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Invited Opinion

Planetary pedology: New horizons for lunar resource mapping

Space agencies, private organizations, and advocacy groups are working to establish a sustainable human presence on the Moon and Mars in the coming decades, which necessitates *in situ* resource utilization. Regolith, the most accessible resource, offers opportunities to extract rare elements and produce high-strength structural materials for habitats. It could also serve as a substrate for food production, functioning similarly to soil on Earth, which is crucial for establishing future extraterrestrial human settlements. Much like the Industrial Revolution on Earth, the demand for resources requires detailed mapping of the surfaces of the Moon and Mars, raising questions about suitable mapping methods and the classification of incoherent materials. We propose that lunar regolith can be classified as soil and assess the applicability of established terrestrial soil nomenclatures, such as the World Reference Base for Soil Resources and the US Soil Taxonomy, for this purpose. We conclude that these systems are not inherently applicable and would require substantial modifications and/or additions to accommodate the unique characteristics encountered. Consequentially, we advance a new nomenclature for lunar soils that highlights differences in pedogenic processes on the Moon, compared to those on Earth.

Since the 2010s, various space agencies and commercial entities have renewed their interest in the Moon, viewing it as a platform for economic development beyond Earth and as a stepping stone for missions to Mars and beyond. Establishing human settlements on the Moon and Mars is becoming increasingly plausible, although current technology is not yet fully reliable (Jakosky and Edwards, 2018). A sustainable human presence on these celestial bodies will depend on *in situ* resource utilization (ISRU), which involves the extraction and processing of materials for fuel, life support, and manufacturing. The first step of ISRU involves detecting and assessing potentially useful materials, including mapping to better understand geographical variations in the composition, quantity, and quality of rocks and regolith or soil. This advancement has sparked a new field of study, known as "planetary pedology", which encompasses the study of both paleosols and contemporary extraterrestrial soils (Retallack, 2016).

On Earth, the Industrial Revolution spurred societies to develop standardized methods for exploring mineral resources. This period led to the establishment of state geological surveys in Western countries, initially tasked with mapping mineral resources and later expanding to include soil mapping. The integration of geological and pedological mapping not only facilitated resource classification but also significantly enhanced scientific understanding of Earth's surface. With interplanetary exploration gaining momentum in recent years due to scientific and economic interests (Elvis, 2012), the Moon and Mars have become prime targets for future missions. The search for *in situ* resources to support these activities is a top priority for both crewed and unmanned missions. The prospect of a human presence on the Moon even suggests the onset of a new geological era, the Lunar Anthropocene (Holcomb *et al*., 2024), akin to Earth's Anthropocene, in which human activities "shape" the planet. Like the 19th-century rush for mineral resources, the groundwork for human settlement on the Moon involves active mapping efforts to locate resources (Ming and Henninger, 1994). This raises fundamental questions about the surface types of rocky planetary bodies in our Solar System and the best methods to classify and map them.

Regolith is a term commonly used in planetary sciences for referring to the layer of fragmental, unconsolidated mineral material, whether residual or transported, that covers the surface of nearly all rocky celestial bodies (Lucey *et al*., 2006). However, the concept of soil is increasingly compatible with extraterrestrial environments, as several recent definitions of soil no longer claim the occurrence of life but only the evidence of mineral weathering (Johnson, 1998; Banin, 2005; Certini and Ugolini, 2013). Soderblom *et al*. (2004) considered any loose, unconsolidated materials distinct from rocks or cohesive sediments to be soil on Mars, without implying the presence of organic matter, while McKay *et al*. (1991) and Banin (2005) argued that Martian soils are defined by attributes that regolith does not have. In this context, using the term soil in place of regolith is becoming more widely accepted (Huggett, 2023). The soils of extraterrestrial bodies exhibit unique properties due to distinctive physical and chemical forming processes, such as space weathering and repeated meteorite impacts (Certini *et al*., 2009).

