# Innovations in arable cultivation systems and their impacts on buried heritage assets

## A Quick Scoping Review

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# Foreword

Agricultural technologies have developed significantly in the last 20 years, especially with the increasing use of GPS and minimum tillage options and movements to more regenerative systems and systems such as paludiculture.

In addition, our expectations of what we want from rural landscapes are changing; particularly when viewed as public goods. Carbon stored in archaeological soils is retained by minimising disturbance, including mechanical disturbance. Such active conservation also contributes to soil health; supporting regenerative agricultural actions to reduce erosion, soil loss and enhance water retention. The various suites of nature-based solutions we now look to deliver more public goods are also beneficial in preserving the heritage sites which are so widely valued, again demonstrating the indivisibility of multi-objectives schemes and delivery.

In light of the above a literature review and selected interview with arable sector advice and delivery specialists is required to:

- help us provide the most up-to-date evidence of arable farming techniques (including paludiculture) and the impact on heritage assets,
- ensure we fully understand current cultivation practices, trends and likely future innovation and the likely impacts on soil health,
- provide a refreshed baseline of understanding from which to develop or re-cast AES options,
- provide a refreshed baseline of understanding from which to review and update existing guidance, best practice and related advice,
- identify evidence gaps,
- recommend further research needs, including field-based trials.

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

# Executive summary

## Background

Conventional agricultural cultivation practices, e.g. ploughing and deep tillage, have been indicated as a threat to buried archaeological sites and historic remains and earthworks, as a result of physical damage to the artefacts as well as increased soil erosion and loss resulting from these agricultural practices (Spandl and others, 2010). However, agricultural technologies, have developed significantly in the last 20 years (since 2002), especially with the increasing use of Global positioning systems (GPS), minimum tillage systems and shift to more regenerative cultivation-methods as well as paludiculture. The aim of this quick scoping review and stakeholder consultation was to investigate the impact on heritage assets of these innovations and any wider implications for soil health, to inform policy, guidance and best practice and identify evidence gaps for future research.

## Methods

This research project was conducted in two-stages 1) a Quick Scoping Review (QSR) of published and unpublished literature and 2) selected interviews with industry practitioners and topic experts. The QSR scoping identified 3324 articles through bibliographic databases searches. A total of 127 publications were considered relevant. This number consisted of 65 primary research papers, which were coded based on abstracts, 51 reviews, which informed conclusions, 4 PhD theses and 7 pieces of grey (unpublished) literature, which informed the report.

## Key findings

Seven categories of novel arable technologies were identified. These were: tracks or low-pressure tyres (LPTs); controlled traffic farming (CTF); machinery and tillage approaches; planning tools; precision agriculture; microorganism soil amendments; robotics. Paludiculture was also included as an eighth category.

Research that directly investigated the impact of novel arable technologies on heritage assets is very scarce, almost non-existent, although one study investigated the effects of different loads on heritage assets, and another investigated the impact of different seed drills on lithics.

A larger volume of research has been conducted to investigate the impacts of novel arable soil techniques on soil properties, which can be used to infer the potential impacts for heritage assets. The most researched categories were tracks or tyres, followed by CTF, machinery and tillage. Less research has been conducted on planning tools, paludiculture, microorganisms, precision agriculture and robotics.

Limited research indicates that LPTs may help to preserve archaeological assets (n=1) and improve soil health in terms of invertebrate abundance and feeding activity (n=1). A greater number of literature (n=28) focused on wider benefits of LPT on soil health, which included reduced soil compaction (soil bulk density (BD), penetration resistance, improved porosity) as well as economic savings (maintenance and fuel). Nevertheless, additional costs for these tyres and a lack of understanding of the benefits of LPTs is seen as a barrier to uptake.

Although there is no direct evidence of the impact of CTF on the historic environment, the benefits of this system can be inferred from its effects on improved soil health. The literature (n=12) indicated that this system significantly improves soil physico-chemical properties (e.g. decreases soil bulk density and penetration resistance, water run-off, enhances porosity, water infiltration) as well as reduces greenhouse gas (GHG) emissions. Barriers to uptake include perceived high investment cost and lack of understanding of the costs and benefits to both – the soil and the crop yields.

Limited research (n=1) has shown that precision farming technology can be used to variably control the depth of cultivation over historic sites and identify previously unknown archaeological sites. Barriers to uptake include high upfront costs, connectivity and access to real-time data in remote or rural areas, and lack of evidence of the benefits to farmers.

Other cultivation practices, e.g. novel machinery design /tillage approach, e.g. basin tillage in root crop cultivation (n=12), aim at improving soil health and mitigate soil compaction. Literature found on paludiculture (n=3) addressed issues relating to GHG emissions after rewetting peatlands (Berglund and others, 2007), soil structure (porosity and hydraulic conductivity) in cultivated peat soils (Hyvaluoma and others, 2020)) and impact of biomass and copper on peat decomposition in agricultural peatlands (Bourdon and others, 2021).

Nevertheless, the volume of literature that looked into the effects of farming practices on historic environment is very scarce (Dain-Owens, 2010 and Dain-Owens and others, 2013; Webber, 2020). The vast majority of literature found investigated the impact of farming technologies on soil properties. In most cases the effects on historic environment can only be inferred indirectly based on the effects of these methods on soil physical properties (e.g. soil movement, erosion, compaction).

At present there isn’t a coherent picture of what arable cultivation techniques are currently being practiced in the UK. Stakeholders interviewed predicted there will be an increase in use of precision farming and robotics in the future. They also cautioned that a ban on broad spectrum herbicides could lead to an increase in deep tillage which has a detrimental effect on soil carbon sequestration and can pose risks of damage to archaeological features.

Farming technologies and systems are often referred to very broadly and there is a lack of precise definition. The impact of novel technologies is likely to be context specific i.e. to specific farming practices that are applied within a system and this needs to be considered when carrying out investigations.

## Limitations of the review

Due to the time constraints of the project, screening was limited to abstracts only, and there is a risk of missing key findings that could be important for informing decision-making. Furthermore, searches for literature were only carried out in English language and therefore some relevant articles may have been missed. Implications for research

- There is a need to conduct fields trials and broader research that can help quantify and understand how different farming techniques and technologies affect soil and historic sites and features;
- There is a need for updated surveys (by DEFRA) to confirm what cultivation practices are currently being used on English farms. This will help understand current practices and help identify where changes to practice may be;
- Research on barriers to uptake of technologies that secure historic assets and soil health is required. Additionally, research is required on how best to disseminate the results of the research to raise farmers’ awareness on benefits of novel technologies on soil and historic assets.
- Precision farming and archaeology can provide another pathway for engaging stakeholders (farmers, land managers, specialists etc.) on managing the historic environment by shifting the focus from the restriction of farming activities over archaeological sites, towards the better understanding of that archaeological site and how it interacts with day-to-day farming practices.

## Contents

# Background

## Impact of arable cultivation techniques on soil

Soil plays a vital role in both crop production and the functioning of global ecosystems (Doran, 2002). The quality of soil and its potential for crop growth depend on various factors, including texture, structure, porosity, available water, and biological activity within the soil. However, the management system employed by farmers also influence soil structure and ultimately quality.

Soil compaction, for example, is a complex issue with economic and environmental consequences in global agriculture (Soane and van Ouwerkerk, 1994). It can lead to substantial changes in soil physical, chemical, and biological processes, as well as various environmental problems such as soil erosion, degradation, and surface water pollution, ultimately resulting in reduced crop production (Soane and van Ouwerkerk, 1994). The decline in soil quality and the reduction in ecosystem services pose a major risk to achieving increased agricultural productivity in the future (Lal, 2015).

Researchers have identified numerous causes of soil compaction. Some factors are natural, such as soil shrinkage due to drying and trampling by grazing animals. However, the most significant cause of compaction is the pressure exerted by farm vehicle wheels. Depending on the crop and agronomic practices, the area affected by wheel marks (wheel passes), known as the trafficked area, can reach up to 86% for conventional (plough-based) tillage, respectively (Kroulik and others, 2009).These wheeled areas are at risk of soil compaction, since compaction is a result of stress upon the soil, and is related to load, tyre pressure and contact area (Raper and others, 1995; Soane and van Ouwerkerk, 1994). Increased machinery wheel loads in turn lead to increased depth of soil compaction in the soil profile (Söhne 1958), and this might have a detrimental effect on archaeological artefacts buried in soil. Dain-Owens and others, (2013) reported that the subsurface pressures within the range of typical agricultural operations fractured more fragile pots (100kPa) and bones (280kPa).

Over the past 50 years, there has been a significant increase in the size and weight of farming machinery: the weight of fully loaded machines increased by a factor of 6, from 4.3 Mg in 1958 to about 25 Mg in 2009 (Schjønning and others, 2015). This trend of increasing machinery weight has resulted in greater soil compaction, which is defined as the process of densification that reduces porosity and permeability, increases strength, and induces various changes in soil structure and behaviour (Soane and van Ouwerkerk, 1994).

Soil tillage can partly alleviate compaction, as it creates favourable soil conditions for optimal crop establishment and growth. It is also employed to incorporate crop residues and nutrients into the soil and to control weed populations (Godwin, 2014). Conventional tillage, widely practiced, involves mouldboard ploughing followed by secondary cultivation to prepare the seedbed, as the larger aggregates resulting from mouldboard ploughing need to be broken down into smaller aggregates using tine- or disc-harrows (Morris and others, 2010; Hallett and Bengough, 2013). In England, conventional tillage remains the predominant method, with approximately 65% of arable land cultivated using this approach (Townsend and others, 2016).

Although cultivated soil provides increased soil warming, improved soil-to-seed contact, and facilitates root development (Hallett and Bengough, 2013), intensive tillage practices have been associated with severe negative environmental impacts (Foley and others, 2011). Deep tillage is often linked to increased field traffic (Kroulik and others, 2011), resulting in a larger area of compacted soil. During ploughing, a compacted layer is formed in the soil at approximately 200-350 mm from the surface due to the passage of two tractor wheels in the open furrow. Subsoiling is often required to alleviate this compaction, but it poses the risk of re-compaction from subsequent traffic (Morris and others, 2010).

Ploughing is likely to reduce the natural soil strength and make soils more vulnerable to compaction. The shallower non-inversion tillage and direct drilling retain a greater level of natural soil strength and make it less prone to compaction, hence less likely require remediation measures (e.g. subsoiling). Additionally, tillage destroys soil aggregates, and in turn increases soil loss by wind and water erosion (Pagliai and others, 2004). Additionally, it depletes soil carbon stocks breaking down the aggregates and exposing them to aeration and decomposition (Pagliai and others, 2004). Decreased soil organic carbon content in turn negatively affects further aggregation and lead to overall soil degradation. To mitigate the negative environmental impacts of ploughing, many scientists suggest "no-tillage" as an alternative. The adoption of this approach has increased since the mid- to late-1990s due to the availability of broad-spectrum herbicides and advancements in no-till technologies (Derpsch and others, 2010). Reduced tillage, combined with residue retention and crop rotation, is referred to as conservation agriculture and is recognized by FAO as a "climate-smart" practice (FAO, 2023). Conservation agriculture is believed to enhance soil fertility and water infiltration (Verhulst and others, 2010), while reducing evaporation in cooler soil temperatures (Gauer and others, 1982).

## Impact of arable cultivation techniques on the historic environment

Arable cultivation techniques may have a significant impact on historic environment. The two main threats to the historic environment are ploughing and soil erosion which is most common on cultivated bare soils and less common on established pasture (Darvill and Fulton 1998). The same authors (Darvill and Fulton, 1998) suggested that cultivation tends to plane minor undulations (i.e. archaeological earthworks) flat, with typical rates of erosion of 0.02 to 0.05m per year. Moreover, despite a consistent cultivation depth, the soil loss resulting from water or wind erosion, peat shrinkage, or soil compaction ultimately cause increased depth of cultivation in ploughing system. This in turn causes the plough to penetrate deeper into any archaeological deposits (and the sub-soil).

The overall effects of erosion on archaeology do not generally result from one particular arable episode but from repeated cycles of ploughing and associated erosion (Darvill and Fulton, 1998). Furthermore, the type and timing of cultivation, different crops as well as soil texture, slope and weather play additional role in exacerbating soil erosion (Boardman 1992).

Additionally, apart from tillage, farming traffic poses extra risks to historic environment as a result of load and transmission of tyre pressure down the soil profile (Dain-Owens, 2010, Dain-Owens and others, 2013). While different pot types and bone orientations break at different subsurface pressures, many typical farming operations exceed the threshold above which the pottery breaks (1.30 bar; 1.6 bar, 3.1 bar and 3.6 bar for shell-tempered, grog tempered, flint tempered, and sand tempered pots respectively at 25 cm depth below the surface), for example, combine harvester (1.30 bar), sprayer (1.31 bar), tractor with a trailer (1.46 bar), shallow mouldboard plough (1.61 bar) and deep mouldboard plough (2.04 bar). The lowest subsurface pressure found to cause damage to bones, estimated at 2.8 bar, was not exceeded by the farming operations mentioned above (Dain-Owens, 2010).

Plough damage to archaeological remains has been acknowledged as a problem since at least the 17th Century, and the problem is still unsolved In 1995 the English Heritage Monuments at Risk Survey - MARS (English Heritage, 1995) showed agriculture to be responsible for 10% of all cases of destruction and 30% of all cultivation damage to ancient monuments in the last 50 years. As a finite and precious resource, once damaged, such sites cannot be fully researched or recreated, and archaeological information is irretrievably lost. The MARS report (English Heritage, 1995) also showed that 32% of all rural archaeological sites and 21% of rural sites protected as designated Scheduled Monuments were still under arable cultivation at that time.

Between 1999 and 2002 Defra commissioned a further review of evidence for the Management of Archaeological Sites in Arable Landscapes (Defra, 2002). This included a generic review of cultivation practices and made recommendations about best practice which could be introduced to better protect archaeological sites in arable landscapes. It was complemented by the subsequent Cranfield University Trials Projects, known collectively as 'Trials' (Spandl and others, 2010). This work looked in much more depth not only at risks, but at site-based mitigation measures. It also made some general recommendations around soil management.

Natural England used recommendations from this work to re-define relevant historic environment-led options for minimum tillage and direct drilling across archaeological sites within Environmental Stewardship (ES) and the development of the subsequent

Countryside Stewardship scheme (CS). The Oxford archaeology project (Defra 2002) and the trials project (Spandl and others 2010) were in turn utilised by Historic England (then English Heritage) to develop site-specific desk-based risk assessments via the East Midlands ‘Conservation of Scheduled Monuments in Cultivation’ (COSMIC) pilots, with the subsequent addition of mitigation methodologies (Oxford Archaeology, 2014). COSMIC risk and mitigation assessments were applied nationally to all Scheduled Monuments not within agri-environment agreements (Oxford Archaeology, 2014).

Together, these research projects influenced the creation of archaeologically benign cultivation methods which would use existing best practice and equipment to allow arable production to continue, whilst also protecting sensitive archaeological sites. This marked a policy shift from an earlier reliance solely upon cessation of cultivation/reversion to grassland to prevent further degradation of archaeological sites (Oxford Archaeology, 2014).

But, whilst implementation of revised options under CS and a better understanding of risk and mitigation as a result of COSMIC have led to the improvement in condition of many rural archaeological sites some 2000 scheduled monuments remain on the Heritage at Risk Register, a third of which are due to continued arable cultivation impacts, and so a new and updated review of current innovation in arable systems and their impacts on heritage assets is required. Additionally, expectations from rural landscapes are changing; particularly when viewed as public goods, e.g. carbon sequestration and soil health, reduced soil erosion and enhanced water retention.

Agricultural technologies have developed significantly in the last 20 years, especially with the increasing use of GPS and minimum tillage options, and movements to more regenerative systems and systems such as paludiculture.

