Soil organic carbon change in UK mineral and organo-mineral soils since 2000: a systematic evidence map and critical narrative synthesis

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Abstract

Soil organic carbon is increasingly embedded in United Kingdom climate and land-use policy, yet the empirical basis for estimating its long-term change in mineral and organo-mineral soils remains uncertain. We conducted a systematic evidence map and critical narrative synthesis of peer-reviewed and grey literature published between 2000 and 2025 to evaluate soil organic carbon stocks and changes associated with land-use transitions and management practices. Seventy-five studies met predefined eligibility criteria. Evidence was unevenly distributed across land uses, depths and study designs, with most measurements restricted to topsoil layers and few long-term, full-profile assessments. Reporting of contextual variables, including soil type, soil properties and management history, was often limited or inconsistent, restricting assessment of how SOC responses vary across environmental settings. Frequently studied cropland-to-grassland and cropland-to-woodland transitions showed predominantly positive SOC stock outcomes, whereas management responses were generally mixed. Only two of 75 studies provided empirical evidence relevant to reversibility, while evidence on the development and persistence of stable SOC states was very limited. Heterogeneity in metrics, depth coverage, study duration and contextual reporting limited comparability and precluded quantitative meta-analysis. As a result, inconsistent signals across the recent UK literature appear to reflect limitations in study design, reporting and evidence availability more than clear evidence that land-use or management interventions lack sequestration potential. The post-2000 UK evidence base has strengthened confidence in qualitative conclusions, particularly for major land-use transitions, but has not substantially reduced uncertainty regarding the magnitude, persistence, reversibility or whole-profile extent of soil organic carbon change. The evidence map supports qualitative interpretation of recurring patterns, including plausible SOC gains under certain land-use changes and management practices, but does not provide robust UK-specific sequestration rates. Soil organic carbon sequestration should therefore be treated as a context-dependent and bounded mitigation option that may deliver important soil-health and ecosystem co-benefits alongside potential climate benefits.

Keywords: soil organic carbon; land-use change; soil management; carbon sequestration; evidence synthesis

Introduction

Importance of soil organic carbon for climate mitigation and soil health

Soil organic carbon (SOC) constitutes the largest pool of organic carbon in terrestrial ecosystems. Globally, the top metre of soils store approximately 1,580 Gt of organic carbon, representing about 72% of the biosphere's total organic carbon (Falloon et al., 2009). This stock substantially exceeds that held in vegetation and the atmosphere combined. Even small percentage changes in SOC stocks can significantly affect atmospheric CO_2 levels and climate (Song et al., 2023).

SOC sequestration refers specifically to the net removal of CO_2 from the atmosphere through plant photosynthesis and its subsequent incorporation and stabilisation in soil organic matter, thereby reducing greenhouse gas concentrations (Sadatshojaei et al., 2021). Because SOC represents a large and relatively long-lived carbon pool, it has been widely considered a potential sink for carbon dioxide, provided that management shifts the balance towards sustained net accumulation (Lal, 2004; P. Smith, 2004). SOC functions as a critical long-term carbon store, with a global mean residence time of approximately 1,200 years, although this varies widely with climate, soil properties, and management (Post et al., 1982). Its persistence depends both on the capacity of soils to accumulate carbon and on the mechanisms that stabilise it against loss. Stabilisation operates through multiple, interacting processes across molecular, aggregate, and ecosystem scales (Nair et al., 2015). Organo-mineral associations, in which clay minerals and metal oxides bind organic compounds, reduce microbial accessibility and slow decomposition, thereby enhancing persistence in soils (Carvalho et al., 2023; Meng et al., 2025; Rani, 2021). Physical protection through aggregate occlusion further limits exposure of SOC to decomposers by entrapping organic matter within soil structural units (Carvalho et al., 2023).

At the biochemical level, microbial pathways are central to SOC stabilisation. Microbial residual carbon (MRC) and mineral-associated organic carbon (MAOC) constitute key stable fractions, with MRC accounting for approximately 39% of stable SOC (Song et al., 2023). Microbial carbon use efficiency (CUE) has emerged as a dominant determinant of global SOC persistence, exerting a stronger influence on long-term storage than carbon input rates alone (Tao et al., 2023). When stabilised under favourable environmental and management conditions, SOC can remain sequestered for decades to centuries. However, this persistence is conditional. Disturbances such as tillage, erosion, and land-use change can destabilise protected carbon pools by disrupting soil structure and exposing previously protected organic matter to microbial decomposition (Sadatshojaei et al., 2021). Climatic warming further accelerates decomposition by increasing microbial metabolism and enzyme activity, shortening organic matter residence times. This effect is particularly strong in high-SOC soils, where larger pools of labile and physically protected carbon become increasingly accessible as temperature, moisture and aeration regime shifts (Qu et al., 2024). Warming may also intensify hydrological extremes, increasing erosion, flooding and fluvial export of soil carbon, thereby enhancing both lateral carbon transport and eventual atmospheric return (Lal, 2022; Y. Zhang et al., 2024). Nutrient limitations may also constrain the capacity of soils to sustain accrued carbon gains over time because insufficient nitrogen or phosphorus reduces microbial carbon use efficiency and biomass formation, limiting the conversion of plant inputs into stable microbial residues while promoting the decomposition of existing SOC to meet microbial nutrient demand (Janes-Bassett et al., 2021).

The global technical potential for additional soil carbon sequestration has been quantified using a range of assumptions regarding adoption rates, sequestration rates, and time horizons. Lal (Lal, 2004) estimated that soil carbon sequestration could contribute 0.4 to 1.2 Gt C yr^{-1} of sequestration per year, equivalent to 5-15% of annual global fossil-fuel emissions. The attainable soil carbon sink capacity was estimated at 50-66% of the theoretical potential, corresponding approximately to a cumulative 55-78 Gt C in total. However, this sink is finite and likely to persist for only 20-50 years before soils approach a new equilibrium (Lal, 2004). It is important to acknowledge that this potential for additional soil carbon sequestration is highly context-dependent, with sequestration rates and saturation capacities sometimes differing substantially across climatic zones, soil types, and land-use systems, limiting the uniform applicability of global estimates (Ghimirey et al., 2025). More recent work has emphasised that SOC responses commonly follow a non-linear trajectory, with rapid initial gains following land-use change or management intervention slowing as mineral-associated carbon pools approach capacity (Song et al., 2023).

Beyond direct climate mitigation, SOC delivers critical co-benefits for soil health and ecosystem functioning. It improves soil structure, aggregate stability, and porosity, enhancing resistance to erosion and compaction. SOC also increases water-holding capacity and supports nutrient cycling, thereby improving fertility and plant productivity. These functions contribute to broader ecosystem services and can reduce reliance on energy-intensive external inputs, while increasing resilience to drought and other climate-related stressors (Maqbool et al., 2025). These co-benefits can also indirectly reduce emissions; for example, improved soil fertility may reduce the need for synthetic fertiliser inputs, thereby lowering associated greenhouse gas emissions (Yin et al., 2026; M. Zhang et al., 2016). Given the very slow rates at which stable SOC accumulates, relative to the speed at which it can be lost, protection of existing stocks is at least as important as efforts to enhance them. Large SOC pools have developed over centuries to millennia, yet losses can occur rapidly under intensive disturbance, drainage or inappropriate land management. Effective climate mitigation strategies must therefore prioritise the avoidance of SOC losses (especially in high-carbon ecosystems such as peatlands, forests and permanent grasslands) alongside any efforts to promote additional carbon sequestration in soils depleted in SOC (such as croplands and some degraded grasslands).

Role of SOC in UK climate policy and land-use decision-making

Soil carbon is increasingly referenced in UK and devolved government net-zero strategies, particularly within land-use, land-use change and forestry (LULUCF) frameworks (Smith et al., 2022). Policy discussions frequently position land-use change and land management practices as potential mitigation levers that can contribute to carbon dioxide removal (CDR) targets (Lezaun et al., 2021). Agricultural mitigation measures, including SOC-enhancing practices, have been identified as important components of land-based decarbonisation strategies (Jebari et al., 2023). The UK's independent Climate Change Committee (CCC) has stated that achieving net zero will require between 75 and 175 $MtCO_2e$ of engineered and nature-based carbon removals annually by 2050 (CCC, 2019). Within this context, SOC sequestration is often cited as a nature-based option that could contribute to the required CDR portfolio (Caldecott & Johnstone, 2024; Lezaun et al., 2021).

However, the scale at which SOC can realistically contribute to national mitigation targets remains limited relative to whole-economy decarbonisation requirements. A UK-wide integrated C-N-P modelling study estimated that achieving realistic targets for grassland restoration and afforestation could sequester approximately 120 Tg C by 2100, equivalent to around 7% of the net emission reductions required for UK net zero under a <2 °C warming scenario, with net soil carbon losses projected under less favourable climate trajectories (Yumashev et al., 2022). Similarly, Welsh Government synthesis using the FABLE framework concluded that even ambitious land sparing and peatland restoration strategies would be unlikely to deliver more than 5-10% of total UK mitigation requirements (Jones et al., 2023). Additional constraints arise from limited restoration area, continued emissions from drained peatlands (Khan et al., 2025; Lunt et al., 2019), and resource and management limits demonstrated in long-term agricultural experiments (Poulton et al., 2018). Collectively, these assessments indicate that soil and peatland carbon sequestration can contribute meaningfully but modestly, typically on the order of 5-10% of required emissions reductions under favourable conditions, while remaining vulnerable to reversal (McGuire et al., 2022).

Policy relevance, therefore, depends not only on theoretical sequestration potential, but on the robustness, consistency and interpretability of the underlying evidence base. Accurate SOC accounting remains technically challenging, particularly in detecting rates of change, attributing impacts to specific management practices, and assessing the long-term persistence of sequestered carbon (Wiese et al., 2021). Reliable decision-making requires quantitative assessments that explicitly address uncertainty, full soil profile depth rather than surface layers alone (Rodríguez-Rastrero et al., 2025), appropriate monitoring timescales to capture potential plateauing or reversal of gains (González-Rosado et al., 2021), and the risk of reversibility under disturbance or climatic variability (Moinet et al., 2023; Wiese et al., 2021). Without such clarity, there is a substantial risk of overstating mitigation potential or misallocating resources within the land-use sector.

Stocks *versus* sequestration: clarifying a persistent source of confusion

Much of the misunderstanding surrounding soil carbon mitigation potential stems from conflating SOC stocks with rates of SOC change. SOC stocks refer to the total quantity of carbon stored in soil at a given time, a static measure typically expressed per unit area and depth. In contrast, SOC sequestration rates describe the annual net change in SOC stocks, representing a net annual removal of carbon from the atmosphere. It is a dynamic measure, usually expressed as mass of carbon per hectare per year (Lal et al., 2015). Failure to distinguish clearly between these two metrics can lead to substantial misunderstandings of long-term mitigation potential.

Over-interpretation frequently arises when short-term experimental gains (typically observed over years to a few decades) are extrapolated linearly to longer time horizons (multiple decades to centuries) without accounting for carbon saturation dynamics or declining marginal accumulation rates. SOC accrual typically follows a non-linear trajectory, with rapid initial increases after management change that slow as soils approach a new equilibrium (Wang et al., 2025; Wenzel et al., 2022). Similarly, short-term increases may reflect transient accumulation of labile organic matter rather than formation of more persistent mineral-associated carbon (Lavallee et al., 2020).

Crucially, interpretation of both stocks and rates of change depend on baseline conditions, sampling depth, and study duration (Amoakwah et al., 2023). Initial SOC stocks and soil properties determine sequestration capacity and constrain achievable equilibrium levels, such that reported rates cannot be interpreted independently of starting conditions (McDonald et al., 2023). Likewise, shallow sampling (e.g., 0-30 cm) may capture changes in surface stocks without reflecting whole-profile carbon dynamics, leading to misrepresentation of net stock change (Hicks Pries et al., 2023a). Short-term studies frequently report elevated annual rates during transitional phases that do not represent sustained long-term sequestration (Wenzel et al., 2022). Without explicit consideration of these constraints, reported rates may be mistakenly interpreted as durable increases in total SOC stocks.

