Teaching soil as a system: interactivity, place, plural knowledge, and AI

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Abstract. Reasoning about soil as a coupled system is a central aim of graduate training in soil science. Soil science is now often taught within broader degrees, without the specialists who once made systems teaching natural. Curriculum compression and lacking interactivity have kept systems reasoning out of many programmes. Large language models, now accessible to students, have made that absence harder to ignore. Here, we set out the design principles for an undergraduate soil science unit built around four requirements: interactivity, place, plural knowledge, and AI discernment. Interactive models, repeated landscape comparisons, Indigenous and Two-Way knowledge, and AI interrogation operationalise these requirements. Assessment, designed from intended outcomes, integrates them into one capability: place-specific reasoning from evidence. We provide a worked example that other soil science programmes can adapt.

1 The catalogue problem and the AI era

Soil science is often taught as a catalogue. The curriculum is delivered mainly through lectures. Students learn to classify profiles, describe morphology, and characterise the properties of soil. This knowledge is foundational and necessary. But turning it into a systems view was rarely the work of any single unit. It was built up across the curriculum, where pedology, soil mineralogy, soil chemistry, soil physics, and soil biology were taught as courses in their own right, and students drew the connections between them. When that curriculum holds, the catalogue does its job. Where it does not, soil as a coupled system is not always made explicit. Soil is a landscape-water-vegetation-biogeochemistry continuum in which carbon and nutrients cycle, water moves, organisms transform materials, and climate and landscape position shape the outcomes of these processes. A graduate who recognises a Vertisol (IUSS Working Group WRB, 2022) profile but cannot reason about how its shrink-swell dynamics interact with altered rainfall has a lexicon, not a model.

Pedology has long taught that soils vary with climate, organisms, relief, parent material, and time (CLORPT) (Jenny, 1941). But simply finding a link between these factors and soil properties does not explain how the change happens. Explaining how soil functions requires reasoning about how physics, chemistry, biology, and landscape history interact.

This expertise once sat under one disciplinary umbrella. ~~In many universities, that structure has fragmented. Soil science is now taught within broader environmental, agricultural, geographical, or general science degrees. Curriculum hours for the physics, chemistry, and biology needed to explain how soil works have contracted (Hartemink et al., 2008; Havlin et al., 2010; Hartemink et al., 2014). The question, then, is how a single undergraduate unit can help students use process knowledge to reason about soil as a dynamic system.~~ Where that structure has fragmented, for example in Australia and North America, soil science is now taught within broader environmental, agricultural, geographical, or general science degrees (Hartemink et al., 2008; Havlin et al., 2010). Elsewhere, soil science has long sat inside agricultural or biological curricula. The pattern varies by region and institution, but where fragmentation occurs, curriculum hours for the physics, chemistry, and biology needed to explain how soil works have contracted (Hartemink et al., 2014). The question, then, is how a single undergraduate unit can help students use process knowledge to reason about soil as a dynamic system.

The work graduates do has also shifted. An expanding phase of agriculture needed graduates skilled in fieldwork, classification and land suitability assessment. As intensification on existing land became the priority, precision management and quantified environmental impact increased the demand for systems thinking and process-based models (Hartemink et al., 2014). Climate adaptation and regenerative agriculture add a further layer of expectation now. Hairiah et al. (2022) trace a comparable shift in Indonesian soil science research over 150 years, from survey and classification towards process, management and environmental themes. The pace differs by country, but the direction is consistent: graduates increasingly need to reason about soil as a system.

~~Several strands of curriculum literature document this.~~ Villa et al. (2025) found that lectures dominated soil science teaching across Europe ~~and computational interactive tools were absent from 96–98% of institutions~~, and that computer or modelling activities were absent or occupied only a small part of courses in 96% of surveyed BSc institutions and 98% of surveyed MSc institutions. Field et al. (2017) found that the core soil science curriculum was content-rich but included little multidisciplinary material, despite soil management requiring multidisciplinary reasoning. International case studies show growing experimentation with active, problem-oriented approaches (Hartemink et al., 2014; Field et al., 2011), and recent reflections have emphasised sustainability, soil literacy, and closer links between teaching and research (Lull Noguera et al., 2026). Research-led teaching is part of that agenda. When focused on soil systems, it draws on current process models rather than textbook approximations. Reform, therefore, exists but remains uneven. Still missing is a design in which process manipulation, place, plural knowledge, AI discernment, and assessment are built around the same soil-system capability.