# Aims and objective of the project

The aim of this quick scoping review and stakeholder consultation was to investigate the impact on heritage assets of these innovations and any wider implications for soil health, to inform policy, guidance and best practice and identify evidence gaps for future research. The scope of the project was set by the funder Natural England.

This research project was conducted in two-stages 1) a Quick Scoping Review (QSR) of published and unpublished literature and 2) interviews with industry practitioners and topic experts.

Novel arable cultivation techniques were defined as those that have been developed since 2002. The rationale for this was that the impact on historical assets of arable cultivation techniques used before 2002 have already been reviewed for Natural England (Defra, 2002).

Although not a cultivation technique Natural England specifically requested that the impact of paludiculture was also investigated.

The specific objectives of the project were to:

- provide evidence of novel (after 2002) arable cultivation techniques or farming systems including paludiculture and their impact on heritage assets,
- provide evidence on novel (after 2002) cultivation practices, trends and innovation and their likely impacts on soil structure and health,
- provide a refreshed baseline of understanding from which to develop or re-cast AES options,
- provide a refreshed baseline of understanding from which to review and update existing guidance, best practice and related advice,
- identify evidence gaps,
- recommend further research needs, including field-based trials.

This project consisted of three main tasks to address the objectives:

a. Investigate the impact of any novel (after 2002) arable cultivation techniques or methods (e.g., controlled traffic farming- CTF), on soil physical degradation, or movement, or soil health, or carbon sequestration to infer on their potential impact on archaeological sites;
b. Identify any research that directly investigates the impact of novel (after 2002) arable cultivation techniques or methods, or of paludiculture on archaeology (in similar geographic/soil/ regions to the UK);
c. Identify future trends and innovation in arable cultivation techniques and methods and how these might impact on soil health.

## Quick Scoping Review

A quick scoping review (QSR) is a method of evidence synthesis that follows structured, transparent protocols that aim to minimise the bias in the collation and appraisal of evidence (Collins and others, 2015). QSRs are seen to be more robust and reliable than traditional literature reviews but quicker and less costly than full systematic reviews or systematic maps. This QSR was conducted following the Defra/NERC guidelines for the production of Quick Scoping Reviews and Rapid Evidence Assessments (Collins and others, 2015). This method focuses on a specific question and aims to answer it, using standardised, systematic methodology to search for evidence (published and unpublished academic and grey literature from multiple sources) and collate, and synthesise it to answer the review question.

## Primary questions

The primary research question was:

“What are the impacts of novel (post 2002) arable cultivation techniques/interventions and of paludiculture on soil structure/movement and consequently on archaeological sites”.

Three types of evidence were required to address the primary question: 1) evidence of the impact of novel techniques/interventions on soil physical degradation, movement, soil health, or carbon sequestration, to infer their potential impact on archaeological sites; 2) evidence that directly investigated the impact of novel techniques/interventions on archaeology; 3) evidence of the impacts of soil on archaeology.

Table 1 shows the population, intervention, comparator and outcome (PICO) key elements of the three evidence components that are required to address the primary question.

**Table 1. PICO key elements of the three evidence components of the primary question**

| Key element for each search string | Intervention and soil | Intervention and archaeological sites/ artefacts | Soil and archaeology |
|---|---|---|---|
| **Population** | Soil under arable farms | Buried archaeological remains/ archaeological sites and artefacts within soil | Buried archaeological remains/ archaeological sites and artefacts within soil |
| **Intervention** | Novel arable farming interventions (post 2002) and paludiculture | Novel arable farming interventions (post 2002) and paludiculture | Different soil organic matter (SOM)/ soil organic carbon (SOC) content/ soil structure/ displacement/ soil compaction |
| **Comparator** | Alternative interventions/no soil disturbance | Alternative interventions/no disturbance | Alternative soil structure/ soil characteristics |
| **Outcome** | Impact on soil movement or structure, soil health (soil organic carbon (SOC)/SOM) | Impact on archaeological sites and artefacts | Impact on archaeological sites and artefacts |

### Secondary questions

The following secondary questions were also addressed using the evidence gathered for the primary question:

- What types of novel arable cultivation practices could secure the archaeological resource better?
- In what ways might soil over archaeological sites be cultivated to improve soil health and increase carbon sequestration?

# Methods

## Searching for the literature

A comprehensive search to capture an un-biased sample of published academic and grey literature was undertaken using multiple information sources including online bibliographic databases and websites of relevant organisations.

The searches endeavoured to be as thorough as possible within the timescale of this project. The search strings were adapted to the syntax of each source searched and a record of each search was made Database and repository searches were conducted in the English language.

The online sources that were searched to identify relevant literature, are presented in Table 2.

**Table 2. Online sources searched for published and grey literature**

| **Bibliographic databases** | **Web of Science**<br>**Ethos (for PhD theses)** |
|---|---|
| **Organisation Websites** | AHDB<br>ADAS<br>Soil Association<br>Agricology<br>Farmers weekly<br>DEFRA<br>Natural England |

We also searched the Defra farm surveys to establish reported current farming practices. A further website, Paludiculture.org.uk was introduced in 2023, and so was not included in the original search list. This was searched after the completion of the review (August 2023), and although no additional primary research projects were added to the findings of the review, the resources were used to inform the discussion.

## Search string and scoping searches

The search strings used to capture literature from the bibliographic database were formulated using the PICO key elements of the primary question (Table 1), in addition to keywords that are specific to the secondary questions.

Scoping searches (see Appendix 1) were carried out to develop search strings to identify articles investigating the impact of arable management techniques on soil and/or archaeological and heritage features. Recent arable cultivation techniques of relevance included advances in e.g., tillage methods, controlled traffic farming, low ground pressure tyres, precision agriculture, use of autonomous machines, paludiculture. These techniques were identified through consultation with experts in agriculture and with agricultural technology manufacturers. It was decided at the inception meeting that the geographical focus would be on similar soils, climate and cropping to the United Kingdom.

The search string was refined to include only relevant crops and countries, and search results were further refined (see Appendix 1, Table 4 for a list of other countries excluded using the web of science filter). Three different search string were developed to investigate the impact of:

1. Impact of novel arable cultivation techniques and methods on soil (see Appendix 1, Table 4 (search #)):

   Tillage OR “soil manag*” OR Cultivat* OR Paludiculture OR “regenerative farm*” OR “tyre pressure*” OR “precision farm*” OR “soil compaction*” OR “controlled traffic farming” OR “CFT” OR “flex* tyre*” OR “flex* tire*” OR “ultra-flex tyre*” OR “ultra-flex tire*” OR “super-flex tyre*” OR “super-flex tire*” OR “high flexion tyre*” OR “high flexion tire*” OR Plough OR Plow (Topic) **AND**

   “soil loss*” OR “water retention” OR “soil health” OR “soil compaction” OR “soil disturbance” OR “horizontal displacement” OR “vertical displacement” OR “soil structure” OR “soil erosion” OR “soil displacement” (Topic) **NOT** mining OR Mediterranean OR tropic* OR dryland* OR desert* OR Asia* OR Chin* OR India* Ethiopia* OR Ghana OR Spain OR Brazil* OR Africa* OR Nigeria* OR Korea* OR Bangladesh OR Nepal* OR forest* OR grass* OR grazing OR pasture* OR biodiversity OR vegetable* OR vineyard* OR olive OR orchard* OR beetle OR pollinat* OR pest* OR rice OR cotton OR Mexico OR Kenya OR Texas OR Florida OR Arizona OR California* OR Nevada OR Mississippi OR Louisiana OR "South

Carolina" OR Tennessee OR "North Carolina" (Topic) **NOT** yield* OR productivity OR dairy OR cattle OR livestock (Title)

2. Impact of novel arable cultivation techniques and methods on historical assets (see Appendix 1, Table 4 (Search #25)):

   “Agri* robot*” OR Tillage OR “soil manag*” OR Cultivat* OR Paludiculture OR “regenerative farm*” OR “tyre pressure*” OR “precision farm*” OR “soil compaction*” OR “controlled traffic farming” OR “CFT” OR “flex* tyre*” OR “flex* tire*” OR “ultra-flex tyre*” OR “ultra-flex tire*” OR “super-flex tyre*” OR “super-flex tire*” OR “high flexion tyre*” OR “high flexion tire*” OR Plough OR Plow (Topic) **AND** archaeolog* OR artefact* OR relic* OR “historic* feature*” OR “heritage feature*” (Topic) **NOT** Chin* OR tropic* OR rice OR forest* OR pasture* (Topic)

3. Impact of soil properties on historical assets (see Appendix 1, Table 4 (Search #26))

   archaeolog* OR artefact* OR relic* OR "heritage feature*" OR "historic* feature*" **AND** “soil loss*” OR “water retention” OR “soil health” OR “soil compaction” OR “soil disturbance” OR “horizontal displacement” OR “vertical displacement” OR “soil structure” OR “soil erosion” OR “soil displacement” **NOT** Mediterranean OR tropic* OR dryland* OR desert* OR Asia* OR Chin* OR India* Ethiopia* OR Ghana OR Spain OR Brazil* OR Africa* OR Nigeria* OR Korea* OR Bangladesh OR Nepal* OR forest* OR grass* OR grazing OR pasture* OR vegetable* OR vineyard* OR olive OR orchard* OR Mexico OR Kenya OR Texas OR Florida OR Arizona OR California* OR Nevada OR Mississippi OR Louisiana OR "South Carolina" OR Tennessee OR "North Carolina" OR rice OR cotton

For the first two search strings (#24 and #25) the publication date was restricted to the date range from 2002-01-01 to 2023-06-01. The rationale behind this was that Natural England have based historical asset advice on reviews and primary research conducted prior to, or in the early 2002’s, and agricultural technologies have developed significantly in the last 20 years. Hence, the aim of this study was to pick up the novel (post 2002) cultivation techniques.

There was no need to restrict time of publication for the impact of soil on archaeological sites (Search #26 in Table 4, Appendix 1), as these relationships are more general and relate to more general effects of soil movement/ structure/health on soil archaeological sites and features, hence earlier studies might be relevant. Search strings for the organisational websites were tailored to the specific website.

In order to try to find specific research areas and clusters in the literature, and potential novel terms, not specifically searched for, we used topic modelling following the initial searching stages. In some cases, this may a) inform priority areas to focus on for the QSR (e.g., novel technologies, research topics) and b) help identify further terms for the QSR.

For the topic modelling, we used Sciome SWIFT-Review software which is based on Latent Dirichlet Allocation to automatically compute topic models from literature imported from searches in bibliographic databases. This statistical method discovers themes and concepts in a large set of documents and will enable groups and subgroups of practices to be identified.

The three final search strings were imported separately into the topic modelling software Sciome SWIFT-Review. Topic modelling did not identify any new cultivation technology which hasn't been available prior to 2002, nevertheless existing technologies may have improved. To overcome this issue, the interviews were used to help identify any new technology terms.

# Screening

## Screening literature

All retrieved relevant articles were imported into the specialised systematic reviewing software (EPPI-Reviewer Web) and screened for relevance against the pre-defined inclusion criteria. Due to the level of literature gathered, screening of articles was conducted based on title and abstract only. The number of articles included and excluded at each stage was recorded. Due to a high number of overall references, and low number of relevant findings collated for searches relating to the impact of arable cultivation techniques and methods on historical assets we screened for title and abstract on the first 300 articles only, sorted according to relevance. A review of the literature beyond this point indicated that there was a low likelihood of finding relevant papers beyond that cut off point. All results from the other searches were screened.

## Inclusion criteria

The inclusion criteria reflected the PICO key elements for each of the three searches.

1. Impact of novel arable cultivation techniques and methods on soil:

   Inclusion criteria

   - Population: Soil under arable farming,
   - Intervention: Novel (post 2002) arable farming intervention or paludiculture
   - Comparator: Alternative interventions/ control (no soil disturbance)
   - Outcomes: Impact on soil movement or structure, soil health (SOC/SOM)

   Exclusion criteria

- Geographical limitations: Studies excluded from overseas countries where soil and climatic conditions are different to the UK, e.g. tropical, sub-tropical, desert and dryland soils or climatic conditions
- Soil health: Soil health aspects were limited to soil organic matter/ soil organic carbon. Soil fungi and soil fauna (e.g. nematodes/ earthworms) were not included.
- Date restrictions: from 2002-01-01 to 2023-06-01
- Language limitations: Abstracts in English language only

2. Impact of novel arable cultivation techniques and methods on historical assets:

Inclusion criteria

- Population: Buried archaeological remains/ archaeological sites and artefacts within soil,
- Intervention: Novel (post 2002) arable farming intervention and paludiculture
- Comparator: Alternative interventions/ control (no soil disturbance)
- Outcomes: Impact on archaeological sites and artefacts

Exclusion criteria

- Geographical limitations: Studies excluded from overseas countries where soil and climatic conditions are different to the UK, e.g. tropical, sub-tropical, desert and dryland soils or climatic conditions
- Date restrictions: from 2002-01-01 to 2023-06-01
- Language limitations: Abstracts in English language only

3. Impact of soil properties on historical assets:

Inclusion criteria:

- Population: Buried archaeological remains/ archaeological sites and artefacts within soil,
- Intervention: Soil displacement/ compaction/ Soil characteristics
- Comparator: Alternative soil structure/ characteristics)
- Outcomes: Impact on archaeological sites and artefacts

Exclusion criteria

- Geographical limitations: Studies excluded from overseas countries where soil and climatic conditions are different to the UK, e.g. tropical, sub-tropical, desert and dryland soils or climatic conditions,
- Date restrictions: No date restriction,
- Language limitations: Abstracts in English language only.

# Coding literature

All included literature was catalogued in a searchable database containing key information for each study in a standard format. Coding was agreed with Natural England at the inception meeting. Detailed coding of metadata (using abstracts) of all the primary research included in the QSR was carried out following the coding structure provided in Table 3.

Coding of PhD theses, reviews, opinions and surveys was limited to bibliographic information and a brief summary of relevant points. A large volume of review articles was found about the impact of novel techniques/interventions on soils. It was not possible in the timeframe of this project to fully code all of these articles. Instead, they were listed with abstracts as additional information.

**Table 3. Data coding information**

| Category | | # | Coding Variable |
|---|---|---|---|
| **Bibliographic Information** | | 1 | Search string |
| | | 2 | Unique article id |
| | | 3 | Full reference |
| | | 4 | Year |
| | | 5 | Publication Type (Journal, Book etc) |
| | | 6 | Publication Title |
| **Study Background** | | 7 | Country of study |
| | | 8 | Study type (lab/ field) |
| **Study Details** | Population | 9 | Soil |
| | | 10 | Landscape |
| | | 11 | Archaeological sites within the soil |
| | Intervention | 12 | Novel cultivation techniques / paludiculture |
| | Comparator | 13 | Alternative interventions |
| | | 14 | No disturbance/ no intervention |
| | Outcome | 15 | Outcome measured (soil movement/ vertical or horizontal displacement/ structure/ erosion/ soil health/ impact to archaeological sites) |

| Category | | # | Coding Variable |
|---|---|---|---|
| | | 16 | Parameter measured |
| | | 17 | Author reported conclusion (effect, no effect, inconclusive) |
| | | 18 | Does the author highlight any research gaps? |
| **Other** | | 19 | Other |
| **Notes** | | 20 | Any other notes |

## Critical appraisal

QSRs do not include critical appraisal of the included evidence (Collins et al 2015). Moreover, it would not have been possible to carry out full critical appraisal of included studies within the timescale of this project and based on abstracts only. This means that the recommendations made by the authors of the included studies should be interpreted with caution.

## Interviews

Interviews were carried out with industry practitioners, advisors, policy workers and influencers (farmers, academia, organisations, arable and soil health specialists). Participants were identified for interview through literature sourced in the QSR, and recommendations from stakeholders (including Harper Adams staff who have extensive links with the farming community and related industries).