Clear differentiation between stocks and rates, together with transparent reporting of baseline conditions, sampling depth, and study duration, is therefore essential for robust assessment of soil carbon mitigation potential.

Why a systematic evidence map is needed

Evidence on SOC change in the UK plays an increasingly prominent role in land-use and climate policy discussions, yet it remains fragmented, methodologically heterogeneous and heavily reliant on legacy datasets. Many quantitative estimates of SOC response derive from long-term experimental platforms such as those from Rothamsted, which provide invaluable multi-decadal treatment comparisons but also illustrate the age and limited geographic scope of much of the foundational empirical base (Jordon et al., 2024; Poulton et al., 2018). National-scale stock assessments similarly depend on archived survey data and historical land-use transitions spanning much of the twentieth century (Bell et al., 2011), underscoring continued reliance on older datasets for contemporary estimates.

The contemporary UK SOC literature is dispersed across multiple institutions, monitoring programmes, experimental networks, and mapping initiatives, with limited integration across datasets. National SOC maps differ systematically, particularly in high-carbon organo-mineral and organic soils, reflecting divergent model inputs, covariates, and methodological choices. In parallel, protocols and carbon standards vary widely in sampling design, baseline definition, stock estimation, and monitoring intervals, leading to inconsistencies in how SOC change is quantified and reported (Beka et al., 2022). Major differences persist in depth intervals (e.g. 0-10 cm, 0-30 cm, 0-100 cm), units of measurement (%, g kg^{-1}, Mg C ha^{-1}), and whether outcomes are expressed as concentration or stock (Beillouin et al., 2023). Such inconsistencies complicate aggregation and comparison across studies.

Depth coverage represents a further structural limitation. Approximately half of the organic carbon in England and Wales is stored below 30 cm, yet subsoil measurements remain sparse and unevenly distributed across soil types (J. U. Smith et al., 2009). Reliance on standard 0-30 cm sampling risks misestimating total stock change and obscuring depth-specific dynamics. More broadly, audits of SOC meta-analyses have identified deficiencies in literature search transparency, effect size standardisation, and treatment independence, highlighting persistent heterogeneity in metrics and reporting practices (Beillouin et al., 2022).

Given the growing policy demand for quantitative, defensible estimates of SOC storage potential and land-use effects in UK mineral and organo-mineral soils, a systematic evidence map is required to provide structured and transparent assembly of the post-2000 literature. Such a map can document the distribution of evidence by soil type, depth, intervention, and timescale; expose incompatibilities that limit quantitative synthesis; and identify spatial and methodological gaps where additional data collection would most effectively reduce uncertainty. In addition, systematic mapping allows assessment of whether the contemporary UK evidence base is sufficient to support robust inference regarding SOC sequestration, persistence and reversibility, and to identify where important limitations remain. By establishing a clear inventory of available evidence before aggregation, a systematic map provides the necessary foundation for robust meta-analysis and policy-relevant interpretation. To provide context for interpreting the UK evidence base, the study also compares evidence availability with global evidence from climatically similar (cool-temperate) regions. This comparison is intended to distinguish gaps specific to the UK from broader structural limitations in SOC research and to provide an interpretive benchmark for assessing the maturity of the UK evidence base.

Aims and research questions

The primary aim of this study is to undertake a systematic evidence map of UK evidence on SOC change in mineral and organo-mineral soils and to provide a critical narrative synthesis of reported patterns and evidence gaps. Against long-standing uncertainty in UK SOC sequestration estimates, the review evaluates whether the post-2000 evidence base has materially strengthened confidence in the effects of land-use transitions and management practices and whether it can support robust UK-specific inference regarding SOC sequestration, persistence and reversibility. The review focuses on reported SOC responses to land-use change and land management practices in UK mineral and organo-mineral soils. The synthesis incorporates all documented soil depths and SOC metrics. Heterogeneity in study design, depth coverage, duration, and reporting conventions was captured during the mapping process.

Deep peat soils are excluded due to their distinct carbon dynamics, regulatory context, and policy treatment.

Research questions

1. What studies have been published in the UK since 2000 on SOC change under land-use transitions and management practices, and how is this evidence distributed across regions, soil depths, and study designs?
2. What directions of SOC change are reported for different land-use transitions and management practices, and how consistent are these findings?
3. To what extent do existing studies address depth, timescales, reversibility, saturation and persistence, and where do remaining evidence gaps limit robust inference regarding SOC sequestration?
4. What are the dominant sources of uncertainty and limitation in the current UK SOC evidence base, and how do these constrain interpretation for policy and practice?
5. How does the coverage and distribution of the UK evidence base compare with global evidence from cool-temperate regions?

Materials and Methods

Review scope and eligibility criteria

This review targeted quantitative evidence on SOC stocks and SOC change in mineral and organo-mineral soils under land use and land management in the United Kingdom. Eligible studies assessed SOC responses to land-use transitions between cropland, grassland and woodland, or to management practices within a single land use. Eligibility criteria for geographic scope, soil type, land use, interventions, outcomes, publication period, and study type are defined in Table 1.

Table 1 Eligibility criteria applied for study inclusion in the systematic review.

Domain	Inclusion criteria	Exclusion criteria
Geography	United Kingdom	Non-United Kingdom
Soil type	Mineral and organo-mineral soils	Deep peat soils; peat-dominated wetlands; marine sediments
Outcomes	Quantitative SOC stocks or SOC change (t C ha^{-1} or equivalent)	Qualitative assessments only; no SOC data
Land use	Cropland, grassland, woodland, mountain moor and heath	Waste-derived systems, mine tailings
Interventions	Land-use change; land management practices	Modelling-only, remote-sensing-only or machine-learning-only studies
Study type	Field-based empirical studies; modelling studies with measured data	Laboratory-only studies;
Publication period	2000-2025	Pre-2000 publications
Language	English	Non-English publications

Literature search and screening

A literature search was conducted in August 2025 using Scopus, Web of Science and Google Scholar. Search strings combined terms relating to SOC, land use and land management, and geographic scope within the United Kingdom. Searches were restricted to English-language publications published between 2000 and 2025. Studies focused on peat and peatland soils were excluded using NOT operators. A summary of the search strategy is provided in Table 2, and full search strings are reported in Supplementary Tables S1 and S2.

Grey literature was identified using targeted Google searches of UK government departments, devolved administrations and UK research institutes and networks. These searches were restricted to documents published from 2000 onwards.

All retrieved records were imported into a reference management database (Zotero version 7.0.22) and screened against predefined eligibility criteria. Duplicate records were removed prior to screening. Remaining records were screened by the lead reviewer at title and abstract level using Rayaan (Ouzzani et al., 2016), to improve consistency, a second reviewer independently assessed approximately 10% of records. Disagreements were discussed and resolved through review of the eligibility criteria and, where necessary, reassessment of the study record. Potentially relevant studies were assessed at full-text. Reasons for exclusion at the full-text stage were recorded and are summarised in Figure 1.

Table 2 Overview of the literature search strategy and sources.

Component	Description
Databases	Scopus, Web of Science, Google Scholar
Search date	August 2025
Timeframe	2000-2025
Language	English
Core concepts	SOC × land use/management × UK
Google Scholar strategy	Four thematic queries; first 200 results per query
Grey literature	Targeted Google searches of UK government and research organisations
Exclusion filters	Peat-related terms excluded via NOT operators

In total, 75 studies met the inclusion criteria and were included in the review; the full list is included in the supplementary materials and cited in the references. Figure 1 summarises the study selection process using a PRISMA 2020 flow diagram.

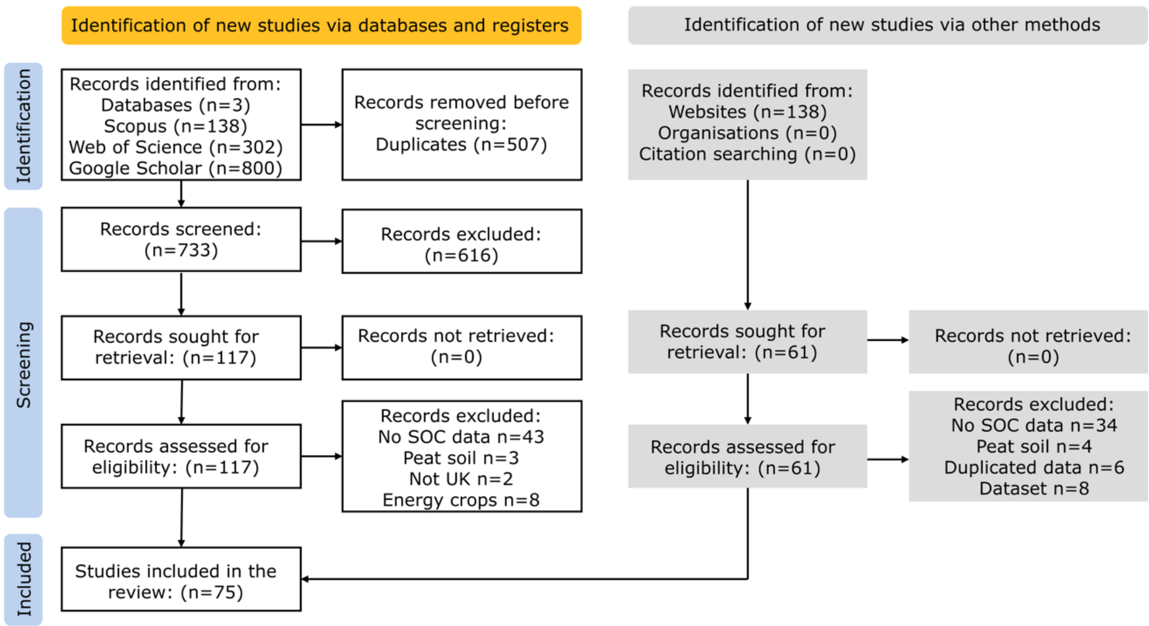

Figure 1 PRISMA 2020 flow diagram of study identification and screening.

Data extraction and variable definition

Data were extracted using a standardised template in Microsoft Excel for Microsoft 365 (Version 2607, Build 16.0.20228.20188; Microsoft Corporation) developed to capture SOC outcomes and associated study characteristics. Metadata recorded for each study included authorship, publication year, title, source, study design, and geographic location. Extracted variables comprised soil type, sampling depth, land use, land-use transition, management practice, and study duration. Variable definitions and coding categories are provided in Table 3.

Land use was classified using a bespoke scheme developed for UK land systems (Table 4). In particular, grassland was subdivided into improved and unimproved categories to distinguish agriculturally managed, high-input systems from semi-natural, low-input grasslands, which differ substantially in management intensity, nutrient status and baseline SOC. Management practices were bundled into broader categories and are described in Table 5.

Table 3 Variables extracted and coding scheme used for evidence mapping.

Variable	Definition
Starting SOC	SOC at baseline or control
End SOC	SOC at final time point or treatment
SOC change	End SOC - starting SOC
Depth category	Reported depth; later grouped analytically
Land-use category	Cropland, grassland, woodland, etc
Land-use change	Cropland ↔ grassland ↔ woodland ↔ mountain moor and heath
Management category	Tillage, grazing, amendments, cover cropping etc.
Design type	Chronosequence, BACI, space-for-time, monitoring
Location	Nation, region, site
Reported variability	SD, SE, CI or qualitative statement

SOC outcomes were recorded as starting SOC, end SOC, and SOC change (t C ha^{-1} or equivalent), where available. Values reported as stock (density) or concentration were recorded as provided and not standardised but distinguished within the dataset for subsequent analysis. Information on measurement and calculation methods, including bulk density determination and the use of equivalent soil mass approaches, was recorded where reported.

A distinct outcome was defined as a unique combination of study (Paper ID), land-use or land-use transition, management intervention (where applicable), soil depth category, and SOC metric. As a result, individual studies could contribute multiple records to the master dataset. One row of data was entered per instance of land-use or management change within each study, with paired starting and end values used to calculate SOC change (where this was not directly reported); only cases where a change in land use or management occurred were included.