AI tools and social media have made the cost of this inertia more visible. Students now encounter soil science not only through lectures but also through YouTube videos, social media feeds, and AI-generated summaries. A catalogue-trained graduate may not detect when an AI-generated answer in soil science is incomplete or plainly wrong. The answer can sound confident even when the causal explanation does not hold for the landscape under study. A student trained in systems reasoning can interrogate that response. They can reason about whether the relationship between clay content and mineral-associated organic matter (MAOM) holds for a highly leached kaolinitic

profile, where Fe–Al oxides drive MAOM formation, or only for 2:1 clay systems, where stabilisation operates through polyvalent-cation bridging. Interrogation requires knowing the causal structure, not just recognising its vocabulary.

Earth-systems education, critical-zone education, ~~InTeGrate, and~~InTeGrate (Interdisciplinary Teaching about Earth for a Sustainable Future) (Kastens and Manduca, 2017), and place-based geoscience education have made strong arguments for systems thinking, modelling, and place-based inquiry (White et al., 2017; Lally et al., 2019; Toolin and Blouin, 2025; Scherer et al., 2017; Holder et al., 2017), but have not yet assembled them for soil science. The contribution here is that assembly, at a time when AI makes soil-specific causal reasoning more important. The AI discernment component could not have been designed before large language models became accessible to students. That transition has occurred only since approximately 2023.

Here, we set out the design rationale for an undergraduate soil science unit. It links soil properties and process reasoning with repeated landscape contrasts, interactivity, Two-Way and Indigenous knowledge, AI discernment, and written and oral assessment. ENST2007 provides the worked example. The Sustainable Development Goals (SDGs) place this approach within a broader sustainability context (Al-Ismaily et al., 2025), connecting soil-system reasoning to food, water, climate, land and biodiversity.

This paper concerns the design of one second-year unit, not a full curriculum review. The capability it targets matters for the careers graduates increasingly enter. Researchers test process models against site evidence. Land managers and consultants apply causal reasoning to local interventions. Surveyors interpret landscape evidence directly, without a textbook answer to check it against. Each role needs the knowledge, skills and values that systems reasoning builds.

2 Four structural requirements for teaching soil as a system

The shift from catalogue to systems teaching changes what students must do with knowledge. Four requirements follow from this decision. Students must manipulate causes and observe consequences. They must see that the same process can produce different outcomes in different landscapes. Questions about soil, water, plants, microbes, and management are also questions of Country and practice. Students must also be able to test generic explanations against the local landscape.

Interactivity. Systems reasoning requires manipulation. Students must alter inputs, observe responses, and construct causal models. Interactive and computational tools should therefore be central to the curriculum design, not supplementary (Hake, 1998; Freeman et al., 2014). Well-designed virtual experiments foster stronger conceptual understanding when the target is the mechanism rather than the procedure (Finkelstein et al., 2005; Rutten et al., 2012). Existing tools have largely focused on visualising profiles rather than manipulating coupled processes (Krzic et al., 2013; Schulze et al., 2021). Directly manipulable tools remain uncommon.

Place. The same soil-forming processes can produce different outcomes depending on landscape position, parent material, and land-use history. Place-based geoscience education shows that learning in local landscapes helps students interpret Earth system processes (Semken, 2005). Toolin and Blouin (2025) argue that place should organise the questions students ask, not merely provide the setting in which they ask them. Without a landscape to return to repeatedly, systems reasoning remains abstract.

Plural knowledge. In this paper, plural knowledge means recognising more than one knowledge tradition, such as Australian First Nation people, while respecting their different epistemologies, responsibilities and authority. Organising a curriculum around coupled processes creates a natural explanatory link to Indigenous knowledge traditions. Indigenous knowledge frameworks are not examples to add to a Western curriculum after the fact. They are traditions with their own epistemologies, responsibilities, and relationships to place (Barnhardt and Kawagley, 2005; Aikenhead and Ogawa, 2007). This requires care. Traditional knowledge is governed, local, and place-specific. Not all of it is public, and not all public knowledge is available for others to interpret without limit. Indigenous knowledge traditions address the same process questions a systems curriculum asks. ~~The CSIRO Two-Way Science program calls this 'weaving, not integrating' (Deslandes et al., 2019).~~CSIRO's Two-Way Science program calls this 'weaving, not integrating' (Deslandes et al., 2019): the careful weaving of Indigenous and Western scientific knowledge, each retaining its own standing.