Semi-structured interviews were used to: (1) to identify the ways the modern practices may secure the archaeological resource better, e.g. GPS, remote sensing, precision farming, no-till, CTF, autonomous machinery; (2) understand the multiple and linked benefits to farmers of soil, water, carbon, and heritage conservation and 3) understand the barriers to uptake of new practices.

Questions prepared for the interviews fell into the following seven categories:

1. Participant attributes – Occupation
2. Knowledge of arable farming techniques/methods developed and practiced in the last 20 years.
3. Perceived impact of these latest arable farming techniques/methods on heritage assets

4. Perceived multiple and linked benefits to farmers of soil, water, carbon, and heritage conservation from practicing these arable farming techniques/methods.
5. Perceived barriers to uptake of these arable farming techniques/methods
6. Knowledge of current cultivation practices (what are most farmers currently practicing)
7. Trends and likely future innovations (what is currently in development) and their likely impacts on soil health and implications for heritage assets

This methodology was designed to enable interviewees to freely discuss their opinions and views on the topic, whilst at the same time allowing the interviewer to impose structure to the interview using open-ended questions. All interviews were conducted using an online video conferencing platform. Interviews were conducted in English language and participants were treated as anonymous. The total number of interviews conducted was 13, out of 16 invited.

## Case studies

Three case studies were selected to demonstrate examples of current and new approaches to cultivation and soil management in arable environments and their potential heritage benefits. The case studies included a farm with heritage features that are following good practice, new technologies/techniques under development/on-farm testing (controlled traffic farming, use of farming robots/ autonomous vehicles) and research on precision farming and archaeology.

# Results

## QSR review descriptive statistics

Figure 1 provides an overview of the literature included and excluded at each stage in the QSR process. A total of 3324 articles were initially identified through bibliographic databases. Following duplicate removal and screening against inclusion criteria, 120 articles remained. A further 7 articles were sourced from grey literature searches. Therefore, in total, 127 articles were included in the database (summarized in Appendix 2) and used to inform the narrative synthesis. This included 65 primary research articles coded using abstracts.

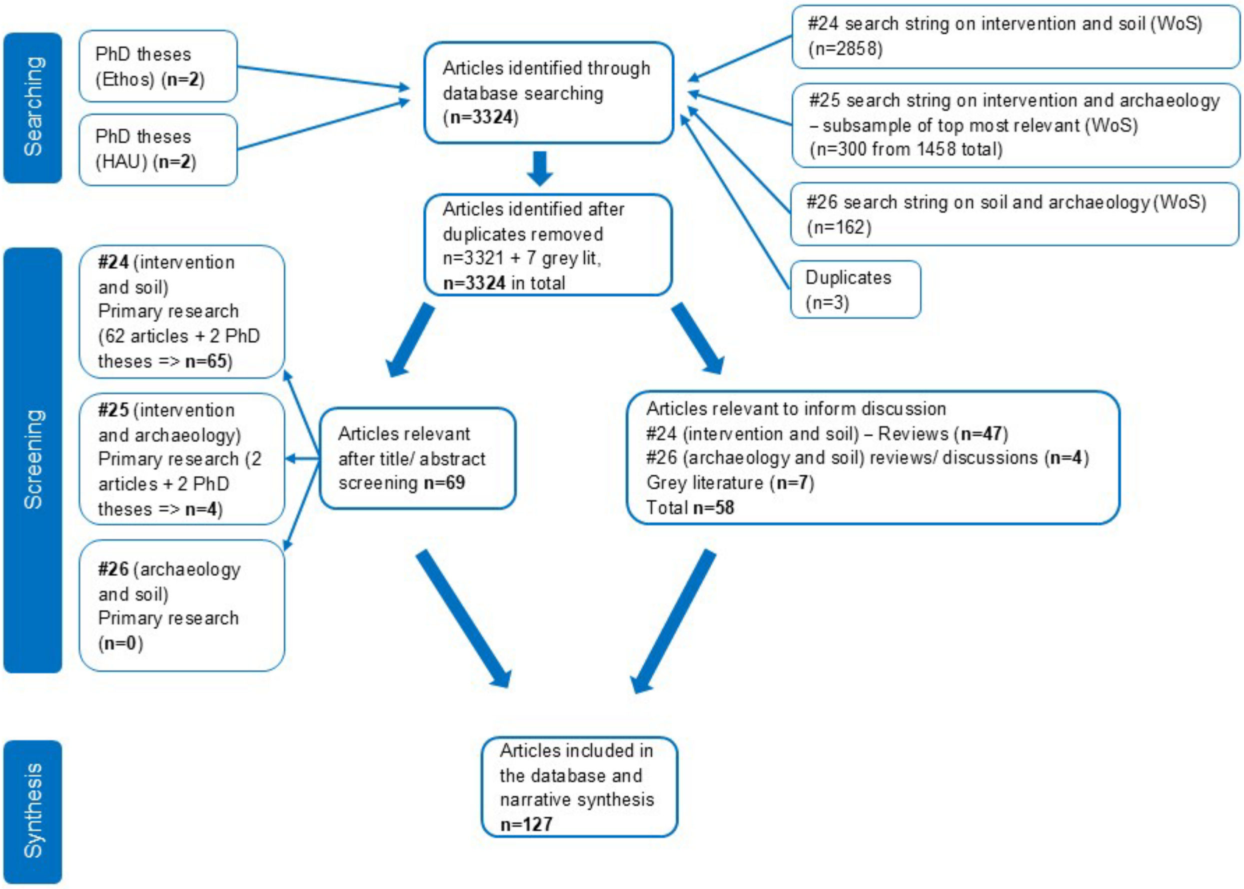

**Figure 1. Literature included and excluded at each stage of the quick scoping review process (adapted from Haddaway and others, 2017)**

Reviews were screened for relevant primary research that may have been missed in the searches, but no more was found. Conclusions reported by authors of the reviews, PhD theses, opinions and surveys were used to put the findings of this review into context.

Details of PhD theses, reviews, opinions and surveys that informed the QSR are provided in Appendix 2.

All the primary research articles (n=65 for all three search strings) considered relevant for inclusion in the screening process, were coded using abstracts in an Excel database. Those 65 papers resulted from two search strings: intervention and soil (n=63) and Intervention and archaeology (n=2). No primary research was found relating to soil and archaeology, however four review/ discussion papers which were found with this search string, were included in the Excel database and informed the discussion of the results.

The sections below describe the findings resulting from screening results of the three search strings:

## Research investigating impact of novel farming practices on soil properties (#24)

A total of 63 articles were found that investigated novel farming practices and soil properties. These could be fitted into 8 general categories of arable techniques/methods (Figure 2):

- Tracks or tyres (low tyre pressures, dual tyres) (28 articles),
- Controlled Traffic Farming (14 articles),
- Machinery and tillage approach (tillage tools, e.g. basin tillage, dyker in root crops or undercutter in cereal) – 12 articles
- Planning tools (mainly route planning tool to optimize the number of passes) – 4 articles
- Paludiculture – 3 articles
- Precision agriculture – 1 article
- Microorganisms – application of soil amendments with microorganisms (EM-A) - 1 article
- Robotics – 1 article

Additionally, there were 47 review articles on the effect of different farming practices, e.g. CTF, new tyres / track technology as well as regenerative agriculture, on soil properties.

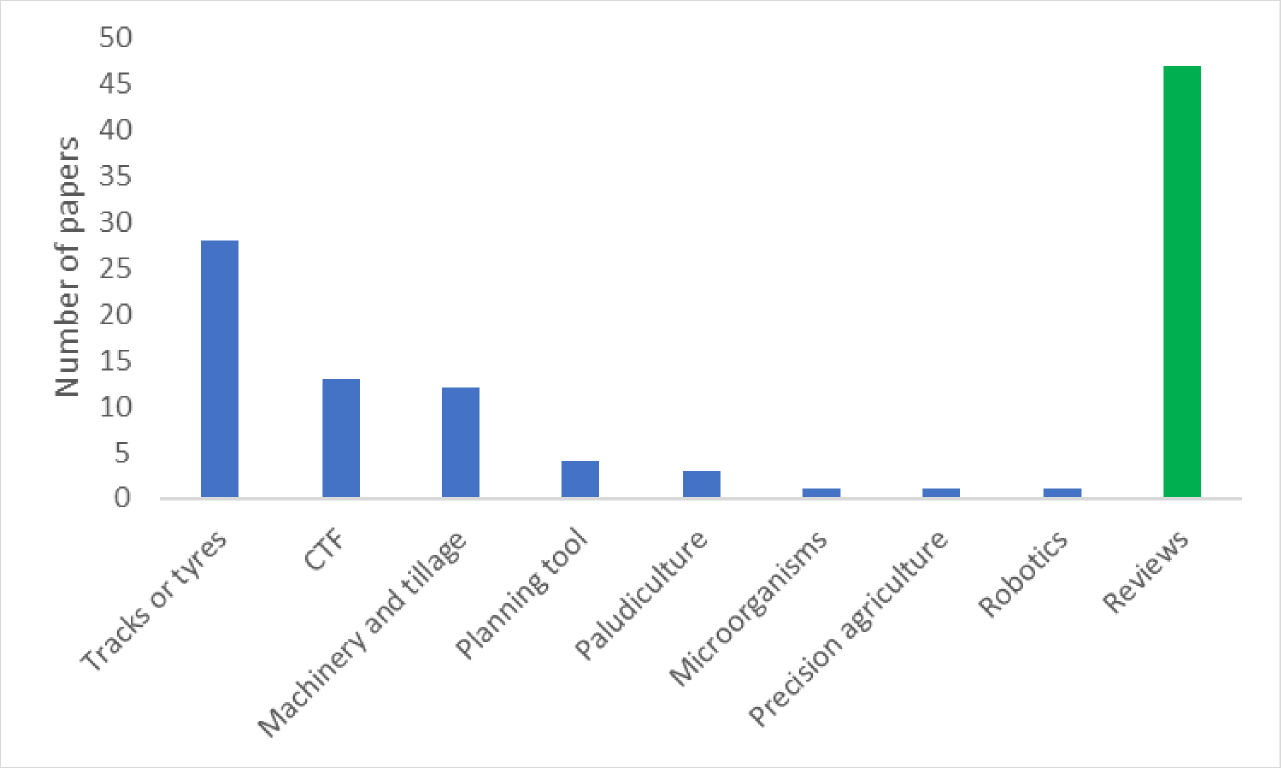

**Figure 2. Number of papers describing the impact of different types of novel techniques on soil**

## Research investigating the impact of arable farming on heritage assets

There were only two research articles that addressed the impact of arable farming techniques/methods on heritage assets. One investigated the fracture risk to buried ceramic pots and bones from the subsurface pressures generated by agricultural operations - Daine-Owens and others (2013), (the same study was reported in a PhD thesis by the same author (Dain-Owens, 2010). Although it did not refer to any specific farming technology. The study provides detailed statistics of the effects of different loads on heritage assets, hence will able to inform future research focused on farming technologies that are benign to heritage assets. The authors suggested that low-pressure tyres, tracks and reduced tillage might protect subsurface archaeological features and artifacts, from damage resulting from subsurface pressure transmission. A second study investigated displacement and damage to lithic artifacts resulting from two different seed drills – zero tillage drill and a “rangeland” drill, which is a commonly-used in the US disc drill (Bryan and others, 2011). The authors concluded minimal effects of drill seeding on lithics.

## Research investigating the links between soil and archaeological features

No relevant primary research articles were found that directly investigated the effects of soil on the archaeological features. One paper, however, may shed light on the risks to the subsurface archaeological remains in Europe from soil loss driven by water erosion (Agapiou and others, 2020). Additionally, there were two review papers that reported on 1) the impact on climate change on archaeology and only indirectly we can draw conclusions on the impact of farming which plays a role in climate change (Howard and others 2008) and, 2) impacts of degradation threats on soil properties in the UK, including archaeological sites (Gregory and others 2015); the latter paper however did not refer to any farming technology specifically. Additionally, we found an analysis of soil stakeholders survey in Scotland – “Priorities towards national-level soil protection” where loss of archaeological sites was one of the topics considered, however the abstract does not include any details in this regard (Adderley and others 2004).

## Topic expert interview descriptive statistics

Out of sixteen invited, thirteen topic experts were interviewed comprising six academics, two industry representatives (including equipment manufacturers), two independent consultants, two farmers and one representative of an executive non-departmental public body. No further interventions were identified to those found in the screening process.

## Implications of different novel techniques for soil and for heritage assets

The literature findings from the QSR were combined with key points from the interviews to assess the potential implications for heritage assets and soils of different arable technique. These have been grouped by category, and are summarised below:

### Low pressure tyres (LPT), rubber tracks or dual tyres

This technology aims to increase contact area between soil and the running gear to mitigate soil compaction, as the contact pressure is a function of wheel load (related to the machinery weight) and contact area as suggested by Spoor and others (2003). Other models relate the contact pressure to tyre inflation pressure and tyre carcass stiffness (Misiewicz 2010). Increasing the tyre size and/ or decreasing the tyre inflation pressure decreases the risk of soil compaction. However, additional tyres mounted on the tractor can cause problems with the external width of a vehicle moving on a highway, hence the majority of studies focus on increased flexion tyres which allow for lower inflation pressure or rubber tracks.

#### Impact on soil properties – (eg. soil compaction etc.)

LPT can reduce soil compaction by spreading the weight of vehicles over a larger area, thus minimizing soil damage and erosion, improving water infiltration and its retention in the soil, and in turn reducing water runoff and erosion (e.g. Arvidsson and Keller, 2007, Arvidsson and others 2011, Pagliali and others, 2003, Ansorge and Godwin, 2007, Ansorge and Godwin 2008; Antille and others 2013). This can lead to reduced rut depths (Antille at al. 2013), and potentially improve soil structure (Vanderhasselt and others, 2020), hence influencing nutrient uptake, and water infiltration.

### Potential implications for heritage assets

Dain-Owens (2010), as well as Dain-Owens and others (2013) found in experimental trials that the effect of tillage implements on pressure transmission to buried objects is small in comparison to that of the tyre/wheels of trucks, tractors, trailers and harvesters, which were found to be two orders of magnitude greater. The author concluded that LPTs can help to preserve archaeological assets by reducing the risk of damage to buried structures and artefacts resulting from farming operations. This can help to maintain cultural heritage and historical records for future generations.

### Potential implications for soil health (carbon etc.)

The impact of LPTs on soil organic matter has not been extensively studied. One PhD thesis, (Kaczorowska-Dolowy, 2022) reported that tyre pressures did not have any effects on soil carbon, however soil invertebrates (Collembola) communities were more abundant under LTP system than under standard tyre pressures, similarly lowering tyre inflation pressures increased soil fauna feeding activity.

### Perceived multiple and linked benefits to farmers from soil, water, carbon, and heritage conservation

By improving soil health, LPTs can potentially increase farm productivity and sustainability. Improved soil health, via increased porosity and air permeability (e.g. ten Damme and others 2019, Ren and others 2019) might potentially increase water retention which is particularly important in the extended dry periods resulting from climate changes. Additionally, LPTs can reduce maintenance costs and fuel consumption, which can provide economic benefits to farmers in the long term (Godwin and others 2022). Moreover, some studies show that if deep tillage is required e.g. to control weeds, LTP can deliver increased cereal crop yields in comparison to tyres inflated to standard pressure (STP), which is suggested to be a result of improved soil health under LTP in comparison to STP (Kaczorowska-Dolowy, 2022).

### Perceived barriers to uptake

The perceived barriers to uptake of the technology is an increased cost of this type of tyre in comparison to standard tyres, as well as lack of awareness of the benefits of this solution. Additionally, inconvenience in adjusting the tyre pressures for driving in the field (low inflation pressure) and on a highway (high inflation pressure) was indicated in the interviews, as a barrier. This however can easily be overcome by a Central Tyre Inflation Systems which allows to change tyre pressures on the move. Nevertheless, this technology is perceived as additional cost and without understanding the benefits of this system, the uptake might be slow.