Table 4 Land-use classification scheme and definitions used to code land use across included studies in the evidence map

Land Use	Land-use class	Description
Cropland	Cropland, arable, horticultural land	Land under annual or perennial crops, includes ley-arable rotations, horticulture
Unimproved Grassland	Semi-natural grassland	Semi-natural grassland with little or no agricultural improvement, low nutrient input, often species-rich and managed by light grazing or occasional cutting.
Improved Grassland	Permanent or temporary grassland subject to management	Permanent or temporary grassland subject to management to maintain or increase productivity, typically through reseeding, fertiliser or slurry application, liming, drainage, or grazing control.
Woodland	Forest, woodland, or tree cover (planted or natural)	Includes conifer and broadleaf, plantations, and natural regeneration
Woody features	Hedges, tree lines (not managed as integrated production systems), shelterbelts or buffers	Linear or scattered woody vegetation not forming continuous woodland
Wetland	Wet grassland, fen, marsh, pond margin (non-peaty)	Seasonally or permanently wet mineral or organo-mineral soils; peat soils (i.e. organic soils exceeding typical peat thresholds) were excluded from this category and from the analysis
Coastland	Saltmarsh, dune, coastal grassland or realignment	Coastal habitats with saline influence
Mountain moor and heath	Mountain, moorland, heath, rough grazing	Semi-natural upland or lowland heath vegetation
Agroforestry	Integrated tree-crop / tree-grass systems	Land-use systems combining deliberately planted trees with arable crops or managed grassland on the same land unit, managed as a single system.
Urban & Parks	Built-up or developed areas	Built-up or developed areas with a mix of impervious surfaces and managed green spaces, including parks, sports fields, gardens, and roadside verges. May include sealed or compacted soils as well as managed turf.

Table 5 Management practices classification scheme and how they were bundled across included studies in the evidence map

Management Practice	Example Practices / Keywords
Tillage management	Reduced till, minimum till, no-till, strip till, controlled traffic farming
Cover cropping	Green manures, catch crops, overwinter cover, legume covers
Organic / soil amendments	Manure, compost, slurry, digestate, crop residue incorporation
Rotation diversification	Crop diversity, inclusion of legumes, temporary leys, mixed cropping
Permanent cropping	Perennial cereals, agroforestry alley cropping, biomass crops
Nutrient management	Optimised fertiliser inputs, precision N management, slow-release fertilisers
Compaction management	Sub-soiling, reduced trafficking, timing of machinery use
Regenerative agriculture (bundled)	Reduced tillage, cover crops, residue retention, improved rotations
Diversified cropping + organic amendments	Rotation diversification combined with organic amendments
Fertiliser and liming	Nutrient optimisation, slurry management, reduced N use
Soil protection / erosion control	Buffer strips, contour ploughing, hedgerows, riparian zones
Drainage management	Controlled drainage, drain blocking, field drainage maintenance
Grazing management	Stocking density control, mob grazing, rotational grazing, rest periods, grazing exclusion
Sward diversification	Multi-species leys, legumes, deep-rooted species, diverse pastures

Management Practice	Example Practices / Keywords
Sward renewal	Re-seeding grassland, ploughing and re-seeding, pasture/ley renewal
Compaction management (grassland)	Aeration, reduced machinery use, seasonal restrictions
Livestock management	Change in livestock type, mixed grazing systems, manure distribution
Grassland management (bundled)	Combined grazing management + fertiliser/liming practices
Woodland management	Thinning, understorey management, selective harvesting, replanting, rotation change, conversion to conifer
Ground preparation / establishment	Mounding, ploughing for planting, herbicide site preparation
Water-level management	Seasonal inundation, controlled flooding, re-wetting, water table adjustment
Vegetation management	Reedbed cutting, scrub control, grazing adjustments
Coastal restoration	Saltmarsh creation, sediment trapping, managed realignment
Grazing (extensive systems)	Reduced grazing, grazing exclusion, restoration of dwarf shrubs
Burning regimes	Controlled burning, wildfire management
Erosion control	Re-seeding, gully blocking, revegetation, sphagnum restoration
Organic management	Conversion to organic farming, low-input systems, integrated farm management
Enhanced rock weathering	Basic silicate rock, basalt fines, crushed mineral amendments
Biochar addition	Charred biomass, biochar-compost mixtures, black carbon amendments
Microbial inoculation	Mycorrhizal fungi, bacterial consortia, biofertiliser inoculants

Management Practice	**Example Practices / Keywords**
Seaweed-based amendments	Seaweed extracts, algal biostimulants, liquid seaweed fertilisers
Novel mineral / chemical amendments	Carbonate-rich by-products, lime-silicate blends, zeolites, gypsum
Integrated emerging systems	Combined ERW-biochar-microbial trials, experimental soil enhancers
Conversion from one land use to another	Fundamental system change involving drainage, vegetation, and management shifts
Arable → permanent grassland	Arable reversion, long-term swards, cessation of tillage
Grassland → woodland (planting)	Afforestation, tree planting, shelterbelts, hedgerows
Grassland → woodland (natural regeneration)	Secondary succession, scrub encroachment
Cropland/grassland → agroforestry	Alley cropping, silvopasture, tree strips, shelterbelts
Woodland creation	Woodland planting and natural regeneration
Energy crop establishment	Miscanthus, short rotation coppice (willow/poplar), switchgrass
Some national monitoring studies report stock change by habitat rather than by specific management practice.	

All study designs, including chronosequence, space-for-time substitution, before-after-control-impact (BACI) and national monitoring studies, were extracted using the same data structure. For chronosequence studies, the earliest and latest reported time points were recorded as starting and end SOC. For space-for-time and BACI studies, control values were recorded as starting SOC and treatment or post-intervention values as end SOC. For national monitoring studies reporting trends only, SOC change or SOC stocks were extracted without explicit start or end values. Where SOC change was not explicitly reported but start and end values were available, SOC change was calculated as the difference between end and starting SOC.

Reported sampling depths were reclassified into three analytical depth categories (topsoil, mid-profile, and full profile). Geographic location was coded hierarchically (nation, region, and site).

Where multiple SOC metrics were reported for the same comparison, SOC stocks expressed on an area basis (t C ha^{-1}) were prioritised; alternative metrics were retained only where stock values could not be derived.

Where land-use change occurred, SOC change was attributed to land-use transition rather than management intervention; management effects were coded only where land use remained constant. Numerical values were extracted from tables or text where possible; values digitised from figures (PlotDigitizer at https://plotdigitizer.com/app) were used only when necessary and were flagged. Additional contextual information (e.g. climate, disturbance factors, and reported uncertainty) was recorded where available.

SOC analytical methods were not used as inclusion or exclusion criteria. Included studies reported SOC using dry combustion (e.g. Dumas method), loss-on-ignition (LOI), or wet oxidation approaches. Where reported, method type was recorded but not used to stratify synthesis due to limited study numbers. Differences among analytical approaches, together with variation in bulk density measurement and equivalent soil mass treatment, were considered as contributors to methodological heterogeneity.

Systematic evidence mapping approach

Extracted data were synthesised using systematic evidence mapping in Microsoft Excel for Microsoft 365 (Version 2607, Build 16.0.20228.20188; Microsoft Corporation). Each row in the master dataset represented a distinct land-use transition or management change linked to a study identifier (Paper ID), based on paired starting and end SOC observations. This structure captured both initiation of a practice (e.g. control vs treatment) and transitions between existing practices or land uses, encoded as start-end pairs rather than direct side-by-side comparisons. Categorical variables included land-use transition, management intervention, soil depth, geographical coverage, study design, and SOC outcome type.

For evidence mapping, records in the master dataset were grouped by category and summarised using distinct counts of Paper IDs within Excel pivot tables. A study could therefore contribute to multiple categories where it reported multiple management practices, land-use transitions, depths, or locations (e.g. reduced tillage and organic fertilisation, or cropland-to-grassland and cropland-to-woodland conversion), but contributed only once to the count within each category. Counts therefore represent the number of unique studies contributing evidence to each category, irrespective of the number of observations or effect estimates reported by an individual study. Cross-tabulated coverage matrices and heatmaps using conditional formatting were used to visualise evidence density across key variable combinations.

The evidence map was used to summarise the available evidence within the predefined categories. The purpose of the mapping was descriptive rather than to estimate pooled treatment effects. Reported SOC responses were interpreted narratively, without quantitative aggregation of effect sizes.

Directional and narrative synthesis approach

A directional narrative synthesis was used to classify SOC change (increase, decrease or no change) for land-use transitions and management practices among studies reporting SOC change attributable to a land-use transition or management intervention. Direction was assigned from reported SOC change or calculated as end minus starting SOC where required; "no change" was assigned for non-significant or below-detection-limit changes. Outcomes involving land-use change were attributed to transitions irrespective of management, and management effects were synthesised only where land use remained constant. Directional outcomes were summarised in Microsoft Excel using pivot tables with distinct counts of study identifiers (Paper ID). Formal meta-analysis was not undertaken because of substantial heterogeneity in SOC metrics, sampling depths, study durations and designs, together with limited reporting of variance and substantial non-independence among outcomes.

Treatment of uncertainty and evidence strength

Uncertainty and evidence strength were assessed qualitatively to support interpretation across a heterogeneous evidence base. Confidence grading was used to characterise methodological robustness and reporting quality and was not used as a statistical weight or to infer effect size, significance, or direction of SOC change.

Confidence was assigned at the study level using a predefined qualitative framework based on study duration, replication, study design, sampling approach, methodological clarity, and reporting of uncertainty. Each study (Paper ID) was assigned a single confidence category (high, medium, or low), which was applied consistently to all records extracted from that study.

High confidence was assigned to studies with long-term observations (≥10 years) or replicated experimental designs where methods were clearly described and uncertainty estimates were reported. Medium confidence was assigned to studies of intermediate duration (3-9 years), partly replicated studies, or otherwise credible studies where uncertainty reporting was limited. Low confidence was assigned to short-duration studies (<3 years), unreplicated studies, model-based assessments, studies with unclear methodological descriptions, or studies with substantial reporting limitations.

Where study characteristics spanned multiple confidence categories, the overall classification reflected the combined methodological limitations rather than study duration alone. For example, long-duration studies that did not report uncertainty were classified as medium confidence, whereas replicated studies of less than three years' duration were classified as low confidence.

Evidence classification for synthesis heatmaps

For Figures 4 and 5, evidence sufficiency for UK studies was classified using study-count thresholds based on the number of independent studies available within each intervention-dimension combination. Categories were defined as follows: blue (≥6 studies), indicating relatively dense evidence considered sufficient for quantitative analysis; yellow (3-5 studies), indicating limited evidence sufficient for qualitative trend inference; and red (0-2 studies), indicating sparse evidence insufficient to infer trends. For the UK heatmaps, classifications were derived from all included studies reporting SOC stock change or rate-based outcomes. These thresholds were developed solely to support visual interpretation of evidence density within the evidence map.

To provide broader contextual comparison, an additional targeted review of published global meta-analyses from temperate and cool-temperate regions was undertaken following completion of the main UK evidence synthesis. For global evidence, sufficiency categories reflect interpretive assessment of published meta-analyses, based on how authors described data coverage, analytical feasibility, and reported limitations. Scores were categorised as strong evidence coverage (blue), moderate or uneven evidence coverage (yellow), or limited evidence availability and high uncertainty (red), rather than through direct application of study-count thresholds. In total nine meta-analyses were reviewed for constructing the heatmaps, this covered the years 2000-2025 (Chatterjee et al., 2018; Encarnation et al., 2026; Guo & Gifford, 2002a; Han et al., 2016; Jordon, Smith, et al., 2022; Jordon, Willis, et al., 2022; Kämpf et al., 2016; McClelland et al., 2025; Pan et al., 2025). Heatmaps were generated in R (version 4.5.2).

