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Commentary

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Bridging research gaps and advancing policy for healthy soils

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Take home statement: Scientific focus to harness soil microbial communities is essential for building a sustainable, resilient, and health-conscious agricultural future.

Abstract

The policy framework previously presented by Neale and colleagues in Sustainable Microbiology highlights the central role of soil microorganisms in sustainable agriculture and global food security, offering actionable interventions grounded in emerging scientific advances. However, the translation of soil science and ecology into impactful policy and practice remains limited. This opinion article revisits the longstanding concept of soil biotechnology, and regulatory/societal barriers to progress. We emphasize that the soil microbiome holds untapped potential for improving plant health, reducing agrochemical reliance, and promoting sustainable food systems through continued research. Interkingdom microbial interactions, especially those involving root exudation as a mechanism for microbial recruitment, are proposed as pivotal but underexplored areas of study. Phenotype-driven, trait-based approaches are advocated over traditional phylogenetic methods to better identify functionally relevant microbial consortia and intervention strategies. Furthermore, we stress the need to integrate ecological, agronomic, and economic insights to develop soil-centric food systems. This includes monetizing ecosystem services provided by healthy soils and implementing incentivized conservation schemes. Unlocking the potential of soil microbial ecology requires coordinated, interdisciplinary efforts and a paradigm shift in policy, funding, and public perception.

Sustainability Statement

This work aligns with UN SDG 2 (Zero Hunger). We highlight how soil microorganisms are essential for sustainable agriculture and global food security. Harnessing the soil microbiome can improve plant health, reduce reliance on chemicals, and lead to more resilient cropping systems capable of meeting global food demand. We call for treating soil as a vital ecosystem and foundational element of planetary health. We stress the importance of safeguarding soil microbial diversity and leveraging microbial ecology for ecosystem services like carbon sequestration and biodiversity support, contributing to sustainable land management and preventing degradation.

Keywords: soil microbiome; sustainable agriculture; plant-microbe interactions; root exudates; soil biotechnology; agroecological policy

Introduction

The policy paper in this journal (Neale et al. 2024) on understanding how microorganisms are critical to sustainable soils and food production sends an optimistic message with the new science available to us. A major question, however, is whether the message can be capitalized on. The article mentions the concept of soil biotechnology, which was in fact first described in 1983 (Lynch 1983), just as the new opportunities with molecular biology and biocontrol of pests and diseases were emerging. However, despite the early promise of soil biotechnology, commercial uptake has remained limited, partly due to high costs of regulatory approval but also resistance from the agrochemical industry, which may perceive such innovations as a threat to its market interests. In the last decade there has been a great deal of interest in the microbiome of the gut controlling human health, including identifying the non-human genome through metagenomic analysis (Qin et al. 2010). Modern molecular techniques have facilitated microbial community analysis to show there are far more species and strains than previously thought, mostly in soils (upwards of 90%; Blakemore 2025). The concept of the microbiome started with microbial communities in the soil/plant ecosystem (Lynch 2024). It should also be recognized that soil communities contain a multitude of interacting organisms across various kingdoms and functional specialisms. This includes functional symbioses, such as root-nodule bacteria, which fix nitrogen; mycorrhiza, which promote phosphorous uptake; and phosphate-solubilizing bacteria that facilitate mycorrhizae P uptake, but also bioremediation agents like Pseudomonads (Mrozik and Piotrowska-Seget 2003). These functions are all part of the soil-sustainability equation to protect the environment and human health, for instance by restricting use of agrichemicals, which can potentially harm the balance of the human gut microbiome (Defois et al. 2018). Plant-based diets feature increasingly in the United Nations Sustainable Development Goals (UN-SDGs) and there is a massive opportunity for governments and international agencies to promote healthy and sustainable living by promoting beneficial gut and soil microbiomes. Also, by re-examining the knowledge base that has built up over the past century, coupled with new bioscience methodologies empowered through artificial intelligence, it is possible to gain max-

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imum potential from soil resources while maintaining their sustainability. Concepts surrounding soil technology may be initially perceived as challenging by the public; such concerns could be effectively explored and addressed through the use of focus groups, such as those prevalent across social sciences.