### Controlled traffic farming (CTF)

CTF is an agricultural management system which aims to minimize traffic-induced soil compaction (Raper, 2005). To confine farming traffic to permanent traffic lanes, the use of in-field machinery equipped with navigation aids and auto-steering systems is required. Real Time Kinematic Global Positioning System (RTK-GPS) provides accuracy to below 20 mm, which allows users to drive farm vehicles on the same permanent traffic lanes every year. This in turn allows the crop zones in-between to remain untrafficked (Gasso and others 2013, Raper, 2005).

#### Impact on soil properties – (e.g. soil compaction etc.)

CTF significantly reduces soil compaction, as it confines the trafficked area to permanent traffic lanes only (Antille and others 2016). This has been reported to decrease the trafficked area from around 86% of the total field area in conventional tillage (as indicated by Kroulik and others, 2011) down to 12-15% depending on the width of machinery adopted for the CTF system (Antille and others 2013). Less compacted soil in turn does not require deep tillage to alleviate soil compaction, hence CTF is often combined with shallow or zero tillage system. As a consequence, soil porosity and water infiltration can be improved (Galambosova and others, 2010; McHugh and others, 2009; Millington, 2019; Kaczorowska-Dolowy, 2022), whereas water run-off and soil erosion decrease (Guenette and others, 2019; Gutu and others, 2018). The benefits from the CTF expressed as the increased crop yield were reported as from the first year after the system was implemented and lasted over the course of 8-year-observation, regardless the tillage depth (Kaczorowska-Dolowy, 2022) indicating short and long-term benefits for the environment and the farmers.

#### Potential implications for heritage assets

None of the articles found in the QSR directly addressed the impact of controlled traffic farming on heritage assets, however since the vertical pressures and load under tyres of farming machinery pose a significant risk to archaeological sites (Dain-Owens at al., 2013) we can indirectly hypothesise, that the reduction of trafficked (and compacted) area has a potential to mitigate the risk to historic assets (buried in the soil). Moreover, if CTF is combined with precision farming, e.g. mapping of historic assets buried in the soil, the permanent wheelways might potentially be allocated in such a way to avoid driving over the historic assets. Additionally, interviewees highlighted that CTF does not require deep tillage as a measure to alleviate soil compaction, because under this system, the majority of field area remains uncompacted. This in turn lessens the risk of damage to archaeological assets resulting from deep tillage or subsoiling.

### Potential implications for soil health (carbon etc.)

Limited evidence of the effect of CTF on soil organic matter (SOM) or soil biology was found in this review. One study investigated the effects of CTF on GHG emissions (Tullberg and others, 2018) and concluded that adoption of CTF could reduce total emissions of GHG from the soil by 30%-50%. Additionally, there is coherent evidence on the effect of CTF on increased soil porosity (Kaczorowska-Dolowy, 2022; Tullberg and others 2018; Guenette and others, 2019; Millington, 2019; Gutu and others, 2018). The increased soil porosity in uncompacted soil is likely to create a better habitat for invertebrate communities as suggested by Kravchenko and Guber., (2017), Kaczorowska-Dolowy, (2022); Pangnakorn, (2002). Moreover, this system facilitates adoption of reduced tillage which in turn is associated with improved carbon sequestration in comparison to deep tillage, as suggested by Hussain and others (2021).

### Perceived multiple and linked benefits to farmers from soil, water, carbon, and heritage conservation

All interviewees highlighted that the farming community strives to obtain net zero as well as maintain sustainable farming and sustainable soil management. Additionally, if possible, farmers would like to avoid damaging the historic assets, because many consider their role as a landscape stewardship. However, these aspects can be considered only if the technology adopted does not compromise the farmer’s income, as participants reported that the farming community often already struggles to ensure viability.

### Perceived barriers to uptake

One of the major barriers to CTF adoption is the cost associated with implementing the system. The initial investment in specialized machinery (to ensure the widths of farming machinery matches or is a multiplication), can be high, and many farmers are reluctant to take the risk, according to the interviewees. Alternatively, it is a long – term process, when the strategy of exchanging farming machinery embraces the CTF principles. However, some interviewees argued that if the CTF is combined with zero tillage, it is just the width of the seed drill which needs to be considered as there is no need for a cultivation machinery. Some interviewees additionally highlighted lack of knowledge: Many farmers are unaware of the benefits of CTF and how the system works. Moreover, adoption of a new technology like CTF requires a significant change in traditional farming practices, which can be challenging for some farmers. The idea of using fixed wheel passes for all operations is a new concept that many farmers may find difficult to accept. This can be even more challenging when some farming operations are delivered by subcontractors, who might not understand the idea or are not willing to adhere. Moreover, although there are already many farming machineries on the market which are equipped with GPS, the systems are not compatible and there is a difficulty in sharing the data or using the farming datasets between tractors or combines from different producers. These barriers are in agreement with a study conducted by Tamirat and others, (2022) who conducted 103 farmers surveys from 8 European countries on farmers' needs and perceptions concerning the application of CTF. Based on this research the authors indicated that the major factors limiting adoption of CTF appear to be: lack of compatibility in machinery and Global Navigation Satellite Systems (GNSS) by different manufacturers; expense (equipment purchase, Real-time Kinematic (RTK) signal, machinery modification). Additionally, there is a lack of demonstrated benefits under local conditions; incomplete knowledge of research findings and decision support tools; and a perception that CTF is not for small farms.

**Novel machinery design and tillage approaches**

Under this category there were 12 papers which investigated a broad range of engineering advancements to address soil compaction, water runoff, soil wind and water erosion:

a) Design of soil openers to create furrows for seed and fertilizer placement in no till (n=1).

   There are studies that investigated design of soil openers to create furrows for seed and fertilizer placement suitable for no-tillage. Currently the operational speeds are limited due to excessive lateral soil throw reducing furrow backfill and causing interactions between adjacent furrows (Barr and others, 2016). The same authors suggested that there is a potential for new opener technology to increase operating speeds of no-till seeding operations by minimising soil disturbance and draft, therefore improving work-rate and timeliness of sowing. This can be obtained by applying bentleg openers rather than the straight ones (Barr and others, 2016).

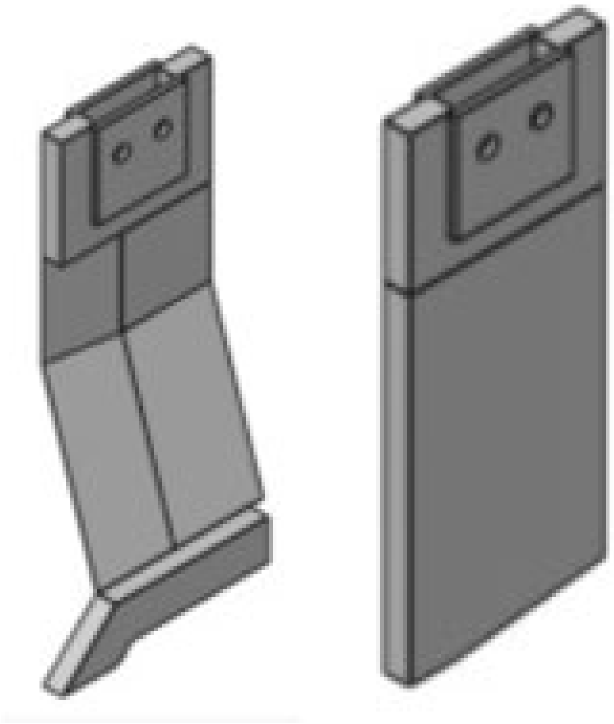

**Figure 3. Isometric view of a bentleg and straight (on the left and right respectively) soil opener for zero tillage – after Barr and others, 2016**

b) Adjustments of tines and tillage depths to soil conditions on potatoes fields to mitigate soil compaction between ridges in potatoes farming (n=1; Kalini n and others, 2019);

c) Improvements of the geometry of the support part of the chain-track tractor (n = 1; Mudarisov and others, 2020);

d) Tricycle-like self-propelled machine with traction on all three wheels used in slurry application to mitigate soil compaction (n= 1; Schjønning and others, 2022

e) Basin tillage (n=3):

Three papers investigated novel tillage technology in wide-row crops (mostly potatoes or beetroots), however there is no agreement on the name of the technology: Vejchar and others (2019) referred to this technology as tied ridging method, Gordon and others (2019) called it basin tillage, whereas Lemann and others (2019) reported on using a device called “Dyker”. Nevertheless, all these techniques aim to reduce water run-off and soil erosion by building individual earth blocks along furrows.

f) Raised beds which have become popular in Australia to overcome waterlogging problems (Holland and others, 2012);
g) Machines with dynamic tillage tools to prepare the soil for sowing allow regulation of soil pulverization intensity and performing a technological operation in one pass to mitigate soil compaction (Nuralin and others, 2021);
h) Agricultural machine made of a plough and a tillage cutter which reduces number of passes required to prepare a seedbed, hence mitigating soil compaction (no more detailed description provided in the abstract) (n=1; Paraschiv and others, 2008)
i) Undercutter tillage – a method which cuts weeds or cover crops, leaving them on the soil surface. By leaving cover crop residue intact, growers can get longer weed suppression from the cover crop mulches in comparison to mowing them into smaller pieces. This method addressed soil loss on fallow fields (Sharratt and Feng, 2009);
j) A fifth wheel located on the front of the mounting system of a tractor to reduce the turning radius and decrease the area of heavily compacted headlands (Trendafilov and Delchev, 2018).

### Impact on soil properties – (e.g. soil compaction etc.):

The literature discussed potential to decrease in water run-off and soil erosion when the novel approach to tillage (basin tillage/ dyker) was applied (Vejchar and others, 2019, Lemann and others, 2019); Similarly, undercutter tillage aims to reduce soil erosion and soil loss as a result of retaining plant residues (Sharratt and Feng, 2009); The novel design of machinery e.g. bentleg opener for no-tillage drill (Barr and others 2016) showed potential for minimising soil disturbance and draft (force required to pull tillage tool through soil), therefore improving work-rate and timeliness of sowing for direct drilling. Similarly, the fifth wheel on the front of a tractor might reduce the soil compaction as suggested by Trendafilov and Delchev (2018); authors of the study on the tricycle-like self-propelled machine with traction on all three wheels for slurry application (Schjønning and others, 2022) did not however report any conclusions.

### Perceived multiple and linked benefits to farmers and historic assets

Under this category of intervention (machinery design and tillage approach) there is limited evidence on each method, so the potential benefits need to be considered with caution.

The improved water infiltration under basin tillage/tied ridging/ dyker (Vejchar and others, 2019, Lemann and others, 2019) might increase water retention hence available water for crop growth, and consequently increase crop yields. Additionally, reduced water erosion and run off have potential to preserve archaeological sites due to decreased soil loss. This technology does not aim to change the level of the water table and so might impact preservation of the archaeological by halting soil loss. The bentleg soil opener in a seed drill

drill for zero -tillage system also might be beneficial for archaeological assets as a result of reduced soil disturbance under this novel design.

### Perceived barriers to uptake

None of the technology mentioned above was mentioned by interviewees. None of the papers found mentioned the barriers to uptake by farming community. On the other hand, this might mean that lack of awareness of the novel machinery and access to it are the barriers in the uptake of this technology.

## Precision agriculture, route planning tools

Precision farming is an advanced agricultural management system that uses technologies (e.g. Global Positioning System (GPS), Geographic Information System (GIS), and sensors) to precisely manage production inputs, e.g. fertilizer, water, and pesticides (Finger et al, 2019). The impact of precision farming on soil structure is a complex issue, however it has not been extensively investigated per se. Route planning tools might be additional part of precision agriculture which via application of a software/ AI/ neural network optimizes in-field routes to mitigate soil compaction as well as reduces farming inputs on fuel and labour.

### Impact on soil properties

Only one paper investigated the impact of precision agriculture on soil physical properties (Kalinin and others, 2021) in which the authors looked into adjustments of the depths of soil rippers following the compaction levels across the field. Additionally, there were 4 papers that considered route planning tools (Edwards and others 2017, Evans and others 2020, Villa-Henriksen and others, 2021 and Green and others 2011) which reported on reduction of trafficked intensity via application of novel planning tools. The conclusions on the effects of precision farming on soil characteristics might be however drawn indirectly, based on the detailed technology involved in this broad term. The interviewees considered precision farming as a way to mitigate the adverse impact of farming on soil and environment in general, particularly thought adjustments in tillage depth to the affected areas by compaction of weeds only. Additionally, by using precision input applications, based on soil maps, precision farming can avoid unnecessary passes of heavy machinery over the field, reducing the amount of soil compaction caused by the weight of the equipment. Moreover, precision farming was suggested to allow for better management of irrigation and drainage, which can improve soil structure by preventing waterlogging and reducing soil erosion.

### Potential implications for heritage assets

In a PhD thesis by Webber (2020), the author provided an example of research in Saxony-Anhalt, Germany, where precision farming technology has been used to variably control the depth of cultivation over historic sites. Archaeological zones were successfully integrated into precision farming tractor-based computer software and hardware so that during cultivation the tractor lifts the implement above a certain depth over the archaeological zone. Webber (2020) also found that precision farming could aid the prospection of archaeological sites, as archaeological sites can impact soil nutrients and soil contaminants. The author highlighted that the contribution of mapping unknown sites (e.g. differences in soil nutrients) in general has not been widely recognised within heritage policy, but in the future farmers could be required to share precision farming data while shaping agri-environmental policies. This in turn could enhance the archaeological record as a cultural and environmental ‘public good’. Additionally, the route planning tools might reduce risks to archaeological assets through the reduction in the trafficked / compacted field area.

Apart from the above-mentioned literature, there was a worth mentioning initiative focused on interoperable remote and near-surface sensing to support sustainable integrated agricultural land management (IPAAST) (Opitz and others, 2023). However, since it was published after completing the literature search for this QSR, it wasn’t picked up by the search string. The IPAAST project looked into whether people involved in using sensors for land management were willing to change their ways of working, capable of doing so, and motivated to do it. The overarching idea behind it was to improve collaboration between stakeholders in accessing data obtained through precision agriculture, environmental management, archaeology, and heritage management. A workshop conducted within the IPAAST project identified several aims for the stakeholders as well as barriers and opportunities for actions. Although data for archaeological purposes is collected at a greater resolution than in many cases is required for precision agriculture, there is potential for coordinated data collection, for multiple applications, and to add value in anthropogenic soil systems (Opitz and others, 2023).

### Perceived multiple and linked benefits to farmers

Webber (2020) suggested that another benefit of integrating precision farming and archaeology is that it provides another pathway for engaging stakeholders (farmers, land managers, specialists etc.) on managing the historic environment by shifting the focus from the restriction of farming activities over archaeological sites, towards the better understanding of that archaeological site and how it interacts with day to day farming. The author stated that where an archaeological site is discovered, it can add to the archaeological record, and also aid in targeting soil nutrients more accurately to reduce fertiliser use. Other interviewees indicated some additional benefits to farmers which derive from reduced inputs, e.g. adjusted levels and targeted fertilizers, irrigation, weed killers as well as depth of tillage only to areas in need for weed control. Additionally, from PF data sets farmers can learn about their particular site and improve the farming methods to protect both soil and archaeological features. This in turn might bring long-term benefits in increased crop yields, reduced costs and enhanced soil health.

### Perceived barriers to uptake

Interviewees highlighted several barriers to uptake the technology:

High upfront costs: The initial investment in precision farming equipment and technology can be expensive, which can make it difficult for farmers to adopt these practices.

Lack of evidence on benefits to the farmers. There is a need for cost-benefit analysis. Additionally, many farmers may not have access to financing or loans that could help them purchase the equipment and technology needed for precision farming.

Limited technical knowledge and expertise: Precision farming requires specialized technical knowledge and expertise, which may be lacking among some farmers, as well as among the consultants and agronomists.

Connectivity and access real-time data may not be available in remote or rural areas.