AI discernment. Students need to use AI thoughtfully because it is now part of how they learn. AI literacy extends beyond technical familiarity with tools to include understanding what AI systems can do, where they fail, and how their outputs should be evaluated (Long and Magerko, 2020). Used well, AI can explain a mechanism in different terms, generate practice problems, and critique a student's own causal explanation. In soil science, however, the risks of uncritical AI use take a particular form. An answer can sound plausible yet fail in the specific landscape, mineralogy, hydrology, or land-use history under study. A student who understands the system can ask whether an AI-generated answer holds for the local soil.

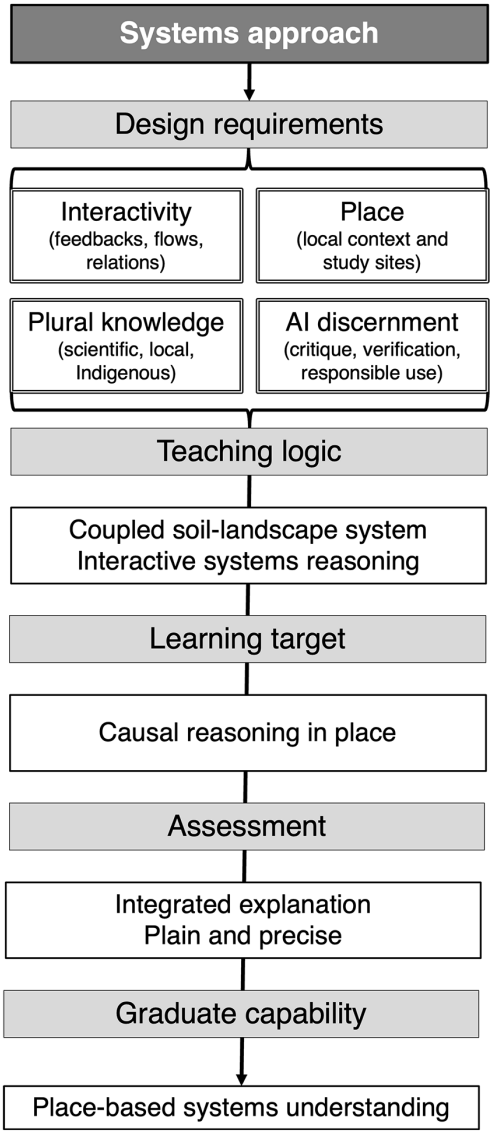

Figure 1. Conceptual framework for teaching soil as a coupled system. Four design requirements: interactivity, place, plural knowledge, and AI discernment, shape the teaching logic and learning target, with assessment as the integrating mechanism that produces place-based systems understanding in graduates.

All four follow from the decision to teach soil as a system (Fig. 1). Backward design operationalises all four as a single problem (Wiggins and McTighe, 2005). Starting with intended outcomes forces a clear decision about what systems reasoning requires of a graduate, which then determines the form of assessment and the activities that prepare students for it. Assessment is the integrator.

3 The four requirements in practice

~~ENST2007 provides the worked example. It is a second-year undergraduate unit in soil and landscape science designed around the four requirements. What follows is a description of the design and its rationale.~~ENST2007, Landscapes, Soils and Surface Environments, provides the worked example. It is a second-year undergraduate unit in the School of Molecular and Life Sciences, Faculty of Science and Engineering, Curtin University, Western Australia. It is worth 25 credit points, Curtin's standard single-unit load, delivered as two 2-hour workshops weekly. Its prerequisite, Land and Water Resources, gives students foundational knowledge of soil and water before they begin coupled-process reasoning across soil, water and vegetation. What follows is a description of the design and its rationale.

ENST2007 has four unit learning outcomes: explain soil and landscape processes and their influence on ecosystems; investigate soil-water-vegetation relationships in carbon storage and nutrient cycling; examine hydrology's role in landscape resilience and management; and demonstrate understanding of Indigenous knowledges and Two-Way science in sustainable landscape management. The activities below address the first three; Indigenous knowledge, introduced from Week 1, addresses the fourth. Both assessment tasks draw on all four together (Table 2).

