May 2025

Research Review 101a

Updating cover crop guidance (Part A): destruction methods

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This scoping review was produced as part of the final report of a five-month project (Updating cover crop guidance – 21140093) that started in November 2024. Part B considered long-term soil health impacts. The work was funded by a contract for £30,000 from AHDB Cereals & Oilseeds.

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1. Abstract

A rapid evidence assessment (REA) was conducted to update cover crop guidance. It considered research on cover crop destruction methods, biomass breakdown after cover crop destruction and the risk of cover crops becoming a weed burden in the following crop. The review also identified knowledge gaps and research opportunities. The REA included research that was conducted in the UK or in other temperate farming systems (with similar characteristics to the UK).

Searching and screening of the literature for this REA was conducted concurrently with an REA of the long-term soil health impacts of using cover crops (Research Review 101b). It resulted in 16,168 articles screened at title and abstract for inclusion.

A total of 70 articles were included for this REA on cover crop destruction methods. Coding for this REA was carried out independently. Due to time and resource limitations, coding only used the abstracts of the included studies with no quality appraisal conducted. However, where evidence had been collated into a meta-analysis or systematic reviews, it was generally assumed that the weight of evidence was stronger than individual primary research studies. Recommendations made by the authors of the included studies should be interpreted with care.

Primary research was identified for the following destruction methods: mechanical only (28 articles); comparing destruction methods (26 articles); grazing only (eight articles); chemical only (six articles); and frost-killed only (six articles). 25 articles were identified that assessed destruction timing of cover crops. Only four articles mentioned cover crops becoming a weed burden in the following crop and three articles mentioned what soil type the experiment was conducted on. Only two primary research studies were found that were conducted in the UK. One study surveyed UK use of cover crops and which destruction method was used (81% of participants used herbicides to terminate cover crops) and the other study demonstrated frost-sensitive cover crop species could not be reliably terminated under a temperate climate due to variable winter conditions. Further sources of UK-based advice were identified following steering group discussions.

This REA identified that research with a focus on destruction methods may not be widely available in the public domain. Much of the research included in the REA had destruction method as part of the experiment and not the focus. Key knowledge gaps identified included: the need for UK-specific research on destruction methods – including termination timing effects; efficiency of destruction methods on different soil types; research on cover crops other than winter cover crops; and research on cover crops becoming a weed burden in following crops (especially in the UK).

Table 7 provides practical guidance for the various destruction methods (in isolation and in combination).

2. Background

Cover crops are grown for a variety of reasons, and the use of cover crops is widespread on arable cropping farms (Storr et al, 2019). Cover crops provide a range of ecosystem services to the grower and to the environment, including potentially minimising soil disturbance (i.e. depending on cultivation for establishment), keeping soil covered, maintaining living roots and increasing crop diversity (all principles within regenerative agriculture). With regards to soil properties, cover crops are key for providing soil health benefits including improvements to soil structure; water infiltration; drainage; soil biodiversity and functioning; increased levels of soil organic matter; and nutrient retention. All these aspects can be affected by the management of cover crops, including termination methods and timing (e.g. cover crop variety and termination influencing soil nitrate levels, Wayman et al.,2014).

Cover crops, in general, appear to have positive effects on most soil physical properties, but that the magnitude can be highly site and management specific (Adetunji et al., 2020; Blanco-Canqui & Ruis, 2020). One management aspect to consider is the timely and effective termination of cover crops. This timing may be critical for preventing competition with the following crops, limiting carry-over of cover crop species as weeds in the following cash crop (e.g. volunteer hairy vetch compromising winter wheat yields, Keene et al., 2017), and managing nutrient dynamics.

Research suggests that cover crops can help support the ecological transition of modern and intensive systems towards sustainable farming systems (for example, Quintarelli et al. 2022). Cover crops can, for example, offer wider benefits than just soil and water properties. For example, they provide resources for pollinators, with studies showing that cover crops can bolster pollinator diversity and abundance, depending on the plant species used (Bryan et al., 2021). Plant species selection can influence whether cover crops attract large numbers of generalist species or benefit fewer individuals that are of potential conservation concern (Mallinger et al., 2019). One way to improve the benefits of cover crops more widely is to use multi-species strategies with the species selected to have functional complementarity (Chapagain et al., 2020). However, what is required is research on how destruction methods and timing can impact the following crops establishment and the challenges of biomass breakdown and cover crops becoming weed burdens.

The Sustainable Farming Incentive (SFI) is a recent bursary scheme in England attempting to provide subsidies and encouragement to farmers and land managers for the adoption of more sustainable farming practices. Within these incentives there are several actions for the use of multi-species cover crops and it is likely that the use of cover crops will continue to increase in the UK. In this scheme, several different types of cover cropping actions were available (at time of writing) including: Multi-species winter cover crop (SAM2/CSAM2); multi-species spring-sown cover crop (SOH2); multi-species summer-sown cover crop (SOH3); and, winter cover following maize crops

(SOH4) looking to establish either a quick growing cover crop immediately after maize harvest or maintaining an under sown cover crop. These are all example of different management practices in the bursary scheme directly involving cover crops. The purpose of all these actions within the scheme are, for example: protect the soil surface and provide root growth that benefits soil structure; support soil biology; to reduce risks of soil erosion and surface runoff; slow water run-off; and, to help nutrient uptake and reduce nitrate leaching. There is no designated action on how to destroy cover crops with these SFI actions. Organisations like AHDB provide guidance on methods of destruction and the best current approaches to timing of destruction.