Reported annual SOC stock-change rates identified in the review were summarised descriptively in Supplementary Table S4. No formal synthesis of sequestration rates was undertaken because of limited study numbers and substantial methodological heterogeneity.

Expert assessment of operational feasibility

An exploratory expert assessment was conducted to identify potential operational barriers to the implementation of SOC-related management practices. This assessment was not part of the systematic review protocol and did not involve formal elicitation methods or structured consensus procedures. Preliminary technological readiness levels (TRLs) and barrier impact scores were assigned based on authors' expert judgement to illustrate potential constraints to uptake. These results are presented descriptively and can be found in the supplementary materials.

Results

Structure and distribution of the UK evidence base

The evidence base comprised 75 studies. Of these, 33 reported SOC change over time attributable to land-use transitions or management interventions. Among these, 25 studies reported SOC stock change, five reported SOC concentration change, and three reported rate-based SOC stock change. Nineteen studies contributed evidence on land-use transitions and 17 on management interventions; these categories were not mutually exclusive, as three studies reported separate comparisons addressing both land-use and management change.

Coverage of SOC studies across frequently reported land-use transitions and soil depth categories is shown in Figure 2. The evidence base was dominated by transitions from cropland to grassland or woodland, and from improved grassland to cropland or woodland. SOC measurements were predominantly restricted to topsoil layers, with limited mid-profile and full-profile reporting.

Land-use transition	Topsoil	Mid-profile	Full-profile
Cropland → improved grassland	7	1	1
Cropland → unimproved grassland	1	1	1
Improved grassland → cropland	4	1	0
Improved grassland → woodland	4	1	1
Cropland → woodland	3	1	1

Figure 2 Coverage of SOC studies across frequently reported land-use transitions and soil depth categories in the United Kingdom. Cell values indicate the number of studies reporting SOC measurements at each depth for a given land-use transition; darker shading indicates higher study density. Transitions reported by fewer than two studies are not shown for clarity.

Coverage of management practices studies across soil depth categories is shown in Figure 3. Management practices most frequently examined in relation to SOC change included fertiliser and liming, nutrient management, organic or soil amendments, rotation diversification, tillage management, and woodland management. As with land-use transition studies, management intervention studies predominantly reported SOC measurements in the topsoil, with limited representation of deeper soil profiles.

Management intervention	Topsoil	Mid-profile	Full profile
Cover cropping	2	1	0
Fertiliser and liming	7	0	0
Nutrient management	4	0	0
Organic/soil amendments	4	1	0
Rotation diversification	3	1	0
Tillage management	3	1	0
Woodland management	3	0	1

Figure 3 Coverage of SOC studies across management intervention categories and soil depth categories in the United Kingdom. Cell values indicate the number of studies reporting SOC measurements at each depth for a given management intervention; darker shading indicates higher study density. Management practices reported by fewer than two studies are not shown for clarity.

Geographical coverage of the evidence base was uneven across the United Kingdom, which is important given that regional differences reflect variation in climate, soil types, and associated controls on SOC dynamics. Studies examining both land-use transitions and management practices were concentrated in England (n=38), which was represented across nearly all transition and intervention categories. Within England, studies assessing SOC stock change were concentrated particularly in southeast and northeast England. Scotland (n=17), and Wales (n=12), were represented in fewer studies, primarily associated with grassland-woodland transitions and a limited subset of management practices. Only a small number of studies explicitly reported sites in Northern Ireland (n=9) and a small number reported together England and Wales (n=6). Several studies reported geographical coverage at the level of Great Britain (n=7), or the United Kingdom (n=8), without disaggregation to individual nations; these were retained as separate categories and not reallocated to specific UK nations.

Study designs varied across the evidence base, with space-for-time and chronosequence approaches forming the largest category (n = 29). Modelling and evidence-synthesis studies (n = 13) and national monitoring or inventory approaches (n = 12) were also represented. Fewer studies used BACI or temporal-resampling designs (n = 9) or repeated-measures and longitudinal experimental approaches (n = 7). Two studies used other observational designs, while study design was a mix of approaches and was unclassified for three studies.

Most studies did not explicitly differentiate mineral and organo-mineral soils, and many reported results aggregated across soil types. Consequently, outcomes could not be consistently stratified by mineral versus organo-mineral soils within the evidence map. Most studies were conducted in agricultural mineral soils, particularly medium-textured loam soils, with comparatively few studies explicitly focused on organo-mineral soils.

Directional responses of soil organic carbon to land-use change

Land-use transitions showed the most consistently reported directional SOC responses within the mapped evidence base. Evidence was concentrated in a small number of frequently studied transitions, particularly cropland-to-grassland and cropland-to-woodland conversions, which accounted for most reported SOC outcomes. Most other transitions were supported by only one or two studies. For these transitions, SOC responses were predominantly derived from topsoil measurements, with full-profile data reported by only a small number of studies, and geographic coverage was uneven across the United Kingdom (see Figure 2).

For cropland to improved grassland and cropland to woodland, SOC stock responses were predominantly positive. Most studies reported increases, with only isolated decreases and neutral responses observed, which were not consistent across studies and appear to reflect site-specific or context-dependent factors rather than a uniform response. Evidence for SOC concentration was sparse, with single studies reporting a decrease for cropland to improved grassland and an increase for cropland to woodland. Overall, the mapped evidence most frequently reported positive SOC stock responses for both transitions, although data remain limited.

Transitions involving improved grassland showed particularly variable outcomes. For improved grassland to woodland, SOC stock outcomes were predominantly negative, while rate-based metrics were mixed. This variability may partly reflect the heterogeneity within land-use categories, as both improved grassland and woodland encompass a wide range of management practices, vegetation types, and site conditions. Improved grassland to cropland was characterised by mixed SOC stock responses, but consistently negative SOC concentration outcomes.

All other land-use transitions, including those involving mountain moor and heath, unimproved grassland, wetlands, urban land, and woodland conversions, were supported by single studies or isolated outcomes only. While both increases and decreases were reported across these transitions, the available evidence does not allow identification of consistent directional SOC responses.

Table 6 summarises the direction of reported SOC responses across the most frequently studied transitions. These counts do not represent independent lines of evidence, as individual studies may contribute more than one outcome and should be interpreted as descriptive context rather than evidence of effect magnitude or comparative effectiveness.

Table 6 Counts of reported SOC outcome directions for frequently reported land-use transitions. Counts represent reported outcomes rather than independent studies; individual studies may contribute more than one outcome. The table provides descriptive context on the direction of reported SOC responses and the relative frequency of evidence across transitions, supporting the narrative synthesis. Outcome counts reflect reporting frequency only and should not be interpreted as evidence of effect magnitude, consistency, or comparative effectiveness between land-use transitions.

Land-use transition	SOC stock change (n+/n0/n−)	SOC stock rate change (n+/n0/n−)	SOC concentration change (n+/n0/n−)
Cropland → Improved grassland	+6 | 1 | −1	NA	0 | 0 | −1
Cropland → Unimproved grassland	+1 | 0 | −0	NA	0 | 0 | −1
Improved grassland → Cropland	+1 | 0 | −2	NA	0 | 0 | −2
Improved grassland → Woodland	+1 | 0 | −3	+1 | 1 | −1	NA
Cropland → Woodland	+5 | 0 | -1	NA	+1 | 0 | 0

Directional responses of soil organic carbon to management practices

In contrast to land-use transitions, reported responses from management interventions within the mapped evidence base were mixed and inconsistent. Evidence on the effects of management practices on SOC was limited in volume and unevenly distributed across intervention types. Most practices were supported by a small number of studies, with reported outcomes concentrated in a subset of management categories, including fertiliser and liming, nutrient management, organic or soil amendments, rotation diversification, tillage management, and woodland management (see Table 5 for definitions and example practices).

Across all practices, reported SOC responses were derived predominantly from topsoil measurements, with limited mid-profile data and very few full-profile assessments.

Fertiliser and liming showed predominantly positive SOC stock outcomes, with three positive outcomes and one no-change outcome. Cover cropping was supported by few reported outcomes, all of which indicated decreases in SOC stock. Nutrient management practices, organic or soil amendments, rotation diversification, tillage management, and woodland management similarly demonstrated variable SOC stock responses, with both increases and decreases reported. Rate-based SOC change metrics were reported for only a small number of practices. Woodland management was the only intervention category for which full-profile SOC outcomes were reported, although these were based on very limited evidence.

Table 7 summarises the counts of reported SOC outcome directions for the most frequently reported management practices across the evidence base. Counts reflect the number of reported outcomes classified as increases, decreases, or no change for each intervention and SOC metric. These counts do not represent independent studies, as individual studies may contribute more than one outcome. Given substantial heterogeneity in intervention definitions, study designs, soil depth coverage, and outcome metrics, the table should be interpreted as descriptive context rather than as a quantitative comparison or an indication of effect magnitude or consistency.

Table 7 Counts of reported SOC outcome directions for frequently reported management practices. Counts indicate the frequency of reported increases, decreases, and no-change outcomes across SOC metrics and are intended to provide a descriptive overview of directional trends and evidence distribution within the reviewed literature. Counts represent reported outcomes rather than independent studies, and individual studies may contribute more than one outcome.

Management practice	SOC stock change (n+/n0/n−)	SOC stock rate change (n+/n0/n−)	SOC concentration change (n+/n0/n−)
Cover cropping	0 | 0 | −3	NA	NA
Fertiliser and liming	+3 | 1 | −0	+3 | 0 | −0	+1 | 0 | −0
Nutrient management	+2 | 0 | −1	NA	NA
Organic/soil amendments	+3 | 0 | −2	NA	NA
Rotation diversification	+2 | 0 | −2	NA	NA
Tillage management	+2 | 0 | −1	+1 | 0 | −0	NA
Woodland management	+2 | 0 | −2	NA	NA

Temporal coverage and evidence for longer-term SOC dynamics

Temporal coverage of SOC change evidence was heterogeneous across outcome types. Among studies reporting SOC stock change (n = 25), eight included long-term observations (>15 years), seven included medium-term observations (5-15 years), one included short-term observations (< 5 years), nine did not clearly report study duration. Of the latter, three involved single time-point comparisons from which temporal SOC change could not be directly assessed. Among studies reporting SOC concentration change (n = 5), four were based on long-term observations, and one did not clearly report duration. Rate-based SOC change estimates were reported in three studies, all of which were based on long-term observations. The long-term evidence base was heterogeneous in terms of land-use transitions, management practices, and SOC metrics, while most SOC measurements were restricted to topsoil, limiting comparison across duration classes and inference on whole-profile responses.

Evidence addressing longer-term SOC dynamics was limited. Only two studies provided substantive information relevant to the development of a new stable SOC state: one reported a timescale of 50 years, while another reported continued SOC accumulation over 43 years with no evidence of stabilisation. Across the 75 included studies, empirical assessment of SOC reversibility was rare. Only two studies included observations relating to SOC change following land-use or management reversion. Qualitative references to SOC reversibility were identified in 16 studies, primarily within discussion sections and without empirical testing. These references noted that SOC gains may be lost following subsequent land-use change or intensified management, including examples related to hedgerow removal, tillage, harvesting, forest disturbance, and land-use conversion. Several studies referred to uncertainty regarding the persistence of SOC gains or recovery following disturbance, but did not quantify reversibility, recovery rates, or recovery timescales.

Evidence strength and uncertainty patterns

Confidence levels were assigned based on study duration, replication, methodological clarity, and reporting of uncertainty, with studies classified as high (≥10 years or replicated, clear methods, uncertainty reported), medium (3-9 years or partly replicated, credible methods, limited uncertainty data), or low (<3 years, unreplicated, unclear or model-based, no uncertainty reported). Across the full evidence base (n = 75), studies were distributed across confidence categories as follows: 29 high-confidence studies, 30 medium-confidence studies, and 16 low-confidence studies.

For studies reporting SOC stock change (n = 25), high-confidence evidence accounted for 12 studies, with a further nine classified as medium confidence and four as low confidence. Rate-based SOC change estimates (n = 3) included two high-confidence studies, and one low-confidence study. Studies reporting SOC concentration only (n = 5) were classified as either high (n = 4) or medium confidence (n = 1). The evidence base for rate-based SOC change estimates was small (n = 3), although two of the three studies were classified as high confidence.