Our Moon is the initial target for ISRU mapping. Lunar soils are layered, poorly sorted, and fine grained (Heiken *et al*., 1973; Duke and Nagle, 1975; Lindsay, 1976) (Fig. 1). The bulk of lunar soils consists of particles < 1 cm in size, with cobbles and boulders, some as large as several meters across. While sand and silt dominate the fine fraction (Kiely *et al*., 2011), recent findings from China's Chang'e-5 mission have also identified clay-sized particles (< 2 μm) (Li *et al*., 2022). Lunar soils reflect the mineralogy of crystalline bedrocks, mixed with secondary particles from meteorite impacts. However, they undergo continuous

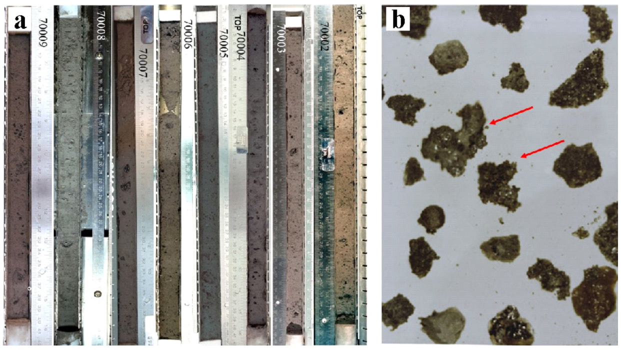

Fig. 1 Compiled image showing the succession of Apollo 17 soil cores from 70009 to 70002, with variation in color similar to Earth soil horizons and layers (a) and image showing typical agglutinates (indicated by red arrows) separated from the 240–500 µm fraction of Apollo 11 soil sample 10084 (b) (images compiled by the authors and reproduced from the National Aeronautics and Space Administration Johnson Space Center Lunar Sample Catalog (https://curator.jsc.nasa.gov/lunar/cores/cores.cfm)).

evolution, a process known as gardening, which involves comminution and agglutination of particles (Heiken *et al.*, 1973; Butler and King, 1974). Finer-textured soils often exhibit better sorting and contain more agglutinates. These are rounded particles composed of dark brown to black glass and mineral grains, with a chemical composition similar to that of the bedrock. Lindsay (1976) described three stages of textural maturity: comminution-dominated, agglutination-dominated, and steady state, all of which are influenced by impacts that can disrupt agglutinate populations. Equilibrium soils result from repeated exposure to lunar weathering and micrometeoroid impacts, which maintain stable grain sizes. Lunar soils originate from billions of years of continuous bombardment by meteorites, galactic high-energy particles, and the solar wind, which break down and mix initial rocks and their fragments. This comminution process, along with erosion, deposition, and the embedding of solar wind gases, transforms regolith into soil rather than just crushed rock. Soil maturity on the Moon is indicated by particle size distribution and the abundance of agglutinates (with soils finer and richer in agglutinates being more mature).

The final product of lunar soil evolution, termed steady-state soil, balances the pulverization by micrometeorites with processes of agglutination and replenishment of coarser particles (McKay *et al.*, 1974). Planetary scientists evaluate the maturity of the lunar surface based on variables such as agglutinate content and the ratio of the amount of iron (Fe) in the space weathering-induced nanophase state, characterized by a grain size on the order of nanometers and exceptional tensile strength, to total Fe (I_s/FeO, a maturity index) (Morris, 1976). In the literature, I_s/FeO values are often reported as whole numbers but implicitly represent a ratio multiplied by 100 for clarity. This ratio categorizes lunar soils into immature (I_s/FeO $=$ 0–30), submature (I_s/FeO $=$ 30–60), and mature (I_s/FeO > 60), providing a framework for understanding soil evolution despite occasional disturbances, such as meteorite impacts, that can disrupt mature soils and create new deposits (Fig. 2). In regions with relatively few impact craters, agglutinate content is believed to increase as lunar soil undergoes prolonged exposure to space weathering, which underscores the utility of the I_s/FeO ratio as a "maturity index".

Fryxell *et al.* (1970) proposed the following equation for lunar soils: $R = f(cl, p, r, t, a, b, \ldots)$, where R is regolith, cl is climate, p is protolith, r is relief, t is time, and new variables, accumulation (a), bombardment (b), *etc.*, were included. Since climate (cl) is likely irrelevant in the lunar context and based on our considerations that regolith on the Moon is soil, we suggest that the equation could be modified to: $S_{\text{moon}} = f(p, r, t, a, b, \ldots)$, where S stands for soil.