AHDB provides information on cover crops online and via its Strategic Farm and Monitor Farm network to disseminate knowledge of on-farm situations around the use of cover crops. AHDB Strategic Cereal Farms network (ahdb.org.uk/news/how-strategic-cereal-farms-evaluate-cover-crops) have been investigating the practical aspects around using cover crops and what benefits this practice can provide from on-farm situations. The work within this network showed that cover crops can provide benefits to soil health and biodiversity without compromising cash-crop performance. They also demonstrated that cover crops can reduce nitrate leaching, when used with appropriate cultivation, and the trade-offs in management with cover crops, where establishing and destroying cover crops early would benefit spring-crop performance. However, if cover crops are maintained through spring, then a boost to beneficial invertebrates was seen.

To further improve the guidance provided to farmers in the UK, AHDB has identified a need for updated information around cover crops with particularly in relation to the destruction methods used for cover crops This rapid evidence assessment will look to update the state of current research, and any gaps in knowledge around cover crop destruction methods.

This report was written at the same time as the report “Updating the guidance on long-term soil health impacts of using cover crops”. As such parts of the review were conducted together for efficient time use. This will be mentioned briefly in the relevant sections of the methodology.

2.1. Objectives of the review

The aim of this research project is to identify, collate, and describe relevant published research and current guidance and to identify potential gaps in current knowledge relating to cover crops destruction methods.

The scope of this research is as follows: information relevant to winter, spring-sown and summer-sown cover crops; cover crop destruction methods; challenges of breakdown of biomass when destroying cover crops; and cover crops becoming a weed burden in the following crop. This review will not include the following: cover crops as a green bridge for pests and disease; cover

crops for biofumigation; and information on cover crop species/ types i.e. benefits relating to growing specific cover crop species, companion cropping, etc.
Information around cover crop destruction methods also included:

- Detail on the ease of termination, and/or challenges, associated with specific cover crop types, according to destruction method.
    - The impact on following crop establishment – or other issues arising – according to cover crop destruction method.
    - The impact on following crop establishment – or other issues arising – according to timing of cover crop destruction.
    - Influence of soil types on cover crop destruction (timing and method), and establishment of the following crop.

2.2. Rapid evidence assessment

A rapid evidence assessment (REA) was chosen as the method to review the literature. The method used in the development of the REA was conducted following Defra/NERC guidelines to produce Quick Scoping Reviews and Rapid Evidence Assessments (Collins et al, 2015).
The REA addressed the following primary question:

2.2.1. Primary question

"What evidence and current guidance exists regarding cover crop destruction?"
The primary question is framed using population (P), intervention (I), comparator (C) and outcome (O) key elements. Table 1 shows the PICO components of the primary question.

Table 1. Components of the PICO key elements

Key element	
Population	UK arable cropping systems and temperate countries with similar farming systems to the UK (defined in inclusion criteria below) and the cover crop species.
Intervention	Cover cropping interventions within fields used for arable farming, where there was any type of destruction method used to remove cover crops: benefits and challenges.
Comparator	Absence of cover cropping interventions or the effects after cover crop destruction. For this question, comparators may not always be present.
Outcome	The benefits and challenges of cover crop destruction and destruction methods including: cover crop destruction methods; challenges of biomass breakdown; and cover crops becoming weed burdens. Outcomes will be included iteratively as they are identified within the relevant literature and guidance, and they will be coded accordingly.

3. Methods

3.1. Searching for literature

A comprehensive search was undertaken using multiple information sources to capture an un-biased sample of literature. The search strategy was developed to identify both published and unpublished (grey) literature. Searches for both this REA (destruction methods) and the REA on long-term soil health impacts were conducted together.

The searches attempted to be as thorough as possible within the timescale of this project. The search string was adapted to the syntax of each source searched and a record of each search made. Database and repository searches were conducted in the English language. Online sources searched to identify relevant literature are presented in Table 2.