Across outcome types, several recurring sources of uncertainty were identified. These included heterogeneity in reported SOC metrics (stocks, concentrations, or rates), inconsistent depth sampling across studies, and limited reporting of bulk density or use of equivalent soil mass adjustments. Among studies reporting SOC change (n = 38), bulk density was reported in only six studies. Additional sources of uncertainty included study durations that were short relative to SOC turnover times and frequent reliance on space-for-time substitutions or unreplicated paired-site designs. These limitations occurred across multiple land-use and management categories.

Summary of reported SOC outcomes

The synthesis of reported SOC outcomes indicates substantial variation in evidence availability across practices and assessment dimensions. As shown in Figure 4, evidence coverage for management practices is uneven. For UK studies, data are concentrated in the upper soil layers and short- to medium-term timescales, particularly for cropland practices including reduced-intensity tillage, cover crops and organic amendments. Across most practices, fewer studies report subsoil responses, long-term trajectories, saturation dynamics, or reversibility. In global cool-temperate studies, coverage spans a wider range of soil types, depth-resolved data and study designs, but explicit treatment of saturation and reversibility remain limited. For UK studies, only a subset of intervention-dimension combinations showed higher evidence density (≥6 studies); others fell within the moderate (3-5 studies) or sparse (0-2 studies) evidence-density categories.

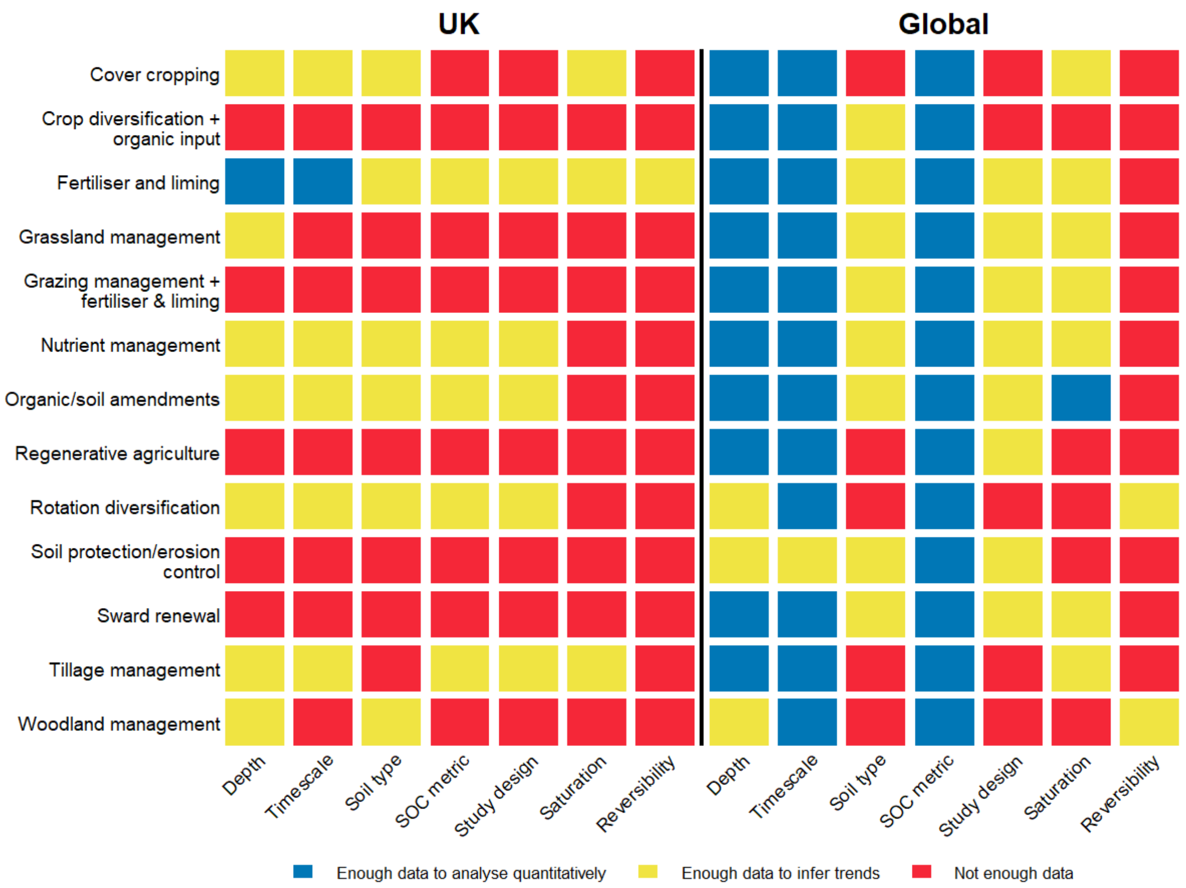

Figure 4. Evidence availability and gaps across land management practices for soil organic carbon (SOC) outcomes. The heatmap summarises the strength of the evidence base across key dimensions (depth, timescale, soil type, SOC metric, study design, saturation, and reversibility) for each management intervention. For the UK evidence base (left), colours represent the number of distinct studies contributing to each intervention-dimension combination: blue = ≥6 studies, yellow = 3-5 studies, and red = 0-2 studies. For the global cool-temperate evidence base (right), colours represent an interpretive assessment of published meta-analyses: blue = strong evidence coverage, yellow = moderate or uneven coverage, and red = limited evidence availability or high uncertainty. Global classifications are therefore not based on the numerical study-count thresholds applied to the UK evidence.

A similar distribution is observed for land-use transitions (Figure 5). UK evidence is concentrated on transitions from cropland to grassland and cropland to woodland, with fewer studies addressing other transition types. Reporting across soil depth, timescale, saturation, and reversibility is inconsistent. Evidence from global cool-temperate regions covers a broader set of transitions, but availability remains uneven across assessment dimensions. Several transition-dimension combinations fell within the sparse evidence category (0-2 studies), particularly for subsoil responses and long-term dynamics.

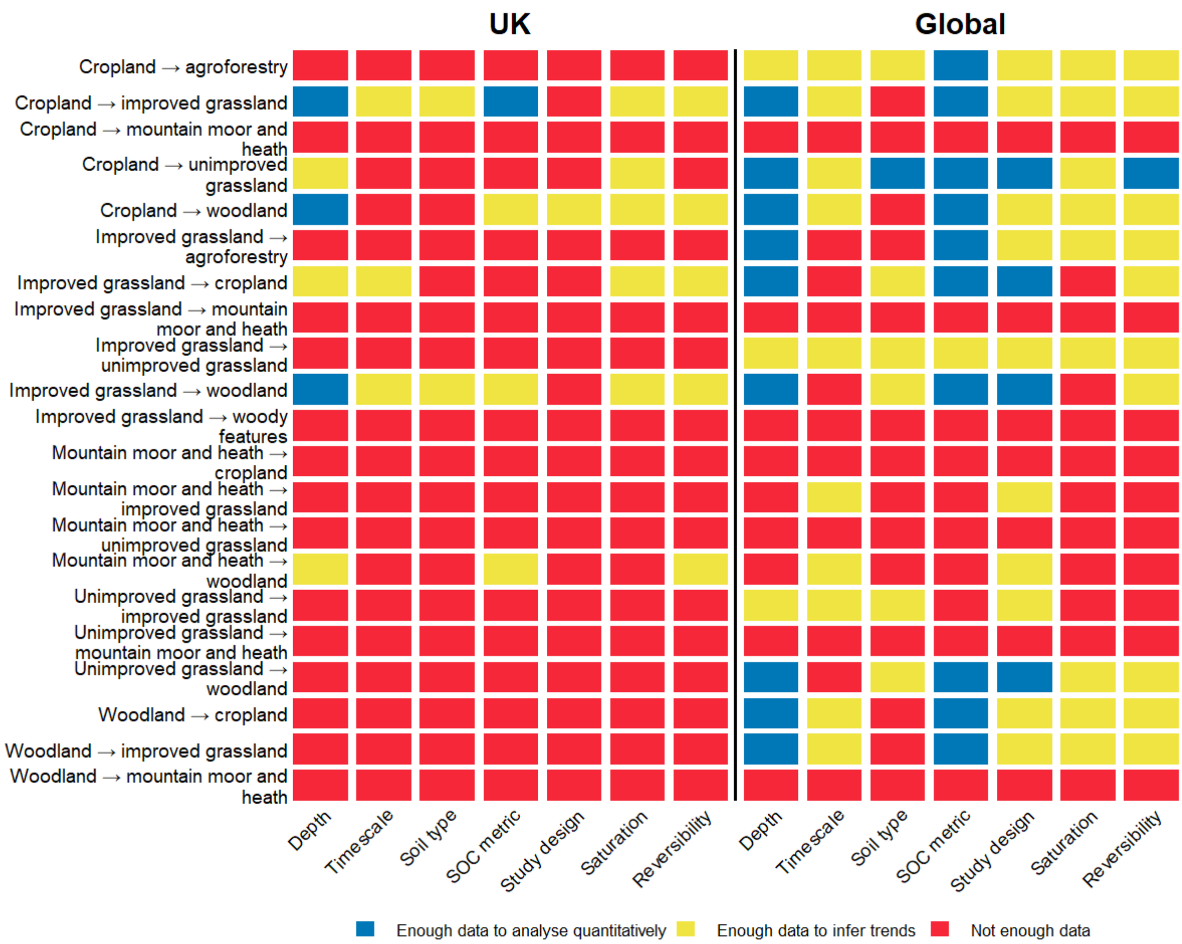

Figure 5. Evidence availability and gaps across land-use transitions for soil organic carbon (SOC) outcomes. The heatmap summarises the strength of the evidence base across key dimensions (depth, timescale, soil type, SOC metric, study design, saturation, and reversibility) for each land-use transition. For the UK evidence base (left), colours represent the number of distinct studies contributing to each intervention-dimension combination: blue = ≥6 studies, yellow = 3-5 studies, and red = 0-2 studies. For the global cool-temperate evidence base (right), colours represent an interpretive assessment of published meta-analyses: blue = strong evidence coverage, yellow = moderate or uneven coverage, and red = limited evidence availability or high uncertainty. Global classifications are therefore not based on the numerical study-count thresholds applied to the UK evidence.

Reported annual SOC stock-change rates exhibited substantial variability across interventions (Supplementary Table S4). Several intervention categories were represented by only two or three studies and observed ranges frequently spanned both gains and losses. This variability likely reflects environmental context, management differences, study duration, sampling depth, and methodological heterogeneity. These findings reinforce a central conclusion of this review: despite 25 years of UK research, the evidence base remains insufficiently extensive and consistent to support robust UK-specific estimates of SOC sequestration rates.

Implementation feasibility and operational barriers

Although implementation feasibility was outside the formal scope of the systematic evidence map, an exploratory author-led assessment was undertaken to identify potential barriers to adoption of SOC-supporting practices. Barriers included infrastructure requirements, skills and guidance gaps, capital costs, investment risk, land suitability, social acceptability, farmer culture, and environmental or food-security trade-offs. Preliminary assessments suggested that infrastructure limitations, economic risks and capacity constraints may limit uptake of some interventions despite evidence for SOC benefits. Because the assessment was based on expert judgement rather than a formal elicitation process, findings are presented as illustrative only. Detailed scores are provided in the Supplementary Material.

Discussion

This review provides the first systematic assessment of the post-2000 UK evidence base on SOC change across land-use transitions and management practices. The evidence supports broad qualitative conclusions regarding the direction of SOC responses to some frequently studied land-use transitions, although it remains insufficiently consistent and comprehensive to provide robust UK-specific estimates of the magnitude, persistence and reversibility of SOC change. The findings indicate that recent UK research has strengthened confidence in broad qualitative understanding of SOC dynamics, while also highlighting important evidence gaps that continue to constrain quantitative assessment and policy interpretation.