Resistance to change: Some farmers may be resistant to changing their traditional farming practices, which can make it difficult for them to adopt new technologies and methods. However, with generation change the uptake is likely to increase.

Moreover, Webber (2020) reported that the difficulty in applying precision farming technology to control the depth of cultivation more widely was in distributing knowledge and making it easy for farmers to carry out as part of their normal operations. Webber (2020) highlighted that there would also be barriers to implementation in the UK: 1) farmers need modified equipment and at the time of writing there was only one current commercial provider in the UK 2) Different types of cultivation equipment are often required across a whole farm depending on the conditions and the need for cultivation, and therefore depth control is not always simple. Fitting the modified equipment across different cultivators is likely to be time consuming. Webber (2020) did suggest however that in the future, with the economic drivers to reduce fuel usage and save costs, the technique may become more popular. Finally, Webber (2020) cautioned that although the modification has benefit, it still leads to the cultivation of sensitive archaeological sites, which may not be the most advised approach for that particular site.

### Paludiculture

“Paludiculture, or farming on rewetted peat, is a system of agriculture for the profitable production of wetland crops under conditions that support the competitive advantage of these crops. In the context of lowland peat soil, it is most usually achieved through raising of the water table to achieve wetland conditions” (LAPTF, 2023). Alternatively, the water table may be raised sporadically on “water meadows”, however this term was not included in the search string.

#### Impact on soil properties – (eg. soil compaction etc.):

The QSR identified only one paper which referred to rewetted peat – and reported on GHG emissions from Swedish peatlands depending on the water table levels (Berglund and others, 2007). There were two other papers in this category – which investigated physical properties of peat soil and potentially might help understand the influence of drained peat on the historic environment: Hyvaluoma and others, (2020) investigated changes in peat soil following “reclamation for agriculture”, namely near-saturated hydraulic conductivity after draining of peat soil for agricultural use (). Another paper reported the effects of copper and biomass on the peat degradation (Bourdon and others, 2021). There was however no research found which investigated impact of paludiculture (or rewetting) on soil physical properties. Interviewees’ suggested, rewetted soils are less susceptible to erosion hence the soil may maintain its structure. This in turn might halt peat loss and keep a safe layer of peaty soil over archaeological artefacts. On the other hand, Söhne (1958) reported that soil compaction is a function of wheel loads as well as the soil moisture content, hence the risk of soil compaction might potentially increase on rewetted soils, where heavy machinery is used. The requirement for machinery innovations to reduce the potential for ground pressure and shearing issues in paludiculture systems has already been recognized by paludiculture and industry experts (Defra, 2022), but the lack of primary research indicates that there is a gap in knowledge which needs to be addressed in future, and that some of the other novel methods already discussed, such as LTP may be particularly valuable in paludiculture systems.

### Potential implications for heritage assets

Similarly, to the impact of paludiculture on soil physical properties, there was no research found investigating the impact of paludiculture on archaeological assets. Interviewees suggested that rewetting of the peatlands might potentially protect the archaeological assets buried in the soil. This is likely to be achieved be as a result of halting soil thinning and soil erosion when previously drained peatlands are rewetted. The archaeological features were suggested to be more prone to damage under a shallow layer of the soil. A thicker layer of soil is likely to protect the historic assets from the pressure from the wheel load of farming machinery, as well as the tillage tines and discs (Dain-Owens 2010, Dain-Owens and others 2013). On the other hand, it has been reported that waterlogged archaeological remains cannot be restored through rewetting, once a damage has occurred resulting from drying out (DEFRA, 2002). Furthermore, deep rooting crops like Typha or Miscanthus might lead to bioturbation of historic environment leading to its damage (Natural England, personal communication).

### Potential implications for soil health (carbon etc.)

Several interviewees considered paludiculture as having the potential to reduce demineralization of peat, and associated carbon losses, and greenhouse gas emissions from drained peatlands, mostly as a result of halted peat degradation which will lead to reduced carbon dioxide ($CO_2$) emissions as well as retaining safe depth of “buffer zone” over archaeological sites and artefacts. However, the research found in our review was very limited, highlighting the need for further primary research and trials.

### Perceived multiple and linked benefits to farmers of soil, water, carbon, and heritage conservation

The use of paludiculture has previously been suggested as having a high potential to mitigate for climate change, by being a cost-efficient way to reduce GHG emissions (Geurts and others 2019). As explained above, this review found limited evidence on the impact of paludiculture on soil. The studies that we did find indicated that the impacts of paludiculture on soil health and other factors, may be influenced by management and water table depth. For example, Mulholland et al (2020) suggested that the optimal climate impact occurs when the water table depth is at approximately 8 cm below the soil surface as the water table depth in rewetted peatland influences GHG emissions, and may even become a source of $CO_2$ and methane ($CH_4$) at suboptimal depths (Couwenberg and others (2011) as reported by Mulholland et al (2020)).

Cropping and farm management decisions are also important to enhance productive paludiculture systems. Mulholland et al (2020) highlighted that paludiculture crops that require continuous inundation of the peat surface may result in high emissions of $CH_4$, and although the balance of evidence suggest that paludiculture will reduce $N_2O$ emissions relative to conventional agriculture, crops that require high rates of plant growth to be economically viable, such as alternative food crops or high-yielding biomass crops, may require fertilization or lower water levels, leading to high $N_2O$ emissions.

Paludiculture farming practices was suggested to help remove excessive nutrients (e.g. phosphates, nitrates) when the biomass is harvested and removed (e.g. Typha). This in turn might mitigate eutrophication of surrounding water bodies.

### Perceived barriers to uptake of these arable farming techniques/methods.

Conventional productive use of peatlands requires effective vehicle access. Overall the evidence suggests that shallow groundwater management will require adaptation from current agricultural methods. Even with vegetation cover, the bearing capacity of soils is unlikely to support conventional agricultural vehicles.

Vegetation cover and other protective measures may be necessary to maintain high surface shear strength and avoid formation of highly impassable areas. Novel methods such as low ground-pressure vehicles and the use of dry ‘ridges’ within wetland production systems could mitigate trafficability and access issues. An alternative method, suggested by one interviewee is using a gantry, which would potentially allow for “zero traffic system” if applied according to the CTF principles.

An additional barrier to uptake of paludiculture is a perceived risk in decreasing farming profitability. According to several interviewees, the peat soils are the most fertile, with valuable crops being grown there. On the other hand, there is a potential to grow high value crops of e.g. Typha for clothing or fruit like cranberry or blueberry which would not compromise the farmer’s profit. However, it is very likely, that rewetting the soil would mean a change in the farming technology which in turn might require high investments. Interviewees raised concerns regarding the time and financial investments needed and the uncertainty around the impacts on productivity.

### Application of Micro-organisms

Screening of the literature found one paper which reported on the effects of application of soil amendment in the form of effective microorganisms (EM-A) on soil physical properties, namely particle density, total organic carbon content, bulk density, total porosity, air capacity, air permeability, soil moisture, field water capacity, available water content, unavailable water content, and water-stable aggregate content (Pranagal and others, 2020). EM-A is a mixture of microorganisms (soil bacteria, yeasts, fungi) aimed to enhance soil fertility and prevent soil degradation (Pranagal and others, 2020). The authors concluded that the EM-A application investigated by them primarily led to a decrease in the content of organic carbon and water-stable aggregates. However, changes in soil compaction and air-water properties did not show significant deterioration.

#### Potential implications for heritage assets, potential implications for soil health, and perceived multiple and linked benefits to farmers

Since there was only one paper reporting on the effects of EM-A on soil, all the potential implication will be discussed together, as there is very little evidence. The depletion of soil carbon resulting from EM-A (Pranagal and others, 2020) might eventually lead to decreased porosity, water infiltration and increased water run-off as suggested e.g. by Franzluebbers (2002), who related the increased SOC with improved infiltration, water-holding capacity, and plant-available water. As a result, this practice is not recommended for preserving archaeological assets or a method to improve soil health and bring any benefits to farmers.

#### Perceived barriers to uptake of these arable farming techniques/methods.

Neither the authors of the paper on this method (Pranagal and others, 2020) nor interviewees considered any barriers to uptake this technology.

### Robotics

Agricultural robots are automated machines or robotic systems that have the capacity to perform tasks on farms or in agricultural environments. They vary in design and can be programmed to perform specific tasks or, increasingly, are designed to be responsive to and react to the unique environment around them (Lowenberg De-Boer and others 2020).

#### Impact on soil properties – (eg. soil compaction etc.)

There was no research found in the QSR that investigated the impacts of autonomous vehicles and/ or agricultural robotics on soil properties.

The conclusions below are based on the interviews with topic experts, as well as on review papers relevant for this project.

Robotics as a novel technology in arable farming includes a vast range of potential machines, hence their impact on soil properties will depend on the particular solution in use. Lowenberg-DeBoer et al (2020) reported that a wide range of environmental benefits are hypothesized to result from crop robotics (Sørensen and others 2005; Duckett and others 2018; Lowenberg-DeBoer 2018; Finger and others 2019), but none have been quantitatively documented. Those environmental benefits include reduced pesticide use, less soil compaction and the ability to farm around trees, rocks, streams and other features of the natural landscape. Crop robotics may or may not be a cost-effective way of achieving environmental goals compared to other management methods. However, some interviewees suggested that this technology allows for smaller and lighter machines working in swarms, hence they might significantly reduce risk of soil compaction and in turn improve water infiltration, reduce erosion and run off. A case study of the Hands-Free Farm at Harper Adams University provides some evidence based on observations of increased water infiltration and lack of water logging in a very wet winter 2017/2018, allowing access of a fertilizer spreader early in spring, on the contrary to neighboring fields which required around 7-10 days more to drain and provide access. Additionally, robots can be part of precision farming approach - with sensors and cameras that can detect variation of soil properties and crop needs. This can allow for precise application of fertilizers, water, and other inputs, which in turn can reduce overuse and minimize soil nutrient depletion. On the other hand, an agricultural engineer from the University of Tasmania John McPhee disagreed with the opinion that autonomous machines will eliminate soil compaction (Lyon, 2019). Harvest may pose a logistical challenge, as the combine harvester's bin must be big enough to ensure timeliness and efficacy of the harvest operation, hence the weight of the machine cannot be small. That is why it is recommended that farming autonomous vehicle are driven following CTF principles, which in turn should not be a problem, providing the driving paths are pre-designed and can easily be optimized.

### Potential implications for heritage assets

If this technology is combined with CTF, precision farming, or smaller and lighter machinery (tractors, combine harvester etc.) soil compaction will be reduced, hence risks to archaeological features decreased. Additionally, alleviating soil compaction would allow for reduced depth of tillage which in turn will reduce risks of damage to the historic assets.

### Potential implications for soil health (carbon etc.)

The effects on soil carbon may be related to reduced tillage which plays a major role in carbon loss/ sequestration rather than traffic (Kaczorowska-Dolowy, 2022). As explained above, autonomous vehicles and farming robots might facilitate adoption of reduced tillage and consequently increase soil organic matter and enhance soil biology and overall soil health.

### Perceived multiple and linked benefits to farmers of soil, water, carbon, and heritage conservation

Farming robots can help in soil as well as historic assets conservation by reducing soil compaction, particularly, if this technology is combined with CTF as suggested by Lyon, (2019). Additionally, farming robots can enhance uptake of precision farming and help reduce inputs by applying target operations, be it weeding or fertilizing. This might reduce risks to archaeological sites buried under soil resulting from changes in soil chemistry. Similarly, robots can also contribute to water conservation by using precision irrigation techniques, based on detection of soil moisture levels, which might lead to reduction of water wastage and improving crop yield. Additionally, precision fertilizing/ irrigation etc. with farming robots (linked to precision farming) might reduce farming inputs hence improve profitability.

### Perceived barriers to uptake of these arable farming techniques/methods

The interviewees indicated several barriers to uptake of this technology as follows: a) High initial cost: The cost of purchasing and installing farming robots can be prohibitively expensive for many farmers, especially smaller farmers who may not have the capital to invest in new technology. b) Limited compatibility: Many farming robots are designed for specific crops or tasks, which can limit their usefulness on farms with diverse operations. Additionally, the robots may not be compatible with existing farm equipment, which can make integration more difficult. c)Lack of technical expertise: Farmers may not have the technical expertise required to operate and maintain farming robots, which can be a significant barrier to adoption. d) Limited access to information: There is scarce evidence on the benefits of this technology, which limits farmer’s willingness to invest in the technology.

### Other methods eg. regenerative agriculture (regen ag), conservation agriculture (CA)

This QSR project did not aim to investigate the effects of regenerative agriculture (regen ag) or conservation agriculture (CA), as although the terms are novel, there are no specific novel practices that have emerged in the last 20 years which are not covered elsewhere in this report. For example, in both regen ag and CA, zero-tillage is central. The novelty of those systems derives from a combination of well-established methods and techniques. Hence, it would be difficult to link individual action/ intervention which is a part of the whole system to the investigated outcomes. However, since these systems were mentioned in the majority of interviews, as novel technology, we decided to provide some details and discuss their potential effects on soil and archaeology. Despite widespread interest in regenerative agriculture, there is no legal or regulatory definition of this term (Newton and others, 2020). Newton et al 2020 reviewed 229 journal articles and 25 practitioner websites to characterize the term “regenerative agriculture and found out that within the research articles, there is no compliance on the meaning: the most commonly mentioned processes were the emphasis on no or low external inputs and the utility of on-farm inputs (26% of publications), the integration of livestock (19%), not using synthetic fertilizers (12%) or pesticides (12%), and reducing or eliminating tillage (12%). On the other hand, on the practitioners' websites reg-ag in most cases involved reducing or eliminating tillage (41%), the integration of livestock (41%), and the use of cover crops (31%). On the other hand, conservation agriculture (CA)'s definition is widely accepted as a system which combines minimal soil disturbance, permanent soil cover (mulch) and rotation involving at least 3 different crops (Hobbs, 2007, FAO un-dated). The interviewees who referred to regenerative agriculture provided the same definition which is accepted for the CA. In view of the soil experts, CA improves physical, biological, and chemical properties and other biotic factors, enabling more efficient use of natural resources. This is in agreement with Hobbs (2007) who reported that CA can improve water infiltration and reduce soil erosion; improves soil aggregates, reduces compaction through promotion of biological tillage and improved soil resilience, as well as increases soil organic matter.

## Trends and likely future innovation (what is currently in development) and their likely impacts on soil health and implications for heritage assets

The majority of interviewees indicated that the most likely direction of change in arable farming will be precision farming as well as robotics and automation. These technologies combined can increase efficiency and reduce labor costs, while also reducing the risk to the environment through reduction of inputs such as water, fertilizer, and pesticides, leading not only to improved yields but to reduced waste and environmental risks. Additionally, autonomous vehicles have the potential to be lighter as well as can easily be programmed to follow the CTF principles which in turn can mitigate the soil compaction and risks to archaeological sites, as well as improve soil health. The soil maps which are central for precision farming could potentially include information on the historic assets, which in turn might mitigate risks to heritage assets, firstly via identification of the sites and secondly via adjusting farming practices depending on the specific site's requirements, e.g. by shallow/ zero tillage over the archaeological sites.

The interviewees highlighted that the technology is already available for precision as well as autonomous farming (GPS, sensors, and drones to gather and analyze data about soil conditions, weather patterns, and plant health). There is already one company which sells commercially autonomous farming seeding and weeding robot (Farmdroid). The interviewees however, underlined the importance of awareness of this technology among farming community, and a need for long-term research on costs and benefits deriving from this technology to both farmers and the environment and historic assets. The major change required is the enhancement of knowledge exchange as well as raising awareness about the effects of novel technology both on soil and farm economics. Parallelly there is a need for "horizontal thinking" which would ensure compatibility of different systems and technology delivered by different manufacturers. This in turn is expected to have a significant effect on the uptake of novel technology which would benefit soil and the environment. Additionally, the majority of interviewees underlined the importance of governmental bodies to provide knowledge and financial support both in research and directly to farmers who undertake changes to their technologies towards net-zero.