Table 2. Online sources searched for published and grey literature

Bibliographic databases	CAB Abstracts (Harper Adams University) PubMed (Harper Adams University) Web of Science (Harper Adams University) Index to Theses Online (PhD Theses) Wiley Online Library (Harper Adams University) Cordis (EU Projects)
Organisation Websites	AHDB Defra Online Databases European Environment Agency Environment Agency (including those in devolved governments) Rothamsted Research Natural Environment Research Council CEH AAB

3.2. Search string and scoping searches

The search string was formulated in discussion with AHDB and using scoping searches to test keywords for specificity and sensitivity using the online database Web of Science. The results of the scoping search informed the final search string. Subject experts were also consulted to ensure all key and relevant terms were used within the search string. The final search string comprised of synonyms and wildcards of cover crop and intervention keywords, to ensure that results returned were not restricted. This search string was combined with that for long-term soil health impacts.
("cover crop*" OR "covercrop*" OR "catch crop*" OR "catchcrop*") AND ("destruction" OR "termination" OR "post-termination" OR "termination method*" OR "cover crop termination" OR "killing" OR "removal" OR "volunteer*" OR "biomass decomposition" OR "organic matter

decomposition" OR "residue decomposition" OR "weed competition" OR "weed pressure*" OR "weed infestation" OR "regrow*" OR "crimp*" OR "frost*" OR "graz*" OR "roll*" OR "herbicide*" OR "glyphosate*" OR "cut*" OR "flail*")

3.3. Screening

3.3.1. Screening literature

All retrieved articles were imported into the specialised systematic reviewing software (EPPI-Reviewer6 – Thomas *et al*. 2023) and screened for relevance against the pre-defined inclusion criteria. Screening of articles was conducted at two levels (i) title, (ii) abstract. Due to the timescale of the project and the high article return of the various searches (totals included in results) it was only possible to screen articles up to abstract level. Screening for both this REA and the REA assessing long-term soil health impacts were conducted together for efficiency. This was then separated at the coding section of each review to create a separate database. Details of screening for long-term soil health impacts are included in that REA.

3.3.2. Inclusion criteria

Inclusion criteria were developed using the PICO key elements of the primary question. Not all criteria needed to be met for inclusion within this REA, and any instances where this was not required has been highlighted below.

Inclusion criteria:

- Population: UK arable cropping systems and temperate countries with similar farming systems to the UK (defined in inclusion criteria below) and the cover crop species.
- Intervention: Cover cropping interventions within fields used for arable farming, where there was any type of destruction method used to remove cover crops: benefits and challenges.
- Comparator: Absence of cover cropping interventions or the effects after cover crop destruction. **For this question, comparators may not always be present.**
- Outcome: The benefits and challenges of cover crop destruction and destruction methods including: cover crop destruction methods; challenges of biomass breakdown; and cover crops becoming weed burdens.

Exclusion criteria:

- Outcome of studies: Studies with outcomes including cover crops as a green bridge for pest and disease, cover crops for biofumigation and information on cover crop species/ types, will not be included.
- Geographical: Studies in climate zones that are not temperature
- Farming systems: Studies in farming systems not comparable to the UK
- Date: No date restrictions were applied
- Language limitations: English language only

3.3.3. Coding literature

All included literature was catalogued in a searchable database, containing key information (metadata) for each study/ review in a standard format. The database will be used to describe the extent of research regarding both primary questions and identify knowledge gaps. The depth of detail of coding was agreed with AHDB. Recent systematic reviews or meta-analyses will be used to summarise topic areas where appropriate, as these types of reviews are considered more comprehensive and reliable than individual studies (or primary research).

3.3.4. Critical appraisal

This review did not critically appraise the included research. Recommendations made by the authors of the included studies should therefore be interpreted with care.

3.3.5. Meta-data coding

Table 3 shows the coding descriptions from which meta-data was extracted from all eligible primary research studies (abstract only), to provide detail about the article the study appears in (i.e. author, title, year, publication type, etc.) and more in-depth detail of each study considering PICO elements and study details (i.e. trial design type, length of study, etc.). Meta-data extracted is presented as a searchable Excel database.

Table 3. Coding descriptions for primary research studies

Category		#	Coding Description
Bibliographic information		1	Unique article ID
		2	Author(s)
		3	Title
		4	Publication date
		5	Publication type
		6	Reference type
		7	DOI number
Study background		8	Location
		9	Latitude
		10	Longitude
		11	Article topic
		12	Sub-topic
		13	Climate zone (Köppen-Geiger)
Study details	Population	14	Population (Cover crop)
	Intervention	15	Destruction method
		16	Destruction method timing
	Comparator	17	Comparator (control/ other destruction method)
		18	Following crop establishment

		19	Treatment category
		20	Treatment(s)
		21	Control(s)
	Outcome	22	Measured outcome (what effect is measure)
	Study design	24	Soil type
		25	Farming system
		26	Study design
		27	Study period
		28	Replication
		29	Scale
		30	Author reported effects
		31	Measured outcome description
Notes		32	Any Other Notes

3.3.6. Description of study

Due to the timescale of this REA priorities of analysis will be given to studies that are perceived as more robust. Where possible, meta-analysis will be used to report information about each topic, as these are seen as more robust research. Where only one meta-analysis or no meta-analyses have been conducted systematic reviews and then narrative reviews will be used. Meta-analyses follow a strict methodology which statistically analyses information gathered from the articles included, summarising the existing research in a quantitative manner. Systematic reviews summarise existing literature in a structured manner, only sometimes statistically analysing information gathered. These reviews follow a strict methodology and often describe the state of the literature and any knowledge gaps. Both meta-analyses and systematic reviews include study quality assessments. Narrative reviews give a broad overview of the existing research, often not following a strict methodology and can be subjective. Narrative reviews do not include statistical analysis and rarely including a study quality assessment. Therefore, without quality appraisal, it is assumed that topics that have a meta-analysis have more robust conclusions than narrative reviews.