A microbial perspective on agriculture

From an ecological and evolutionary standpoint, one of the most significant events in the history of life, i.e. the evolution of land plants, and the genesis of soils on which they now thrive, was facilitated by microorganisms (fungi, bacteria, and archaea; de Vries et al. 2024). These microbial interactions are still fundamental components of plant fitness and knowledge of their biology, and the chemical language that defines them, is a major component of future sustainable agricultural practice (Vishwakarma et al. 2020). Developing an advanced understanding of plant-microbe interactions, despite how multifaceted and complex these might be, is a pre-requisite for building effective, science-led technologies and interventions. From a plant perspective, the rhizosphere signals used to recruit microbes (largely in the form of root exudates) and the plasticity of these during environmental perturbation are still poorly understood (de Vries et al. 2020, Williams and de Vries 2020, Delory et al. 2024). Identifying new microbial partners and understanding which plant hosts benefit from their presence and in which environments is central to developing effective, crop-specific interventions, e.g. fungal endophytes (Field and Pressel 2018).

Similarly, it is necessary to identify the mechanisms through which various bacteria promote growth, both for plants and for other symbionts like fungi, and how microbial consortia work in tandem to promote healthy plants (Chaparro et al. 2013). The soil microbiome is more complex than tripartite (fungal-bacterial-plant) interactions and includes archaea (single-celled organisms evolutionarily distinct from bacteria) as important emerging functional components. Holistically, interkingdom interactions require much more scientific scrutiny and research tackling basic questions around this topic, including how do microbes like fungi, bacteria, and archaea interact? How does this inform plant-host fitness and survival? More expansively, how do we strike a balance within the continuum of beneficial to deleterious microorganisms in the soil and leverage that toward the specific land-use requirements of the soil? Exploring the immense diversity of soil ecosystems remains one of biology's final frontiers and humanity's greatest potential for generating applied solution to move agriculture toward a sustainable future. Neale et al. (2024) highlight multiple practices that UK agriculture must employ to safeguard the diversity of soil communities, but understanding the biological tapestry of plant-soil interactions is paramount to develop knowledge-led technologies to fully harness the potential within soil-microbial diversity (summarized in Fig. 1).

However, this is no arbitrary undertaking; soil is the most chemically and biologically complex ecosystem on earth (Anthony et al. 2023). The potential interactions between living organisms are as numerous as the diversity of organisms themselves (more so considering the rapid differentiation of short-generational organisms like bacteria, resulting in many functional ecotypes within a single species), of which a typical soil contains many millions (Blakemore 2025). Within this complexity are organisms that have historically received little research attention (like archaea) that demonstrate various central roles around soil health, nutrient acquisition, bioremediation, and symbiosis (Martinez-Espinosa 2024). It is therefore imperative to identify the functional significance of different interactions in the soil. In one sense, trait-based approaches can aid, as they provide functional information about soil based on phenotypic information, rather than relying on phylogeny (Lajoie and Kembel 2019, Zanne et al. 2020, Delory et al. 2024)—a surprisingly inaccurate measure of function (Goberna and Verdú 2018, Matthews et al. 2021). Traits provide direct, or proxy, measurements of function and focus on ecosystem functioning (i.e. nutrient acquisition or stress tolerance). For example, root diameter, a typical root trait, is often discussed as a plant strategy to outsource nutrient acquisition to microbial partners (Williams et al. 2022). Root N content is equally predictive of plant association with fungal partners (Wu et al. 2024). Dioecy, or the presence of more female plants, may improve plant resilience to pathogens (Williams et al. 2011).

A tailored microbiome

Promoting advantageous traits in crop species could ensure better outcomes for crop survival, health, and fitness, as well as promoting beneficial legacies through plant-soil-feedback mechanisms (Delory et al. 2024). Similarly, microbial enzyme activity directly responds to soil environment and influences soil function. If known soil parameters (such as nutrient availability) alter microbial enzymatic activity, such as those associated with P-solubilizing and N-cycling, manipulating causal relationships or promoting specific enzyme activity could result in more preferable growth conditions for plants (as is the case in South African grasslands; Ndabankulu et al. 2022). To build upon the arguments presented above, many microorganisms can fill a functional niche, regardless of their phylogeny (Malard and Guisan 2023). To understand which organisms can fill certain niches, focus on phenotype rather than identity is necessary, albeit although recognizing the potential of understudied organisms, like archaea, first requires their identification. Furthermore, the recruitment of microbes and the desirable functions they fill, being independent of phylogeny, can occur through expressing plant traits involved in that recruitment, i.e. root exudation (de Vries et al. 2019).