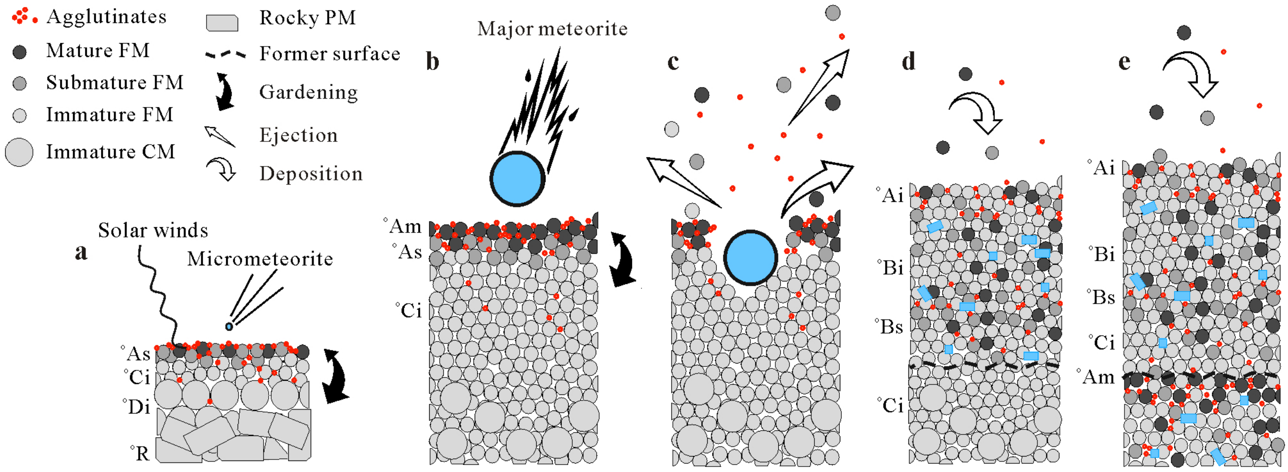

Fig. 2 Schematic diagram showing lunar soil formation processes with time (t) from $t0$ to $t2$ in Profiles 1 (a–d) and 2 (e): formation of different horizons under the influences of space weathering and soil gardening processes by $t0$ (a), ejection of soil material under the disturbance of a major meteorite at $t1$ (b and c), and deposition of the ejected soil material on top of Profile 1 (d) or 2 not impacted by meteorites (e) at $t2$, leading to a buried surface and mixed soil horizons in Profile 2. FM = fine material; CM = coarse material; PM = parent material. °A = agglutinic horizon; °B = mutaric horizon; °C = inceptic horizon; °D = lapidic horizon; °R = PM. For the suffixes following the master symbols (°A, °B, °C, and °D): i = immature; s = submature; m = mature.

Classifying and mapping lunar soils will enable their optimized utilization in technology design, building materials, agriculture, and mission planning, thereby ensuring efficient resource exploitation. However, understanding lunar soil properties and their geographic variability remains challenging due to resolution limitations of remote sensing instruments and the scarcity of samples. For a comprehensive soil classification, detailed morphological data, such as layering, color, texture, and structure, are essential. Such data can mainly be obtained through the collection of core samples, which are still few (primarily derived from the Apollo missions) and represent an insignificant fraction of the potential lunar soils. From the available cores (Fig. 1), National Aeronautics and Space Administration (NASA) researchers identified millimetric-to-centimetric layers formed by chemical and/or physical alteration, suggesting pedogenesis (Duke and Nagle, 1975; Lindsay, 1976).

The observed morphological diversity of lunar soils may raise questions about classification and comparison with our terrestrial soils. Soil classification systems condense knowledge about soils and their related characteristics into specific names, which are essential for scientific reporting. However, these Earth-based systems may not suit extraterrestrial soils because of their different forming processes (Certini *et al.*, 2020). The World Reference Base for Soil Resources (WRB) is more inclusive after incorporating many revisions (IUSS Working Group WRB, 2022). However, it still begins by defining soil as "a living, heterogeneous and dynamic system that includes physical, chemical, biological components, and their interactions", which excludes extraterrestrial soils from classification. This definition curiously contradicts the "abiotic" definition of the classifiable materials: "any material within 2 m of Earth's surface that is in contact with the atmosphere, excluding living organisms, continuous ice not covered by other materials, and water bodies deeper than 2 m".

