left) and plane polarized light (right), and (B) an optical thin-section of a pseudosand in the CS fraction.*



A B C

Figure 9 *(A) Secondary backscatter image of polished thin section from sample of the fine sand fraction containing pseudosand (PS-mixture) in the FS fraction, with (B, C) EDS-mapping of Si and Al highlighting the distribution of quartz-rich particles (bright blue) and gibbsite- and kaolinite-rich grains (faint blue and bright orange).*

3.2.4 Water repellency

We tested the water repellency of sand and pseudosand particles to strengthen our hypothesis that relevant differences in physicochemical properties exist and could even influence the water budgets and movement (Woche et al., 2005). Water repellency or wettability of the particles was determined by contact angle (CA) measurements by the sessile drop method (Goebel et al., 2004). Shortly described: Soil wetting properties can be determined in terms of the angle at the three-phase-line among liquid, solid, and vapor. Surfaces with CA = 0◦ are hydrophilic or fully wettable, surfaces with CA≥90◦ are hydrophobic or water repellent, and all CAs in between are considered wettable surfaces. The initial CA is determined after the placement of a drop of water on the surface and again after 5 s to estimate CA stability (Bachmann et al., 2021). We tested the after and before standard laboratory procedures of the sand fractions containing pseudosand (PS-mixture), which resulted in a sample with pseudosand and another composed mainly of quartz sand (QS) and a commercially available QS from Carl Roth (7898.1). Water repellency increased from CS to FS for all samples; in fact, only FS showed relevant differences in water repellency and stability between the samples. Only QS was water repellent also in the MS fraction, but with hardly any drop stability. The sample with pseudosands (PS-mixture) was distinctly wettable and can therefore be categorized as hydrophilic. Interestingly, the FS fraction had a slight initial water repellency, and that was, however, not stable (Figure 10). These results suggest that assuming similar hydrological properties of pseudosand and sand is inadequate and does not accurately represent the physicochemical interaction of water moving into and through the soil matrix. As exemplified by pseudosands, total wettability has significant implications for various properties related to fluid flow and storage. In particular,

processes like infiltration, preferential flow, hydraulic conductivity, and water retention are inevitably impacted by wettability and thus require further testing.

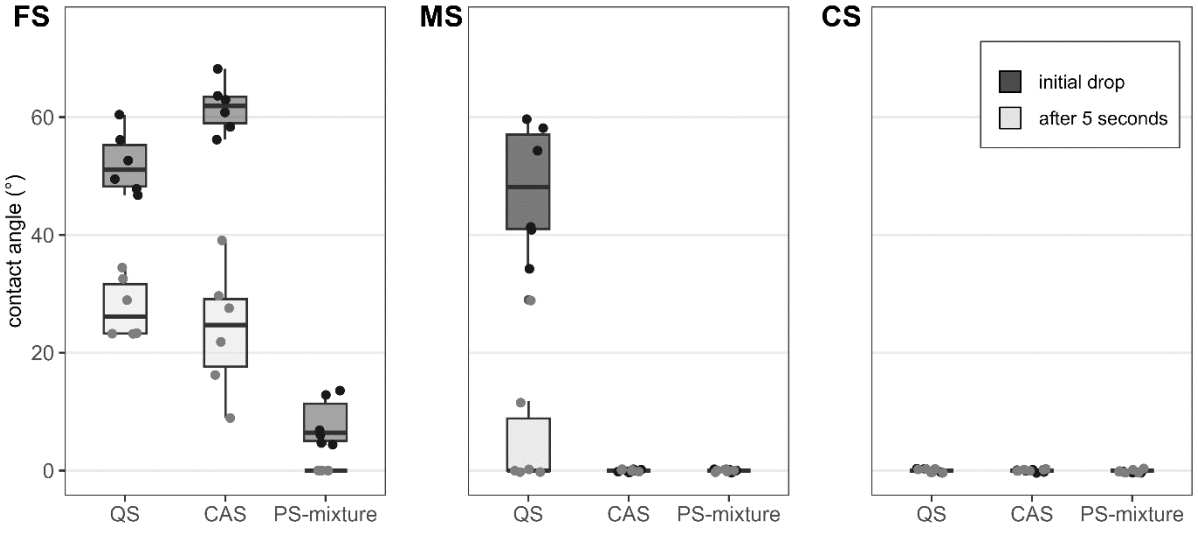


Figure 10. *Contact angle (CA) as proxy for water repellency of particle surfaces, tested on different sand sizes. Dark colors indicate initial values, lighter values the CA stability of a drop after 5 seconds.*

3.3 | EFFECTS OF PSEUDOSANDS ON HYDROLOGICAL AND BIOGEOCHEMICAL MODELING

Simply categorizing pseudosands as sands fails to capture their true complexity and functionality expected for physical and biogeochemical process understanding, thereby compromising the reliability of models. We performed a model manipulation experiment with the biogeochemical model CANDY (carbon and nitrogen dynamics; Franko et al., 1995) to test the effect of presupposing the properties of sand for pseudosand on volumetric water content in 10 cm depth as a proxy for physical/hydrological processes, as well as on N_2O emissions (kg ha^{-1} d^{-1}) for biogeochemical processes. CANDY has been developed for temperate conditions but has shown to be more suitable for tropical conditions than other models (Meurer et al., 2016, 2019). However, when applied to field observations on Brazilian cattle pastures, the model’s performance significantly deteriorated, particularly for soil water content after strong precipitation events (Meurer et al., 2016). In this study, we reran the simulations done by Meurer et al. (2016) with the model CANDY (Figures 11A and 12A) but used the strong precipitation events as a threshold to depict periods of different wetness over time (more details in Supplement II and Figure S3-2). Furthermore, we altered the sand content stepwise to

simulate the inclusion of pseudosands as sands through relative adjustments in clay and loam contents, in addition to its implications for soil hydraulic parameters. The performance of the model to reproduce the observed soil water content and N_2O emissions was evaluated using the root mean- square error, defined by the difference between the model's predicted and measured values.

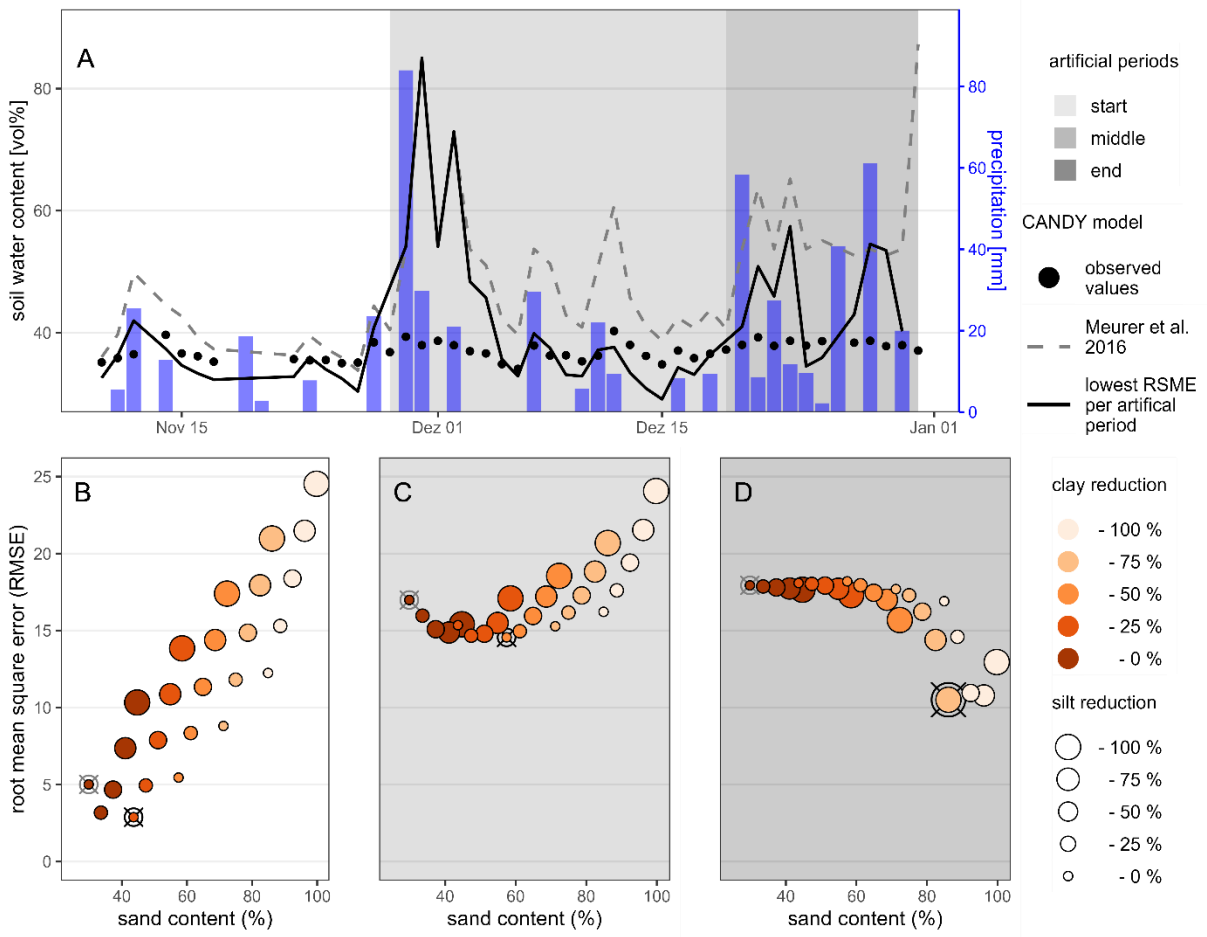


Figure 11. *(A) Precipitation [mm] in relation to simulated and measured soil water contents [vol%]. (B-D) RMSE for soil water content [vol%] for the three periods with texture manipulation. Background colors delimit the three artificial periods after strong precipitation events.*

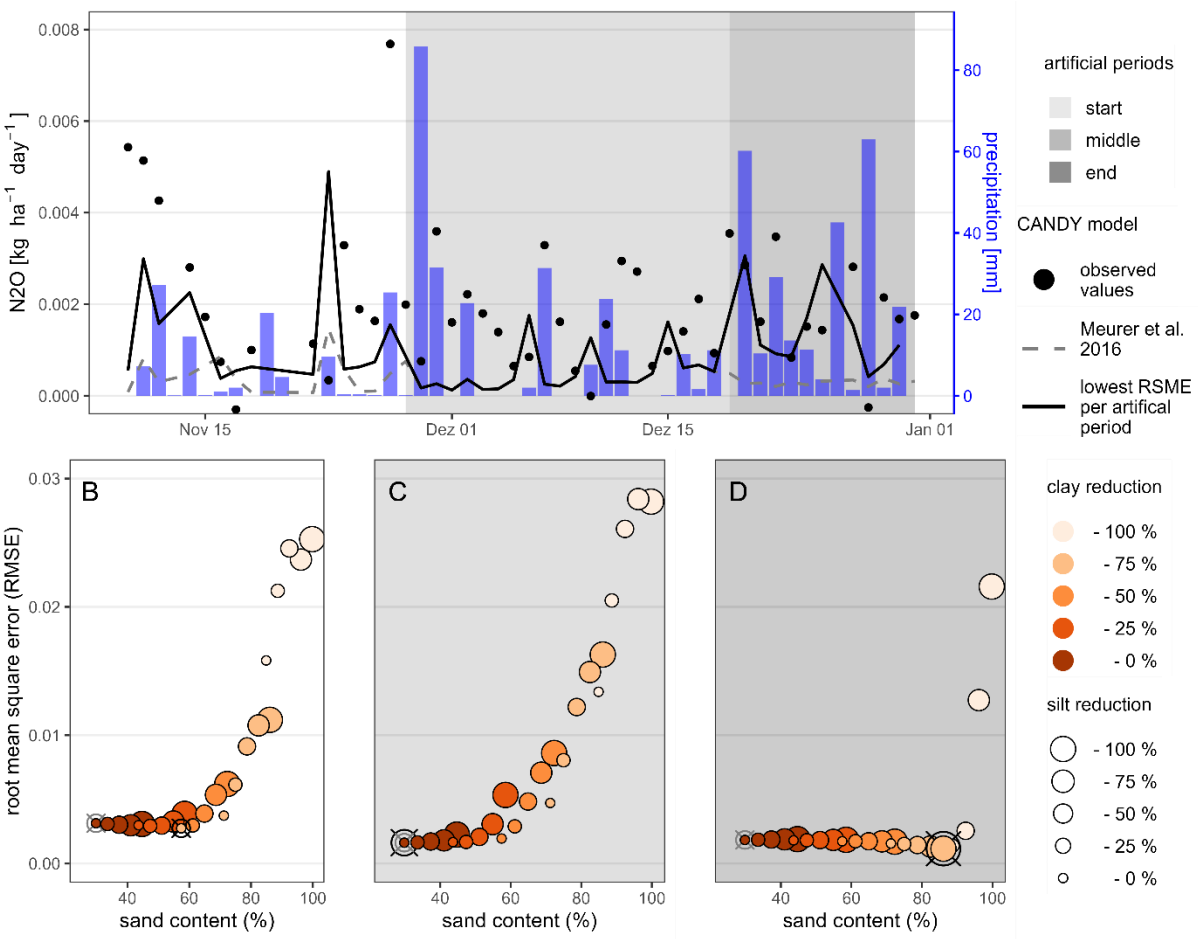


Figure 12. *(A) Precipitation [mm] in relation to simulated and measured N_2O emission rates [kg ha^{-1} d^{-1}]. (B-D) RMSE for N_2O emission rates for the three periods with texture manipulation. Background colors delimit the three artificial periods after strong precipitation events.*

Overall, the model’s performance did not improve substantially when pseudosands were categorized as sands for the first two periods (Figure 11 B,C). In fact, model performance turned out to be worse for very high sand contents and still very responsive to heavy precipitation events. However, decreasing the amount of clay and silt in the model to subsequently increase the sand content was successful for the last period when precipitation events were rather frequent and conditions wet (Figure 11D). The volumetric soil water measurements show that the infiltration into the soil is increased after heavy precipitation events, indicating that no surface runoff occurred. In general, clay minerals in pseudosands are expected to also exhibit changes in size as a result of swelling and shrinking, exposing variable characteristics with time and wetness. Through seasonal adjustments, these effects could be included assuming that pseudosands impact hydrological parameters strongly during wetter seasons than in drier seasons. For biogeochemical processes, however, this becomes entirely obsolete, as we

encounter niches in pseudosands that are not depicted in the models. Not accounting for them led to only very minimum model improvement for modeling greenhouse gas emissions when pseudosand was replaced by sand in our model manipulation experiment, with, however, a better representation of the variability in N_2O emissions (Figure 12 B-D).