Manipulation of plant exudation signals provides a strategy to promote healthier, more diverse soils as they directly recruit a microbiome conducive to plant health, such as disease suppression (Rolfe et al. 2019). Altering phytogenic signals into the rhizosphere might be an efficacious and potentially financially preferable alternative to soil inoculation. The practices could aid in areas where soil improvement is desperately required prior to crop development. Root exudates remain poorly understood due to the difficulty of their measurement, their chemical complexity, and a historical dearth of focus on their role (Williams and de Vries 2020); although, there has been increased research focus on these processes more recently, particularly from an agronomic viewpoint (de Vries et al. 2020).

Plants dynamically alter their root exudation profiles to recruit beneficial soil microbes in response to various stresses, including pathogen attacks, nutrient limitations, and drought conditions. Hence, exudates are vitally important for tailoring protective rhizosphere microbiomes. For example,

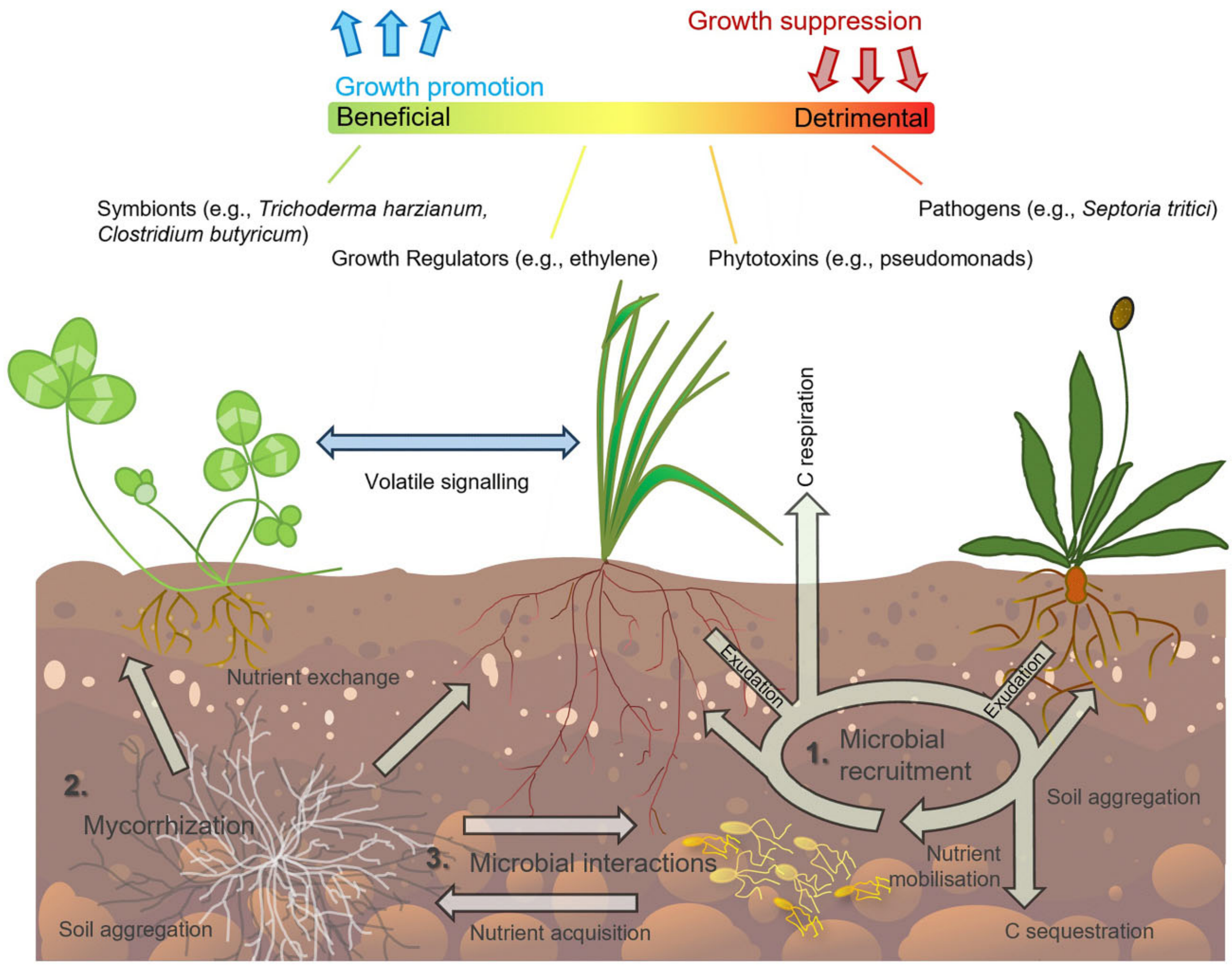

Figure 1. Understanding Plant–Microbe Interactions to Support Sustainable Ecosystem Practices. This schematic illustrates key gaps in our current understanding of plant–soil–microbe interactions, highlighting priority areas for future research to enhance our knowledge of plant–soil feedback mechanisms. (1) Root exudation serves as the primary input and mode of chemical communication within the rhizosphere, linking global carbon cycles with microbial recruitment, microbial function, soil biodiversity, and overall plant health. Deeper insights into these processes could inform strategies to better protect soils that are vulnerable to climatic extremes. (2) Mycorrhization and nutrient acquisition are critical for promoting plant development and improving nutrient content in host plants. While significant focus has been placed on glomeromycotina and their fungal symbiosis, this narrow view overlooks other important fungal associations that may also influence plant nutrient uptake and health—either directly or indirectly. (3) Edaphic interactions and broader soil biota dynamics influence microbial function and resilience. Interactions among soil microorganisms—including endobacteria that function as fungal symbionts—can impact soil quality and, in turn, enhance plant function and ecosystem health.