Interactivity. Interactivity was designed to make students active participants in explaining soil processes, rather than passive recipients of information. Activities were sequenced so that students first made a prediction, then changed a condition or compared settings, observed the result, and explained the process responsible. This approach helps students work with processes that are slow, invisible, coupled, or dependent on place. It also encourages them to test ideas, identify assumptions, and connect changes in one part of the soil system with consequences elsewhere.

Browser-based apps provide the main opportunity for this kind of exploration. Students can directly change inputs and observe how soil processes respond under realistic presets from local and contrasting Australian sites. The suite includes a soil water-balance explorer similar to that by Gannon and McGuire (2022), as well as apps on carbon dynamics, spatial prediction, soil profile ~~develpment~~development, soil property interactions and nutrient cycling. Each runs in a browser without installation and is freely accessible (see code availability statement). Expandable sections set out the model assumptions, equations and supporting detail. Embedded questions ask students to predict the direction of change, explain an output, or compare results between landscapes.

The carbon game extends this approach through a longer-term management scenario. Students select land uses over a 50-year recovery period and observe how vegetation carbon, soil organic matter pools and CO_2 loss respond. Rather than presenting one correct outcome, the game asks students to trace how management decisions alter the system over time.

Short, curated videos support the same learning sequence by making otherwise difficult processes visible, including water potential, rhizosphere dynamics, and fire-and-nutrient pulses. Videos are used before activities that model the same process analytically, so students return to the landscape with more informed questions (Wang et al., 2022).

Other videos introduce perspectives that simulations cannot represent fully, including Indigenous fire management, habitat restoration and land-use decision-making.

Structured class activities then develop collaborative reasoning. These include a naïve hillslope sketch before formal vocabulary is introduced, and a soil-property prediction challenge comparing two contrasting landscape areas. Together, the apps, games, videos and activities provide repeated opportunities for students to predict, test, discuss and revise their explanations of how soils work in particular places.

Place. The Darling Scarp and the Swan Coastal Plain in south-western Australia provide the unit's central landscape contrast. They differ in parent material, vegetation, hydrology, and formation history, but both are local and accessible. Applying the CLORPT framework (Jenny, 1941) makes the contrast explicit. The same Mediterranean climate, acting through contrasting parent material and formation time, has produced two soil and landscape systems that diverge at every level. The transferable principle is to repeatedly return to the same two-area contrast, from regional landscape and soil-forming patterns to the catena, profile, and rhizosphere. The specific landscapes are local. The method is not.

Plural knowledge. In ENST2007, students encounter the two landscape areas in Week 1 as 'Country' (the term Aboriginal and Torres Strait Islander peoples use to refer to the land in its physical, cultural and spiritual dimensions) rather than as study sites. Whadjuk Noongar custodianship is introduced before soil science vocabulary (Bonyhady and Griffiths, 2002). Indigenous knowledge recurs throughout the unit, addressing the same process questions considered through Western scientific methods. Cultural burning, for example, is incorporated as the management scenario in the carbon model rather than presented as a traditional practice separate from it. The teaching uses publicly shared Indigenous-led resources and guidance, all cited to their sources. Students are explicitly told that the unit is not speaking for Indigenous communities or for Country and that knowledge is local, governed, and place-based. Teaching materials are drawn from Noongar organisations and relevant government land-management programs rather than from instructor interpretation.

AI discernment. ENST2007 treats AI as a permitted learning aid, introduced from the outset and revisited throughout the unit. The design is deliberately LLM-agnostic: students use publicly available, general-purpose models of their choice, such as ChatGPT or Claude, with full web access during workshops. The unit adds no retrieval-augmented grounding, fine-tuning, or custom context window, so the models draw only on their general training, the same access most students will have after they graduate.

Students ~~may use it~~may use AI to define a concept in different terms, generate practice questions, or critique a plain-language explanation they have written. Each use keeps reasoning and judgement with the student. The central question is not whether students use AI, but whether they can test its explanations against the soil and landscape system under study. As students encounter carbon dynamics and contrasting organic-matter pools, for example, they test AI-generated mechanism descriptions against local conditions. A typical prompt asks whether an account of

mineral-associated organic matter formation holds for the highly leached kaolinitic laterite of the Darling Scarp, where Fe–Al oxide surfaces drive stabilisation, or whether it assumes the cation-bridging mechanisms of 2:1 clay systems. AI cannot describe this landscape accurately without its mineralogy.