These niches impact biogeochemical processes through microbial activity and are influenced by the spatial configuration of clay minerals (Martinez & Souza, 2020; Rabbi et al., 2015). In tropical soils, pseudosand forms under acidic pH conditions through the sorption of the negatively charged low-activity clays onto positively charged sesquioxides, that is, Fe- and Al-(hydro)oxides, alongside organic substances such as plant residues, microbial biomass, and exoenzymes (Martinez & Souza, 2020). By the use of organic substances as gluing agents, pseudosands possibly enhance the sequestration ability of tropical soils for organic carbon (Villasica et al., 2018) and increase its stabilization (Six et al., 2002). Pseudosands are water-stable aggregates and, depending on their size, their internal pore system constitutes a stable microhabitat for active soil bacteria and soil fungi, where microbial processes, such as denitrification, phosphorus turnover, and litter decomposition, may be performed. As bacteria are known to prefer clayey environments (Li et al., 2019), the assignment of pseudosand that consists of clay particles to the sandy fraction leads to a misevaluation of the bacterial living conditions. Although it is conceivable that pseudosands may impact physical properties as moisture levels fluctuate, their role in the biogeochemistry of nutrients has not been quantified yet sufficiently. Rather than targeting our process understanding of tropical soils, the improvement of model performance for tropical soils has primarily addressed the adaptation and validation of pedotransfer functions to tropical regions (e.g., Botula et al., 2014; Giarola et al., 2002; Ottoni et al., 2018, 2019; Severiano et al., 2013; Tomasella et al., 2000; Tomasella and Hodnett, 1998; van den Berg et al., 1997 for Brazilian soils).

3.4 | CONCLUSIONS AND OUTLOOK

With this opinion article, we provide sound evidence that it is possible and highly needed to study the properties of pseudosands more systematically to eventually introduce them as an individual soil texture class. Future studies may reveal if pseudosilt has to be included or not, and, if so, which relevant and practicable consequences will arise from it. Here, we propose that *pseudo* is an ideal term to show that sand is imperfectly mimicked. These stable microaggregates do not really function like sand, silt nor clay, and in important cases, it falls short to simply treat pseudosands as sands as pragmatic hydrological modeling frequently did.

These hydrological models were the first to acknowledge the influence of pseudosands and not merely acknowledge their existence and therefore have paved the way to more in-depth studies. However, not much has happened since then which motivated us to write this opinion. The biogeochemical role of pseudosands in delimitation to other soil aggregates has not been quantified yet, neither in the supply of nutrients nor of microhabitats for microbes suggesting the need for further studies. Based on some examples, we could demonstrate that, contrary to less stable microaggregates, it is possible to study pseudosands’ properties at the scale of a single particle scale or across an entire soil profile. The challenges will be to address the potential variations in properties of pseudosands due to the shrinking and swelling of their clay minerals - provided clay minerals involved have these properties - and the effect as bioreactor due to internal niches. Pseudosands have not been included at all into the process understanding of tropical soils even though it has been very clear that they do not simply behave like its sand, silt, and/or clay particles. Therefore, we are confident that adding that “extra pinch” of pseudosand will substantially improve our understanding of the processes that determine fluxes of matter in and out of intensively weathered soils and eventually will improve Earth System modeling.

ACKNOWLEDGMENTS

Motivated by the commitment of authors and early-career researchers who are dedicated to understanding aggregates and investigating soil opacity, we want to express our gratitude to everyone actively involved in uncovering the essence of aggregation and exploring the profound inquiry into the importance and meaning of them. We acknowledge *Svenja Roosch* for laboratory instructions and *Simone Strey* for providing the soil samples.

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CHAPTER 4 |
Pseudosands do not simply mimic sand

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KEYWORDS water-stable aggregates, pedo-transfer functions, sand correction, pF curves, pore size distribution

HIGHLIGHTS

- Soil structure derived from soil texture alone is not reflective of soils' true nature
- Pseudosands show distinct hydraulic behavior, not equivalent to sand
- Fine sand fraction shows the strongest divergence, a size-dependent effect
- Pseudosand quantity does not predict its functional hydraulic impact

ABSTRACT

Soil hydraulic properties are governed by soil structure, but, for standardization purposes, mostly inferred from soil texture. Soil texture is based on single-grain size distribution, whereas soil structure in field conditions can be dominated by labile or stable aggregates. One reason for relying on soil texture instead of soil structure, despite well-known shortcomings in understanding and modeling soil water movement, lies in the mainly short-term and fragile nature of most soil aggregates. Water-stable aggregates offer one way to bridge this gap, as they partly retain their structure under wetting stress such as slaking. Among these, pseudosands are the most stable. Yet, they are commonly treated as functionally equivalent to sand of the same size, for example through sand correction or recalibrated pedotransfer functions, despite being composed of sand-, silt-, and clay-sized particles. Here we hypothesized that pseudosands do not behave hydrologically like sand, and that this divergence is size-dependent. We measured water holding capacity (WHC) and pore-size distribution (via pF curves) in three sand fractions from a set of (sub-)tropical soils, comparing sand fractions with (S+PS) and without (S-PS) pseudosands. S+PS consistently retained more water than S-PS, most strongly in the fine sand fraction, where WHC was 54% greater than in S-PS, driven by a smaller proportion of wide coarse pores and a larger proportion of medium and fine pores. Notably, this effect was decoupled from pseudosand abundance in a subset of samples that were analyzed in more detail: the fine fraction contained the least pseudosand by mass yet showed the largest hydraulic divergence. Despite comparable pseudosand content to the middle fraction, the coarse fraction showed no significant structural difference from S-PS. This suggests that pseudosand quantity alone does not predict its functional impact, and that treating pseudosands as hydrologically equivalent to sand misestimates key hydraulic properties, with direct consequences for water balance and movement. Given this size-dependent behavior, we explore that analogously overlooked pseudosilts may warrant further investigation, despite the added methodological challenges of working at silt-sized scales.

4.1 | INTRODUCTION

Soil structure regulates key soil functions such as water infiltration, aeration, root penetration, and habitat provision for soil organisms, making it a critical property for both agricultural productivity and ecosystem services (Bronick & Lal, 2005; Letey, 1991). Conventionally, soil texture is at the basis of soil structure and describes the size distribution of distinct sand-, silt-, and clay-sized particles when all kinds of cementing or gluing agents are removed (Gee & Or,

2002). Soil structure describes how these particles are arranged in situ in a three-dimensional soil matrix (Dexter, 1988; Vogel et al., 2022). While established laboratory protocols for texture determination make soil texture comparable across different sites (Gee & Bauder, 1986; Gee & Or, 2002), the outcome hardly ever represents soil structure. We are, thus, left relying on particle-size determination based on laboratory protocols which by design cannot fully capture soil structure.

What at first glance appears to be a matter of methodology, expands to soil structure only rarely being accounted for in studies at all. Largely this can be explained because soil texture is a poor predictor for soil structure. This causes difficulties both in assessing soil structure itself and in using it as an input parameter, for instance in soil modelling. Reported pronounced discrepancies between field-measured and model-predicted N_2O emissions (Meurer et al., 2016) can potentially be traced back to the conflation of soil texture and soil structure. This is especially true for tropical, intensively weathered soils, where strong aggregation is a well-known phenomenon (Barthès et al., 2008; Kilian Salas et al., 2024) and has even been given the distinct name of *pseudosands*. Considerable effort has, therefore, been directed toward reparametrizing pedotransfer functions (PTFs) at regional scales (Botula et al., 2014; Medeiros et al., 2014; van den Berg et al., 1997). This is intended to improve, for example, model performance by reconciling field observations with modeled outputs. However, without explicit consideration of aggregation dynamics and effects, this approach mostly enhances over-regionalization and specialization to one area or region only (Pachepsky & Rawls, 2003).

A further widely adopted shortcut has been the so-called sand correction: rather than modelling aggregates explicitly, the parameters derived from texture analysis are adjusted to the sand content (e.g. Wasner et al., 2024) to ultimately increase model performance. The implicit assumption underlying sand correction is that models can account for sand-sized aggregation by adopting properties equivalent to sand. A calculation exercise by Kilian Salas et al. (2024) illustrated the limits of sand correction: while it could yield partially acceptable hydrological results, it totally fails when applied to biogeochemical processes, such as N_2O fluxes. Such processes are not only impacted by interaggregate porosity but also by microbial niches.

Pseudosands have largely been characterized descriptively since the early 1960s (Bui et al., 1989; Sharma & Uehara, 1968). Their unique name reflects that they are often perceived tactilely, therefore, resembling sand to the touch. Their resistance to slaking upon wetting exerts a strong control on soil structure, more than any other aggregate or water-stable aggregate

(Martinez & Souza, 2020). This also explains a widely reported paradox from many intensively weathered soils: despite containing very high clay contents, these soils behave hydrologically more like sandy soils, exhibiting rapid infiltration and fast percolation of water following precipitation events (Lilienfein et al., 1999; Miguel & Vilar, 2009; Pessoa et al., 2024). Understanding the behavior of pseudosands is therefore not only a question of methodology but a prerequisite to accurately represent water and nutrient dynamics in soils where these very stable aggregates are present. This study evaluates whether pseudosands exhibit distinct hydrological properties compared to sands, thereby functioning as a distinct soil component. We state following specific hypotheses: I) pseudosands confer distinct hydrological properties, II) pseudosands' heterogeneous nature translates into variability in their hydrological behavior, and III) pseudosands' effects depends on pseudosands particle size.

4.2 | MATERIAL AND METHODS

4.2.1 | Soil samples

Soil samples originated from Brazil, Uganda, and Australia from different depths and land-uses. More detailed information can be found in Table S4-1. All selected soil samples stem from tropical or subtropical Holdridge Life Zones.

4.2.2 | Sample preparation

Approximately, 10 to 50 g of soil sample was first shaken for 16 h to isolate only the most water-stable aggregates, which are sands and pseudosands. Through wet-sieving, these samples were separated into three sand fractions into size classes according to the World Reference Base (WRB, FAO, 2014) classification: fine (63 – 200 µm), middle (200 – 630 µm), and coarse sand (630 – 2000 µm). Pseudosands cannot be physically separated from the true sand fraction to perform targeted analysis. Instead, each sample was measured as sand with pseudosands (S+PS) and compared against the sand fraction without pseudosands (S-PS), with the latter obtained via standard laboratory texture analysis (Table 3). The difference in particle-size distribution between these two fractions was used to quantify the proportion of pseudosands present. For a subset of samples (n = 6), called here calibration, S-PS was also determined from S+PS. All other S-PS samples are the validation dataset (n= 20).

Table 3. *Overview of samples and locations of samples used. Additional to the classical method to determine texture in the laboratory where all aggregates are destroyed, the samples were wet sieved to be able to derive hydrological properties. Classical laboratory texture determination was extracted from cited sources. Further information can be found in Table S4-1.*

Origin of samples	Location	n	Classical laboratory method for texture determination, verbatim from original source	Source
Australia	Diverse Locations in Western Australia	2	"Particle size analysis (PSA) was determined by the hydrometer method"	(Amenkhienan et al., 2025; Mia et al., 2026)
Uganda	Budongo Central Forest Reserve	4	"Soil texture was determined using a Bouyoucos hydrometer"	(Tamale et al., 2021)
	Ratoon sugarcane field in Kanyege	4	"Grain size distribution was determined following the van Reeuwijk (1993) protocol"	(Tamale et al., 2022, 2024)
Brazil	Pará State	16	"after iron destruction with dithionite and dispersion with 0.05 M $Na_4P_2O_7$ using the pipette-method (Gee &Bauder, 1998)"	(Strey et al., 2016)

For nuclear magnetic resonance (NMR) measurements, sample preparation involved saturating 3 g of soil (placed in a mesh-bottomed container) via capillary rise from an underlying water column for 12 to 24 hours to achieve maximum saturation. Composite samples were produced to merge spatial repetitions of soil samples. Water holding capacity was determined on the same samples prior to NMR measurements.

4.2.3 | Environmental Scanning Electron Microscopy

Morphological and structural features were exemplarily examined using one representative sample of S+PS and S-PS via Environmental Scanning Electron Microscopy (ESEM), using a Quanta 250 ESEM (FEI Company, United States) equipped with a backscattered electron detector (BSED). All measurements were performed under high vacuum ($< 10^{-4}$ Pa) at an acceleration voltage of 30 kV and spot size of 4.0 to 5.0.