# Case studies

## Traffic and tillage research project – Harper Adams University, UK

A globally unique ongoing research trial (started in 2011) at Harper Adams University that is investigating the combined effects of three traffic systems subject to three tillage depths on soil properties and crop yields.

**Leader:** Dr Paula Misiewicz – lecturer and researcher

**Location:** Harper Adams University, UK

**Soil:** Sandy Loam

**Area:** Approximately 3.2 ha (flat area)

**Aim:** To find optimal traffic and tillage systems for soil health without compromising crop yields.

**Systems being used:** Three traffic systems: controlled traffic farming (CTF), traffic with low tyre pressure (LTP) and standard tyre pressure (STP), subject to three tillage depths: deep non-inversion (250mm), shallow (100mm) and zero-tillage.

**Results:**

- 10 years of research showed that CTF brings many benefits to soil health and crop yields, including increased porosity, water infiltration and soil fauna feeding activity, as well as root growth.
- Deep tillage did not bring any benefits to either soil health (soil biology, SOM, water infiltration) or crop yields. Additionally, reduced tillage reduces fuel consumption and labour (Godwin and others 2002), hence reduced tillage (shallow and zero) is recommended.
- Under zero tillage yield penalties were observed in the first five years, however cost-benefit analysis showed that the loses are overcome by the lower inputs.

**Key message:**

- **CTF** together with **reduced tillage** (shallow or zero) are recommended farming practices to improve soil health without compromising farm's income.
- Additionally, based on the effects of these farming systems on soil health, it can be indirectly concluded that these faming systems might help preserve archaeological assets.

## Hands Free Farm (2019-2022) – Harper Adams University, UK

This was the first experiment in the world, which planted, tended and harvested crops without a driver in the seat or agronomists on the ground. All the field operations wee planned based on remote sensing and delivered by automated vehicles.

**Leader:** Dr Kit Franklin – lecturer and senior engagement fellow

**Location:** Harper Adams University, UK

**Soil:** variety of soil types including sandy loam, clay, peaty soils

**Area:** approximately 5 fields comprising 35 ha of flat fields

**Technology used:**

- Robotics
- Autonomous vehicle control systems
- Precision faming
- Zero-tillage
- CTF (autonomous vehicle followed the permanent tramlines every year)

**Reasons for researching this technology**

- To address soil compaction problem – light autonomous vehicles working in swarms might reduce risks of soil compaction.
- There is a potential labour shortage in the future.
- To seek for a solution to improve work/life balance for farmers: autonomous vehicles might reduce workload for farmers.

**Results:** Field observations indicated enhanced trafficability as a result of reduced weight of the machinery as well as of zero tillage. Water infiltration was also improved and there was no water logging compared to conventionally managed fields. The leader of this research is not aware of any archaeological sites under the experimental fields. However, he expects this technology might bring many benefits not only directly to soil health but also to archaeological sites as there is less soil compaction and less soil disturbance.

**Key message:** Autonomous farming has the potential to bring many benefits to farmers, soil and historic assets.

# Precision farming (PF) and archaeological assets (PhD by H. Webber, 2020)

Dr Henry Webber's research investigated the interconnectedness between Precision Farming (PF) and archaeology. His research investigated how archaeology and OF interconnected and where areas of mutual understanding or information exchange could be possible.

The results demonstrated that precision farming can:

- Help discover new archaeological sites, and information about existing sites.
- With the increasing volume of data being collected, e.g. satellite imagery, drone imagery and farm nutrient maps, PF data can help evaluate parts of fields not covered by existing archaeological surveys. The author says "The contribution of mapping unknown sites in general has not been widely recognised within heritage policy, especially policy interconnected with the CAP. Yet in the future, it could be a requirement that farmers who receive subsidies, whether for managing land or for achieving certain environmental objectives, should share PF data for enhancing the archaeological record – a cultural and environmental 'public good' (The Heritage Alliance, 2017)", (Webber, 2020).

Additionally, PF can:

- Help preserve historic sites, once they are mapped:

  An example of research in Saxony-Anhalt, Germany, displays how PF technology has been used to variably control the depth of cultivation over historic sites (M. Strobel pers. comm., after Webber, 2020). The location of the archaeological zones was inputted into tractor-based computer software so that when the farmer cultivates the field, the tractor lifts the implement above a certain depth over a certain archaeological zone. The author however highlighted some barriers in up-taking the technology as well as discussed disadvantages of it, which included lack of knowledge of such technology. Additionally, on a farm where different tillage machinery is required (e.g. subsoiler, tine and disk cultivators etc), this technology might not be available. Lastly, any tillage might be detrimental to archaeological sites so the preferred option would be zero-tillage.

- Help engage the modern farming community:

  Integrating PF and archaeology might provide pathways for engaging famers, land managers, specialists and even governments, on managing the historic environment. Shifting the focus from the restriction of farming activities over archaeological sites, towards the better understanding of that archaeological site and how it interacts with what farmers do on a daily basis – grow crops and manage soils. "This approach

> feeds back into the accuracy and development of the PF system, where an archaeological site is discovered, it can add to the archaeological record, but also aid target soil nutrients more accurately to reduce fertiliser use.”, Webber (2020).

**Key message:** Precision farming might bring many benefits not only to the farming community but also to historic assets. There is however a need to extend the research in this regard and promote knowledge exchange in both the archaeological and agricultural worlds, at a practical, academic and a policy level.

## Controlled traffic farming (CTF) and zero tillage on Nick August’s farm over archaeological sites

For 15 years Nick August has been farming with CTF and zero tillage on his farm in Oxfordshire/ Cotswold hills. By using CTF and zero tillage he found there was no need for subsoiling or even a one-off ploughing, as the soil structure has improved significantly as a result of the adopted system.

**Soil:** Silty clay loam, silty clay, Cotswold limestone brash

**Area:** Approximately 320 ha

**Reasons for uptake of the technology:**

- Reduction of costs in cereal crop production and water conservation in the area, where water resources are limited.
- He was inspired by a study visit in Australia, where zero tillage and CTF are very common.

**Archaeological features on the farm:**

- Roman road
- Mediaeval village
- Mediaeval dump

**Impact on soil health and archaeology of the technology used:**

- Significant increase in soil carbon and number of earthworms,
- Increased soil water holding capacity,
- Lower inputs (fuel and labour),
- Increased trafficability, hence extended time window for farming operations.

**Key message:** CTF and zero tillage might bring many benefits to farmers (lower input) and soil health as well as potentially protect historic assets, however no direct testing of impact on the archaeological features has taken place.

# Limitations of the review

Due to the time constraints of the QSR, the search strategy was limited, which can potentially result in the exclusion of relevant studies that may not have been captured by the search terms used. Additionally, as the screening was limited to abstracts only, so the synthesis of the available evidence is limited, and there is a risk of missing key findings that could be important for informing decision-making. Furthermore, searches for literature were only carried out in English language and therefore some relevant articles may have been missed.

# Knowledge of current cultivation practices

There is lack of coherent picture on the current cultivation practices. Evidence from industry representatives shows that there has not been an increase in the machinery width (cultivators/ seed drills) since 2002.

The majority of interviewees indicated that the reduced tillage (shallow and zero tillage) is the prevailing cultivation practice, but there is a great discrepancy in the estimates of farms under zero tillage: some estimated over 50% of farms under zero tillage, with other saying that there is around 5-7% of zero tillage farms in UK. There is no up-to-date survey available on the farming technology in use.

Defra surveys - in 2019 (DEFRA, 2019) on precision farming, showed only 8% of farms use controlled traffic farming; 29% used soil mapping; 25% used variable rate application; 17% Yield mapping and 10% used telemetry. Other Defra surveys that may be useful to inform current practice on prevailing cultivation techniques are out of date (last surveyed 2006: DEFRA, 2006), soil management practices (last surveyed 2018: DEFRA, 2018), innovations (last surveyed 2018: DEFRA, 2018).

# Conclusions

The QSR, as well as interviews have shown that some of the novel farming technologies have potential to improve soil health and protect the archaeological sites and features, e.g. low tyre pressure (LTP), controlled traffic farming (CTF), or novel design of machinery to reduce soil disturbance or water run-off. However, although the precision farming (PF) and robotics have been indicated by vast majority of interviewees as the most likely direction of farming in the future, there is very little evidence in the literature on their impact on historic assets. Moreover, these are very broad terms, and their actual impact will depend on specific farming practices applied within the system, e.g. reduced tillage or LTP and CTF.

This shows the need of precise definitions of farming technologies and systems before considering their impact on the environment.

Paludiculture is a very novel farming approach, and, to date, there is scarce evidence on its effects on soil and GHG emissions. Although there is a potential to reduce $CO_2$ through rewetting peatlands, the risks of increased $CH_4$ or $N_2O$ may pose a risk to the environment. On the other hand, rewetting peatland as suggested by NE, has potential to halt peat loss, and keep a safe layer of soil over archaeological remains, which can help maintain the artefacts intact, but no literature was found which would quantify the process. This shows there is a requirement for further studies on the impact of paludiculture on soil and archaeology.

Additionally, many interviewees highlighted that the soil and archaeology benign cultivation (zero tillage) practices will be used only as long as access to a broad spectrum weed killer is available, e.g. glyphosate. With the onset of the ban of that chemical, there is a risk to return to deep tillage which has detrimental effect on soil carbon sequestration and pose risks of damage to archaeological features.

As a result, there is a need to conduct fields trials and broader research that can help us quantify and understand how different farming techniques and technologies affect soil and historic sites and features. This needs to go alongside research on barriers in uptake, and work on disseminating the results of the research to raise farmers’ awareness on benefits of novel technologies on soil and historic assets.

As it was highlighted by several interviewees and a case study (Webber, 2020), by working together, archaeologists, farmers, and policymakers can develop effective strategies and guidelines that will allow us to continue to farm the land while also protecting our past.

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# Glossary

Basin tillage – It is a tillage technology in wide-row crops (mostly potatoes or beetroots), which aims to reduce water run-off and soil erosion by building individual earth blocks along furrows.

Bentleg soil openers – A type of soil opener for seeding operations in zero tillage system aimed to minimise soil disturbance and draft, therefore improving work-rate and timeliness of sowing (see Figure 3).

Conservation agriculture – A farming system which combines minimal soil disturbance, permanent soil cover and crop rotation involving at least 3 different crops (Hobbs, 2007).

Controlled traffic farming (CTF) – CTF is an agricultural traffic management system which aims to minimize traffic-induced soil compaction (Raper, 2005). In this system all farming traffic is confined to permanent traffic lanes, and the width of space between wheels of all the machinery matches, whereas width of implement might be a multiplication (e.g. width of sprayer is three times wider than the combine harvester's header). It requires accurate RTK-GPS navigation. This in turn allows the crop zones in-between the wheelways to remain untrafficked (Gasso and others 2013, Raper, 2005).

Dual tyres – A system in which additional external tyres are added to a tractor in order to increase the contact area and reduce risk of soil compaction.

Dyker – A machinery to create basin tillage (see definition above)

Effective microorganisms (EM-A) – a mixture of microorganisms (soil bacteria, yeasts, fungi) aimed to enhance soil fertility and prevent soil degradation (Pranagal and others, 2020).

Low pressure tyres (LPT) – LTP is a way to increase contact area and mitigate the risk of soil compaction.

Paludiculture – Paludiculture is a system of agricultural production of wetland crops under conditions that support the competitive advantage of these crops. In the context of lowland peat soil, it is most usually achieved through raising of the water table to achieve wetland conditions.

Precision agriculture – Precision agriculture is an advanced agricultural management system that uses technologies (e.g. Global Positioning System (GPS), Geographic Information System (GIS), and sensors) to precisely manage production inputs, e.g. fertilizer, water, and pesticides as well optimize in-field traffic route planning.

Regenerative agriculture (regen ag) – although there is no compliance on the definition, it is a farming approach with the emphasis on no- or low- external inputs and the utility of on-farm inputs the integration of livestock, not using synthetic fertilizers or pesticides, and reducing or eliminating tillage and utilizing cover crops.

Robots/ robotics – Agricultural robots are automated machines or robotic systems that have the capacity to perform tasks on farms or in agricultural environments. They vary in design and can be programmed to perform specific tasks or, increasingly, are designed to be responsive to and react to the unique environment around them.

Rubber tracks –In this system tractor’s running gear uses rubber tracks instead of tyres. Similarly to LTP (see above) rubber tracks is a method to increase contact area and mitigate risk of soil compaction.

Tied ridging method – see Basin tillage.

Undercutter tillage – Undercutter tillage is a method which cuts weeds or cover crops, leaving them on the soil surface. By leaving cover crop residue intact, growers can get longer weed suppression from the cover crop mulches in comparison to mowing them into smaller pieces. This method addressed soil loss on fallow fields.

# Appendices

## Appendix 1: Scoping searches

Scoping searches were carried out to develop search strings to identify research investigating the impact of arable management techniques on soil and/or archaeological and heritage features. Three different search string were developed to investigate the impact of:

a) Arable cultivation on soils
b) Arable cultivation directly on historical assets
c) Soil properties on historical assets

Scoping searches were carried out using the bibliographic database Web of Science. First, simple keywords and search strings were tested to examine volume and relevancy of literature returned. Next, more complex search strings were built and tested by combining the most relevant keywords (Table 4). The search strings finally used to search for literature in Web of Science were #24,25 &26 highlighted in yellow (Table 4).

For the first two searches (#24 and #25), the date was restricted from 01/01/2002 to 01/06/2023 (2023 date set to June to capture any later release dates), no date restrictions were applied for #26.