The SDGs operate at a different level from the four requirements. They give students a vocabulary for the consequences of sustainability. ENST2007 introduces SDGs 2, 6, 13, and 15 from the start. Towards the end of the unit, students map landscape processes to SDG outcomes and work in reverse, identifying a relevant process and management intervention for each goal (Table 1). The SDGs are treated critically as a shared language for governance and communication, not as the curriculum's organising principle.

Table 1: Process–SDG mapping activity used in ENST2007. Students connect unit content to SDG outcomes through place-specific mechanisms and management interventions.

Unit content and approach	Example mechanism or intervention	SDG outcome
Soil and landscape processes	Site-matched species	SDG 2
Soil C, N, P and vegetation dynamics	Revegetation increases carbon	SDG 13, 15
Hydrology and connectivity	Corridors buffer waterways	SDG 6
Heterogeneity	Diverse species mosaics; measurement and monitoring	SDG 15
Two-Way science	Indigenous, Noongar-led management	SDG 2, 13, 15

4 Assessment as the integrator

Assessment is where students show what they have learned. Constructive alignment means that the learning outcomes, teaching activities and assessment task should fit together (Biggs, 1996). The four requirements are not assessed separately. Instead, students use them together in one authentic task. ENST2007 also includes incremental workshop exercises (20 % of the grade, regular feedback through the semester). The two tasks below make up the remaining 80 % and are where the four requirements come together.

In ENST2007, two assessment tasks assess a common capability: explaining soil and landscape processes to a non-specialist without sacrificing accuracy. The stakeholder brief (~~2,500–3,000 words~~2,000 words, 40 % of the final grade) places students in the role of an environmental consultant. They advise a partnership of Traditional Owners, local government, and state agencies on one of four management problems set in the two reference landscapes. Two-Way science recommendations are required. The rubric assesses whether students use publicly shared Indigenous-led sources accurately and respectfully, and whether those sources are causally connected to the soil and landscape analysis, not appended in a closing sentence. The assessment does not ask students to speak on behalf of Indigenous knowledge holders or to interpret knowledge beyond what has been shared for public use.

The oral examination (20 minutes; 40 % of the final grade) assesses the same construct through speech. Five questions, each aligned with one unit learning outcome, are released one week in advance. They address soil and landscape processes; carbon, nitrogen, phosphorus, water and vegetation dynamics; hydrology; sustainability, resilience and land management; and Indigenous knowledge and Two-Way science, which are integrated across all unit learning outcomes. Each student draws one question at random on the day. Examiners act as curious non-specialists. There are no slides or prepared notes. Students must accurately explain a soil-landscape system to a non-specialist and respond to follow-up questions (Table 2).

Interactive oral assessment offers an authentic way to test judgement, communication, and authorship (Ward et al., 2023; Huxham et al., 2012). Students must explain how something works in clear everyday language, not just name the outcome. The rubric example 'Roots release organic acids that can displace phosphorus from mineral surfaces, increasing the phosphorus available in the soil solution' meets it. 'The roots help the plant get more nutrients from the soil' does not. The difference is epistemic, not stylistic. A student who cannot state the mechanism plainly does not yet understand it. Releasing these materials one week in advance gives students time to practice explaining rather than memorising.

Table 2: Oral examination rubric used in ENST2007. Students explain one pre-released soil-landscape system question to examiners acting as curious non-specialists.

Criterion	Weight	What the examiner assesses	Idea
System understanding	30 %	Mechanism explained accurately at each step	Interactivity, Place
Causal reasoning	25 %	Causation traced across coupled processes	Interactivity, Place
Explaining to a novice	15 %	Mechanism stated plainly without accuracy loss	All four threads
Connection and integration	15 %	Landscape contrast and other threads used unprompted	Place, Plural knowledge
Response to questioning	15 %	Reasoning about the local system under follow-up	AI discernment

Combining written and oral assessments constrains uncritical reliance on AI rather than attempting to ban its use (Perkins et al., 2024; Elshall and Badir, 2025; Bearman et al., 2024; Tai et al., 2017; Eachempati et al., 2025). Students cannot delegate spontaneous reasoning to AI. Oral examinations have been associated with improved assessment performance and course grades, without differences by gender, international enrolment or language background (Davey et al., 2025). A student who uses AI in preparing the written brief must nevertheless demonstrate sound soil and landscape reasoning in their own words during the oral examination.