4.2.4 | ^{1}H-NMR relaxometry and derivation of pF curves

^{1}H-NMR relaxometry detects the relaxation behavior of hydrogen (H) protons in water molecules under a magnetic field. Following excitation, these protons return to equilibrium at a rate (T2 relaxation time) that depends on the degree of water confinement governed by pore size: water in small pores relaxes faster, while water in larger pores relaxes more slowly. Measurements were performed using a Bruker Minispec MQ (Bruker, Germany) at a magnetic field strength of 0.176 T (proton Larmor frequency of 7.5 MHz). Transverse relaxation (T2) decay curves were acquired using a Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence with an echo time of 0.3 ms (300 µs); gain was adjusted individually for each saturated sample to achieve 70–90% signal intensity. Decay curves were processed in MATLAB via inverse Laplace transformation (ILT), using the Butler, Reeds, and Dawson (BRD) algorithm, yielding relaxation time distributions (RTDs) of 200-time constants and associated amplitudes, with the amplitude sum (100%) representing total water proton content. Based on the established relationship between T2 and pore size, RTDs were converted into pore-size distribution (PSD) (Meyer et al. 2018). Later, pore radius was related to matric suction using the Young–Laplace equation, allowing PSD to be expressed as pF curves.

Because the investigated soils were strongly weathered and free of swelling clays, they were considered well-suited for this NMR-based approach, as the absence of clay swelling avoids the discrepancies between NMR-derived and classical water retention curves that have been reported for swelling-clay-rich soils (Meyer et al., 2018). Additionally, this method has been tested already successfully with aggregation in soils (Buchmann et al., 2015).

4.2.5 | Data Analysis

Background data on Holdridge Life Zones of sampling points were extracted from Jungkunst et al. (2022). All data was analyzed and visualized with R and RStudio (version 4.5.2), with the R packages *ggplot* (Wickham et al., 2007), *tidyverse* (Wickham, 2016), and *sf* (Pebesma, 2016). Prior to statistical analysis, the assumptions of normality and homogeneity of variance were assessed for each dataset. Normality was tested using the Shapiro-Wilk test (*stats* R package), and homogeneity of variance was tested using Levene's test, implemented with the *car* R package (Fox et al., 2001). Where both assumptions were met, differences between groups were tested using a one-way analysis of variance (ANOVA, *stats* package), followed by Tukey's honestly significant difference (HSD) test as a post hoc test (*agricolae* R package, Felipe de Mendiburu, 2006). Where the assumptions of normality or homogeneity of variance were not

met, the non-parametric Wilcoxon rank-sum test was used instead to compare groups from the *rstatix* R package (Kassambara, 2019). Statistical significance was determined as a p-value below 0.05.

4.3 | RESULTS

On a descriptive level, ESEM micrographs revealed clear morphological and structural differences between S-PS and S+PS. Sand without pseudosands (S-PS) was dominated by grains with a crystalline, quartz-like appearance: sharp, well-defined edges and smooth to conchoidal fracture surfaces, consistent with a homogeneous mineralogical composition. Surface texture was largely uniform, and grain interiors appeared solid and non-porous, with no evidence of internal structural heterogeneity (Figure 13). Sands with pseudosands (S+PS), in contrast, displayed a heterogeneous mixture of particle morphologies. A subset of particles exhibited markedly rough, irregular, "cauliflower-like" surfaces. Alongside these, additional particles displayed angular to rounded shapes with smoother surfaces. Despite their similarity in particle size, their differences in external surface morphology and internal porosity impact hydrological properties, that are presented below.

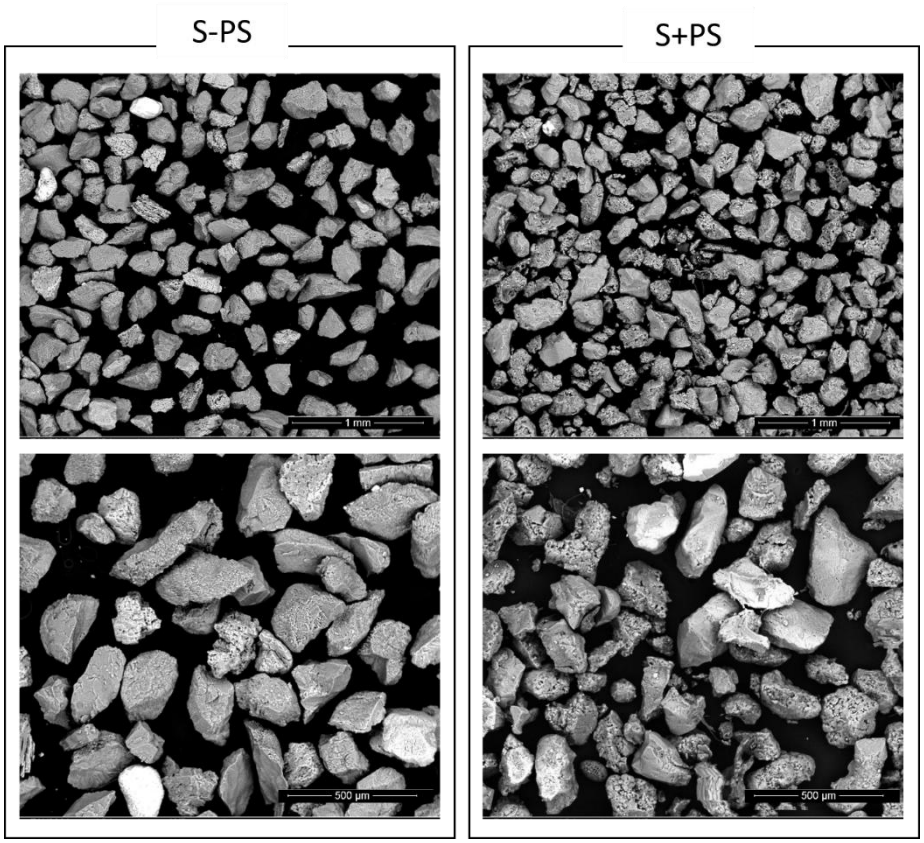


Figure 13. *ESEM of on composite sample of sites in Brazil in the fine sand fraction with sand containing pseudosand (S+PS) and sand without pseudosand (S-PS).*

4.3.1 | Textural comparison and water holding capacity

All analysed samples contained pseudosands, which added an average of 19% of sand-sized particles. The sand content from S-PS to S+PS, therefore, increased significantly from 42.2% (±15.7) to 61.2% (±14.5) (Figure 14). The distribution of pseudosand content showed substantial spread, with 50% of values falling between 9.8% and 22.9% (Q1–Q3) around a median of 17.1%. This variability of pseudosand content differed by latitude: sites in tropical regions showed a narrower interquartile range (IQR: 13.9-20.5%), while subtropical sites showed a wider spread (IQR: 8.8-40.4%) (Table S4-2).

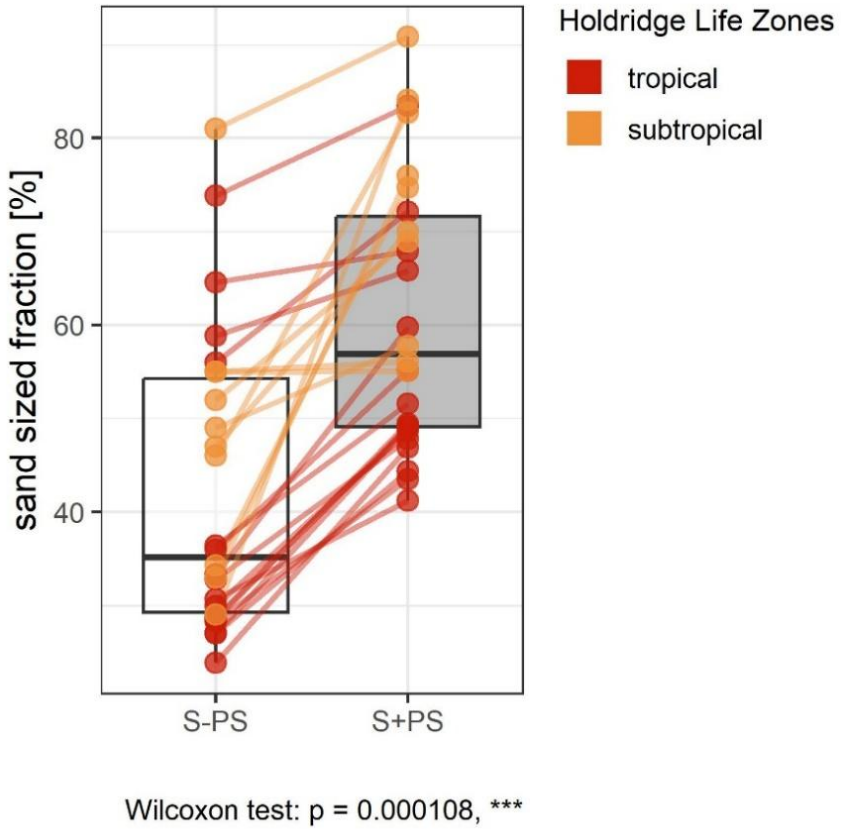


Figure 14. *Direct comparison of sand content without (S-PS) and with pseudosands (S+PS). P-values are from Wilcoxon tests to determine significance levels. Further metadata in Table S4-4.*

For S+PS, the water holding capacity (WHC) increased with decreasing sand size fraction (Figure 15): the fine sand fraction had the greatest mean WHC (65.0% ± 7.3), followed by the middle sand fraction (54.0% ± 10.1) and the coarse sand fraction (43.9% ± 10.2). The range for the calibration and validation dataset was comparatively similar, demonstrating that the variability within S+PS does not only reflect the amount of pseudosand but also has further

effects on soil structure. For the calibration dataset, the pseudosand contents were proportionally greater in the middle sand fraction with a mean of 11.5% of pseudosands within the sand fraction (IQR: 9.7-13.6%). The greatest difference to S-PS in WHC was in the fine sand fraction, where the mean content of pseudosand in the calibration dataset was 6.8% (IQR: 6.2-6.8%). The coarse sand fraction had pseudosand contents similar to that of the middle sand fraction, with a mean of 10.9% of pseudosands (IQR: 8.7-13.3%). In contrast, S-PS showed a mean WHC of 42.2% (±7.5), which did not differ significantly between size fractions (coarse, middle, fine sand).

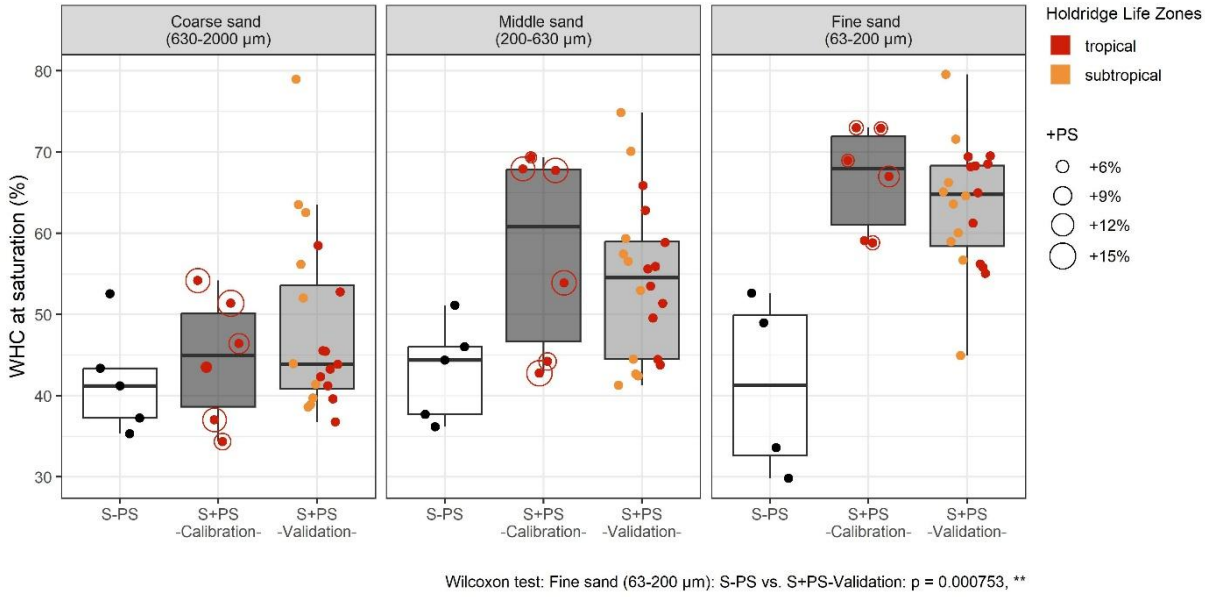


Figure 15. *Water holding capacity (WHC) at saturation with circle sizes explaining the relative amount of pseudosands per sample (+PS) in the calibration dataset, ranging between 3.6 and 15.2%. P-values are from Wilcoxon tests to determine significance levels.*

4.3.2 | pF curves and pore size classes

In general, S-PS and S+PS displayed a greater proportion of wide and narrow coarse pores, consistent with typical sand-dominated pore structures (Figure S4-2). A pattern similar to that observed for WHC (section 4.3.1) emerged (Figure 16): for S+PS, the proportion of wide coarse pores was generally lower and more variable, and decreased further with decreasing fraction size. Conversely, from narrow coarse pores through to fine pores, S+PS showed a greater proportion of pores in these ranges, with this proportion tending to increase as size decreased. In the fine sand fraction, medium and fine pores together represented up to 5% of total pore volume and narrow coarse pores were almost 50% in some samples in subtropical Holdridge Life Zones. For S-PS, PSD remained relatively similar across size fractions with no significant

differences, though proportions differed between pore size classes. Medium and fine pores together accounted for less than 1% of total pore volume on S-PS, and narrow coarse pores were accounted for more than 9.1 %.