Where none of the above are available, or there is a small number, manipulative studies will be used to assess results. These studies are assumed of higher quality to correlative, monitoring and sampling studies. Manipulative studies are those that are set out with replicates and are a plot-based trial. Correlative studies compare results from two farms to each other, for example. These studies merely see any correlation between practices. Monitoring studies are when sampling is conducted several times on one farm looking at the temporal change in the selected measured outcome. Sampling studies are those in which conclusions are drawn from one sampling session.

4. Results and Discussion

4.1. Summary

The combined search results for both long-term soil health and destruction methods – yielded a total of 30,041 results. Of these, 13873 duplicates were removed, and 16,168 articles were screened at title and abstract level for inclusion. Priority screening was adopted to ensure rapid assessment of the academic research, and this was capped at screening of 5600 articles due to low (one inclusion per 100 articles) inclusion rates.

A total of 70 articles were included for the topic of cover crops and destruction methods. These included 63 primary research articles, one meta-analysis, one book chapter and 5 general literature reviews. Information was only extracted from the abstract of these articles and categorised appropriately.

Both primary research and review authors reporting on destruction methods of cover crops showed considerable variation within findings and therefore will be discussed fully in each individual section.

4.2. Weight of evidence for destruction methods

For this review, no quality appraisal of included studies was carried out, but where evidence has been collated into a systematic review or meta-analyses, it is generally assumed that the weight of evidence is stronger than by considering individual primary research studies. Although even meta-analyses and even systematic reviews may be subject to bias, this is likely to be reduced when compared to traditional literature reviews. Where systematic reviews or meta-analyses were not available on a sub-topic area, we have collated author findings from primary research, but these must be interpreted with care as studies have not been quality appraised.

There were no systematic reviews found that investigated destruction methods, and only one meta-analysis was found that discussed destruction methods in the abstract, although this was not the central focus of the research. The meta-analysis focussed on the impact of cover crops on the soil microbiome, but the authors also reported that when a cover crop is chemically terminated (i.e. using a herbicide such as glyphosate), that the effects of cover cropping on the soil microbiome were less pronounced (Kim et al. 2020). There were five narrative reviews for this topic. Narrative reviews are more likely to be subject to bias and so should be interpreted with more caution.
The primary research (63 articles) was not quality appraised, so any summary of author findings needs to be interpreted with care. However, only the manipulative studies have been used to specific highlight findings. Manipulative studies may be of higher quality than correlative or monitoring studies.

The sections below highlight the narrative review and primary research (mostly manipulative studies) reported impacts of destruction method. These will be separated into grazing, mechanical destruction, chemical destruction, frost-killed and any studies that compare any of the previous methods to one another. There will also be a section regarding destruction timing of cover crops.

4.3. Destruction methods

4.3.1. Grazing

There were eight articles included that evaluated the use of grazing as a destruction method: three narrative reviews; one book chapter; and four primary research articles (one manipulative study and three monitoring studies).

General author findings suggest that grazing could be a viable option for farming systems when it comes to terminating cover crops. This action could be beneficial in no-till systems which may not affect subsequent crop yields, whilst also providing a nutrition source for livestock that reduces the cost of feed. There are some potential trade-offs with grazing as this termination method may have an impact on soil such as increasing bulk density (suggesting an increase in compaction) and increasing penetration resistance (potentially limiting root growth and nutrient uptake).

The one book chapter included in this REA focussed on the impact of grazing cover crops – Blanco & Lal (2023) “Grazing and Harvesting”. This chapter mentioned cover crop removal by grazing. The abstract for this book chapter states that although cover crops were not initially designed for grazing; grazing cover crops does not generally reduce subsequent crop yield. It also states that one of the main concerns with grazing cover crops is soil compaction.

There are also site-specific factors that can affect grazing impacts on soil properties and crop yields, including the amount of cover crop biomass removal, stocking rate, years under grazing, and soil water content. However, book chapters are subjective, so the reported effects in this chapter should be interpreted with care.

Table 4. Author reported effects of the three narrative reviews on grazing cover crops

Author reported effect	Reference
18-92% of cover crop biomass removed by grazing. Increase soil bulk density and penetration resistance (54% of cases). Small and mixed effects on soil carbon concentration; wet aggregate stability; water infiltration; water retention; and soil microbial mass. Did not affect crop yield (61% of cases).	Blanco-Canqui *et al*. 2023
The review found that grazing cover crops generally led to increased bulk density, especially in no-till systems. The negative effects of grazing on penetration resistance and aggregate stability were more prominent under conventional tillage compared to no-till. The negative effects on soil physical properties were most severe when grazing implemented at high intensity and on wet soils. Microbial biomass carbon was higher under grazed conditions to ungrazed. As was nitrogen, however this was only true for conventional systems. Generally, grazing cover crops did not affect subsequent crop yield and provided a nutritious forage for cattle and reduced feed costs.	Poffenbarger, 2010
Positive effect on health and growth of grazing animals. Soil compaction was sometimes observed, but this was dependent on the climate conditions during grazing and weight of the animal. Little to no effect on the following crop and the environment. Beneficial from an economic point of view.	Herremans *et al*. 2021

Only one primary research article contained a manipulative study which compared grazing with mechanical mowing. This will therefore be further assessed in a later section. The final three primary research articles assessed a monitoring experiment.