The latest edition (the thirteenth) of the Keys to US Soil Taxonomy (ST) does not address the classification of extraterrestrial mineral surfaces and reiterates the concept of soil as "a natural body consisting of solids (minerals and organic matter), liquids, and gases, occurring on the land surface and characterized by distinguishable horizons or layers due to energy and matter transformations, or the ability to support rooted plants" (Soil Survey Staff, 2022). This definition is inclusive of soils in Antarctica and other extreme environments where pedogenesis occurs despite harsh climates. Given that many pedogenic processes responsible for soil horizonation, such as the transformation of carbonates, anhydrite, and gypsum and the concentration of oxides and silicate clay, also occur in extraterrestrial environments, we believe that this definition could be extended to extraterrestrial soils as well.

On the Moon, the absence of biodiversity and the uniform climate limit soil differentiation on a regional scale. Instead, parent material, duration of exposure to the surface, and topography play crucial roles (Cameron, 1963). This challenges the classification of extraterrestrial soils using Earth-based systems. A new, specific classification system should emphasize soil-forming processes, mineralogy, and factors unique to extraterrestrial environments. Separate systems may even be necessary for each rocky celestial body.

Regardless of signs of pedogenesis, the first diagnostic horizon to classify lunar soil is the WRB's cryic horizon or its ST equivalent, permafrost. This requires the recognition of at least 5 cm of visible water ice for $\geqslant 2$ consecutive years or soil temperatures < 0 °C with insufficient water to form visible ice crystals. Surficial water ice has been suggested to exist in the lunar polar regions (Li *et al.*, 2018); however, we still lack visual confirmation of it, or of any regolith-ice mixture. Since the Moon lacks atmospheric pressure, the temperature required for ice crystal formation is far below 0 °C. This compels us to disregard soil temperature when attempting to achieve a meaningful classification of the Moon soils using WRB and ST.

Given the widespread thinness of lunar soils and their abundant rock fragments, common WRB soil groups on the Moon could include Leptosols (shallow, < 25 cm, rocky soils) and Regosols (immature soils from an Earth perspective). The presence of sandy, virtually stone-free soils on the Moon is improbable and, if present, likely restricted to very small areas. In such cases, Arenosols could be assumed. Pyroclastic deposits, which are a small proportion of lunar volcanic material, were sampled during the Apollo program (Gaddis *et al.*, 2000; Keske *et al.*, 2020). Being glass-rich, they could be described as tephric material with vitric properties, akin to weakly weathered Andosols according to WRB.

Under ST, hypothetical lunar soil orders might include Entisols (soils with minimal pedogenic development) and, less likely, Andisols (soils developed on volcanic material with at least 30% of particles between 0.02 and 2.0 mm and 5% volcanic glass or more). Less likely still are Aridisols—characterized by an arid soil moisture regime, which is evident on the Moon—in their version with one or more of the following within 100 cm of the soil surface: i) a cambic horizon with a lower depth of 25 cm or more; ii) a cryic soil temperature regime and a cambic horizon; iii) an anhydritic, calcic, gypsic, petrocalcic, petrogypsic, or salic horizon; and iv) a duripan.

On Earth, ongoing updates to soil classifications are driven by anthropogenic soils, which are heavily influenced by human activity (Capra *et al.*, 2015), and the emerging concept of regolith pedology (Juilleret *et al.*, 2016; Huggett, 2023). Both aspects are of potential interest for categorizing lunar soils. However, classifications still heavily rely on variables like temperature and horizon thickness, which are irrelevant on the Moon. The lack of biota further complicates the direct application of Earth-based soil classifications to lunar soils (Cannon, 2023).

The available soil classifications are therefore poorly suited to the Moon. In these systems, soil horizons are designated with capital letters (master symbols), such as A for topsoil, B for subsoil, and C for transition to geological substratum R. Lowercase letters (suffixes) following the master symbols denote specific properties, such as organic matter content or mineral accumulations. For instance, a soil rich in organic matter in the topsoil and with significant secondary carbonate in the subsoil would be labelled Ah-Bk-C. Horizon symbols serve a useful function in the labeling of soil horizons and facilitate discussion about them, which is valuable in both the theoretical and practical aspects of soil science (Bridges, 1993). However, soil horizons are artificial concepts, and in many soils, horizons are irregular, fragmented, or have nearly invisible boundaries (Hartemink and Minasny, 2014).