**Table 4. Scoping searches conducted in Web of Science, using the 'Topic' search function, to identify search strings that will return potentially relevant literature that can be run in 'topic modelling software'. N.B., Final search strings used were #24,25 &26 highlighted in yellow.**

| ID | Search term | Results returned | Results returned date restricted 2000/01/01-2023/01/06 | Notes | Date |
|---|---|---|---|---|---|
| **#1** | Tillage | 40288 | 30979 | General articles on tillage not all relating to the impact on soil or archaeological | 05/01/2023 |

| ID | Search term | Results returned | Results returned date restricted 2000/01/01-2023/01/06 | Notes | Date |
|---|---|---|---|---|---|
| | | | | heritage features | |
| **#2** | "Novel tillage" | 10 | 5 | Results not relevant | 05/01/2023 |
| **#3** | tillage and "soil disturbance" OR "horizontal displacement" OR "vertical displacement" | 903 | 814 | Added some soil terms results appear to be low relevance | 05/01/2023 |
| **#4** | “new soil management techniques” | 1 | 1 | Results not relevant (Soil carbon) | 05/01/2023 |
| **#5** | “soil manag*” | 6964 | 6258 | General articles on soil management not all relating to the impact on soil or archaeological heritage features | 05/01/2023 |
| **#6** | “regenerative farm*” | 38 | 37 | General articles on regenerative farming not all relating to the damage of archaeological heritage features | 05/01/2023 |
| **#7** | Tillage and traffic OR “tyre pressure” | 757 | 587 | General articles on tillage and traffic and soil compaction not all relating to damage of | 05/01/2023 |

| ID | Search term | Results returned | Results returned date restricted 2000/01/01-2023/01/06 | Notes | Date |
|---|---|---|---|---|---|
| | | | | archaeological heritage features | |
| **#8** | “precision farm*” | 1947 | 1795 | General articles on precision farming not all relating to the impact on soil or archaeological heritage features | 05/01/2023 |
| **#9** | “soil compaction*” | 5800 | 4890 | General articles on soil compaction not all relating to damage to archaeological heritage features | 05/01/2023 |
| **#10** | “controlled traffic farming” | 115 | 111 | General articles on controlled traffic farming along with management strategies not all relating to damage to archaeological heritage features | 05/01/2023 |
| **#11** | “increased flexion tyres” | 0 | 0 | No search results | 05/01/2023 |
| **#12** | Cultivat* | 269618 | 237792 | too broad | 05/01/2023 |
| **#13** | Paludiculture | 103 | 103 | few relevant | 05/01/2023 |

| ID | Search term | Results returned | Results returned date restricted 2000/01/01-2023/01/06 | Notes | Date |
|---|---|---|---|---|---|
| **#14** | Arable AND (archaeolog* OR “historic environment*” OR “historic feature*” OR artefact* OR relic* OR heritage) | 309 | 288 | Majority don’t look relevant | 05/01/2023 |
| **#15** | (Tillage OR “soil manag*” OR Cultivat* OR Paludiculture OR “regenerative farm*” OR “tyre pressure” OR “precision farm*” OR “soil compaction*” OR “controlled traffic farming” OR “increased flexion tyres” OR plough OR plow) AND (archaeol* OR “historic environment*” OR “historic feature*” OR artefact* OR relic* OR heritage) | 3269 | 3098 | Combined cultivation terms with historic asset terms results returned include some relevant studies | 05/01/2023 |
| **#16** | Paludiculture AND ("soil structure" OR "vertical displacement" OR "horizontal displacement" OR archaeolog*) | 0 | 0 | No results returned | 05/01/2023 |
| **#17** | Arable AND ("soil structure" OR "vertical displacement" OR "horizontal displacement" OR archaeolog*) | 539 | 102 | low relevance | 05/01/2023 |
| **#18** | cultivat* AND archaeolog* or artefact* or historic environment* | 1954 | 1832 | not relevant | 05/01/2023 |
| **#19** | "ridge tillage" AND "soil structure" NOT "china" | 27 | 5 | low relevance | 05/01/2023 |
| **#20** | "rotary till*" AND "soil structure" NOT "china" | 12 | 12 | some relevant studies | 05/01/2023 |
| **#21** | Tillage OR “soil manag*” OR Cultivat* OR Paludiculture OR “regenerative farm*” OR “tyre pressure*” OR “precision farm*” OR “soil compaction*” OR “controlled traffic farming” OR | Not searched | 8025 | some relevant studies. Topic modelling showed many studies from China which | 10/01/2023 |

| ID | Search term | Results returned | Results returned date restricted 2000/01/01-2023/01/06 | Notes | Date |
|---|---|---|---|---|---|
|  | “CFT” OR “flex* tyre*” OR “flex* tire*” OR “ultra-flex tyre*” OR “ultra-flex tire*” OR “super-flex tyre*” OR “super-flex tire*” OR “high flexion tyre*” OR “high flexion tire*” OR Plough OR Plow AND archaeolog* OR historic* OR artefact* OR relic* OR heritage |  |  | were unlikely to be of relevance to UK soils & climate. |  |
| **#22** | Tillage OR “soil manag*” OR Cultivat* OR Paludiculture OR “regenerative farm*” OR “tyre pressure*” OR “precision farm*” OR “soil compaction*” OR “controlled traffic farming” OR “CFT” OR “flex* tyre*” OR “flex* tire*” OR “ultra-flex tyre*” OR “ultra-flex tire*” OR “super-flex tyre*” OR “super-flex tire*” OR “high flexion tyre*” OR “high flexion tire*” OR Plough OR Plow AND “soil loss*” OR “water retention” OR “soil health” OR “soil compaction” OR “soil disturbance” OR “horizontal displacement” OR “vertical displacement” OR “soil structure” OR “soil erosion” or “soil displacement” | Not searched | 14401 | Some relevant studies. Topic modelling showed many studies from China. | 10/01/2023 |
| **#23** | archaeolog* OR historic* OR artefact* OR relic* OR heritage AND “soil loss*” OR “water retention” OR “soil health” OR “soil compaction” OR “soil disturbance” OR “horizontal displacement” OR “vertical displacement” OR “soil structure” OR “soil erosion” OR “soil displacement” | Not searched | 2172 | some relevant studies | 10/01/2023 |

| ID | Search term | Results returned | Results returned date restricted 2000/01/01-2023/01/06 | Notes | Date |
|---|---|---|---|---|---|
| **#24** | (topic) • Tillage OR "soil manag*" OR Cultivat* OR Paludiculture OR "regenerative farm*" OR "tyre pressure*" OR "precision farm*" OR "soil compaction*" OR "controlled traffic farming" OR "CFT" OR "flex* tyre*" OR "flex* tire*" OR "ultra-flex tyre*" OR "ultra-flex tire*" OR "super-flex tyre*" OR "super-flex tire*" OR "high flexion tyre*" OR "high flexion tire*" OR Plough OR Plow (Topic)<br>• AND "soil loss*" OR "water retention" OR "soil health" OR "soil compaction" OR "soil disturbance" OR "horizontal displacement" OR "vertical displacement" OR "soil structure" OR "soil erosion" OR "soil displacement" (Topic)<br>• NOT mining OR Mediterranean OR tropic* OR dryland* OR desert* OR Asia* OR Chin* OR India* Ethiopia* OR Ghana OR Spain OR Brazil* OR Africa* OR Nigeria* OR Korea* OR Bangladesh OR Nepal* OR forest* OR grass* OR grazing OR pasture* OR biodiversity OR vegetable* OR vineyard* OR olive OR orchard* OR beetle OR pollinat* OR pest* OR rice OR cotton OR Mexico OR Kenya OR Texas OR Florida OR Arizona OR California* OR Nevada OR Mississippi OR Louisiana OR "South Carolina" | Not searched | 5,121 This was narrowed down by: countries/ regions (to exclude tropical and subtropical climate) down to 2,858. This number of papers was exported to RIS files and uploaded to Eppi Reviewer. | Added NOT criteria to #21. | 31/01/2023 |

| ID | Search term | Results returned | Results returned date restricted 2000/01/01-2023/01/06 | Notes | Date |
|---|---|---|---|---|---|
|  | OR Tennessee OR "North Carolina" (Topic)<br>• NOT yield* OR productivity OR dairy OR cattle OR livestock (Title)<br>YEAR restriction 2002-01-01 – 2023-06-01<br>• Exclude – Countries/Regions Peoples R China OR Brazil OR India OR Iran OR Spain OR Turkey OR Argentina OR Japan OR Ethiopia OR Pakistan OR Egypt OR South KORea OR Chile OR Greece OR Israel OR Malaysia OR Portugal OR Mexico OR Colombia OR Nigeria OR Morocco OR Saudi Arabia OR South Africa OR Vietnam OR Indonesia OR Thailand OR Jordan OR Taiwan OR Tunisia OR Cuba OR Syria OR Iraq OR Sudan OR Bangladesh OR Ecuador OR Philippines OR Zimbabwe OR Singapore OR U Arab Emirates OR Ghana OR Laos OR Sri Lanka OR Tanzania OR Venezuela OR Algeria OR Costa Rica OR Oman OR Uruguay OR Burkina Faso OR Kenya OR Benin OR Bolivia OR Cameroon OR Kuwait OR Madagascar OR Moldova OR Papua N Guinea OR Trinidad Tobago OR Uganda OR Cambodia OR Fiji OR Malawi OR Mauritius OR Niger OR Palestine OR Peru OR Senegal |  |  |  |  |

| ID | Search term | Results returned | Results returned date restricted 2000/01/01-2023/01/06 | Notes | Date |
|---|---|---|---|---|---|
| | OR Togo OR Zambia OR Angola OR Antigua Barbu OR Bahrain OR Cape Verde OR Dem Rep Congo OR Guatemala OR Haiti OR Lebanon OR Libya OR Mongolia OR Nepal OR Palau OR Panama OR Paraguay OR Rep Congo OR Rwanda | | | | |
| **#25** | "Agri* robot*" OR Tillage OR "soil manag*" OR Cultivat* OR Paludiculture OR "regenerative farm*" OR "tyre pressure*" OR "precision farm*" OR "soil compaction*" OR "controlled traffic farming" OR "CFT" OR "flex* tyre*" OR "flex* tire*" OR "ultra-flex tyre*" OR "ultra-flex tire*" OR "super-flex tyre*" OR "super-flex tire*" OR "high flexion tyre*" OR "high flexion tire*" OR Plough OR Plow AND archaeolog* OR artefact* OR relic* OR "historic* feature*" OR "heritage feature*" NOT (Topic) Chin* OR tropic* OR rice OR forest* OR pasture* | Not searched | 1,458; Beyond the first 300 sorted according to relevancy, no relevant papers found. Hence those most relevant 300 were exported for further screening in Eppi Reviewer software. | Added NOT criteria to #22. Results put into Topic modelling software. Time restricted to 2002-01-01 till 2023-06-01 | 26/01/2023 |
| **#26** | archaeolog* OR artefact* OR relic* OR "heritage feature*" OR "historic* feature*"<br>AND<br>"soil loss*" OR "water retention" OR "soil health" OR "soil compaction" OR "soil disturbance" OR "horizontal displacement" OR "vertical | Not searched | 162 | | 07/02/2023 |

| ID | Search term | Results returned | Results returned date restricted 2000/01/01-2023/01/06 | Notes | Date |
|---|---|---|---|---|---|
|  | displacement” OR “soil structure” OR “soil erosion” OR “soil displacement”<br>NOT<br>Mediterranean OR tropic* OR dryland* OR desert* OR Asia* OR Chin* OR India* Ethiopia* OR Ghana OR Spain OR Brazil* OR Africa* OR Nigeria* OR Korea* OR Bangladesh OR Nepal* OR forest* OR grass* OR grazing OR pasture* OR vegetable* OR vineyard* OR olive OR orchard* OR Mexico OR Kenya OR Texas OR Florida OR Arizona OR California* OR Nevada OR Mississippi OR Louisiana OR "South Carolina" OR Tennessee OR "North Carolina" OR rice OR cotton<br>NO YEAR restriction – as the volume was of literature is low<br>• Exclude – Countries/Regions<br>Italy, Spain, Greece, Australia, Mexico, Peoples Republic of China, Japan, South Africa, Argentina, Malaysia, Peru, Portugal, Turkey, Tunisia, Thailand, Antigua Barbu, Ehiopia, Guatemala, India, Irsael, Kuwait, Oman, Panama |  |  |  |  |

## Topic modelling

The aim of the topic modelling was to identify the breadth of the topic, and specific research areas and clusters in the literature, which may a) inform priority areas to focus on for the

QSR (e.g., novel technologies, research topics) and b) help identify specific search terms for the QSR.

The topic modelling uses the Sciome SWIFT-Review software which is based on Latent Dirichlet Allocation to automatically compute topic models from literature imported from searches in bibliographic databases. This statistical method discovers themes and concepts in a large set of documents and will enable groups and subgroups of practices to be identified.

The three search strings (#24,25,26) were imported separately into the topic modelling software Sciome SWIFT-Review. Topic modelling did not identify any new cultivation technology which hasn’t been available prior to 2002, nevertheless existing technologies may have improved. To overcome this issue, some of the interviews will be used to help identify any new technology terms.

# Appendix 2: Literature which informed the Report

| Type of publication | Full reference | Year |
|---|---|---|
| **Primary research paper** | Dain-Owens, A., Kibblewhite, M., Hann, M. and Godwin, R., 2013. The risk of harm to archaeological artefacts in soil from dynamic subsurface pressures generated by agricultural operations: Experimental studies. Archaeometry, 55(6), pp.1175-1186. | 2013 |
| **Primary research paper** | Bryan, N.M., anderson, V.J. and Fugal, R.A., 2011. Disturbance to surface lithic components of archaeological sites by drill seeding. Rangeland Ecology & Management, 64(2), pp.171-177. | 2011 |
| **Primary research paper** | Cann MA, Pearl DJ and Peries RR; deCourcey-Ireland N. (2018). Innovations in cropping systems - a step change towards sustainable soil management across Victoria's grain growing regions. NEW ZEALAND JOURNAL OF AGRICULTURAL RESEARCH, 61(3), Pp.377-388. | 2018 |
| **Primary research paper** | Chamen WCT. (2006). Controlled traffic farming on a field scale in the UK. Soil Management for Sustainability, 38(17th Conference of the International-Soil-Tillage-Research-Organisation), pp.251-260. | 2006 |
| **Primary research paper** | Etana A, Holm L and Rydberg T; Keller T. (2020). Soil and crop responses to controlled traffic farming in reduced tillage and no-till: some experiences from field experiments and on-farm studies in Sweden. Acta Agriculturae Scandinavica Section B-Soil and Plant Science, 70(4), pp.333-340. | 2020 |
| **Primary research paper** | Galambosova J, Rataj V and Vasek M; Czech Univ Life Sci; Fac Engn. (2010). Effects of Controlled Traffic Farming. Trends In Agricultural Engineering 2010, (4th International Conference on Trends in Agricultural Engineering), pp.158-162. | 2010 |
| **Primary research paper** | Guenette KG, Hernandez-Ramirez G and Gamache P; andreiuk R; Fausak L. (2019). Soil structure dynamics in annual croplands under controlled traffic management. Canadian Journal of Soil Science, 99(2), pp.146-160. | 2019 |
| **Primary research paper** | Gutu D, Hula J and Novak P; Kovar S. (2018). Influence of Controlled Field Traffic on Soil Quality Indicators. 17th International Scientific Conference: Engineering For Rural Development, (17th International Scientific Conference on Engineering for Rural Development), pp.234-239. | 2018 |
| **Primary research paper** | Hobson D, Harty M and Tracy SR; McDonnell K. (2022). The effect of tillage depth and traffic management on soil properties | 2022 |

| Type of publication | Full reference | Year |
|---|---|---|
|  | and root development during two growth stages of winter wheat (Triticum aestivum L.). SOIL, 8(1), pp.391-408. |  |
| **Primary research paper** | Latsch A and Anken T. (2019). Soil and crop responses to a "light" version of Controlled Traffic Farming in Switzerland. SOIL & TILLAGE RESEARCH, 194, pp.. | 2019 |
| **Primary research paper** | Liu K, Benetti M and Sozzi M; Gasparini F; Sartori L. (2022). Soil Compaction under Different Traction Resistance Conditions-A Case Study in North Italy. AGRICULTURE-BASEL, 12(11), pp.. | 2022 |
| **Primary research paper** | McHugh AD, Tullberg JN and Freebairn DM. (2009). Controlled traffic farming restores soil structure. SOIL & TILLAGE RESEARCH, 104(1), pp.164-172. | 2009 |
| **Primary research paper** | Stanek L, Hojkova H and Novak P; Herout M; Petrasek S; Prochazka P; Stankova V; Nidlova V. (2010). Possibilities of Introducing System Control Traffic Farming In Practice. Uclio 2010: University Conference In Life Sciences - Proceedings, (University Conference in Life Sciences (UCOLIS 2010)), pp.401-406. | 2010 |
| **Primary research paper** | Kroulík, M., Kvíz, Z., Kumhála, F., Hůla, J. and Loch, T., 2011. Procedures of soil farming allowing reduction of compaction. Precision agriculture, 12, pp.317-333. | 2011 |
| **Primary research paper** | Tullberg J, Antille DL and Bluett C; Eberhard J; Scheer C. (2018). Controlled traffic farming effects on soil emissions of nitrous oxide and methane. Soil & Tillage Research, 176, pp.18-25. | 2018 |
| **Primary research paper** | Weissbac M, Isensee E and Brunotte J; Sommer C. (2003). The use of powerful machines in different soil tillage systems. Conservation Agriculture: Environment, Farmers Experiences, Innovations, Socio-Economy and Policy, (1st World Congress on Conservation Agriculture), pp.367-373. | 2003 |
| **Primary research paper** | Barr JB, Desbiolles JMA and Fielke JM. 2016. "Minimising soil disturbance and reaction forces for high speed sowing using bentleg furrow openers". Biosystems Engineering 151:53-64. | 2016 |
| **Primary research paper** | Kalinin AB, Teplinsky IZ and Ustroev AA; Kudryavtsev PP; IOP. 2019. "Selection and substantiation of cultivator adjustment parameters for differential soil treatment on potato based on the rheology state of soil horizons". III International Conference Cognitive Robotics 516(3rd International Conference on Cognitive Robotics). | 2019 |