4.3.2. Mechanical destruction

Articles that reported findings solely on mechanical destruction methods included: two narrative reviews; five manipulative studies; and 21 monitoring studies.

General author reported findings suggest that mechanical destruction, depending on the desired goals of the user (for example destruction methods that demonstrate weed control/ suppression or purely cover crop termination efficiency of the method), could affect what technique or machinery would be most beneficial to meet those goals.

Table 5. Author reported effects of the two narrative reviews on mechanical destruction of cover crops

Author reported effect	Reference
In this literature review three experiments were selected for further review and discussion. The second study selected investigated mechanical termination method efficiency. The authors reported that with a rye/vetch cover crop mix: 100% was killed by mowing and 90% by roll-chopping. The third study investigated evaluated three methods of mechanical termination of summer cover crops. The authors reported that: Undercutting killed 95% of cover crop for five out of six broadleaf species and two out of five grasses; Mowing effectively killed all six broadleaf species, but regrowth occurred with three out of five grass species; Rolling, in general, did not effectively kill broadleaf or grass cover crops.	Creamer & Dabney, 2002
The focus of the review was promoting soil health in organically managed systems. However, within the abstract it was reported that: Roll-killed cover crops suppressed weeds better than disking.	Tully & McAskill, 2020

Of the five manipulative studies, three conducted experiments over three years, one over two years and the final one was a one-year experiment. Three studies only investigated winter rye cover crops, one investigated cover crop mixes and the other several different cover crop species. With rye cover crops, author reported effects with mechanical destruction methods suggest that roller-crimping methods are not a suitable stand-alone weed control method (Brackenridge et al. 2024a) and that roller-crimper direction did not have a consistent effect on rye mortality or number of upright tillers (Brackenridge et al. 2024b). The third study on rye cover crops reported that whilst the roller machinery outperformed the roller-crimper with regards to effectively terminating cover crops, the roller-crimper demonstrated more uniform weed suppression and greater subsequent crop yield (Dhakal et al. 2024).

The other two manipulative studies reported that with legume cover crops, to ensure a successful termination with a roller-crimper, termination timing was species-specific (Crimson clover – late April; Hairy vetch and Austrian winter pea – mid-May; Berseem clover and common vetch – late May. Northern states, USA) (Parr et al. 2011). The final manipulative study investigated termination methods and their effect on soil fertility and health. They reported that when comparing termination methods (roller-crimper, flail mowing, rotary mowing, sickle bar mowing, and occultation using black tarps) flail mowing appeared to be a good method for managing cover crops of choice in terms of soil microbial functionality and fertility.

4.3.3. Chemical destruction

Articles that reported findings solely on chemical destruction methods included: one meta-analyses; two manipulative studies; and three monitoring studies.

General author reported findings suggest that chemical destruction methods varied with destruction timing, as well as which cover crop species was being used to evaluate the chemical destruction method.

The one meta-analysis mentioning chemical termination of cover crops focussed on cover crop benefit to the soil microbiome. With regards to chemical termination the authors reported that the effects of cover cropping on the soil microbiome were less pronounced under conditions like chemical cover crop termination.

There were two manipulative studies focused solely on chemical destruction of cover crops. The first investigated combinations of different chemical controls of rapeseed cover crops. The authors reported that using a combination of two herbicides, glyphosate and 2,4-D, was the most effective at controlling rapeseed cover crops with 96% termination efficiency 28 days after early termination (Askew et al. 2019). The other manipulative study investigated herbicide selection to terminate grass, legume and brassica cover crop species. The authors reported that grass cover crop species were controlled effectively by glyphosate alone 4 weeks after application (94-98% termination efficiency). Legume species varied in response to single active-ingredient treatments, and control increased with the addition of glyphosate and paraquat. No treatment adequately controlled rapeseed in this study, with a maximum termination efficiency of 58% with single active-ingredient treatments and 65% with combinations (Pittman et al. 2020).

4.3.4. Frost-killed

Articles that reported findings solely on frost-killed cover cropping methods included: one manipulative study; and five monitoring studies.

General author reported findings suggest that frost-killed destruction shows different sensitivity to different cover crop species and that using frost-based killing methods had different implications for soil organic matter and the environment.

The one manipulative study mainly focused on the carry-over effects of weed management by different destruction methods (rolling and herbicide) with using winter-kill as a control. Rouge *et al* (2023) demonstrated that the alternative destruction methods showed beneficial carry-over effects in the first year (i.e. lower weed biomass and higher crop productivity). However, in the second year, they showed either no or detrimental carry-over effects.