Strengths and limitations of the post-2000 UK evidence base

The evidence map identifies important differences between land-use change and management practices as drivers of SOC change. Within the mapped evidence base, land-use transitions were associated with more consistently reported directional responses than management interventions within existing land uses. The recent (post-2000) UK evidence base is sufficient to support qualitative statements about the plausibility of SOC gains under certain land-use transitions (e.g. cropland to grassland or woodland) and management practices (e.g. organic amendments, nutrient management). However, it does not provide sufficient evidence to derive robust UK-specific sequestration rates or to confidently assess the magnitude, persistence, or reversibility of SOC change resulting from land-use change or management practices in mineral and organo-mineral soils. Even for the most frequently studied land-use transitions and management practices, reported SOC responses are limited in depth coverage and derived from a small number of studies employing diverse and often non-comparable experimental designs, with substantial variation in sampling depth, study duration, and SOC metrics. These limitations constrain the ability to compare outcomes across studies or derive robust quantitative estimates of sequestration potential.

Limited reporting of soil classification prevented consistent differentiation between mineral and organo-mineral soils, despite the importance of this distinction for SOC dynamics. More detailed reporting of soil characteristics was often lacking, making it difficult to assess how differences in soil type and condition may influence SOC responses to land-use and management change (Guo & Gifford, 2002b). Factors such as soil texture, mineral composition, drainage, and baseline SOC condition are known to strongly affect SOC stabilisation, sequestration potential, and vulnerability to carbon loss (Six et al., 2002). For example, clay-rich soils often have a greater capacity to stabilise SOC than coarse-textured sandy soils because clay minerals can protect SOC through aggregation and physicochemical binding, including the sorption of organic matter onto mineral surfaces and protection of microbial biomass (Rakhsh et al., 2020), whereas in sandy soils, carbon is less stable and more susceptible to decomposition (Li et al., 2024). Inconsistent reporting of soil characteristics therefore reduces the ability to explain variability between studies, assess context dependency, or determine the transferability of observed SOC responses across UK landscapes.

Mixed directional SOC stock outcomes were observed for several land-use transitions and management interventions, with increases, decreases, and no-change outcomes reported within some categories. These contrasting responses likely reflect both genuine context dependency and substantial heterogeneity in study design, sampling depth, SOC metrics and study duration, all of which are known to strongly influence inferred SOC responses (Dlamini et al., 2016; Jordon, Smith, et al., 2022; Kämpf et al., 2016).

At a global scale, using vastly more comprehensive datasets, multiple syntheses indicate that certain land-use changes and management practices can enhance SOC and deliver broader soil health benefits, particularly under specific climatic, edaphic, and management contexts (Bai et al., 2019; Beillouin et al., 2022; Encarnation et al., 2026; Huang et al., 2024; Karstens et al., 2022). For example, sequestration estimates for cover cropping in the recent UK literature were derived from only two studies and included negative SOC responses, limiting confidence in the representativeness of these estimates. In contrast, a global meta-analysis focused on temperate systems reported average SOC stock increases of 18.7% under cover cropping (Jian et al., 2020). Similarly, a recent modelling study by Jordon et al., indicates that cover cropping and ley-arable systems could increase soil organic carbon (SOC) stocks across Great Britain (Jordon, Smith, et al., 2022).

The evidence map presented here, while not providing enough data to derive robust UK-specific sequestration estimates, does not broadly contradict the directionality of the SOC responses to land use and land management change reported in the broader evidence base. When considered alongside earlier and international evidence, the growing UK literature therefore supports the plausibility of SOC gains under UK conditions for some land-use changes and management interventions, while substantial uncertainty remains regarding the magnitude, persistence, and whole-profile extent of sequestration. It is also important to note that the relevance of SOC-focused land management extends beyond carbon sequestration alone. Increases in SOC are also associated with a range of broader soil health and ecosystem benefits, including improvements in soil structure, water retention, nutrient cycling, erosion resistance, and biological functioning (Lal, 2016).

Why uncertainty remains despite 25 years of research

Uncertainty in the recent UK SOC evidence base arises from a convergence of structural and methodological limitations. Although there is an active body of recent research on SOC in UK soils, the overall volume of directly relevant empirical studies remains limited, with only 75 studies meeting the inclusion criteria of this review. Across the literature, studies differ widely in design (e.g. chronosequence, space-for-time substitution, BACI, and monitoring approaches), SOC metrics (stocks, concentrations, or rates), depth coverage, and study duration. Together, the limited number of studies and their methodological heterogeneity constrain comparability across studies and limit the feasibility of formal quantitative synthesis.

Most SOC measurements in the recent UK literature are restricted to the topsoil, despite well-established evidence that land-use change and management can alter the vertical distribution of SOC within the soil profile (Angers & Eriksen-Hamel, 2008; Jobbagy & Jackson, 2000). In the absence of consistent mid-profile and subsoil data, it becomes difficult to robustly evaluate whether SOC gains observed near the surface reflect changes in whole-profile SOC stocks(Blanco-Canqui et al., 2021). This distinction is important because increases in SOC confined to surface layers may not represent persistent net carbon sequestration at the whole-profile scale. Surface SOC can respond relatively rapidly to changes in residue inputs and disturbance regimes, whereas deeper SOC pools often turnover more slowly and may respond differently to land-use or management change. Without whole-profile sampling and long-term observations, apparent gains in topsoil SOC cannot be assumed to reflect durable increases in total soil carbon storage (Hicks Pries et al., 2023b).

While some studies report long-term observations, many assessments remain short relative to the timescales over which mineral-associated SOC accumulates, stabilises, or approaches saturation (Georgiou et al., 2022). Short-term increases in SOC concentration or stock may therefore reflect transient accumulation of labile organic matter rather than persistent sequestration (P. Smith et al., 2020). This limitation is compounded in studies that lack repeated measurements or rely on space-for-time substitutions, where inferred temporal dynamics are sensitive to assumptions about site comparability. Although a subset of studies reported long-term observations, these were rarely combined with whole-profile sampling, consistent metrics, or replicated designs capable of constraining persistence. Consequently, the recent UK evidence base remains limited in its ability to determine whether observed SOC increases represent persistent whole-profile sequestration or relatively short-term surface accumulation.

Additional uncertainty arises from inconsistent approaches to SOC quantification and reporting. Studies varied in their use of SOC concentrations, stocks and sequestration rates, while reporting of bulk density, equivalent soil mass corrections, variability estimates, and analytical methods was often inconsistent. Differences in SOC analytical approaches (e.g. dry combustion versus loss-on-ignition), bulk density measurement methods, and stock calculation procedures can introduce systematic variation in reported SOC change estimates, reducing comparability between studies and complicating robust inference regarding the magnitude and persistence of SOC change. The inconsistent signals observed across the UK literature therefore appear to reflect limitations in study design, reporting, and evidence availability more than clear evidence that land-use or management interventions lack sequestration potential.

The absence of consistent directional signals for many land-use transitions and management practices in the most recent UK literature should not be interpreted as evidence of no effect, but rather as evidence of insufficient, fragmented, or methodologically constrained data.

Implications for interpreting SOC sequestration options

The distinction between SOC stocks and SOC sequestration rates is well established yet remains central to the interpretation of SOC sequestration claims in scientific, policy, and land-management contexts (Minasny et al., 2017; P. Smith, 2014). Large SOC stocks do not imply ongoing sequestration, and short-term increases in SOC concentration or stock (often sensitive to sampling depth, soil physical change and study duration) should not be extrapolated as sustained annual removal of atmospheric CO_2 or assumed to persist over the decadal timescales relevant to climate mitigation (Rovira et al., 2022; P. Smith, 2014). SOC stock supports long-term land evaluation, soil fertility, and identifying deficits (e.g., SOC deficits or potential storage capacity) (Somenahally et al., 2025), while sequestration rate evaluates whether a management practice increases SOC over a given period (Mayer et al., 2022). While this evidence map does not evaluate how individual studies interpret reported SOC changes, the heterogeneity of outcome metrics identified across the recent UK literature reinforces the need for caution when translating reported SOC changes into sequestration claims. In addition, SOC responses may approach saturation over time. Sequestration rates are generally highest immediately following intervention and decline progressively as soils approach a new equilibrium or saturation state, meaning that early gains following land-use change or management intervention cannot be assumed to continue indefinitely, particularly where mineral-associated carbon pools are already near capacity (Zhao et al., 2022).

The evidence base shows a clear dominance of topsoil measurements in the UK SOC studies, with depth-resolved data remaining limited. Most SOC change measurements are limited to the upper 30cm, despite over 70% of total SOC stocks being stored below 20cm depth (Dubeux et al., 2024), leaving responses of deeper SOC pools often unquantified. SOC changes are not uniform with depth, and interpreting topsoil results as indicative of whole-profile gains without direct subsoil measurements can lead to under or over reporting carbon sequestration claims (Tan & Kuebbing, 2023). For example, a recent global synthesis of organic fertilisers effects found that SOC increases were greater when both topsoil and subsoil (30-60 cm) were measured, with whole-profile gains being 41% higher than estimates based on topsoil alone (Alvarez, 2025). Consequently, where mid-profile and subsoil data are absent, uncertainty remains regarding the extent to which observed surface-layer SOC gains reflect changes in whole-profile stocks.

Claims of predictable or universally beneficial SOC sequestration outcomes risk oversimplifying complex soil-carbon dynamics and obscuring site-specific trade-offs (Chang et al., 2026). As a result, sequestration estimates derived from limited, heterogeneous, or short-term evidence should be interpreted cautiously rather than as expected or guaranteed outcomes under widespread implementation. This distinction is particularly important where SOC sequestration is proposed as a mechanism to offset ongoing emissions, as overestimation of rates or permanence risks undermining the credibility and effectiveness of climate mitigation strategies.

Individual studies reporting large SOC increases should therefore be interpreted within their specific environmental and management contexts and considered alongside the wider evidence base, rather than treated as representative of the SOC sequestration potential achievable across different soils, land uses, or management systems(Bai et al., 2019; Beillouin et al., 2023).

Policy relevance and risk of overinterpretation

From a policy perspective, the primary value of assessing the recent UK SOC evidence base lies in identifying where confidence is low and uncertainty is high, rather than in providing precise sequestration estimates, taking into account site-specific conditions. Evidence from policy-driven SOC schemes outside the UK illustrate both the potential and the limitations of relying on SOC gains for climate mitigation. For example, evaluations of Swiss agri-environment schemes, combining mandatory cover crops, minimum crop rotations, and reduced tillage, demonstrate that policy interventions can be associated with detectable SOC improvements at scale. Analysis of more than 30,000 topsoil samples showed a shift from net SOC losses (-5‰ yr^{-1}) to gains (+6‰ yr^{-1}) over two decades but also revealed large regional variability in SOC status and sequestration potential across districts (Dupla et al., 2021). These contrasts highlight both the value of long-term, on-farm monitoring and the importance of targeting agri-environment schemes to local soil and environmental conditions rather than assuming uniform outcomes across regions. However, assumptions that SOC can deliver rapid, large, or permanent SOC gains without accounting for climate-driven losses, disturbance risks, and management reversals are likely to overestimate SOC mitigation potential. Regional analysis illustrates these constraints clearly. For example, assessments in Bavaria have shown that ambitious targets like the “4 per 1000” initiative are not feasible across many agricultural contexts, with achievable SOC sequestration rates far below policy expectations (Wiesmeier et al., 2020).

SOC sequestration potential is highly dependent on baseline soil carbon stocks and land-use context (Post & Kwon, 2000). Depleted arable mineral soils may offer greater scope for additional SOC accumulation under improved management, whereas carbon-rich grassland may have a more constrained and context-dependent capacity for further gains and instead require policies focused primarily on maintaining existing stocks and preventing losses (Paustian, 2014). Consequently, the feasibility of using SOC sequestration to offset ongoing emissions is likely to differ substantially across agricultural sectors and accounting scales. Systems with already high SOC stocks, such as permanent grasslands, may have limited ability to offset farm-level emissions through additional SOC gains alone, whereas some arable systems may offer greater scope for SOC recovery (Dersch & Böhm, 2001). In many cases, protecting existing SOC stocks and avoiding further losses may provide more reliable climate benefits than attempting to maximise additional sequestration. These risks are particularly acute where SOC sequestration is proposed as a mechanism to offset ongoing emissions. SOC pools are inherently dynamic and can shift from sinks to sources under environmental change, altered management, or disturbance, meaning that offsets based on assumed permanence may fail to deliver long-term climate benefits (Cao et al., 2025). Without explicit consideration of reversibility, claimed mitigation gains may therefore be temporary.