5 Transferability

Transfer does not require the same landscapes, interactive tools, or cultural context. It requires the same design logic: choose two locally meaningful contrasting soil landscapes; return to them repeatedly across landscape description, profile, water, carbon, nutrients, vegetation, and management; use interactive tools to manipulate the processes that distinguish them; and assess whether students can explain those processes clearly to a non-specialist. Indigenous, local, or community knowledge should be woven through the unit. It should enter only through governed and publicly available sources, and through partnerships appropriate to each place. ENST2007 itself is therefore not the transferable object. The transferable object is a curriculum design for place-based soil-system reasoning.

The oral examination rubric (Table 2) can be adopted directly, with clear and precise explanation as its unifying criterion. The sustainability context can also be adapted. Students first need to understand how soil, water, vegetation, carbon, nutrients and disturbance interact. They can then use the SDGs to explain why this matters for sustainability, including the choices and trade-offs involved. Open access is essential. Apps and materials gated behind institutional logins cannot be genuinely adopted elsewhere.

Two design cautions follow. First, tokenistic integration of Indigenous knowledge is a structural problem. Adding a discrete Indigenous knowledge lecture to an otherwise catalogue-style curriculum, without reworking its explanatory structure, creates content with no meaningful points of connection. Second, the oral examination requires scheduled individual time with each student. Although total staff time may be comparable to other assessment formats, the scheduling demand is less flexible and should be costed from the outset. Students commonly report initial anxiety about the oral format. This tends to lessen with structured preparation and does not appear to harm performance (Davey et al., 2025).

6 Implications for the field

Soil science has disciplinary strengths that are site-specific in ways AI cannot reliably generalise. Local knowledge, landscape analysis, Two-Way science and the capacity to read soils in terms of the processes that formed them cannot be reproduced from generic training data alone. A systems curriculum is therefore not simply a pedagogical improvement. It is, in principle, the discipline's response to the epistemic conditions students now inhabit.

We have described a design rationale, not yet evidence of effectiveness. A planned two-cohort evaluation before and after redesign will address this directly. ~~The design is defensible across the varied careers pursued by soil science graduates. Researchers, land managers, consultants and soil surveyors each depend on the capacity to reason with disciplinary knowledge. A catalogue curriculum provides necessary vocabulary, but it does not necessarily build that capacity.~~ The design is defensible across the careers introduced in Section 1. A catalogue curriculum supplies the vocabulary those careers need. It does not reliably build the reasoning capacity the work itself requires.

The implications extend beyond soil science. Any discipline where graduates must reason about a coupled, place-specific system faces the same challenge. Ecology, geomorphology, hydrology, and agronomy are immediate examples. The catalogue model persists because it is efficient and can be delivered to large cohorts, not because it prepares graduates for the problems the discipline faces in practice. A systems curriculum requires more of instructors and careful evaluation design.

That distinction has a sharper edge in the AI era. AI can now reproduce catalogue knowledge and practical guidance with enough fluency that self-directed learning through AI, video and social media may seem a plausible alternative. This is especially so for students preparing for applied roles. Yet AI-generated explanations may remain weak where evidence is incomplete, conditions are locally specific, or the relevant question has not already been framed. A research-led systems curriculum prepares students for this uncertainty. Students encounter current process models, learn where their limits lie, and develop the habit of asking when an explanation no longer fits the evidence in a particular setting.

Universities that have shifted teaching towards staff without active research programmes may face this issue most directly. Where the curriculum is primarily catalogue transmission, AI can reproduce much of its content. The institution's distinctive contribution then risks narrowing towards credentialing rather than education.

7 Code and data availability

No data were generated or analysed in this study. The browser-based app suite described in this paper is freely accessible at https://ravr19.github.io/lsse_teaching/, with no login or installation required. All apps run in a standard web browser and include embedded concept questions and guided instructions.

8 Author contributions

R.A.V.R.: Conceptualisation, Methodology, Software, Writing – original draft, Writing – review and editing, Visualisation, Funding acquisition, Project administration, Supervision. L.W.: Methodology, Investigation, Writing – review and editing. A.B.-E.: Investigation, Writing – review and editing.

9 Competing interests

R.A.V.R is an Executive Editor of *SOIL*. The authors declare no competing interests.

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