Given the partially limited number of samples used in this study, statistical significance here is sensitive, therefore, these results are to be better interpreted as trends. Within S+PS, only the fine sand fraction differed significantly from the coarse sand fraction across all pore size classes (Table S4-3). When comparing S+PS and S-PS, significant differences were found across all pore size classes for both middle and fine sand fractions (Table S4-3). For the coarse sand fraction, variability was high across all pore size classes, which could explain why no statistical difference could be determined.

4.4 | DISCUSSION

Our findings highlight that hydrological properties of soil are not fully captured by the determination of discrete particles. Sand-sized material can comprise not only individual disaggregated grains but also stable aggregates, which occupy the same textural size domain but present own properties. In our samples, pseudosands contributed, on average, approximately 20% of sand-sized material and reached up to 65% in individual samples. Importantly, their hydraulic behavior was not simply determined by their occurrence within the sand fraction: pseudosands exhibited distinct water-holding properties and substantial variability among size fractions. Rather than representing sand particles, pseudosands can therefore be considered a structurally distinct component of the sand-sized fraction with their own functional properties.

Together, our results support all three hypotheses. Pseudosands conferred distinct hydrological properties relative to true sand (H1), evident in significantly higher WHC and a markedly different PSD across all sand fractions (Sections 3.1 and 3.2). This behavior was also heterogeneous rather than uniform (H2): pseudosand content and its hydraulic expression varied substantially, and, in the calibration subset, did not scale proportionally with pseudosand amounts. Finally, these effects were size-dependent (H3), with the fine sand fraction showing the greatest divergence from true sand in both WHC and PSD, despite containing comparatively little pseudosand by mass.

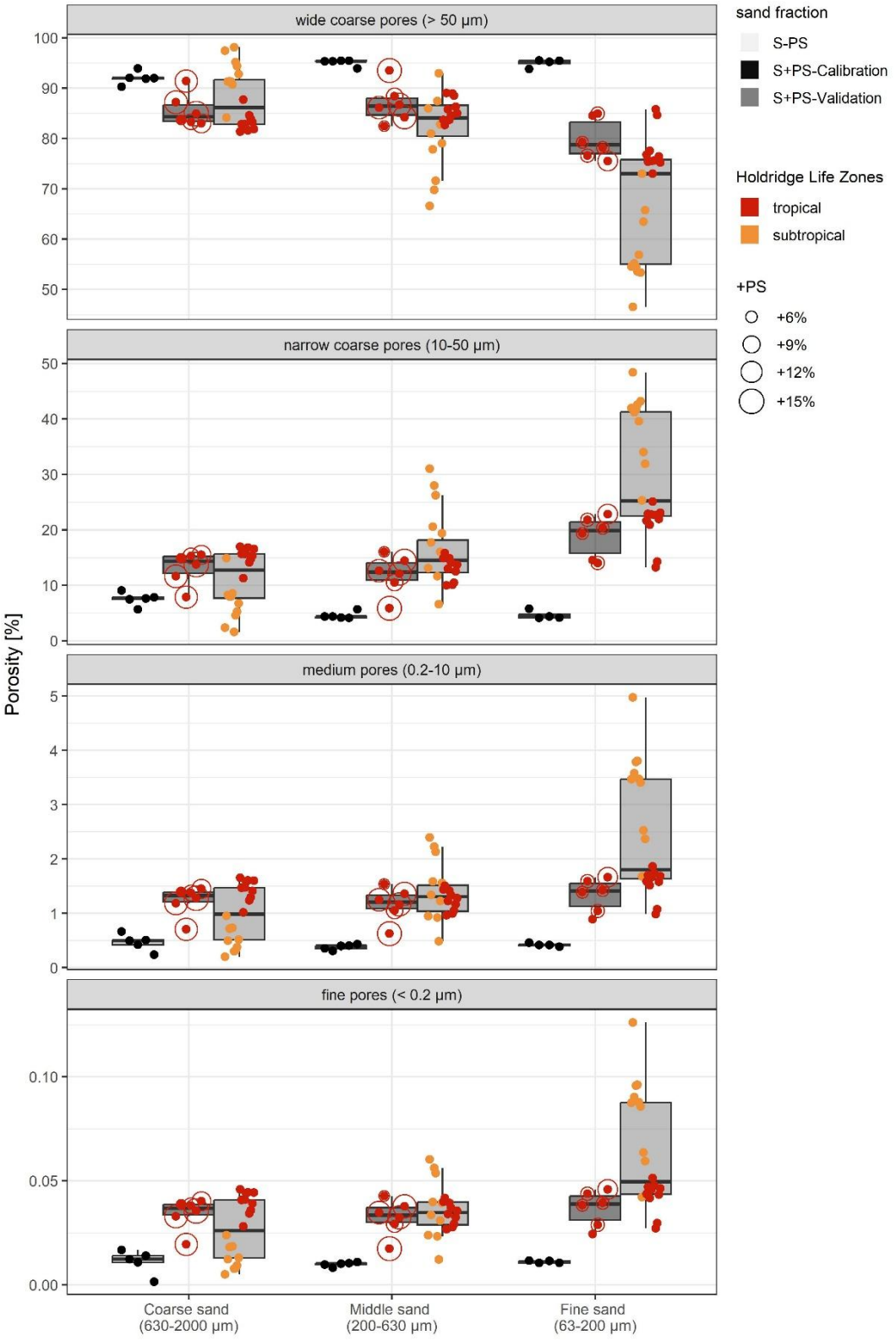


Figure 16. *Relative proportion of pore volume across pore-size classes, derived from pF curves based on ¹H-NMR relaxometry measurements (Figure S4-1). Notably, the fine sand fraction of S+PS differs significantly from S-PS and from the other size fractions. Statistical details are provided in Table S4-3.*

4.4.1 | Hydraulic properties

Pseudosands are an integral part of soil texture that enables to better grasp on soil structure. Their stability allows them to withstand the mechanical and hydraulic stresses applied during wet sieving (Martinez & Souza, 2020), causing them to be classified operationally as sand-sized particles. In this respect, pseudosands resemble sand in their physical stability and size, but their internal structure gives them additional functional properties. This distinction becomes apparent when considering water-holding capacity (WHC). In S−PS, WHC remained comparatively similar across coarse, middle and fine sand fractions, consistent with the relatively homogeneous, solid quartz-like morphology observed by ESEM and the comparatively consistent PSD among fractions. In contrast, WHC in S+PS increased with decreasing fraction size, a pattern consistent with the greater surface-to-volume ratio expected for smaller particles (Schlüter et al., 2018), but which may additionally reflect differences in pseudosands' internal porosity. Thus, particle size provides an important control on water retention, but does not fully describe the hydraulic behavior of pseudosands.

The distinct behavior of S+PS is further supported by its PSD and morphology. S−PS showed a comparatively consistent distribution of pore-size classes across sand fractions, whereas S+PS exhibited a substantially more heterogeneous pore system. ESEM observations likewise revealed a greater diversity of particle morphologies in S+PS, ranging from rough, irregular, "cauliflower-like" structures to smoother and more rounded particles. This morphological heterogeneity may reflect a continuum of pseudosand formation and structural development rather than a single, uniform particle type. Differences in particle shape and surface roughness can influence the way particles pack and consequently modify inter-particle porosity (Dal Ferro et al., 2014; Wang et al., 2025). In pseudosands, this effect may be accompanied by internal porosity, resulting in a combination of inter-particle pores between pseudosand particles and intra-aggregate pores within them. The resulting pore geometry is influenced both by the arrangement of particles and by the internal architecture of the particles themselves. Pseudosands therefore represent not simply a different form of sand, but a structurally distinct component whose properties emerge from aggregation and internal organization.

It should be noted that these findings characterize the sand-sized fraction in isolation. In a natural bulk soil, pseudosands occur together with silt-sized, clay-sized particles and other aggregates, and interactions among these particles may modify their expression within the overall pore network. Nevertheless, the distinct properties observed here demonstrate that

pseudosands can contribute an additional structural level to soil hydraulic behavior and should therefore be considered when interpreting the functional properties of sand-sized material.

4.4.2 | Variability

The pronounced variability in PSDs among S+PS further indicates that particle size alone is insufficient to describe the structural organization of pseudosand-containing material. While S−PS showed a comparatively consistent PSD across sand fractions, S+PS exhibited a much more heterogeneous pore system, with greater proportions of narrow coarse, medium and fine pores, particularly in the fine sand fraction. This greater heterogeneity coincided with the higher WHC observed in S+PS and suggests that the presence of pseudosands introduces an additional level of structural organization beyond that associated with the primary particle-size distribution. The ESEM observations support this interpretation by revealing substantial morphological heterogeneity among pseudosands. Consequently, aggregates of similar apparent particle size may nevertheless possess different internal structures and therefore different hydraulic properties (Menon et al., 2020).

One possible explanation for this variability is that pseudosands contain heterogeneous intra-aggregate pore networks with varying degrees of connectivity to the external pore space (Menon et al., 2020). Internal pores that are connected to the exterior may contribute directly to the hydraulically accessible pore system, whereas poorly connected or isolated pores may contribute differently to water storage and transport. Such internal porosity could also create additional surfaces within particles of a given apparent size, resulting in a greater effective internal surface relative to particle volume than in comparatively solid quartz grains. The extent to which these internal pores are connected to the external pore space may therefore influence both the effective surface-to-volume relationship and the fraction of the internal pore system that participates in water retention. Aggregates with similar apparent particle sizes could consequently exhibit substantially different PSDs and WHC depending on their internal pore architecture and pore connectivity.

Although internal surface area and pore connectivity were not directly quantified in this study, the morphological and pore-size differences observed in S+PS are consistent with this interpretation. In particular, the greater occurrence of smaller pore classes and the higher WHC of S+PS suggest that internal structural complexity may be an important contributor to the hydraulic properties of pseudosands. Direct measurements of internal surface area and pore connectivity would be required to test this mechanism. The proposed relationship can therefore

be viewed as a hypothesis for how aggregation generates functional properties within the sand-size fraction: aggregation potentially increasing structural complexity, not only by changing the external morphology of particles, but also by creating internal pore networks and additional surfaces that are in contact with air and water.

4.4.3 | Size dependency

The divergence between S+PS and S−PS was not evenly distributed across the sand fractions but was particularly pronounced in the middle and fine size fractions. Notably, this pattern occurred despite the fine sand fraction containing proportionally less pseudosand by mass (6.8%) than the middle (11.5%) and coarse (10.9%) fractions. This comparison is based on the calibration dataset. Nevertheless, the fine sand fraction showed the largest increase in WHC and the strongest divergence in PSD from S−PS, supported by the validation dataset. This decoupling between pseudosand quantity and its functional effect suggests that the hydraulic importance of pseudosands is not simply proportional to their mass contribution. Instead, their influence appears to depend on the scale and architecture of aggregation.

One possible explanation is that smaller pseudosands provide a greater surface relative to their apparent volume, while simultaneously generating a greater number of particles and potentially smaller intra-aggregate and inter-particle pores. Thus, a relatively small mass fraction of fine pseudosands may contribute disproportionately to the hydraulic behavior of a sample. This interpretation is consistent with the increasing surface-to-volume relationship expected with decreasing particle size, but may also involve differences in internal porosity and pore connectivity (Lipiec et al., 2007). The results therefore suggest that the functional significance of pseudosands depends not only on how much pseudosand is present, but also on the size and structural organization of the pseudosand particles themselves.

This raises the assumption that the weight of structural and hydraulic effects observed here may extend below the sand-size domain to the so called pseudosilts. Such material is currently difficult to isolate and investigate at the individual-particle level, particularly because manual separation becomes increasingly challenging toward smaller size classes. Methodological development will therefore be required before the existence and functional significance of such smaller aggregate units can be assessed empirically. Nevertheless, the size-dependent behavior observed here highlights the need to consider aggregation as a hierarchical structural process rather than as a property restricted to a particular particle-size class.

4.4.4 | Broader Implications

The results have implications for how soil texture and structure can be integrated into process-based descriptions of soil processes. Particle-size distribution provides an efficient and widely applicable representation of soil texture, but they do not necessarily distinguish between individual mineral particles and structurally organized aggregates occurring the same size range (Wu et al., 2026). Pseudosands demonstrate that a single textural class can contain physically distinct entities with different internal architectures and functional properties. Recognizing this additional structural information could therefore improve the interpretation of texture-based estimates of soil hydraulic properties.

This is particularly relevant for models that use particle-size distributions to estimate hydraulic or other soil properties. Even approaches that incorporate aggregation often represent aggregate effects through empirical relationships or pore-based proxies (Baveye, 2023; Meurer et al., 2020). Pseudosands present an opportunity to complement such approaches by explicitly considering stable aggregates as functional components of the particle-size distribution. Rather than treating aggregation solely as a modification of bulk soil porosity, pseudosands can be viewed as identifiable structural entities that contribute their own pore architecture, surface characteristics and water-retention behavior. Their inclusion could therefore provide an additional link between soil texture, soil structure and soil processes.

4.5 | CONCLUSIONS

Soil texture is conventionally derived from the distribution of primary particles, and this remains one of the most practical approaches for characterizing soils and parameterizing soil properties at larger scales. Yet, it does not fully capture soil architecture. Pseudosands mimic sand in size, but our results indicate that they do not in their hydraulic behavior. Across (sub-)tropical soils, pseudosand increased WHC and displayed a markedly different PSD than samples without pseudosands of the same size, with the fine sand fraction showing the strongest divergence despite containing comparatively little pseudosand by mass. This decoupling between pseudosand quantity and functional impact indicates that mass-based corrections, such as sand correction, are insufficient to capture how pseudosands actually shape soil hydraulic properties. Beyond hydrology, particle contacts, pore geometry, and internal porosity also govern soil thermal and gas-transport properties, so the structural distinctiveness of pseudosands may extend to these processes as well. Testing this, together with characterizing pseudosands' role in bulk soil where they co-occur with silt- and clay-sized components, are

natural next steps for establishing pseudosands as a functionally distinct component of soil structure.