To account for these risks, robust measurement, reporting and verification (MRV) frameworks are essential, including repeated measurements, transparent uncertainty treatment, and mechanisms to address potential SOC losses over time (Medeckytė-Žydelė, 2026). Taken together, the limited magnitude of achievable SOC gains, the risk of saturation and reversal, and the substantial methodological uncertainty identified across the evidence base support treating SOC sequestration as a complementary mitigation strategy alongside direct emission reductions, rather than a substitute for them.

Research priorities arising from the evidence map

The evidence gaps identified in this review point to clear priorities for future UK SOC research.

Priority 1: Long-term, full-profile monitoring

Foremost among these is the need for replicated studies that combine repeated SOC measurements with modelling approaches over decadal to multi-decadal timescales. While robust assessment of SOC permanence ultimately requires long-term, full-profile monitoring, interim estimates can be strengthened through process-based modelling, chronosequence studies, and repeated measurements at shorter intervals. Such approaches would support earlier policy learning while reducing uncertainty about net SOC change, saturation dynamics, and reversal risks. Although a growing body of evidence suggests that certain land uses and management practices can enhance SOC and deliver co-benefits, the limited availability of long-term, replicated, full-profile SOC measurements remain a critical gap that limits certainty about net SOC change and permanence (Hicks Pries et al., 2023a).

Priority 2: Quantifying reversibility and permanence

Empirical assessment of SOC reversibility remains limited within the recent UK evidence base. While the broad directional responses of SOC to major land-use transitions (e.g. forest to cropland leading to SOC loss; cropland to forest or grassland leading to SOC gain) are well established, the magnitude, rate, depth distribution, and permanence of SOC change are highly variable and context-dependent. Experimental and mechanistic evidence clearly demonstrates that SOC stocks are dynamic and vulnerable to loss through disturbance, altered management, warming, and microbial decomposition processes (Taghizadeh-Toosi et al., 2014). However, long-term field evidence quantifying the rates and persistence of SOC reversibility under UK conditions remains scarce. Improved understanding of reversibility will therefore require complementary approaches combining long-term monitoring, targeted disturbance and management-reversal experiments, and modelling frameworks, rather than treating these as competing priorities. This gap is especially important for management practices within existing land uses, where SOC responses are less predictable and where policy instruments, carbon markets, and climate strategies increasingly depend on accurate, context specific estimates of reversibility and risk (Gocke et al., 2023).

Priority 3: Improved measurement, reporting and verification (MRV)

Greater standardisation in SOC measurement, reporting, and uncertainty characterisation would substantially improve the interpretability of future studies. Adoption of equivalent soil mass (ESM) approaches, consistent depth reporting, and transparent uncertainty estimates should be prioritised. These methodological improvements directly address known biases, enable robust cross-study comparisons, and strengthen the credibility of SOC change assessments in both scientific and policy contexts. For example, ESM approaches account for changes in bulk density associated with compaction, erosion, or management, ensuring that SOC stocks are compared for equivalent soil masses rather than fixed depths (Fowler et al., 2023).

Priority 4: Improved representation across soils, regions and environmental conditions

Integration of SOC measurements with contextual data on soil type, climate, and management history would improve understanding of context dependency. Improving transferability of findings and supporting more nuanced inference about where, when, and under what conditions SOC sequestration can be expected to persist. Future research should also address the uneven geographical and environmental distribution of the current UK evidence base. Studies assessing SOC stock change were concentrated primarily in England, particularly southeast and northeast England, with comparatively fewer studies from Scotland, Wales, and Northern Ireland. Evidence was also strongly biased towards mineral soils, especially medium-textured loam soils, while organo-mineral soils were rarely represented and soil type was not reported in a substantial proportion of studies. Improved representation across a broader range of UK regions, soil types, and environmental conditions would strengthen understanding of the extent to which observed SOC responses are transferable across UK landscapes.

Conclusion

The post-2000 UK evidence base largely reinforces existing understanding of SOC sequestration, supporting the plausibility of SOC gains under some land-use changes and management practices while highlighting persistent limitations in the evidence needed to quantify their magnitude, persistence and reversibility. It is also important to acknowledge that the inconsistent signals observed across the recent UK literature appear to reflect limitations in study design, reporting, and evidence availability more than clear evidence that land-use or management interventions lack sequestration potential.

Although the recent evidence reviewed here cannot provide robust new UK-specific SOC sequestration rates to derive new estimates, it does not provide evidence that would invalidate the rates reported in earlier studies. Consequently, the pre-2000 evidence base has not been superseded by more robust or contradictory recent evidence. In the absence of reliable new UK-specific estimates, sequestration rates derived from pre-2000 studies, considered alongside evidence from comparable agro-climatic zones, therefore remain relevant for informing estimates of likely SOC sequestration rates in the UK.

SOC sequestration can contribute to climate mitigation and deliver important co-benefits, including improved soil fertility, soil structure, water retention, nutrient cycling, and climate resilience. However, the mapped evidence reinforces the conclusion that opportunities for additional SOC sequestration are highly context-dependent rather than uniformly distributed. In this context, for soils with large existing SOC stocks, including many permanent grasslands and semi-natural systems, maintaining existing stocks is likely to be an important mitigation priority, while the scope for additional sequestration remains highly context dependent and cannot currently be quantified reliably from the UK evidence base. In contrast, opportunities for additional SOC sequestration are likely to be greatest in SOC-depleted systems, particularly croplands and degraded grasslands.

Reducing current uncertainty will require long-term, replicated, full-profile monitoring, improved understanding of reversibility and persistence, greater methodological standardisation, and improved representation of UK soil types and environmental conditions. Until these evidence gaps are addressed, SOC sequestration should be treated as a context-dependent and bounded mitigation option that complements, rather than replaces, direct emissions reductions.

Author contributions

Licida Giuliani: Conceptualisation, Methodology, Investigation, Data curation, Formal analysis, Funding acquisition, Writing-original draft, Writing-review & editing.

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Use of Artificial Intelligence (AI)

Microsoft Copilot was used for grammar checking and language editing to improve the clarity of selected sentences; all scientific content and interpretations were developed and verified by the authors.

Conflict of Interest

The authors declare no conflicts of interest.

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Supplementary material

Search strategy

Table S1. Academic database search strategy and results

Database	Search String	Filters Applied	Records Retrieved
Scopus	TITLE-ABS-KEY(("soil organic carbon" OR SOC OR "soil carbon sequestration") AND ("United Kingdom" OR UK OR England OR Scotland OR Wales OR "Northern Ireland") AND ("land use" OR "land use change" OR "farm management" OR tillage OR grazing OR cropland OR grassland OR woodland)) AND NOT TITLE-ABS-KEY(peat OR peatland*)	2000–2025; English; Country filter: United Kingdom	138
Web of Science	#1 TS=("soil organic carbon" OR SOC OR "soil carbon sequestration")#2 TS=("United Kingdom" OR UK OR England OR Scotland OR Wales OR "Northern Ireland")#3 TS=("land use" OR "land use change" OR "farm management" OR tillage OR grazing OR cropland OR grassland OR woodland)#4 TS=(peat OR peatland*)(#1 AND #2 AND #3) NOT #4	2000–2025; English	302
Google Scholar (GS1 – SOC stock)	"soil organic carbon" "United Kingdom" stock -peat -peatland	2000–2025; English; Top 200 results screened via Publish or Perish	200
Google Scholar (GS2 – Land use change)	"soil organic carbon" "United Kingdom" "land use change" -peat -peatland	2000–2025; English; Top 200 results screened via Publish or Perish	200
Google Scholar (GS3 – Management practices)	"soil carbon sequestration" "United Kingdom" management -peat -peatland	2000–2025; English; Top 200 results screened via Publish or Perish	200
Google Scholar (GS4 – Depth/erosion/reversibility)	"soil organic carbon" "United Kingdom" depth OR erosion OR reversibility -peat -peatland	2000–2025; English; Top 200 results screened via Publish or Perish	200

Table S2. Grey literature search strategy and results

Source	**Search String**	**Filters Applied**	**Records Retrieved**
Google Search (England)	"soil organic carbon" OR "soil carbon sequestration" site:gov.uk filetype:pdf after:2000	After 2000	15
Google Search (England)	"soil carbon stocks" "land use change" site:defra.gov.uk OR site:environment-agency.gov.uk filetype:pdf after:2000	After 2000	3
Google Search (England)	"soil health" "carbon stock" report site:parliament.uk OR site:gov.uk filetype:pdf after:2000	After 2000	16
Google Search (England)	"soil carbon" "evidence synthesis" site:gov.uk OR site:naturalengland.org.uk filetype:pdf after:2000	After 2000	5
Google Search (Wales)	"soil organic carbon" site:gov.wales OR site:naturalresources.wales filetype:pdf after:2000	After 2000	13
Google Search (Wales)	"soil carbon sequestration" "Wales" site:erammp.wales OR site:ceh.ac.uk filetype:pdf after:2000	After 2000	4
Google Search (Wales)	"carbon in soil" "Welsh Government" site:gov.wales filetype:pdf after:2000	After 2000	3
Google Search (Wales)	"soil health" "carbon stock" site:gov.wales filetype:pdf after:2000	After 2000	4
Google Search (Scotland)	"soil organic carbon" OR "soil carbon storage" site:gov.scot OR site:climatexchange.org.uk filetype:pdf after:2000	After 2000	19
Google Search (Scotland)	"soil carbon sequestration" "Scotland" site:hutton.ac.uk OR site:gov.scot filetype:pdf after:2000	After 2000	2
Google Search (Scotland)	"land use change" "soil carbon" site:gov.scot OR site:forestresearch.gov.uk filetype:pdf after:2000	After 2000	12
Google Search (Scotland)	"soil carbon" "evidence review" site:gov.scot OR site:sniffer.org.uk filetype:pdf after:2000	After 2000	3

Source	Search String	Filters Applied	Records Retrieved
Google Search (Northern Ireland)	"soil organic carbon" OR "soil carbon stocks" site:daera-ni.gov.uk filetype:pdf after:2000	After 2000	1
Google Search (Northern Ireland)	"carbon sequestration" "soil" site:daera-ni.gov.uk OR site:afbini.gov.uk filetype:pdf after:2000	After 2000	7
Google Search (Northern Ireland)	"soil health" "carbon" site:daera-ni.gov.uk filetype:pdf after:2000	After 2000	4
UK Research Institutes	"soil organic carbon" OR "soil carbon sequestration" site:ceh.ac.uk OR site:forestresearch.gov.uk filetype:pdf after:2000	After 2000	13
UK Research Institutes	"soil carbon" "land use change" site:hutton.ac.uk OR site:jncc.gov.uk filetype:pdf after:2000	After 2000	1
UK Research Institutes	"soil carbon" "UK" site:bgs.ac.uk OR site:environment.gov.scot filetype:pdf after:2000	After 2000	4
UK Research Institutes	"soil organic matter" "carbon" site:ceh.ac.uk OR site:hutton.ac.uk OR site:ukclimateexchange.org.uk filetype:pdf after:2000	After 2000	9

Studies included in the systematic evidence map

The studies included in the systematic evidence map were: Ashwood et al. (2019); Ball et al. (2025); Beckert et al. (2016); Bell and Worrall (2009); Bentley, Reinsch, et al. (2025); Bentley, Thomas, et al. (2025); Berdeni and Williams (2021); Biffi et al. (2022, 2025); Braby (2024); Bradley et al. (2005); Brainard et al. (2003); Brown et al. (2020); Cantarello et al. (2011); Carolan and Fornara (2016); Chapman et al. (2013); Coch (2024); Collier et al. (2021); Cooper et al. (2021); Elias et al. (2023); Emmett et al. (2010); Eze et al. (2018); Ford et al. (2019); Fornara et al. (2011, 2016, 2018, 2020, 2022); Gardi et al. (2016); Gosling et al. (2017); Gregory et al. (2014, 2016); Hathaway-Jenkins et al. (2011); Hazarika et al. (2009); Hopkins et al. (2009, 2011); Horrocks et al. (2016); Johnston et al. (2017); Jones et al. (2017); Jordon et al. (2022); Judson et al. (2024); Keith et al. (2015); Lawson et al. (2023); Levy et al. (2024); Lilly and Baggaley (2013); Mahmood et al. (2024); Matthews (2020); Matthews et al. (2022); Maxwell (2022); Moxley et al. (2014); Poulton et al. (2018); Powlson et al. (2012); Prosser et al. (2008); Pulley et al. (2023); Razauskaite et al. (2020); Rees et al. (2018); Reynolds et al. (2013); Rivas Casado et al. (2022); Saraev et al. (2022); Smith et al. (2010); Sun et al. (2011); Tang et al. (2025); Thomas et al.