The five monitoring studies demonstrated varying effects of frost-killed cover crops, with studies suggesting that frost-killed cover crops may cause an increased risk of N leaching and potentially increase nitrous oxide emissions. However, other studies demonstrated that frost-killed cover crops can be beneficial for soil organic matter. These effects and the efficiency of frost-kill destruction is highly variable depending on cover crop species and this method could be used in combination with other destruction methods, such as rolling, especially if species are relatively sensitive to frost.

4.3.5. Comparison of destruction methods

26 studies identified in the REA investigate comparisons between different destruction methods. Of these studies two were narrative reviews (focussing on comparing different mechanical methods), six manipulative studies and 19 monitoring studies. These studies ranged one to three years in experimental length.

Table 6. Information on the differences between destruction methods

Destruction method comparison	Outcomes	Sources (examples)
Mechanical method comparison	17 articles investigated mechanical method comparisons. These experiments demonstrated variable outcomes depending on measured benefit (e.g. termination efficiency alone, termination efficiency and weed suppression combined). The two reviews comparing mechanical methods demonstrated the following: • Rye/ vetch cover crop (100% termination by mowing vs >90% roll-chopping) (Creamer & Dabney, 2002). • Roll-killed cover crops suppressed weeds better than disking termination methods (Tully & McAskill, 2020). Other key outcomes from primary research include: • Many mechanical termination methods as efficient as each other. • Can have differing knock-on effects comparatively (e.g. roller-crimper more effective at weed suppression compared to roller; undercut and sicklebar mowed reduced weed biomass to regular tillage and flail-mowed; disking of hairy vetch contributed the highest level of soil nitrogen across all termination combinations used).	Creamer *et* al. 1995; Liebman *et al*. 2018; Dhakal *et al*. 2024
Chemical method comparison	Only one article specifically investigated different chemical methods of cover crop destruction. This experiment specifically investigated termination of rapeseed cover crops. They found that all the herbicide treatments provided at least 80% termination rate on both early and late termination. Glyphosate combined with 2,4-D was the most effective early termination method (96%) and Paraquat combined with 2,4-D was the most effective late termination method (85%).	Askew *et al*. 2019

Mechanical vs. Chemical	Nine articles investigated mechanical vs chemical destruction methods. Some of these experiments offered direct comparisons, and some used a herbicide as a control for the experiment for comparison. Chemical methods generally provide higher and more consistent termination rates compared to mechanical methods. These can be effective but often allow some regrowth, requiring either multiple passes or integration with herbicides for more effective termination. One experiment demonstrated that mechanical methods would be effective against hairy vetch when it was flowering but not when it was not flowering. The mechanical methods used (mowing, chopping and light disking) were not as effective as the herbicide used, which was also more effective at weed suppression. Another experiment compared the termination efficiency of herbicide termination vs. roller-crimping termination of different cover crops. This experiment showed that roller-crimping alone did not provide effective termination of any of the cover crops (wheat, cereal rye, hairy vetch and rapeseed). In comparison, herbicides had between 85% to 95% termination efficiency across the cover crops.	Teadale & Rosecrance, 2003; Kumar *et al.* 2023a

4.3.6. Destruction timing

25 studies identified in the REA either specifically, or as part of a wider experiment, investigated termination timing of cover crops. Of these, eight studies were manipulative, 15 were monitoring studies and two were simulations based on field data collected in France. Within the eight manipulative studies, four investigated different termination timings in the spring, three investigated early and later termination timing and one investigated termination in the days before planting the subsequent cash crop. All these studies (bar one) were undertaken either in the northern states of the US or in Canada. The one study not conducted in North America, investigated cover crop biomass, termination efficiency and rapeseed volunteers in subsequent crops with termination at different length of days before cash crop planting.

One of the monitoring studies conducted a two-year trial comparing different termination methods and termination dates on perennial ryegrass in the Netherlands (van Schooten, 2024). This study demonstrated that early destruction improved the amounts on mineral soil N compared to late destruction (and no significant differences between destruction methods).

4.3.7. Cover crops becoming a weed burden

Only four studies (at abstract level) in this REA showed studies information with regards to cover crops potentially becoming weed burdens in subsequent years. Creamer & Dabney (2002) investigated killing cover crops mechanically and studied the regrowth of cover crops after termination. They found that with summer cover crops undercutting saw regrowth in one out of six broadleaf species and three out of five grass species; mowing saw no regrowth of broadleaf species and regrowth in two out of five grass species; rolling was not effective against most species in the trial except for mature cover crops. This highlights the fact that termination method efficiency (especially with mechanical termination) is highly cover crop species dependent. Therefore, a detailed management plan is required with the cover cropping strategy.
Of the other studies that investigated weed burden of cover crops two were manipulative studies and the other a monitoring study. The two manipulative studies investigated cover crop sowing date and termination date, respectively. When a rye cover crop was sown in September, compared to October, in a northern state in the US, saw that the cover crop species accumulated a higher biomass but also a greater regrowth of rye after terminating by roller-crimper (Dhakal *et al*. 2024). The other manipulative study investigated volunteer rapeseed in a corn production system after chemical/roller crimper termination. This study found that delaying rapeseed termination from 28 days pre-corn planting to 14, five or one day saw an area of volunteer rapeseed from 0m2, for 28 days, to 5m^2, 12m^2 and 22m^2 for 14, five and one day, respectively (Kumar *et al.* 2023b). Thus, demonstrating that delaying termination increases the risk of volunteer cover crops in subsequent cash crops. The monitoring study, Keene *et al*. (2017), investigate cover crop termination timing in organic no-till systems and as part of their investigation studied volunteer cover crops compared at different termination timings.