tomato plants under attack by *Ralstonia solanacearum* secrete flavonoids (like riboflavin and 3-hydroxyflavone) that attract *Streptomyces*, enhancing pathogen resistance through production of antibiotics (Feng et al. 2024). Similarly, *Arabidopsis* infected by the foliar pathogen *Pseudomonas syringae* pv. tomato increases malic acid exudation that acts as a chemoattractant for *Bacillus subtilis* FB17, resulting in better immune defence through induced systemic resistance (Doornbos et al. 2012). Arabidopsis can also adjust its root exudate composition to influence the surrounding microbial community to enhance nutrient mineralization and improve nutrient availability (Zhao et al. 2021). During drought, alfalfa recruits specific root-associated bacteria that aid in the plant's adaptation to water scarcity (Fan et al. 2023).

These examples underscore the sophisticated mechanisms plants employ to interact with their rhizosphere microbiome, tailoring root exudation profiles to recruit beneficial microbes that mitigate stress impacts and enhance survival. By over-expressing specific transporter genes in rice and wheat, the release of organic acids like malate and citrate from root apices can be modified, altering the composition of the root-associated microbial communities across different root types and soil conditions (Kawasaki et al. 2021). Such manipulations influence plant-microbe interactions, potentially leading to improved plant growth outcomes, but the impact of manipulation on soil C-cycling dynamics and microbial diversity must be properly evaluated prior to agricultural exploitation. Making use of naturally active exuders (such as legumes; Williams et al. 2022) could provide a low-risk avenue to directly increase soil nutrient availability for neighbouring crops. For example, increased exudation of citrate by faba bean improved phosphorus availability, which in turn stimulated root growth and phosphorus uptake in neighbouring maize (Zhang et al. 2016). The use of Trifolium in cover crops presents a simple practice to exploit this type of neighbour stimulation (e.g. in canola; Vaillancourt et al. 2018), and exudation may explain its effectiveness (Seitz et al. 2024). Exudate-mediated strategies for improving soil health are still in their infancy but show a huge amount for developing effective agronomic technologies.