(2020); Upson et al. (2016); Upson and Burgess (2013); Vanguelova et al. (2013, 2019); Ward et al. (2016); Watts et al. (2006); Webb et al. (2001); Zani et al. (2023); and Zhang et al. (2024).

Confidence-classification framework

Table S3 Confidence-classification framework

Confidence category	Criteria
High	≥10 years or replicated design; methods clearly described; uncertainty reported
Medium	3-9 years duration, partly replicated design, or otherwise credible methods with limited uncertainty reporting
Low	<3 years duration, unreplicated design, model-based assessment, unclear methods, or no uncertainty reporting

Exploratory expert assessment of operational feasibility

The systematic synthesis undertaken in this study focuses on empirical evidence of SOC responses to land-use change and management at experimental and field scales. However, the ease with which management practices can be deployed will be critical for long-term carbon sequestration outcomes at national and regional scales. Whilst the multiple operational barriers that will impact potential uptake are beyond the scope of this review, a more detailed consideration of these operational barriers is likely warranted. Implementation feasibility may be assessed using a two-pronged approach, in which each management practice is 1) assigned a Technological Readiness Level (TRL) score [126] and 2) qualitatively assessed against a range of operational barriers to determine the impact of each barrier type on uptake potential. This latter assessment could be carried out independently by experts at regional or national scales, to support decision-making and the identification of barriers that may be reduced or mitigated in the future. Eight operational barrier types were identified as relevant for consideration:

1. Infrastructure Gaps - e.g. Processing and market gaps legal/ licencing/ permitting constraints
2. Skill/Guidance Gaps – e.g. Guidance gap to support the decision making around the "What Where When and How" of a management to get successful outcomes and avoid unintended outcomes
3. Capital and operational costs – e.g. Capital requirements of equipment and upskilling
4. Risk – Risk of no return on investment e.g. due to length of tenancies or risks to productivity
5. Land availability and suitability – e.g. Insufficient land for growing trees to produce biochar domestically; or intervention is only appropriate for a small amount of land
6. Social acceptability - e.g. Public and farmer responses to methane-reducing livestock feed additives
7. Farmer culture – e.g. Personal values/identity of farmer

8. Environmental & Food security trade-offs - e.g. overall reduction of yield, over-all GHG emissions, biodiversity

To demonstrate the potential utility of this approach, a preliminary exploratory assessment of operational feasibility was undertaken by the authors using expert opinion (Figures S1 and S2). As described in Methods (Section 2.8), this assessment was not part of the systematic evidence mapping protocol and did not involve structured elicitation or formal consensus methods. Scores therefore reflect author expert judgement and are presented descriptively.

The outcomes of these preliminary assessments of operational barriers suggest that most management practices have a high level of technological readiness, with the exception of cross system and emergent soil improvers categories, which had TRL scores between 4 and 7 (Figure S1). The preliminary assessment of operational barrier impact indicates that infrastructure constraints were most frequently identified as higher-impact barriers to uptake, whereas social acceptability was generally assigned lower impact scores (Figure S2). Major impacts were the most common for emergent soil improvers, particularly across infrastructure gaps, skills gaps, risk, and potential environmental trade-offs. Management of woodland or woodland creation were also scored as having multiple major operational barriers, although the relevance and magnitude of these constraints are likely to vary regionally. For cropland and rotational systems, as well as grassland management, skill and guidance gaps and capital or operational costs were most frequently assigned higher impact scores relative to other barrier categories.

Taken together, this exploratory assessment highlights that even where evidence suggests potential SOC gains, implementation may be constrained by technological maturity, economic risk, infrastructure and market capacity, regulatory constraints, and other contextual factors. In addition, greater consideration of the susceptibility of outcomes to climate change may be needed in future assessments, as some reported benefits of management practices for carbon sequestration could be reduced with increasing climate change severity.

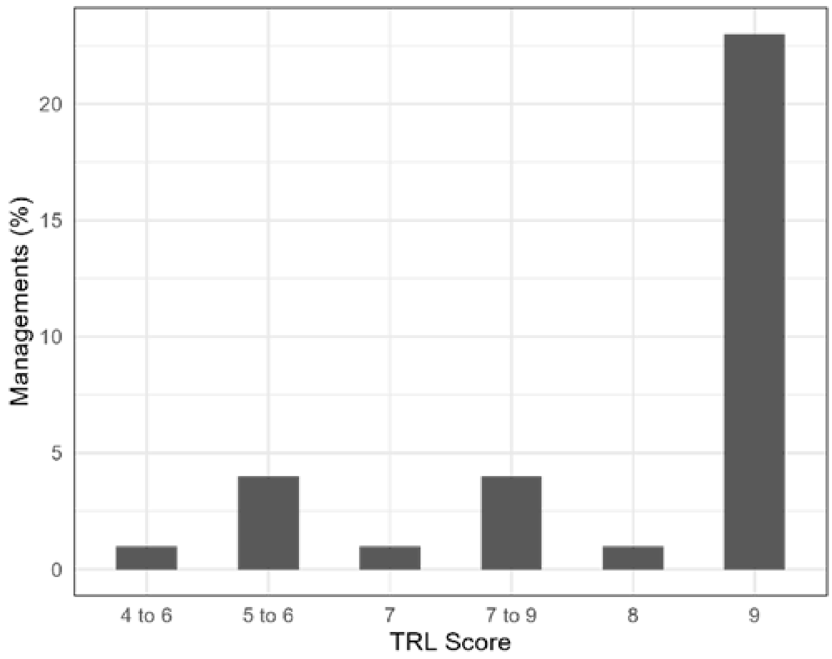

Figure S1. Distributions of TRL scores assigned to management groups via rapid expert review.

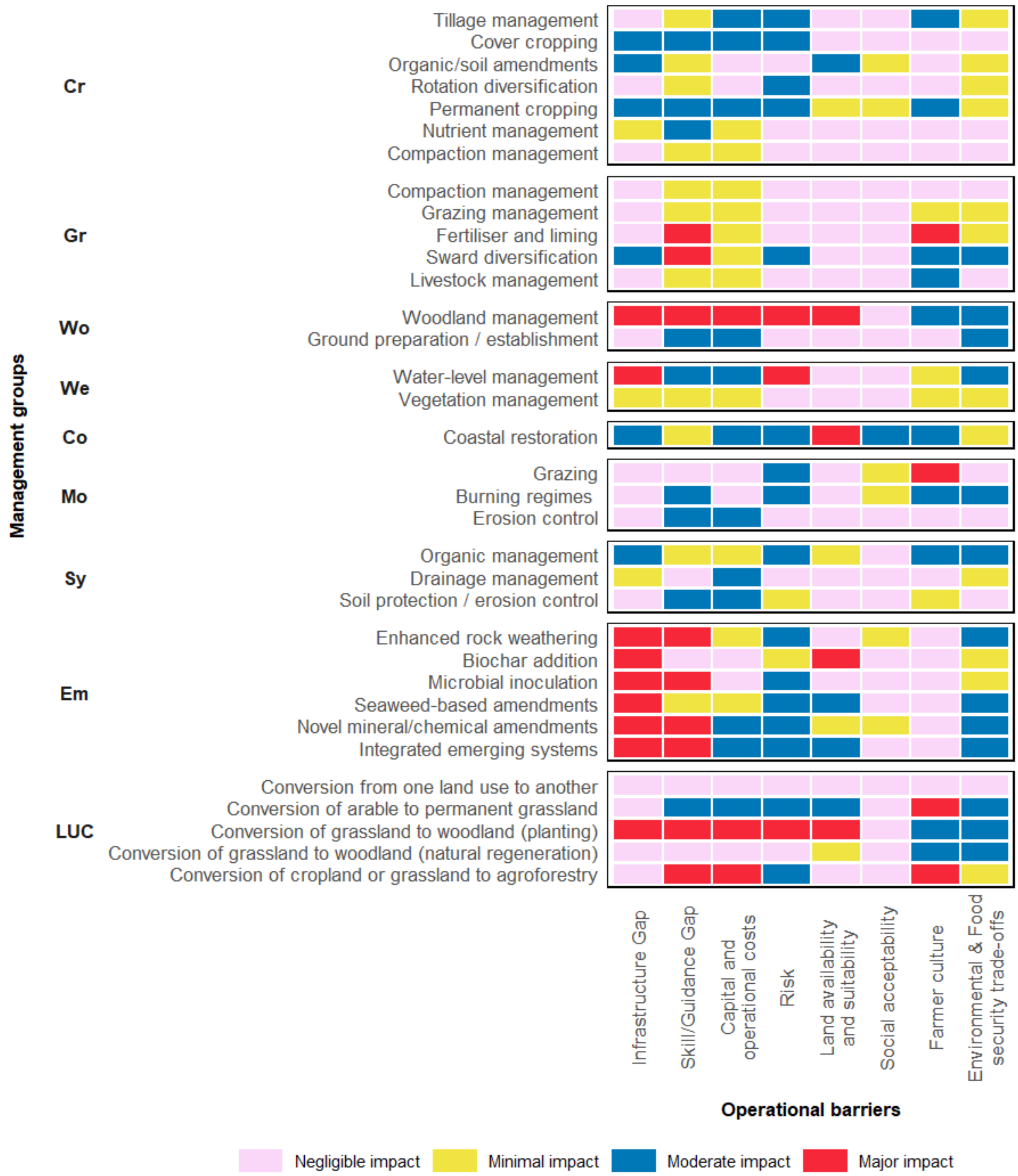

Figure S2 Expert-rapid opinion assessment of operational barrier assessments for management groups, grouped by land use or system of managements, where Cr = Cropland and rotational land; Gr = Grassland; Wo =Woodland/agroforestry/woody features; We = Wetlands; Co = Coastal; Mo = Mountain, moorland, heath; Sy = System/cross-habitat actions; Em = Cross-system/Emerging soil improvers; LUC = Land use change.

Reported ranges of annual SOC stock change identified in the reviewed literature

Table S4 Reported ranges of annual SOC stock change identified in the reviewed literature.

Land use	Intervention	Observed range from current review *	Number of studies in current review
Cropland	Organic amendments	−0.11–20.69	3
	Reduced-intensity tillage	-13.33 – 3.95	2
	Cover crops	−4.00– -2.01	2
	Ley–arable rotations	−0.31–2.69	3
	Improved fertiliser management	0.46–2.29	2
Permanent grassland	Improved grazing and fertiliser management	−0.15–1.13	4

* Reported sequestration rates represent average annual changes in soil carbon during transition towards a new equilibrium (steady state) soil carbon stock under changed management or land-use. Rates are therefore time-dependent and generally decline as soils approach saturation.

Woodland estimates assume conversion from grassland over an 80-year time horizon. Cropland and grassland estimates refer to cool moist systems.