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CHAPTER 5 | Conclusion

5.1 | Pseudosands as a blueprint for aggregation

Information on soil texture fails to capture soil structure. Especially in deeply weathered soils, the texture of soils is determined as clayey via standard laboratory protocols, but described as behaving as coarse-textured soils in the field (Lilienfein et al., 1999). Biogeochemical models that built on texture-based assumptions systematically present a mismatch in biogeochemical processes like overestimating N_2O emissions (e.g. Meurer et al., 2016) and assuming saturation where, in reality, water continues to infiltrate and percolate.

Addressing this gap requires first specification on soil structure. The literature offers two dominant answers: aggregates or pores (Baveye, 2020; Kravchenko et al., 2019; Rabot et al., 2018). These two concepts are often treated as competing frameworks, yet the distinction is arguably a false one (Roosch, 2024): the arrangement of particles and aggregates gives rise to pore space, while pore space in turn constrains the very processes that form or transform those aggregates. The surface properties of particles, such as their composition, roughness, and chemical reactivity, govern how substances such as water, nutrients, and organic matter interact within pores, with the association of mineral and organic matter being a prominent example (Totsche et al., 2018). Soil structure, then, is not a binary matrix of pores and non-pore space, but a dynamic space of interaction between solid, liquid, and gaseous phases. It is recursive by nature, where particles combine to form aggregates, whilst the resulting structure feeds back to shape how those same particles continue to transform.

Precisely the volatile and dynamic nature of aggregates is what makes them so difficult to study. Here, pseudosands offer a great opportunity due to their great stability to water. However, the lack of any consistent classification or nomenclature for pseudosands made it difficult to even establish their basic properties or distribution, let alone compare findings across studies (Chapter 2). The argument that differences in resistance to water and crushing are associated with binding and glueing agents could further provide a basis to differentiate pseudosands within water-stable aggregates. Analyzing the state factors behind the formation of water-stable aggregates, we found that water-stable aggregates arise from dynamic water balances within soils, rather than being, as often assumed, predominantly or exclusively a phenomenon of deeply weathered tropical soils. Their formation instead depends on a specific combination of interacting conditions: a *Goldilocks zone* that spans humid and perhumid climates from tropical

to temperate regions. Central to the formation of water-stable aggregates is the presence of drying-wetting phases, acting simultaneously as a stabilizing and selective force (Du et al., 2023): aggregates capable of withstanding these cycles become progressively more stable through repeated wetting and drying. In contrast, those that cannot withstand are chemically weathering and physically comminuting, leaving only the most resilient structures behind. Our findings support the case for a distinct textural subclass, but they also make clear that considerable work remains in defining pseudosands within water-stable aggregates, as the most stable aggregate.

Far from novelty, pseudosands have been described in the literature since the 1960s, but are recently experiencing a renewed wave of scientific interest. This is particularly striking given that they can even visually be distinguished from other soil particles by eye (Chapter 3). Astonishingly, their mechanical stability appears largely independent of aggregate size and remarkably uniform compared to the highly variable energy required to crush singe sand grains. Mechanical stability to crushing therefore has the potential to better describe the energy required to hold particles together (Felde et al., 2020), like the case of pseudosand.

Furthermore, a calculation exercise tested if the assumption that pseudosands can be treated as sand for modeling purposes showed that this approach only works moderately for hydrological purposes, but fails when translating to biogeochemical processes (Chapter 4). When examining hydrological properties as one of these biochemical processes in greater detail, pseudosands exhibited own hydrological behavior, differing from sand without pseudosands in water retention and porosity. Notably, pseudosand quantity alone does not predict its functional hydraulic impact, which further challenges the reductionist ontology in which soil properties are assumed to be fully derivable from the sum of their individual substances and particles. Evidently, the interactions between these constituents also play a defining role in shaping aggregates and pores properties (Ghorbani et al., 2025).

5.2 | Research outlook

Pseudosands are a lens onto much larger and still unresolved processes in pedogenesis: the dynamic reorganization of particles and substances toward a diversity of equilibria. Aggregation, in this sense, never reaches an end state but is an ongoing process, constantly renegotiated between consolidating forces of pedogenesis such as mineral weathering, biological activity, the slow accumulation of binding agents, and the destructive forces of the environment, including raindrop impact, freeze-thaw cycles, or just the sheer passage of time

(Aehnelt & Totsche, 2025). Therefore, rather than a static state, aggregation is a dynamic process that requires to be analyzed also at different space and time scales. This raises a deeper question: is there be a final state to this process at all? Does aggregation ultimately culminate in stable structural endpoints like pseudosands, or does it inevitably reach total dissolution given enough time? Will all soils have water-stable aggregates such as pseudosands at some time and point in their pedogenesis? Answering this would require process-based studies capable of tracking aggregate (trans-)formation over time rather than relying on static snapshots, and could fundamentally reshape how stability itself is defined and measured in soil structure research.

On an applied level, a deeper incorporation of aggregation into urgent contemporary questions is particularly pressing. For example, interactions between microplastics and soil aggregates remain poorly understood (Berenstein et al., 2024; Fang et al., 2024): as microplastic contamination becomes ubiquitous in agricultural soils, understanding how these particles influence aggregate formation, stability and structure is becoming an increasingly important research area in soil science. Moreover, the role of aggregates in long-term carbon storage under climate change scenarios remains also largely unknown: if aggregate stability additionally governs the physical protection of organic matter, then understanding how aggregation processes respond to shifting climatic or land-use conditions is directly linked to whether soils act as a durable carbon sink or a source of future emissions (Nie et al., 2014; Zhou et al., 2023).

For biogeochemical modelling purposes, pseudosands should not merely serve as empirical correction factors, calibrated after the fact to reconcile model predictions with field observations. Rather, their distinct hydrological and biogeochemical behavior should be incorporated into the functional basis of these models, as a mechanistically grounded component of water, nutrient, and gas dynamics. Some progress in this direction has already been made, for instance, through improved formulations of functions such as the van Genuchten equation for water retention, which now account for surface properties in addition to capillary and adsorptive forces (Ghorbani et al., 2025). Extending this kind of mechanistic development to pseudosands specifically would mark a great step toward biogeochemical models that reflect soil structure, rather than relying on soil texture alone with fitted pedotransfer functions or input parameters adjusted merely to match observed values

5.3 | On the transdisciplinary melting pot

The study of soil aggregation has never belonged to a single discipline. It has instead been claimed, examined, and debated by a remarkably diverse range of scientific fields, from

hydrology to microbiology. Each approached similar question through the lens of its own conceptual framework, and their practical and theoretical priorities. Different disciplines often highlight different aspects of the same phenomenon, with the consequence that well-established findings in one field may remain overlooked in another. Australian dune studies offer a striking example: geomorphologists have recognized since the 1930s that aeolian clay mantles, such as parna, form stable aggregates with also sand-like hydraulic behavior (Dare-Edwards, 1984). These particles have remained largely invisible within mainstream soil science. Notably, the pedogenesis of parna is potentially entirely contradictory to that of pseudosands, yet functionally fulfil the function of water-stable aggregates. Moreover, soil engineers such as termites and other soil macrofauna have been described as playing a comparable role in aggregate formation. Aggregates produced by termites persist within the soil matrix due to combination of saliva or other body fluids with soil particles (Ayuke et al., 2019; Jungerius et al., 1999). These examples show how crossing disciplinary boundaries can meaningfully improve our process-level understanding of soil structure.

The very categories used throughout this thesis, from particle-size classes to soil taxonomies to the aggregate definitions proposed here, are not neutral descriptions, but human-made conventions that facilitate communication without necessarily mapping natural boundaries (Churchman, 2010). Standardization enables reproducibility and comparability, as demonstrated by protocols for soil texture determination, yet the same standards that enable comparability must periodically be questioned and revised, to check if they still fit the contemporary status of science. This is particularly relevant for methods that were originally calibrated on far simpler systems, similar to chemical extractions being calibrated on pure minerals (Stein et al., 2026), whilst dismissing the diversity and complexity of natural systems. This calls primarily for a mutual understanding and reflexivity amongst scientists: we must be more explicit about why certain categories, or classifications are foregrounded over others (Churchman, 2010).

As this thesis has shown through the case of pseudosands, no single discipline holds a complete picture of soil structure. Sometimes, advancing understanding requires crossing disciplinary boundaries and revisiting objects that have quietly receded into the background of scientific attention. Pseudosands are precisely such a case: described decades ago, but never fully understood, are now meeting analytical tools capable of better explaining them and their effects within the soil matrix. Civilizations may rise from the soil, but potentially it is in structures no larger than a grain of sand that we find what sustains them.

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SUPPLEMENTARY MATERIAL

For Chapter 2

Additional information and metadata of this review can be found at DOI: 10.5281/zenodo.20821786

Table S2-1. *Number of total publications retrieved from each database at every filtering step. Step 1 - Initial hits: All publications returned by the initial database search before any filtering. Step 2 - Unique records: Duplicate publications appearing across multiple search approaches were identified and removed, keeping only the first occurrence. Step 3 - Keyword filtering: Publications were screened by keyword to exclude studies not focused on soils (e.g., road construction, pure microbiology, or pure chemistry). Step 4 - Geolocation availability: Remaining publications were checked for extractable geolocation data, using AI-assisted approximation where possible, though some - particularly older studies - lacked any retrievable information on geolocation. Step 5 - Spatial buffering: A ~5.565 km buffer (3 arc-minutes at the equator) was applied around each point to reduce strong spatial clustering (e.g., around research stations) and minimize spatial autocorrelation.*

	Review approach	**Database**	**Number of papers**				
			Initial hits	**Accessible and unique records**	**Keyword filtering**	**Geo-location availabi-lity**	**Spatial inde-pendence**
A	Protocol-derived	SCOPUS	27	27	19	14	13
B			72	69	65	56	48
C		Web of Science - All Databases	19	2	2		
D			69	19	18	16	15
E	Cross-lingual	SCIELO	2	2			
F			31	31	29	27	23
G		REDALYC	9	7	4	4	4
H			10	10	5	4	3
I		African Journals Online (AJOL)	1	1	1	1	1
J			20	20	17	9	8
K	Manually-curated		30	30	30	28	28
	Total		290	218	190	159	143

Table S2-2. *Distribution of data points to Holdridge Life Zones (HLZ) after Jungkunst et al. (2022) in comparison to global distribution. Goldilocks zone was identified for humid and perhumid provinces within tropical to cold temperature latitudinal regions. P-D= protocol-derived approach, C-L = cross-lingual approach, M-C = manually-curated represent the hits in the multi-approach review. The ratios were calculated as the proportion of the global distribution to the number of data points to evaluate under- or overrepresentation of determined HLZ classes.*

Main class	**Type**	**Global distribution [%]**	**Number of data points from review**			**ratios**			
			P-D	**C-L**	**M-C**	**P-D**	**C-L**	**M-C**	**total**
tropical	perhumid	2.76	4	6	7	0.5	1.5	1.4	1.0
	humid	3.54	23	7	16	2.1	1.3	2.5	2.0
	other	6.04							
subtropical	super humid	1.50	0	0	1	0.0	0.0	0.4	0.1
	perhumid	8.18	29	49	51	1.1	4.0	3.4	2.4
	humid	4.52	11	0	2	0.8	0.0	0.2	0.4
	subhumid	2.51	3	1	0	0.4	0.3	0.0	0.2
	semi-arid	3.15	1	0	0	0.1	0.0	0.0	0.0
	other	4.32							
warm	super humid	0.12	0	1	1	0.0	5.6	4.5	2.6
temperate	perhumid	1.77	18	2	2	3.2	0.8	0.6	1.9
	humid	2.06	10	0	0	1.5	0.0	0.0	0.8
	subhumid	1.44	3	0	0	0.7	0.0	0.0	0.3
	other	1.76							
cold	super humid	1.01	3	0	0	0.9	0.0	0.0	0.5
temperate	perhumid	6.23	25	0	1	1.3	0.0	0.1	0.6
	humid	5.43	9	0	0	0.5	0.0	0.0	0.3
	other	3.53							
other	other	40.13							

Table S2-3. *Distribution of data points on the main classes of bedrock* from the *Global Lithological Map (GLiM) by Hartmann & Moosdorf (2012) in comparison to their global distribution. P-D= protocol-derived approach, C-L = cross-lingual approach, M-C = manually-curated represent the hits in the multi-approach review. The ratios were calculated as the proportion of the global distribution to the number of data points to evaluate under- or overrepresentation of determined bedrock types and classes.*

Main class	**Type**	**Global distribution [%]**	**Number of data points from review**			**ratios**			
			P-D	**C-L**	**M-C**	**P-D**	**C-L**	**M-C**	**total**
sedimentary	unconsolidated	16.39	32	15	25	1.0	1.0	1.3	1.1
	siliciclastic	13.25	30	17	15	1.2	1.4	1.0	1.2
	mixed	13.32	11	2	13	0.4	0.2	0.9	0.5
	carbonatic	5.79	11	2	0	1.0	0.4	0.0	0.6
	evaporites	0.18							
metamorphic	metamorphic	10.23	26	18	19	1.3	1.9	1.6	1.5
magmatic	basic	2.93	12	5	5	2.1	1.9	1.5	1.9
volcanites	intermediate	1.45	5	1	1	1.8	0.7	0.6	1.2
	pyroclastics	0.45	5	1	1	5.6	2.4	1.9	3.9
	acid	0.78	2	0	0	1.3	0.0	0.0	0.6
magmatic	acid	4.82	5	4	2	0.5	0.9	0.4	0.6
plutonites	basic	0.74							
	intermediate	0.32							
other	water, ice, glaciers	29.35							
	no data		0	1	3				