Expanding complexity

Most research into microbial recruitment, including those discussed above, uses reductive approaches—single plant-microbe interaction—to capture the impact on host health. However, the reality is that plant rhizospheres are a biochemical factory of thousands of interacting species. Multipartite interactions between plants, microbes (fungi, bacteria, archaea) and the environment are fundamental to plant survival and ecosystem resilience. These complex relationships facilitate nutrient acquisition across ecosystems, enhance stress tolerance, and bolster disease resistance. For instance, arbuscular mycorrhizal (AM) fungi form symbiotic associations with plant roots, extending hyphal networks into the soil to access nutrients like phosphorus. These hyphae can host specific bacteria that further aid in nutrient mobilization and pathogen suppression, creating a synergistic effect that enhances plant health (Zhang et al. 2024). Environmental factors such as drought and soil salinity can disrupt these interactions. However, certain microbial consortia have shown resilience under such stresses. A notable example involves the cooperative interaction between *Bacillus velezensis* and *Pseudomonas stutzeri*, which form a multispecies biofilm that enhances plant salt stress tolerance (Yang et al. 2024). Similarly, the addition of *Pseudomonas*- and *Bacillus*-containing consortia has been shown to improve maize yield in weathered soils in sub-humid, rainfed systems (Manjunath et al. 2023). Archaea also represent an underutilized resource for enhancing crop health. These organisms are typically underexplored in soil science due to challenges associated with culturing and a historical focus on fungal and bacterial species. Their emerging roles in diverse ecologies, like methane metabolism and hydrocarbon cycling, are becoming increasingly clear (Baker et al. 2020). Archaea are now known to contribute to soil nutrition through processes such as nitrification (Jung et al. 2020), phosphorus solubilization (Naitam et al. 2023), and bioremediation (particularly in high-salinity environments; Martínez-Espinosa 2024), with growing potential for biofertilization (Masmoudi et al. 2023). Understanding and harnessing interkingdom interactions between archaea, bacteria, and fungi offer further promising avenues for sustainable agriculture. By moving toward a more ecological mindset to promote beneficial plant-microbe relationships, it is possible to reduce reliance on chemical fertilizers and pesticides, leading to more resilient cropping systems.

It is clear that soils are complex and thriving ecosystems. Organisms that live in the soil (including plants) mediate some of the more devastating effects of climate extremes on soils, through physical and chemical intervention, but extensively managed agricultural soil is largely degraded (Bai et al. 2018). Yet, the soil microbiome is not just a case of good *vs* bad actors. A healthy soil microbiome is a continuum—from pathogens that must be suppressed, through conditionally harmful phytotoxin producers (Lynch 1977), to beneficial consortia whose cooperative metabolism (e.g. *Clostridium butyricum*, *Trichoderma harzianum*, and polysaccharide–producing *Enterobacter cloacae*) can drive nitrogen fixation and organic–matter turnover (Veal and Lynch 1984)—underscoring the need for management strategies that favour the latter.

Similarly, plant growth regulators span a range of beneficial versus harmful effects. For example, ethylene, produced by beneficial microbes (such as *Mucor hiemalis*) is a major regulator of plant development (e.g. Dubois et al. 2018), can suppress crop growth in anaerobic soil conditions (Lynch 1972, 1975). It would be pertinent to leverage microbial ecology in the soil to provide the ecosystem services we need, which requires understanding soil ecology, particularly the emerging field of rhizomicrobiomics (utilizing plant-associated microbes for sustainable agriculture; Lynch 2024). Currently, the physiochemical context of the rhizosphere—intricate root systems, rhizosphere chemical factories, hyphal networks, and microbial biofilms—are all routinely disrupted via intensive management strategies (Banerjee et al. 2019), damaging complex microbial consortia. Opportunistic members of the microbial community can bounce back most rapidly, resulting in potentially long-term deleterious impacts on plant health (Wortmann et al. 2008). While it seems unlikely that sustainable practices, particularly those making use of rhizomicrobiomics, can match the yield potential of conventional management practices (Seufert et al. 2012, Knapp and van der Heijden 2018), the writing is on the wall regarding degradation and destruction of global soil stocks (FAO 2015). Some of the interim solutions discussed by Neale et al. (2024; biostimulants, biofertilizers and microbial inoculation) may aid in the shift toward sustainable practices and promoting more beneficial microbes, but advancing ecological understanding surrounding microbial interactions will provide a mechanistic basis for context-dependent intervention.