4.3.8. Studies including soil type

Three studies were found that included soil type in the abstract. All three studies were monitoring experiments ranging between two and three years. The first study was conducted on sandy loam in an experiment in Denmark comparing roller-crimper to full incorporation in an organic white cabbage production system (Hefner et al. 2020). This study found that subsequent cabbage yield was 100% (2016) and 24% (2017) lower with roller-crimper termination compared to full incorporation. However, roller-crimping was more effective at reducing weed growth by 63% compared to full incorporation and decreased N leaching risk.

Van Schooten (2024) investigated different destruction methods (disking, rototilling and herbicide) of perennial ryegrass on sandy soil in the Netherlands. They found that there were no significant differences in the amount of mineral soil N or N uptake by maize between treatments.

The final study that mentioned soil type in the abstract was conducted over three years and investigated the impacts of summer legume cover crops and termination method on N availability to subsequent corn in Canada (Yang *et al*. 2023). This study was conducted on a clay loam soil and investigate legume termination via plow-cultivation, herbicide and tillage. They found that there were no significant differences in N levels between autumn and spring termination. However, they demonstrated that autumn plow-down termination provided more N availability than herbicide spray-down in the spring.

4.3.9. UK Studies

Only two studies were found during the screening within the REA. One study surveyed UK use of cover crops and found that 81% of participants in the survey used herbicides to terminate cover crops (Storr *et al*. 2018). The other study was a monitoring study that demonstrated that frost-sensitive cover crop species could not be reliably terminated under a temperate climate (Storr *et al*. 2021).

During a steering group meeting (with AHDB), it was discussed that lots of specific research undertaken on different termination method equipment and more recent study into the termination of cover crops could not be accessed within the public domain. This means that there is a potential for this REA to have missed research specifically into destruction methods of cover crops. This research may have been undertaken by either farm machinery or agronomy company research and development teams.

Following the steering group discussion regarding additional sources, a further search was made specifically on UK based studies within research institutes or for specific authors that were not found during the initial grey literature screening. These found the following on-going long-term trials (N.B. these are sourced straight from the websites and should be interpreted with caution):

- Agrovista Project Lamport (https://www.agrovista.co.uk/lamport-agx-2023): Choice of herbicide is crucial depending on the cover species used.
- Cover Crops Guide (https://covercropsguide.co.uk/termination/): Utilising data from David Purdy, provide information on termination timing and destruction methods:
    - Termination timing advised in this guide, using data, show that earlier planted and late terminated cover crops accumulate more biomass for mixes and single stands. This guide suggests aiming to destroy cover crops as far ahead of the following crop (often six to eight weeks before intended drilling date), unless 'drilling on the green'. It also suggests that terminating cover crops earlier on heavy soils as soil moisture will persist much longer on these soils to the more forgiving light/ medium soils.
    - Grazing: Well managed can reduce cover crop biomass and start the process of breaking down organic matter. This helps balance C:N ratios and allow nutrients availability to the following crop be quicker. Cattle can increase poaching risks, particularly on heavy soils (could favour sheep grazing).
        - Many cover crop species are potentially toxic to livestock:
            - Red clover – high levels of phytoestrogens can cause fertility issues. Do not feed to breeding ewes six week before or after tupping.
            - Linseed – can release cyanide when grazed.
            - Buckwheat – can be toxic in high concentrations.
    - Mechanical destruction: Use of rolling to terminate cover crops works best when there is frost. Although, this method does not terminate grass species well, which are likely to require glyphosate. Temperatures of -4°C is generally required to achieve termination, and generally several days prior to rolling.
    - Chemical destruction: Glyphosate alone or with 2,4-D, is often the most reliable and typical route for cover crop destruction.
        - If cover crops used to manage weeds such as black grass, more than one glyphosate application may be needed.
        - Typically cover crops needs at least 4.5l/ha of 360g/l glyphosate.
        - In general, the earlier the spray off the better the results.
        - Aim to spray six to eight weeks ahead of drilling.
- Defra (Farming blog):
    - Destroy cover crops at least three weeks before establishing a cash crop.
        - Mechanical destruction:
            - Rolling or crimping:
                - Can be used on cereals. Will only kill cereals when they are producing ears.
                - Can be used in conjunction with herbicide application.
            - Ploughing:

        - Reliable method to kill a growing cover crop.
        - Increased risk of:
            - Damage soil beneficial organisms.
            - Increasing compaction, soil erosion and runoff.
- Chemical destruction:
    - One of the easiest and most cost-effective methods.
    - Avoid excessive contact with soil.
- Frost:
    - A frost is likely to kill: all herbs; brassicas like mustards, oil radish and stubble turnip. Less likely to kill legumes and cereals.
    - Low-cost but can:
        - Reduce range of useable plants.
        - Can leave soil bare over winter if early frosts.
        - Can leave cover crop alive if mild winter.
- Grazing can be used to prepare the cover crop for other destruction methods and help control weeds.
    - Over-grazing can increase soil compaction, leaching of nutrients and runoff. Also, it reduced the amount of organic matter that the cover crop adds to the soil.