| Type of publication | Full reference | Year |
|---|---|---|
| **Primary research paper** | Ansorge, D. and Godwin, R., 2006. High axle load–track–tire comparison. Soil Management for Sustainability, 38, pp.9-14. | 2006 |
| **Primary research paper** | Ansorge D and Godwin RJ. 2007. "The effect of tyres and a rubber track at high axle loads on soil compaction, Part 1: Single axle-studies". Biosystems Engineering 98(1):115-126. | 2007 |
| **Primary research paper** | Ansorge D and Godwin RJ. 2008. "The effect of tyres and a rubber track at high axle loads on soil compaction - Part 2: Multi-axle machine studies". Biosystems Engineering 99(3):338-347. | 2008 |
| **Primary research paper** | Antille DL, Ansorge D and Dresser ML; Godwin RJ. 2013. "Soil Displacement and Soil Bulk Density Changes As Affected By Tire Size". Transactions of The ASABE 56(5):1683-1693. | 2013 |
| **Primary research paper** | Arvidsson J and Keller T. 2007. "Soil stress as affected by wheel load and tyre inflation pressure". Soil & Tillage Research 96(1-2):284-291. | 2007 |
| **Primary research paper** | Arvidsson J, Westlin H and Keller T; Gilbertsson M. 2011. "Rubber track systems for conventional tractors - Effects on soil compaction and traction". Soil & Tillage Research 117:103-109. | 2011 |
| **Primary research paper** | Cujbescu D, Ungureanu N and Vladut V; Persu C; Oprescu MR; Gheorghita NE. 2019. "Field Testing of Compaction Characteristics For Farm Tractor Universal 445". Inmateh-Agricultural Engineering 59(3):245-252. | 2019 |
| **Primary research paper** | Keller T, Trautner A and Arvidsson J. 2002. "Stress distribution and soil displacement under a rubber-tracked and a wheeled tractor during ploughing, both on-land and within furrows". Soil & Tillage Research 68(1):39-47. | 2002 |
| **Primary research paper** | Keller T and Arvidsson J. 2004. "Technical solutions to reduce the risk of subsoil compaction: effects of dual wheels, tandem wheels and tyre inflation pressure on stress propagation in soil". Soil & Tillage Research 79(2):191-205. | 2004 |
| **Primary research paper** | Lamande M, Greve MH and Schjønning P. 2018. "Risk assessment of soil compaction in Europe - Rubber tracks or wheels on machinery". CATENA 167:353-362. | 2018 |
| **Primary research paper** | Mohieddinne H, Yatskul A and Ugarte C; Thibaut J; Guidet J; Ritz S. 2023. "Trade-off between agronomical and energetical performances during barley sowing varying adjustable parameters in a tractor-tire-tool system". Soil & Tillage Research 226. | 2023 |

| Type of publication | Full reference | Year |
|---|---|---|
| **Primary research paper** | Mohsenimanesh A and Lague C. 2017. "Impact of Load and Inflation Pressure on Traffic-Induced Soil Compaction For Two Types of Flotation Tires". Applied Engineering In Agriculture 33(4):499-507. | 2017 |
| **Primary research paper** | Molari G, Bellentani L and Guarnieri A; Walker M; Sedoni E. 2012. "Performance of an agricultural tractor fitted with rubber tracks". Biosystems Engineering 111(1):57-63. | 2012 |
| **Primary research paper** | Molari G, Mattetti M and Walker M. 2015. "Field performance of an agricultural tractor fitted with rubber tracks on a low trafficable soil". Journal of Agricultural Engineering 46(4):162-166. | 2015 |
| **Primary research paper** | Mudarisov S, Gainullin I and Gabitov I; Hasanov E; Farhutdinov I. 2020. "Soil compaction management: Reduce soil compaction using a chain-track tractor". Journal of Terramechanics 89:1-12. | 2020 |
| **Primary research paper** | Pagliai M, Marsili A and Servadio P; Vignozzi N; Pellegrini S. 2003. "Changes in some physical properties of a clay soil in Central Italy following the passage of rubber tracked and wheeled tractors of medium power". Soil & Tillage Research 73(1-2):119-129. | 2003 |
| **Primary research paper** | Ren LD, D'Hose T and Ruysschaert G; De Pue J; Meftah R; Cnudde V; Cornelis WM. 2019. "Effects of soil wetness and tyre pressure on soil physical quality and maize growth by a slurry spreader system". Soil & Tillage Research 195. | 2019 |
| **Primary research paper** | Schjønning P, Munkholm LJ and Lamande M. 2022. "Soil characteristics and root growth in a catena across and outside the wheel tracks for different slurry application systems". Soil & Tillage Research 221. | 2022 |
| **Primary research paper** | Schlee R, Renard-Lafleur F and Puel B; VDI-MEG. 2003. "XeoBib - a new tractor-tyre-concept from Michelin". Conference: Agricultural Engineering, 2003 1798(Conference on Agricultural Engineering):137-141. | 2003 |
| **Primary research paper** | Servadio P, Marsili A and Vignozzi N; Pellegrini S; Pagliai M. 2005. "Effects on some soil qualities in central Italy following the passage of four-wheel drive tractor fitted with single and dual tires". Soil & Tillage Research 84(1):87-100. | 2005 |
| **Primary research paper** | Simeckova J, Polcar A and Votava J. 2016. "The Influence of Tractor Tyres Inflation on Physical Soil Properties". Proceedings of International PhD Students Conference, (Mendelnet 2016) (23rd International PhD Students Conference (MendelNet)):922-927. | 2016 |

| Type of publication | Full reference | Year |
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| **Primary research paper** | Svoboda M and Cervinka J. 2013. "The Influence Inflation Pressure In The Tires on Soil Compaction". Mendelnet 2013 (20th International PhD Students Conference):872-876. | 2013 |
| **Primary research paper** | Svoboda M, Cervinka J and SGEM. 2015. "The Rating of Soil Compaction After The Movement of Agricultural Machinery". Water Resources, Forest, Marine and Ocean Ecosystems, SGEM 2015, VOL II (15th International Multidisciplinary Scientific Geoconference (SGEM)):387-392. | 2015 |
| **Primary research paper** | ten Damme, L and Stettler M; Pinet F; Vervaet P; Keller T; Munkholm LJ; Lamande M. 2019. "The contribution of tyre evolution to the reduction of soil compaction risks". Soil & Tillage Research 194. | 2019 |
| **Primary research paper** | ten Damme, L and Stettler M; Pinet F; Vervaet P; Keller T; Munkholm LJ; Lamande M. 2020. "Construction of modern wide, low-inflation pressure tyres per se does not affect soil stress". Soil & Tillage Research 204. | 2020 |
| **Primary research paper** | Ungureanu N, Vladut V and Voicu G; St Biris S; Ionescu M; Dinca M; Vladut DI; Matache M. 2016. "Influence of Wheel Load and Tire Inflation Pressure on Footprint Area In Static Regime". Aktualni Zadaci Mehanizacije Poljoprivrede: Zbornik Radova 44(44th International Symposium on Actual Tasks on Agricultural Engineering):99-110. | 2016 |
| **Primary research paper** | Vanderhasselt A, Euben R and D'Hose T; Cornelis W. 2022. "Slurry Spreading on a Silt Loam Soil: Influence of Tyre Inflation Pressure, Number of Passages, Machinery Choice and Tillage Method on Physical Soil Quality and Sugar Beet Growth". LAND 11(6). | 2022 |
| **Primary research paper** | Weissbach M, VDI and VDI; VDI. 2002. "The use of soil protected undercarriages in the sugar beet harvest". Conference: Agricultural Engineering 2002 1716(Conference on Agricultural Engineering):273-278. | 2002 |
| **Primary research paper** | Zabrodskyi A, Sarauskis E and Juostas A; Kukharets S. 2021. "Effect of Pneumatic Tire Pressure and Deformation Parameters on Decreasing Soil Compaction". 20th International Scientific Conference Engineering For Rural Development (20th International Scientific Conference on Engineering for Rural Development):1127-1132. | 2021 |

| Type of publication | Full reference | Year |
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| **Primary research paper** | Edwards GTC, Hinge J and Skou-Nielsen N; Villa-Henriksen A; Sorensen CAG; Green O. 2017. "Route planning evaluation of a prototype optimised infield route planner for neutral material flow agricultural operations". Biosystems Engineering 153:149-157. | 2017 |
| **Primary research paper** | Evans JT, Pitla SK and Luck JD; Kocher M. 2020. "Row crop grain harvester path optimization in headland patterns". Computers and Electronics in Agriculture 171. | 2020 |
| **Primary research paper** | Gordon RJ, VanderZaag AC and Dekker PA; De Haan R; Madani A. 2011. "Impact of modified tillage on runoff and nutrient loads from potato fields in Prince Edward Island". Agricultural Water Management 98(12):1782-1788. | 2011 |
| **Primary research paper** | Holland JE, Johnston TH and White RE; Orchard BA. 2012. "An investigation of runoff from raised beds and other tillage methods in the high rainfall zone of south-western Victoria, Australia". Soil Research 50(5):371-379. | 2012 |
| **Primary research paper** | Nuralin B, Galiev M and Kubasheva Z; Kozhabergen O; Khairullina S. 2021. "Study of Combined Tool Tiller Modes Intended for Graded Tillage". Fme Transactions 49(2):463-471. | 2021 |
| **Primary research paper** | Paraschiv G, Maican E and Biris SS; Bungescu S. 2008. "Researches regarding the development of a soil preparation unit, according to the demands of sustainable agriculture". Actual Tasks on Agricultural Engineering 36(36th International Symposium on Agricultural Engineering):135-+. | 2008 |
| **Primary research paper** | Pranagal J, Ligeza S and Smal H. 2020. "Impact of Effective Microorganisms (EM) Application on the Physical Condition of Haplic Luvisol". AGRONOMY-BASEL 10(7). | 2020 |
| **Primary research paper** | Sharratt BS and Feng G. 2009. "Windblown dust influenced by conventional and undercutter tillage within the Columbia Plateau, USA". Earth Surface Processes and Landforms 34(10):1323-1332. | 2009 |
| **Primary research paper** | Trendafilov K and Delchev N. 2018. "Headland turns using the tractor's "fifth wheel" steering device instead of front steering wheels". Bulgarian Journal of Agricultural Science 24(6):1137-1147. | 2018 |
| **Primary research paper** | Vejchar D, Vacek J and Hajek D; Bradna J; Kasal P; Svobodova A. 2019. "Reduction of surface runoff on sloped agricultural land in potato cultivation in de-stoned soil". Plant Soil and Environment 65(3):118-124. | 2019 |

| Type of publication | Full reference | Year |
|---|---|---|
| **Primary research paper** | Villa-Henriksen A, Skou-Nielsen N and Munkholm LJ; Sorensen CAG; Green O; Edwards GTC. 2021. "Infield optimized route planning in harvesting operations for risk of soil compaction reduction". Soil Use and Management 37(4):810-821. | 2021 |
| **Primary research paper** | Berglund O, Berglund K and Persson L. 2007. "Effect of drainage depth on the emission of CO2 from cultivated organic soils". Wetlands: Monitoring, Modelling and Management (International Conference Wetlands - Monitoring, Modelling and Management):133-137. | 2007 |
| **Primary research paper** | Bourdon K, Fortin J and Dessureault-Rompre J; Caron J. 2021. "Agricultural peatlands conservation: How does the addition of plant biomass and copper affect soil fertility?". Soil Science Society of America Journal 85(4):1242-1255. | 2021 |
| **Primary research paper** | Hyvaluoma J, Raty M and Kaseva J; Keskinen R. 2020. "Changes over time in near-saturated hydraulic conductivity of peat soil following reclamation for agriculture". Hydrological Processes 34(2):237-243. | 2020 |
| **Primary research paper** | Green O, Lamande M and Schjønning P; Sorensen CG; Bochtis DD. 2011. "Reducing the risk of soil compaction by applying 'Jordv ae rn online'(R) when performing slurry distribution". Acta Agriculturae Scandinavica Section B-Soil and Plant Science 61(3):209-213. | 2011 |
| **Primary research paper** | Kalinin AB, Teplinsky IZ and Ruzhev VA; Kalinina VA; Gerasimova VE; IOP. 2021. "Methods and means of digital measurement of soil parameters and conditions of functioning of tillage machines for deep loosening of soil". International Conference on Engineering Studies and Cooperation In Global Agricultural Production 659(International Conference on Engineering Studies and Cooperation in Global Agricultural Production). | 2021 |
| **Primary research paper** | Hameed IA and IEEE. 2018. "A coverage planner for multi-robot systems in agriculture". Proceedings of 2018 IEE International Conference on Real-Time Computing and Robotics (IEEE RCAR) (IEEE International Conference on Real-time Computing and Robotics (IEEE RCAR)):698-704. | 2018 |
| **Primary research paper** | Lemann T, Sprafke T and Bachmann F; Prasuhn V; Schwilch G. 2019. "The effect of the Dyker on infiltration, soil erosion, and waterlogging on conventionally farmed potato fields in the Swiss Plateau". CATENA 174:130-141. | 2019 |

| Type of publication | Full reference | Year |
|---|---|---|
| **PhD thesis** | Dain-Owens A P 2010. The damaging effect of surface-traffic-generated soil pressures on buried archaeological artefacts. PhD Thesis. Cranfied University | 2010 |
| **PhD thesis** | Webber H R 2020. Precision Farming and Archaeology.PhD thesis. Bristol University. | 2020 |
| **PhD thesis** | Kaczorowska-Dolowy, M., 2022. Traffic and tillage effects on soil health and crop growth (Doctoral dissertation, Harper Adams University). | 2022 |
| **PhD thesis** | Millington, A., 2019. The effect of low ground pressure and controlled traffic farming systems on soil properties and crop development for three tillage systems (Doctoral dissertation, Harper Adams University). | 2019 |
| **Grey literature that informed the Report** | Chamen T 2006 'Controlled traffic' farming: Literature review and appraisal of potential use in the U.K. Research Review No. 59 HGCA. https://projectblue.blob.core.windows.net/media/Default/Research%20Papers/Cereals%20and%20Oilseed/rr59_final_research_review.pdf [Accessed 25.02.23] | 2006 |
| **Grey literature that informed the Report** | Lowenberg-DeBoer, J., Huang, I.Y., Grigoriadis, V. and Blackmore, S., 2020. Economics of robots and automation in field crop production. Precision Agriculture, 21, pp.278-299. | 2020 |
| **Grey literature that informed the Report** | Lyon N 2019 Lightweight robotic machines no magic cure for soil compaction https://www.graincentral.com/cropping/lightweight-robotic-machines-no-magic-cure-for-soil-compaction/ | 2019 |
| **Grey literature that informed the Report** | Mulholland, B., Abdel-Aziz, I., Lindsay, R., McNamara, N., Keith, A., Page, S., Clough, J., Freeman, B., Evans C. (2020). An assessment of the potential for paludiculture in England and Wales. Report to Defra for Project SP1218, 98 pp | 2020 |
| **Grey literature that informed the Report** | Oxford Archaeology 2002. The Management of Archaeological Sites in Arable Landscapes report for Defra BD1701 | 2002 |
| **Grey literature that informed the Report** | Pearson, S., Camacho-Villa, T.C., Valluru, R. and others Robotics and Autonomous Systems for Net Zero Agriculture. Curr Robot Rep 3, 57–64 (2022). https://doi.org/10.1007/s43154-022-00077-6 | 2022 |
| **Grey literature that informed the Report** | Defra farm surveys - information from relevant past surveys extracted | 2018,<br>2019 &<br>2006 |

www.gov.uk/natural-england