Funding and regulatory landscape

To fully capture the complexity of soil systems, we need a coordinated, well-funded, and highly organized effort, as outlined by Neale et al. (2024). Sustainable, soil-centric models of food production must recognize and assign a real economic value to healthy soils (Pereira et al. 2018, Brady et al. 2019). The Environmental Land Management Scheme (ELMs) in the UK offers a promising precedent (Natural England 2024), showing that under-recognized ecosystems like soils can be integrated into national policy. Yet, despite being mentioned in the UK Environmental Improvement Plan, soils are not prioritized to the same extent as air or water (Defra 2023)—a critical oversight given their foundational role in primary productivity. Determining which metrics to monitor for soil health remains a nuanced and complex challenge (Defra 2022), contributing to slow uptake from a policy standpoint. A key opportunity lies in structuring monetary service allocations through existing subsidy systems, such as ELMs mentioned above. These could be applied across land types (including agricultural greenbelt) and embed soil health directly into the framework of land management support. Importantly, soil health is context-specific, varying with land use and how that use is changing (including the gradual shift from agriculture toward forestry; DLUHC 2022). Whether in agriculture, horticulture, forestry, or agroforestry, metrics for healthy soils must align with land use goals: from wood decay capacity to nutrient availability, or from carbon storage to nitrogen retention.

The concept of ecosystem services (ES) builds a further practical method for evaluating soil functionality—including carbon sequestration, biodiversity support, and land stabilization—all of which are pressing issues in the UK (Gregory et al. 2015), but also more broadly. Valuing ES could, in some cases, balance against benefits of high-yield cropping, potentially encouraging landowners to reduce high-intensity practices in favour of long-term soil stewardship. Adopting an ES framework may prove mutually beneficial: farmers maintain productive land (albeit potentially at lower yields, but with improved resilience and quality), while simultaneously safeguarding soil health and environmental integrity. Crucially, uptake of schemes to promote soil health must be backed by secured funding for soil science, particularly in plant-microbe communication, microbial ecology, trait-based ecosystem understanding, and management of microbial consortia; areas currently underrepresented in soil health assessments. By aligning its funding criteria with the UN Sustainable Development Goals (SDGs) and conservation priorities, UKRI is setting a global standard for responsible research funding, but policy must keep pace with these developments. Prioritizing collaboration among stakeholders—scientists, land managers, industry, and policy-makers—as advocated by Neale et al., will allow soil science to advance meaningfully with application in mind. With rapidly evolving technologies for investigating below-ground systems (Box 1), funding and policy infrastructure need to align to capitalize on current technological momentum and ensure resilient national soil systems for the future.

Box 1. Emerging tools for embracing ecosystem intricacy
Understanding and leveraging the complexity of soil ecosystems demands consideration of numerous interwoven factors. Soil type—shaped by the parent rock, climatic history, vegetation and fauna, land use, and geographic context—strongly determines microbiome composition. In addition, seasonal cycles and exposure to climate extremes modulate soil biology and function at every level, influencing plant-derived inputs (e.g. litter, root exudates), microbial activities, and the soil's physicochemical structure.

To capture and interpret these multifactorial, temporally dynamic processes, advanced computational tools are essential. Emerging machine learning and artificial intelligence frameworks offer unprecedented opportunities to disentangle multi-species interactions, chemical signalling networks, and spatial-temporal patterns of function across diverse ecosystems. Tools such as random forest modelling, Bayesian network inference, and platforms like QIIME2, PICRUSt2, and DEICODE are being applied to pinpoint functional keystones (such as allelochemical signalling, osmolyte production, or nutrient mobilization traits) within complex microbiomes.

In parallel, trait-based plant breeding and rhizosphere engineering are becoming important strategies to enhance plant recruitment of beneficial microbes. By selecting for plant genotypes that promote these critical soil functions, we can reduce reliance on synthetic inputs and move toward more resilient and sustainable agricultural systems.

Humanity has survived various existential threats and devastating climate-change events, via development of agricultural technologies. The growth and continuous survival of agricultural, globally necessitates healthy soil for food. To allow the microbial communities in soils to thrive and permit quality agricultural output at the rate required, a move toward safeguarding soil resources through political, scientific, societal, and economic harmony is essential. In the UK, there is an urgent need to adapt land-use practices that emphasize soil health. We are in a unique position to spear-head the societal and scientific thinking on soil globally through integrated incentives, sustainability-focused funding, research-led policy changes, and land-management strategies that reflect a continued investment in sustainable British agriculture.

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Author contributions

Alex Williams (Conceptualization [equal], Writing – original draft [lead], Writing – review & editing [lead]), Jim Lynch (Conceptualization [equal], Writing – original draft [supporting], Writing – review & editing [supporting])

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Data availability

No new data were generated or analysed in support of this research.

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