4.4. Knowledge gaps and future research

Within this REA it is noted that much of the research specifically on destruction methods may not be widely available within the public domain. It is also shown that much of the primary research often assesses destruction method as a secondary outcome compared to other outcomes such as soil impacts or weed suppression effects. With both reasonings it is difficult to assess the knowledge gaps with destruction methods, so the authors advise taking the following recommendations with caution.

One key knowledge gap identified is UK specific research being undertaken (or publicly available) on destruction methods (and destruction method comparisons). Research within the UK show that most farmers are using herbicides to terminate cover crops (81% - Storr *et al*. 2017), frost-sensitive species may not be viable for a temperate climate (Storr *et al*. 2021) and long-term experiments in the UK suggests that choice of herbicide is crucial depending on the cover crop species used (Agrovista – Project Lamport). There are some websites that offer advice on best practice for the different termination methods in the UK. However, more primary research is one area in which further research can be conducted, especially investigating destruction methods with a manipulative experimental design. Adding to this would be more UK based studies investigating how termination timing affects destruction method efficiency. Most of this research found in this

REA was conducted in North America. These knowledge gaps may be filled by recent academic studies which are not yet available for public viewing.

Further to this, another area in which research could be conducted is the implications on following crop establishment, especially with the timing and type of destruction. Within this REA, at abstract level, little detail was found on the effect of cover crop destruction on the following crops establishment. This research is important to best advise farmers on the best destruction method to use, and the best time to use that method, for different subsequent crops. This is vital to ensure that beneficial impacts of cover crops are not negated by any potential effects causing establishment problems for the following crop.

Another research gap potentially identified in this REA is research conducted on specific soil types, as well as comparing destruction methods, and timing of destruction, across different soil types. Due to screening at abstract level, this could just have been missed in this REA. However, not many studies mentioned soil type, and if they did, they tended to mention only a single soil type. Further research that accounts for soil type, and compares destruction methods across different soil types, would help improve advice for farmers on the most efficient and cost-effective way for them to terminate various cover crop species.

A further knowledge gap identified by this REA (with the caveat that this information was obtained from abstract only), is the seeming lack of research into any other cover cropping strategy than winter cover cropping. This might be due to the fact information was only obtained from the abstract so was not picked up during screening. Further recommendations for cover crop type would be to either conduct a more in-depth systematic review specifically to investigate cover cropping seasonal strategies, or to conduct research that compares the long-term effect of cover crops sown at different periods of the year. This could be key research for future guidance on cover cropping as articles included in this REA generally study a cover crop sown at a single point in the year compared to a bare fallow or soil.

Finally, although there are a few studies investigating cover crops becoming weed burdens, further research (especially conducted in the UK) of cover crop regrowth under different destruction methods would fill another knowledge gap.

Overall, more UK based studies investigating termination methods and termination method comparisons are required to provide better advice for UK farmers.

4.5. Practical guidance

Table 7. Practical guidance associated with the main destruction methods

Method	Information

Chemical	• Easy, cost-effective and the most widely used method in the UK.
	• Aim to spray six to eight weeks before sowing the next crop.
	• Herbicide choice depends on the cover crop species:
	  ○ Grass cover crop species can usually be controlled by glyphosate alone
	  ○ Legume cover crop species vary in response to single active-ingredient herbicides
	  ○ Glyphosate alone or in combination with 2,4-D may be the most effective herbicide programme across cover crop species

Grazing	• Potentially particularly beneficial in no-till systems. • Can cause soil compaction and poaching, particularly in heavy soils. • Sheep, rather than cattle, are better on heavier soils. • Limiting the time spent grazing cover crops may also reduce potential negative impacts on the soil. • Certain cover crop species are toxic to livestock (red clover, linseed and buckwheat). • Use sparingly and combine with other methods.
Mechanical	• Can be combined with rolling, when temperatures drop under -4°C. • Termination timing with a roller-crimper is key with legume cover crop species. • Rolling or crimping can be used with cereal species, but only when the cereal is producing ears. • Ploughing can destroy cover crops, but it may negatively impact the soil. • Mechanical destruction is best used in combination with other methods.
Frost	• Frost-sensitive species may not be viable for the UK due to variable winter conditions. • Best combined with other destruction methods, where frost provides partial destruction with another method used to finish the job.
Combinations	• Using frost-kill or grazing before chemical or mechanical destruction methods could be a cost-effective practice to destroy cover crops, as it requires fewer passes of a chemical or mechanical termination method. For example, rolling or crimping combined with a herbicide.

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