Table S2-4. *Distribution of data points on the WRB classification of soil types (HWSD 1.2) in comparison to their global distribution. Overlapping and common properties between soil types are described in the column "Commonality". P-D= protocol-derived approach, C-L = cross-lingual approach, M-C = manually-curated represent the hits in the multi-approach review. The ratios were calculated as the proportion of the global distribution to the number of data points to evaluate under- or overrepresentation of determined soil types.*

Commonality	**Type**	**Global distribution [%]**	**Number of data points from review**			**ratios**			
			P-D	**C-L**	**M-C**	**P-D**	**C-L**	**M-C**	**total**
	ferralsol	4.43	19	35	34	2.4	9.3	7.1	5.4
	cambisol	7.54	22	4	9	1.6	0.6	1.1	1.3
	plinthosol	0.74	4	0	1	3.0	0.0	1.3	1.8
	andosol	0.68	2	2	0	1.6	3.5	0.0	1.6
argic	acrisol	4.53	6	4	17	0.7	1.0	3.5	1.6
argic	lixisol	1.37	11	1	7	4.5	0.9	4.7	3.7
argic	luvisol	5.38	15	1	0	1.6	0.2	0.0	0.8
argic	nitisol	0.80	3	6	0	2.1	8.8	0.0	3.0
argic	alisol	0.26	4	0	0	8.6	0.0	0.0	4.1
low developed	leptosol	11.28	11	3	4	0.5	0.3	0.3	0.4
low developed	arenosol	5.65	2	0	5	0.2	0.0	0.8	0.3
low developed	veticol	1.74	3	0	0	1.0	0.0	0.0	0.5
low developed	regosol	8.67	1	0	0	0.1	0.0	0.0	0.0
hydromorph	fluvisol	2.72	7	1	0	1.4	0.4	0.0	0.8
hydromorph	gleysol	6.17	3	2	2	0.3	0.4	0.3	0.3
hydromorph	planosol	0.55	3	0	0	3.1	0.0	0.0	1.5
	phaeozems	2.03	9	6	3	2.5	3.5	1.4	2.4
	kastanozem	2.67	5	0	0	1.0	0.0	0.0	0.5
	solonetz	1.36	1	1	0	0.4	0.9	0.0	0.4
	anthrosol	0.35	3	0	0	4.8	0.0	0.0	2.3
	urban	0.02	2	0	0	56.0	0.0	0.0	26.9
	podsol	6.57	1	0	1	0.1	0.0	0.1	0.1
	podzoluvisol	2.35	1	0	0	0.2	0.0	0.0	0.1
	water	1.06	1	0	0	0.5	0.0	0.0	0.3
	no data		0	0	1				
	other	21.08							

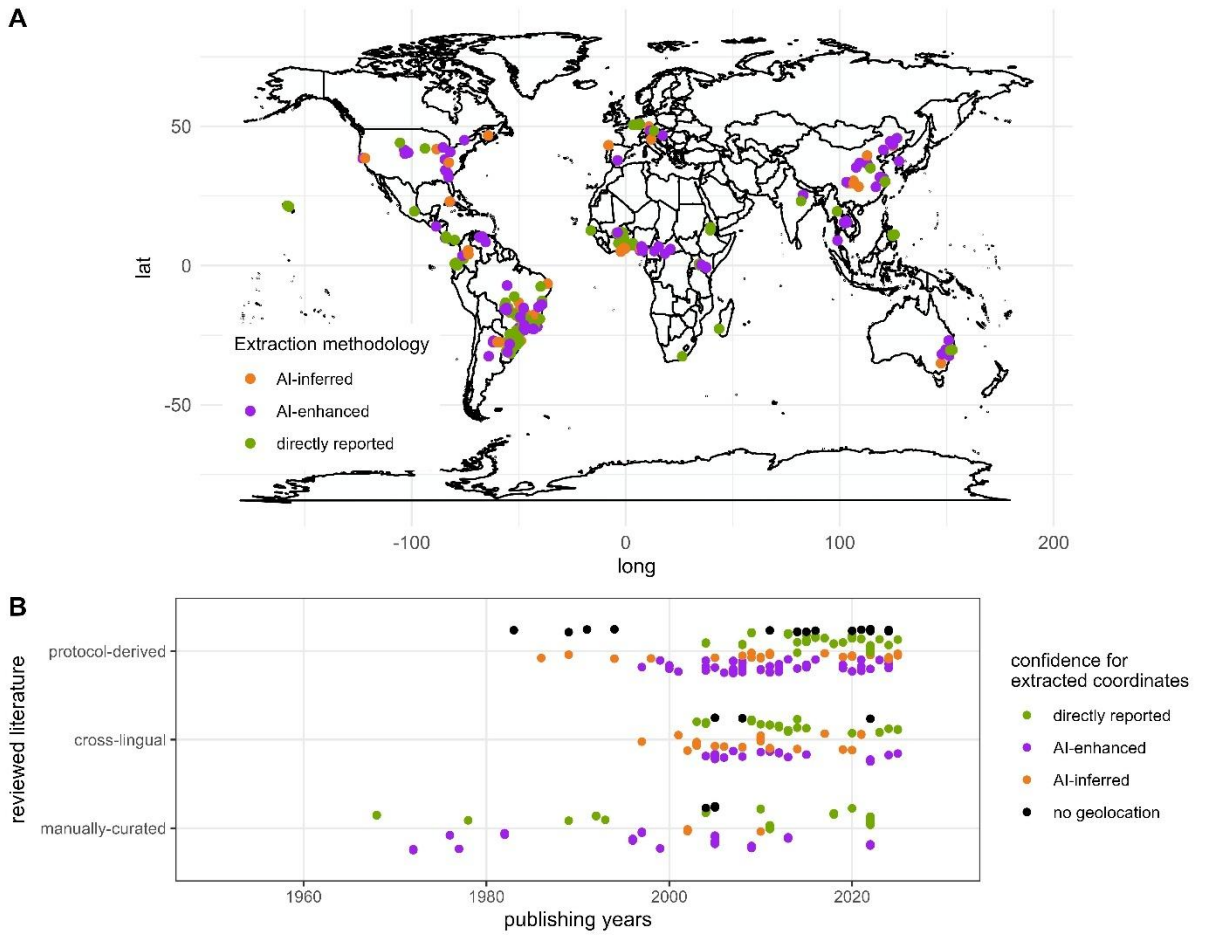


Figure S2-1. (A) *Distribution of data points of reviewed literature presented in this paper for different coordinate extraction methods, and* ***(B)*** *coordinate extraction confidence of all databases in relation to directly reported data points and data points where AI helped to extract information of geolocation for years of publication publishing. Further information in Zenodo repository.*

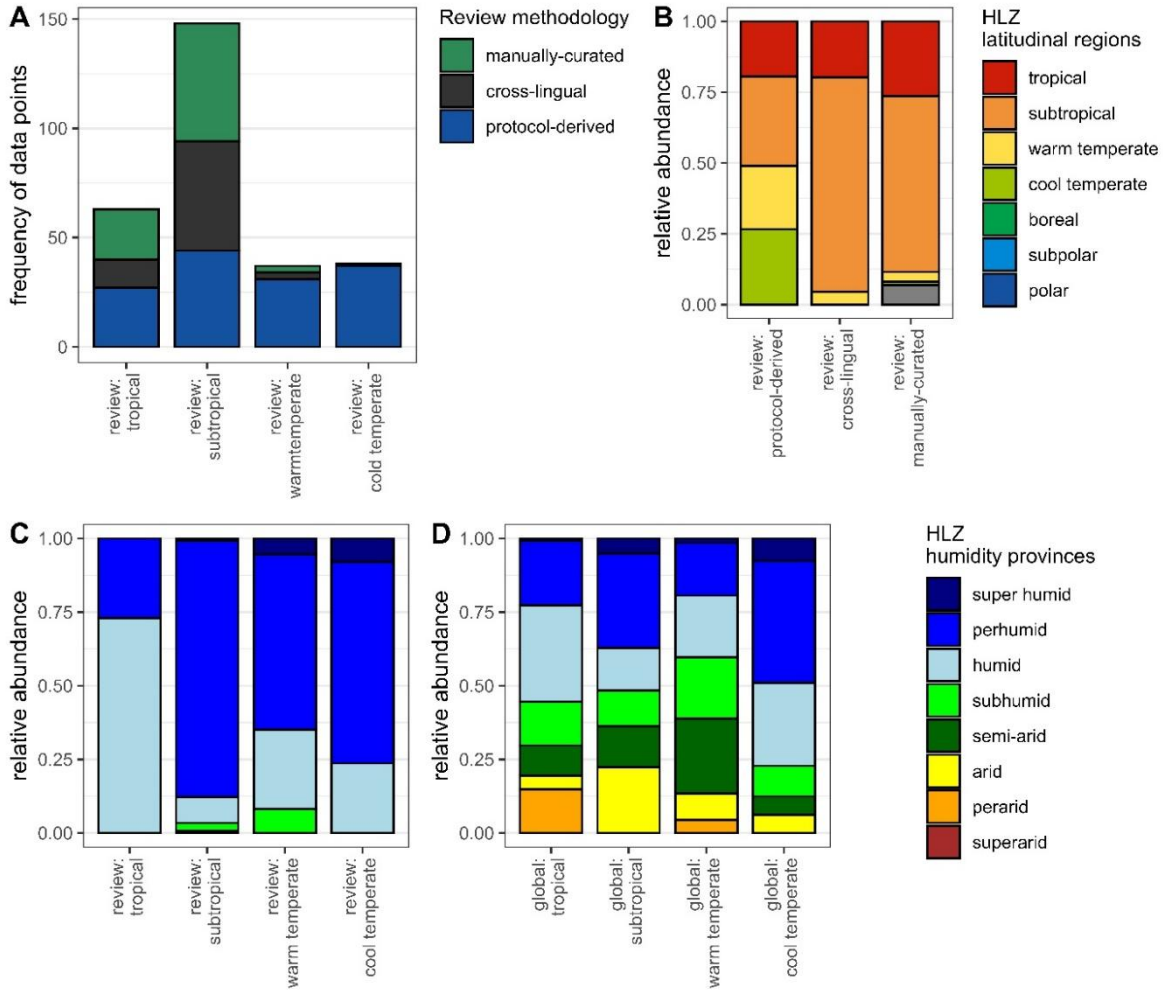


Figure S2-2. (A) *Frequency of data points from review separated in search approaches for HLZ latitudinal regions;* ***(B)*** *proportion for each HLZ latitudinal region for search approaches. Humidity provinces within HLZ latitudinal regions for* ***(C)*** *data points from the review, and* ***(D)*** *global land surfaces. Superarid surfaces are too small to be visible in the barplot. Further information in Table. S2-2.*

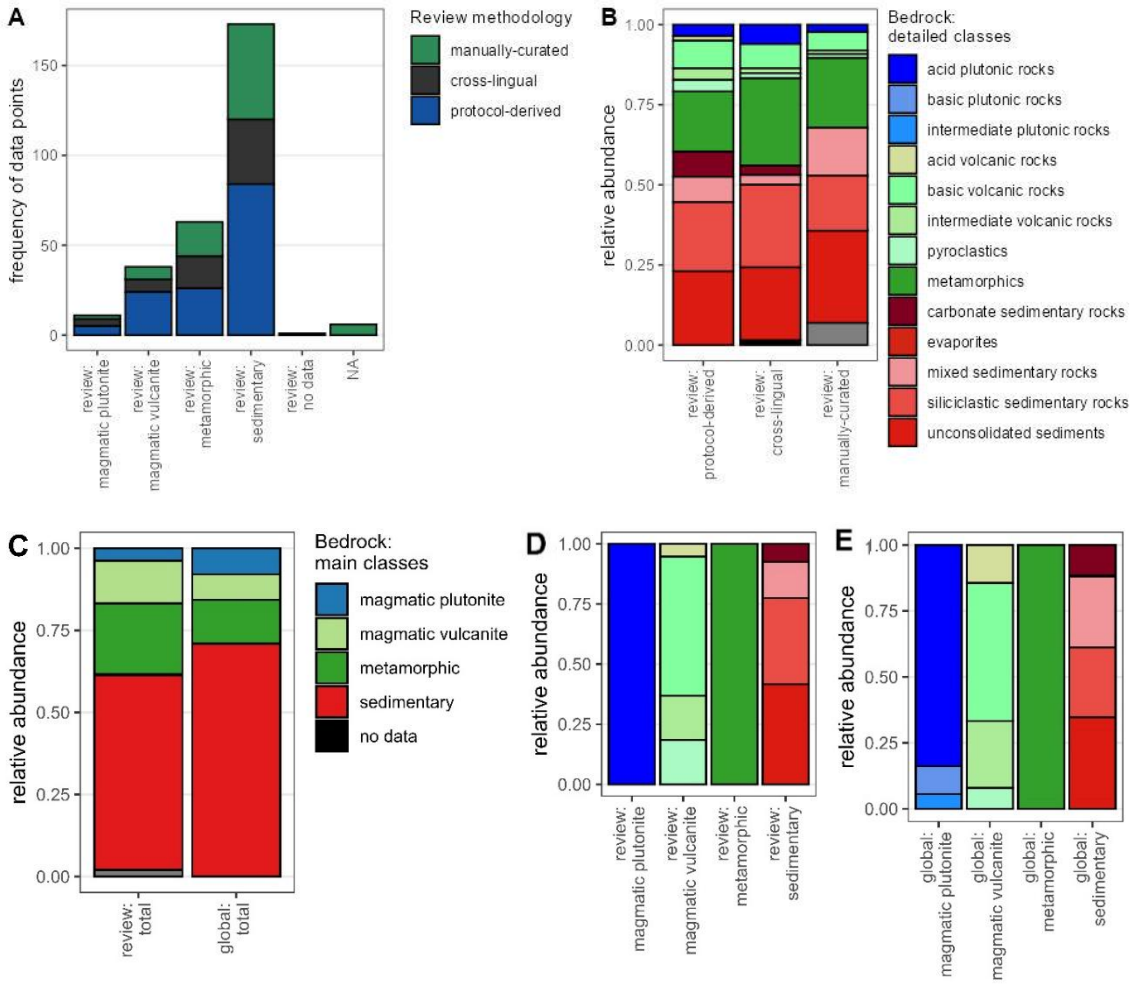


Figure S2-3. ***(A)*** *Frequency of data points from review separated in search approaches for bedrock classes,* ***(B)*** *relative weights for each search approach for detailed classes,* ***(C)*** *relative abundances of review hits and global surfaces for bedrock main classes. Relative abundances of details bedrock subclasses for* ***(D)*** *review and* ***(E)*** *global surfaces. Further information in Table S2-3.*