As soil horizons are typically defined as layers distinguishable from adjacent layers by a distinctive set of properties produced by soil-forming processes (Soil Survey Staff, 2022), we consider the layers observed in the Apollo cores as soil horizons. To distinguish these from terrestrial soil horizons and highlight the distinct processes influencing their formation on the Moon, we propose using the degree symbol ° (Unicode U+00B0) as a prefix for master horizons in lunar soil labeling (*e.g.*, °A). We further suggest employing a combination of agglutinate content (a diagnostic material) and the maturity index I_s/FeO (a diagnostic property) to differentiate genetic soil horizons, reflecting the lunar soil's exposure time to weathering. In addition, we propose a labeling system inspired by Earth's pedology but adapted to lunar conditions. We define four master horizons (°A, °B, °C, and °D), each characterized by varying agglutinate content and further differentiated with the suffixes i, s, and m based on the increasing value of I_s/FeO. This nomenclature allows for the definition of 12 reference soil genetic horizons, as outlined in Table I.

Given the limited field data acquisition on the Moon and the consequent difficulty in determining the most meaningful thickness of diagnostic horizons, we propose labeling the top meter of the lunar surface by aggregating horizons in 25-cm increments to define four master horizons. For instance, if the majority of the top 25 cm consists of °A horizon material despite the presence of other horizons (°B, °C, or °D), it will be classified as °A. We suggest naming the soil master horizons as follows: "agglutinic" for the °A horizon, *i.e.*, the one with the highest content of agglutinates, "mutaric" (from Latin *mutāre*: to change) for the °B horizon with intermediate content of agglutinates, and "inceptic" (from Latin *incipĕre*: to initiate) and "lapidic" (from Latin *lapis*, *-dis*: stone) for the °C and °D horizons, respectively, showing little and no weathering.

TABLE I

Proposed soil genetic horizon designation for the Moon based on agglutinate content as a diagnostic material and the ratio of the amount of Fe in the space weathering-induced nanophase state to total Fe (I_s/FeO) as a diagnostic property

Agglutinate %[b]	Master horizon	I_s/FeO[a]	Reference horizon
> 30	°A	> 60	°Am
		30–60	°As
		< 30	°Ai
15–30	°B	> 60	°Bm
		30–60	°Bs
		< 30	°Bi
5–15	°C	> 60	°Cm
		30–60	°Cs
		< 30	°Ci
< 5	°D	> 60	°Dm
		30–60	°Ds
		< 30	°Di

[a] To enhance clarity and align with common reporting standards in the literature, the I_s/FeO values shown here are the true values scaled by a factor of 100.

[b] By weight.

We designated 30 topsoils in terms of master horizons based on samples from the Apollo 17 mission, using data available from NASA's Lunar Sample Compendium (https://curator.jsc.nasa.gov/lunar/lsc/), excluding all material not related to soil (Table SI, see Supplementary Material for Table SI). We focused on the upper sections of the cores because current remote sensing technologies only allow for surface observations, and used high-resolution (50 cm) images from the Lunar Reconnaissance Orbiter Narrow Angle Camera (LRO-NAC) to delineate the soil boundary units.

Using this labeling, we created a first, preliminary soil map of the Moon (Fig. 3). We focused on the Taurus-Littrow (TL) Valley, working at a scale of about 1:250 000 which, on Earth, is generally used to represent the geometries of soil mapping units on a regional scale, defined according to criteria of pedogenesis and the functional properties of the soil. The low resolution is due to limitations in the available data. Primary sources included soil samples collected during the Apollo missions and imagery from NASA's LRO-NAC (50-cm spatial resolution). The lack of precise geographic information for the samples introduces inherent positional uncertainties. Additionally, the resolution of the orbital imagery is not sufficient for detailed mapping, further limiting the map's precision.