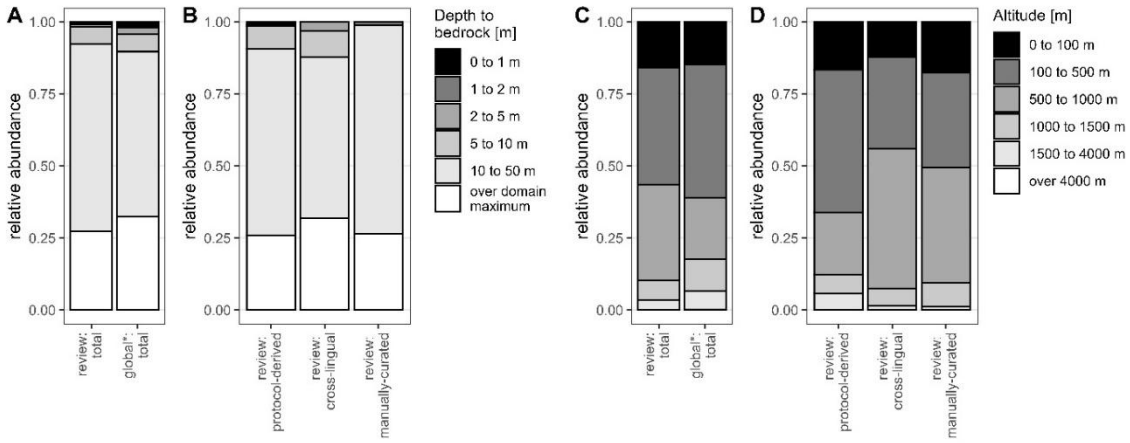


Figure S2-4. *Distribution of depth to bedrock at* ***(A)*** *global scale and results from the review, and* ***(B)*** *sampling sites from reviewed literature within each search approach. Depth to bedrock was capped at 50 m following the maximum detection depth specified in Hengl et al. (2017) as it reached the maximum domain. Additionally, altitudinal data at* ***(C)*** *global scale and results from the review, and* ***(D)*** *sampling sites from reviewed literature within each search approach. Global distribution for latitudinal ranges from tropical to cold temperate (marked with star *) was selected as comparison to review data.*

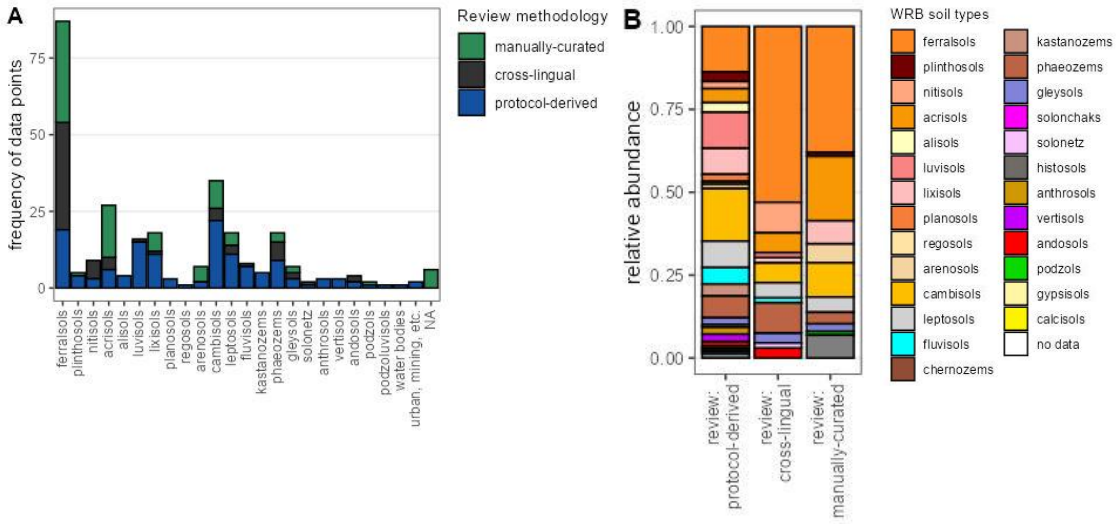


Figure S2-5*. (A) Absolute frequency of data points from reviewed literature for each search approach for soil types after WRB (HWSD, version 1.2) and (B) relative weights of soil types for each search approach. Further information in Table S4-4.*

Prompt for coordinate extraction used in AI to get an approximated sampling location where no detailed information was given in publications. AI tool used here was ChatGPT.

> "I will provide you with a section of a research paper that may contain location descriptions (for example in text, tables, or figure captions).
>
> Your task is to:
>
> Extract all GPS coordinates you find, written in degrees–minutes–seconds (DMS) or any other format
>
> If no explicit coordinates are provided, or if they are only partially specified (e.g., only the site name or an approximate region or only degrees or degrees–minutes), use the description in the text to give the best possible spatial approximation of the sampling site, clearly marking it as "approximate".
>
> For each extracted or inferred location, include:
>
> Original text (verbatim)
>
> Normalized decimal coordinates (WGS-84)
>
> Confidence level (high / medium / low)
>
> A short note about any assumptions made"

The prompt was improved if no approximation was reached or evident hallucination was present.

For Chapter 3

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Table S3-1. *Overview of samples composed of different sizes, origin, (chemical) treatment and classes of water-stable particles for testing specific properties of pseudosands in comparison to sand.*

Name	Particle classes	Treatment	Origin	Sizes	Measurements
PS-mixture	All sand-sized and water-stable aggregates and particles (including pseudosands)	Wet sieving	Soil samples from Brazilian Ferralsols	FS, MS, CS	Visual microscopy, EDS, contact angle
QS	Sands	Chemical dispersion as standard laboratory procedures dictate*	Soil samples from Brazilian Ferralsols	FS, MS, CS	Contact angle
CAS	Quartz sands	Wet sieving	Commercially available, Carl Roth® (#7898.1; Karlsruhe, Germany)	FS, MS, CS	Contact angle
PS-single	Pseudosands	Hand-picked after optical identification	From PS-mixture	CS	Crushing
S-single	Not Pseudosands	Hand-picked after optical identification	From PS-mixture	CS	Crushing

* Treatment of samples with sodium dithionite ($Na_2S_2O_4$) as the reducing agent and 0.05 M $Na_4P_2O_7$ as dispersion substance. Organic matter was scarce; therefore, treatment with hydrogen peroxide treatment was skipped. The presence of carbonates could be ruled out due to the acidic pH (Strey et al, 2016).

SUPPLEMENT II with further methodological details

For the **particle crushing**, the loading frame was equipped with a high-resolution load cell (Xforce HP 10 N and Xforce HP 100 N). Preliminary data showed that the 10 N cell was sufficient to crush pseudosands (PS-single), but not all other water-stable aggregates (S-single, Table S3-1). Single particles were placed on the table of the loading frame. Subsequently, the distance between load cell and table was reduced from 1.5 mm to 50 µm at a constant speed of 250 µm min^{-1} to ensure that the particles are completely crushed. The mechanical energy required to crush each microaggregate was recorded and the work, which equals to the area of the load–displacement curves, was normalized by the particles size, which resulted from the distance to first contact between load cell and particle. During the crushing process, PS-single samples underwent fragmentation, although without breaking apart. This occurred at approximately 75% of the grain size, which translates to the higher peaks. The S-single samples experienced spontaneous splitting, which translate to high number of peaks (Figure S3-1).

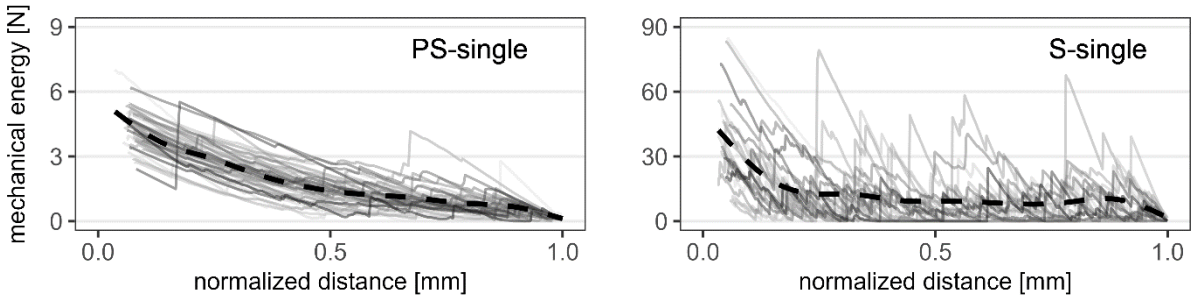


Figure S3-1. *Mechanical energy required to crush each microaggregate all within the CS fraction size, normalized to the particles size.*

Energy dispersive spectroscopy (EDS) was performed using a Hitachi SU3900 scanning electron microscope (SEM), which employs variable pressure. Images were collected using Oxford EDS system. This system benefits from not having to coat samples with a conductive surface to minimize charging. Uncoated samples were probed for secondary electrons and backscattered electrons. Elemental mapping allowed imaging of major chemical compositions.

For the **model manipulation experiment**, the soil texture was manipulated during each of the three periods, with clay and/or silt content reduced in increments of 25% up to a depth of 1 m, which automatically led to an increase in sand content throughout the entire soil profile. Soil hydraulic parameters were determined using the pedotransfer functions from Ottoni et al. (2018 for hydraulic conductivity) and Tomasella and Hodnett (1998 for field capacity and permanent wilting point). These parameters were then used as input for modelling soil water content

[vol%] and N_2O emissions [kg ha^{-1} d^{-1}]. Intense precipitation events within the 99% percentile of daily precipitation in 2013 (Figure S3-2) were used to identify three artificial periods (start, middle, and end) to describe changes in the general wetness with ongoing time. After each of these strong precipitation events, the model's performance significantly deteriorated, particularly for soil water content.

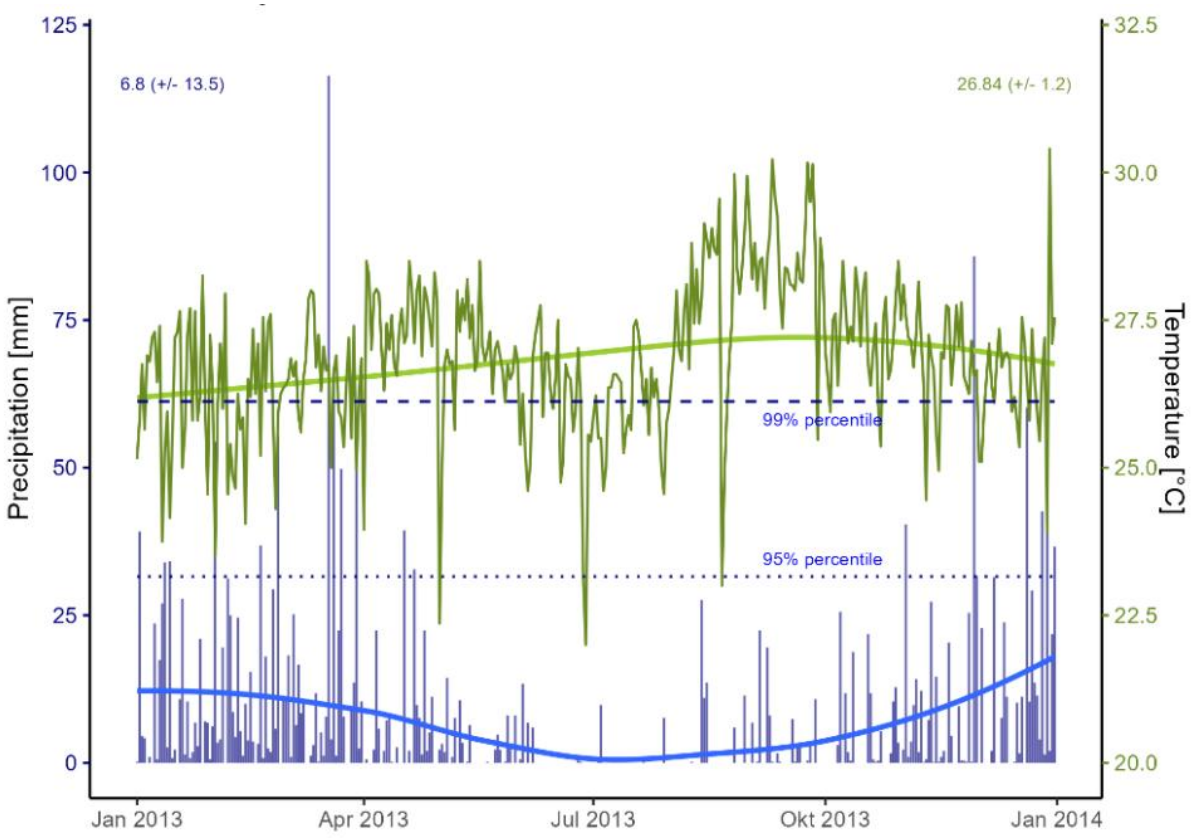


Figure S3-2. *Overview of climatic data for the year 2013 in Pará (Brazil) at the sampling site.*

For Chapter 4

Metadata on pF curves can be found at DOI: 10.5281/zenodo.21911531.

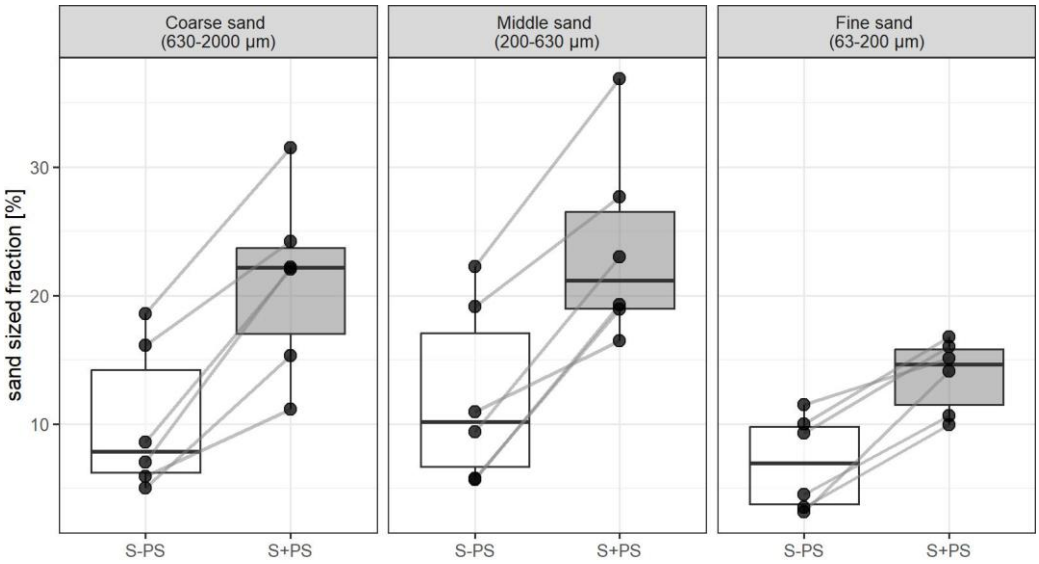


Figure S4-1. *Relation of sand with (S+PS) and without pseudosand (S-PS) in different size fractions. This subset of samples was used as calibration of dataset.*

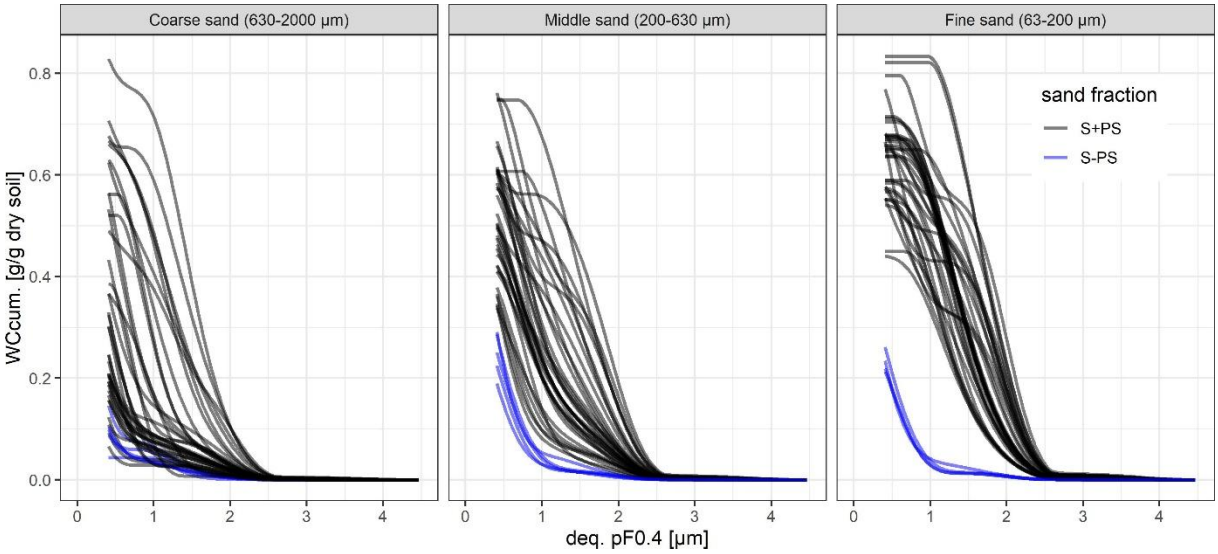


Figure S4-2. *pF curves based on ^{1}H-NMR relaxometry measurements at saturation for different sand size fractions for samples containing pseudosand (S+PS) and without pseudosand (S-PS).*

Table S4-1. *Further information of sampling sites: Holdridge Life Zone from Jungkunst et al. (2022), and number of samples (n) from each site which represent different sampling depths up to 1 m.*

Site	ID	Latitude	Longitude	n	Holdridge Life Zone
Brazil	Pasture 1987	-7.1762556	-55.3739972	4	tropical
Brazil	Pasture 1988	-7.1746972	-55.3671028	4	tropical
Brazil	Pasture 1998	-7.1836139	-55.4016	4	tropical
Brazil	Floresta	-7.1792667	-55.3823444	4	tropical
Australia	Cudgen	-28.26087538	153.5547373	1	subtropical
Australia	Baradine	-30.8857431	149.2635272	1	subtropical
Uganda	Sugarcane - 50yrs	1.68503	31.49605	4	subtropical
Uganda	Forest Control	1.73928	31.53406	4	subtropical

Table S4-2. *Descriptive statistics for pseudosand content [in %] in S+PS samples, differentiated by sample origin.*

	All	Tropical	Subtropical
Min	0.0837	3.361	0.0837
1st Qu.	9.8242	13.877	8.7553
Median	17.1348	16.755	19.9748
Mean	19.0374	16.260	23.4813
3rd Qu.	22.9860	20.507	40.3917
Max	55.0648	26.426	55.0648

Table S4-3. *Significant results (p.adj. < 0.05) of Wilcoxon rank-sum tests calculated for each pore- and particle-size class. N1 and N2 = number of observations in the two compared groups; W = test statistic; p.adj. = p-value adjusted for multiple comparisons using the Holm method.*

Pore size classes	Within…	Group1	Group2	N1	N2	W	p.adj.
Wide coarse	S+PS	Coarse sand	Fine sand	26	26	623	< 0.001
Narrow coarse				26	26	51	< 0.001
Medium				26	26	89	< 0.001
Fine				26	26	95	< 0.001
Wide coarse	S+PS	Coarse sand	Middle sand	26	26	581	< 0.001
Narrow coarse				26	26	92	< 0.001
Medium				26	26	139	< 0.001
Fine				26	26	135	< 0.001
Wide coarse	Middle sand	S+PS	S-PS	26	5	0	< 0.001
Wide coarse	Fine sand			26	4	0	< 0.001
Narrow coarse	Middle sand			26	5	130	< 0.001
Narrow coarse	Fine sand			26	4	104	< 0.001
Medium	Middle sand			26	5	130	< 0.001
Medium	Fine sand			26	4	104	< 0.001
Fine	Middle sand			26	5	130	< 0.001
Fine	Fine sand			26	4	104	< 0.001

Table S4-4. *Textural data of samples with (S+PS) and without (S-PS) pseudosands differentiated by size and CS = Coarse Sand, MS = Middle Sand; FS = Fine Sand.*

Sample-ID.		**Depth**	**S-PS**						**S+PS**			
		cm	**Sand**	**Silt**	**Clay**	**CS**	**MS**	**FS**	**CS**	**MS**	**FS**	**Silt + Clay**
Brazil	Pasture 1987	0 to 10	36.4	20.1	43.5	8.6	5.7	4.5	22.1	18.9	10.6	48.4
		10 to 30	30.7	14.2	55.1				15.0	14.6	11.6	58.8
		30 to 60	27.0	11.9	61.1	5.9	10.9	10.0	11.1	16.5	16.8	55.7
		60 to 100	28.3	13.6	58.1				12.2	13.1	18.2	56.5
	Pasture 1988	0 to 10	33.3	17.3	49.4				33.9	19.1	6.7	40.3
		10 to 30	28.8	9.1	62.1				21.7	19.3	8.2	50.9
		30 to 60	23.9	7.4	68.7				20.1	17.1	9.6	53.1
		60 to 100	27.0	4.6	68.3				19.5	18.4	11.3	50.8
	Pasture 1998	0 to 10	73.9	5.5	20.6	18.6	22.2	11.5	31.5	36.9	15.1	16.5
		10 to 30	56.0	8.9	35.1				30.1	27.1	14.9	27.9
		30 to 60	64.5	6.9	28.6	16.1	19.1	9.3	24.2	27.7	16.0	32.1
		60 to 100	58.8	8.2	33.0				27.3	24.1	14.5	34.2
	Floresta	0 to 10	36.0	7.2	56.9	7.0	9.4	3.5	22.2	23.0	9.9	44.9
		10 to 30	32.8	9.2	58.0				19.5	19.1	9.2	52.2
		30 to 60	29.9	8.4	61.7	5.00	5.7	3.2	15.3	19.3	14.1	51.3
		60 to 100	28.5	6.6	64.8	8.6	5.7	4.5	14.2	19.2	16.1	50.5
Australia	Cudgen	0 to 20	34.3	34.3	31.4				40.4	25.4	8.8	25.3
	Baradine	0 to 20	81	7	12				62.4	23.8	4.6	9.2
Uganda	Sugarcane	0 to 10	55	27	18				13.3	22.9	19.9	43.9
		10 to 30	55	21	23				11.4	25.2	18.6	44.9
		30 to 50	49	14	38				11.7	27.0	19.0	42.2
		50 to 100	46	25	29				24.3	37.0	21.4	17.3
	Forest	0 to 10	52	21	27				13.2	34.1	21.6	31.1
		10 to 30	47	18	35				17.2	33.0	19.8	30.0
		30 to 50	33	13	54				22.9	32.6	20.5	24.0
		50 to 100	29	15	56				24.7	37.5	21.9	15.9

DECLARATION

Declaration according to §8 of the Promotionsordnung of the Faculty for Natural and Environmental Sciences (Fachbereich Natur- und Umweltwissenschaften) of the Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Campus Landau (14.06.2013, last updated 19.08.2014):

I hereby declare that this dissertation entitled "A Renaissance of Pseudosands: On Improving the Understanding of Soil Architecture in Deeply Weathered Soils" is my own work. All aids and sources have been specified and the contribution of other authors has been documented and referenced.

I further confirm that this thesis has never been submitted for the award of any other degree at any university or other tertiary institution. I am aware that a violation of any of the aforementioned points may result in the withdrawal of the doctoral degree and may also have further legal consequences.

Simone Kilian Salas

Landau, 7th of October 2026

DECLARATION ON THE USE OF AI

The author of this thesis used generative AI tools (Claude AI) to improve the language and readability of this thesis. Most relevant prompt: "*Improve the clarity and readability of this text*".

All content modified with AI assistance was subsequently reviewed and edited by me and I take full responsibility for the accuracy and integrity of the final text.

Simone Kilian Salas

Landau, 7th of October 2026

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We are living in urgent times that demand ecological and societal responsibility if we hope to secure a sustainable and just future. This means embracing a responsible use of resources,

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ATTENDED CONFERENCES

Total number of contributions as posters or talks: 10 as first author + 10 as co-author

Kilian Salas, S., Meurer, KH. E, Andrino, A., Tamale, J., Singh, B., Díaz García, E., Guggenberger, G., Boy, D., & Jungkunst, H.F. (2025) Revisiting soil architecture in deeply weathered soils through the effect of pseudosands on soil hydrology. *General Assembly American Geoscience Union (AGU), New Orleans, USA* – **poster**

Kilian Salas, S., Meurer, KH. E., Andrino, A., Tamale, J., Singh, B., Díaz García, E., Guggenberger, G., Boy, D., & Jungkunst, H.F. (2025) Challenging structure in deeply weathered soils: Pseudosands' potential distribution and effects on soil hydrology. *General Assembly of Association for Tropical Biology and Conservation (ATBC), Oaxaca, Mexico* – **oral presentation**

Kilian Salas, S., Meurer, K.H.E., Andrino, A., Tamale, J., Singh, B., Guggenberger, G., Díaz García, E., Boy, D., & Jungkunst, H.F. (2025) Where and how does pseudosand drive soil biogeochemistry and hydrology? *Biennial Meeting of Deutsche Bodenkundliche Gesellschaft (DBG), Tübingen, Germany* – **oral presentation**

Kilian Salas S., Boy, D., Díaz García, E., Andrino, A., Horn, M.A., Boy, J., Guggenberger, G., & Jungkunst, H.F. (2024) Exploring N_2O emissions as early warning indicators for tipping points in Amazonian soils. *Centennial of the International Union of Soil Sciences (IUSS), Florence, Italy* **– oral presentation**

Kilian Salas, S., Schroeder, P.A., & Jungkunst, H.F. (2023) Reconstructing pseudo-sands to improve our understanding of tropical soil biogeochemistry. *Biennial Meeting of DBG, Halle (Saale), Germany* – **poster**

Kilian Salas, S., Schroeder, P. A., K. Woche, S.K., Peth, S., Boy, J., Guggenberger, G., & Jungkunst, H.F. (2023) Do pseudo-sands' internal structures determine biogeochemistry of tropicals' critical zone? *GEOBerlin Conference, Berlin, Germany* – **oral presentation**

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