The mapping process was conducted using Quantum Geographic Information System to integrate sample data with orbital imagery. Unfortunately, there is currently no more accurate data on other potential covariates that could influence the properties of the lunar regolith. This limitation arises because past lunar data acquisition efforts were not

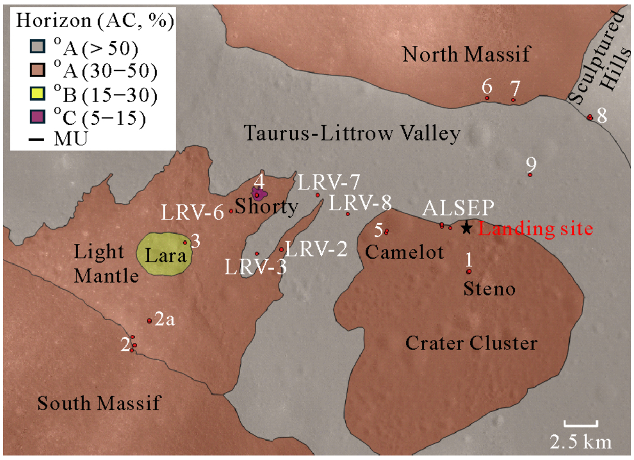

Fig. 3 Topsoil horizon map of the Taurus-Littrow Valley on the Moon based on agglutinate content (AC) by weight. The black star marks the Apollo 17 landing site, and the black circles filled with red are sampling stations with their names in white. MU = morphological unit.

specifically designed to meet the needs of planetary pedology. As a result, key variables that could improve the precision of soil mapping are either unavailable or insufficiently detailed. Nonetheless, our approach reveals spatial heterogeneity and provides a foundational tool for identifying patterns in lunar soil distribution.

The TL Valley is located a few tens of kilometers outside the southeastern edge of Mare Serenitatis, a 740 km-diameter mascon basin. The valley trends east-southeast and is bounded by the North and South Massifs, which are filled with approximately 1 400 m of basaltic lava. The subfloor basalt is overlain by deposits of unconsolidated material, including major units such as a pyroclastic deposit of orange and black glass beads, impact-generated regolith of ejecta from a cluster of craters on the valley floor, and a light mantle derived from the South Massif. This site was chosen because it is the largest explored area in any Apollo mission, where a substantial number of soil cores were collected (Fig. 1) and, in a single case, descriptive comments were provided by a geologist.

The map reveals a high prominence of the mature °A horizon (°Am), indicating a long history of exposure to space weathering in the TL Valley morphological unit. Interestingly, the agglutinate content is higher in the Sculptured Hills area (station 8) compared to the North and South Massifs (highlands) and the floor of the TL Valley. We assume that samples taken from the Steno and Camelot Craters are representative of the Crater Cluster unit. These samples are consistent with °A horizon material; however, their agglutinate content is lower than that of samples from outside this region (*i.e.*, the TL Valley unit). This finding is consistent with the older age of the Crater Cluster unit, though the TL Valley is even older. The Lara and Shorty Craters exhibit much lower agglutinate contents and maturity index values, reflecting their younger age and, consequently, lower exposure to space weathering. While our map does not achieve high resolution, it represents a step toward understanding lunar soil variability and highlights the need for higher-resolution imagery and a more extensive network of geolocated samples. The path forward could follow the approach used on Earth, where the high costs of acquiring higher resolution data have led to gradual investments in areas of economic or other interest.

We discuss the possibility of applying the nomenclature established by pedology for terrestrial soils to classify lunar soils as well. To avoid confusion with Earth's soils and emphasize the distinct pedogenic processes operating on the Moon, we propose a specific labeling system for lunar soil horizons. This system, though largely inspired by Earth's pedology, is designed to reflect the unique characteristics of lunar soils. The labeling system differentiates reference genetic horizons based on a combination of agglutinate content (diagnostic material) and the maturity index I_s/FeO (diagnostic property), as these variables reflect the lunar soil's exposure time to weathering. The system includes four master horizons (°A, °B, °C, and °D), each defined by agglutinate content, and further differentiates them with three suffixes of i, s, and m based on the increasing value of I_s/FeO for immature, submature, and mature, respectively. Such nomenclature enables the definition of twelve reference genetic horizons. Lunar soil maps could be developed based on accurate pedological surveys conducted during future missions. Here, we present a preview of one such map, created using soil samples and the upper sections of core samples from the Lunar Apollo Sample Compendium, along with images from the LRO-NAC. The more refined these maps become, the more useful they will be for future ISRU on the lunar surface. Finally, by establishing planetary pedology as a subfield of pedology, we aim to stimulate discussion that will advance scientific exploration beyond Earth.

DECLARATION OF COMPETING INTEREST

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

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SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version.

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