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REVIEW

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Cost-effective approach to explore key impacts on the environment from agricultural tools to inform sustainability improvements: inversion tillage as a case study

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Abstract

The United Nations Food Systems Summit and the European Green Deal have prompted various policy and regulatory initiatives aiming to transition agricultural practices to become more sustainable. An array of agricultural systems (e.g., regenerative, conservation agriculture, integrated crop management) have been lauded as potential solutions to improve food production sustainability. These systems use combinations of agricultural tools (e.g., crop rotation) to modify the crop environment to reduce weeds, pests and disease, alongside chemical (e.g., plant protection products) tools. Each tool has the potential to impact both the abiotic and biotic environment, with different combinations of tools having different overall outcomes. To improve the sustainability of agricultural practices it is important to understand, and where possible, quantify the environmental costs and benefits of the various tools that are applied within diverse cropping systems, as well as their potential interactions. While extensive literature exists, practical approaches are needed to cost-effectively synthesise key impacts and interactions to support decision making. A cost-effective methodology, adapting a rapid evidence assessment, was developed to review evidence and enable identification of the key environmental impacts for commonly applied agricultural tool options. The approach was applied to each tool individually (e.g., inversion tillage, crop rotation) to, where possible, isolate their specific impacts on the environment. Focused categories were assessed, considering biotic (insect, earthworms, etc.) and abiotic (soil, water, air quality, climate) impacts. This paper considers inversion tillage (also known as ploughing) as a case study to illustrate findings using the approach. Evidence is presented for direct and indirect impacts on the environment, selectivity of impacts and data gaps. The approach quickly provided robust evidence summaries of the key environmental implications of inversion tillage, facilitating identification of opportunities and trade-offs that can inform practice. The evidence highlighted how inversion tillage can offer effective weed control to reduce herbicide use, but carries increased risk to soil health, with connected implications for water, air and climate. This time-efficient review methodology can facilitate development of clear guidance to inform farmers in their decision making to improve on-farm sustainability, while serving as a useful starting point for conducting evidence reviews for policy development.

Keywords Inversion tillage, Ploughing, Agriculture, Sustainability, Agricultural tools, Biodiversity

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Background

The sustainability of global food systems has climbed higher up the international agenda in recent years, with the European Green Deal launching it's 'Farm to Fork' strategy to develop '*a fair, healthy and environmentally-friendly food system*' [23], and the convening of the Food Systems Summit by the United Nations, forming part of the '*Decade of Action*' to achieve the Sustainable Development Goals by 2030 [93]. Agricultural production is increasingly at the centre stage of sustainability focused EU policy and regulatory initiatives [24], presenting further drivers and targets for farmers with the intent to adopt more sustainable agricultural practices. However, within these top–down level initiatives, detailed guidance for addressing related agronomic challenges or consideration of the potential environmental and economic trade-offs associated with managing these challenges remain largely absent.

In addition to the increasing prominence of the environmental dimension of sustainability, the management of agricultural practices by farmers is influenced by a range of economic and social drivers (e.g., demand, profitability, availability of labour) which must be balanced alongside environmental goals [81]. Furthermore, different elements of sustainability (e.g., greenhouse gas emissions, biodiversity) may present conflicting objectives for land management [61, 70], with the order of priorities dependent on farm level conditions. A wide range of agricultural (e.g., tillage, cover crops, crop rotation) and chemical (e.g., plant protection products, fertilisers, biostimulants) tools are available to farmers to manage crop health and weed, pest and disease pressures [17, 82], with their combinations dependent on the specific agricultural systems employed (e.g., regenerative, conservation agriculture, integrated crop management). To reliably improve the sustainability of agricultural practices, greater understanding is required of the environmental costs and benefits for the various tools that are applied within diverse cropping systems [42, 77]. With each farm requiring a nuanced and tailored approach to address different climates, topographies and environmental goals, further research is also required to understand interactions between different combinations of agricultural and chemical tools [1].

Concerns surrounding the environmental impacts of chemical tools, such as plant protection products, have resulted in many product withdrawals in recent years based on evaluations from regulatory authorities [33]. Indeed, the use of plant protection products and their environmental impacts are closely monitored within the EU, with approval processes (i.e., EU Regulation (EC) No 1107/2009 [25] the most stringent in the world [73]. Active substances must undergo thorough environmental risk assessments before being made available for use, with any identified risks carefully managed through mitigation actions and the inclusion of product warning labels [25]. While non-chemical approaches may pose fewer obvious risks in terms of toxicity [67], they may pose other risks to the environment [83, 85], such as mortality of injured soil organisms, soil erosion, decreased water retention. Applications of agricultural tools are rarely considered within a similar risk assessment style framework that would permit chemical and non-chemical approaches to be compared. Part of the challenge is that the environmental impacts of one specific agricultural tool are difficult to isolate from the impacts of suites of agricultural tools that have been applied. Therefore, unlike chemical tool assessments, the impacts of agricultural tools are much more challenging to quantify.

There is growing urgency for farmers and policymakers to take action to meet sustainability goals and avert climate and ecological breakdown. However, there are currently limited resources and incentives available to conduct multi-faceted environmental assessments of well-established agricultural practices. While an extensive body of academic research exists that considers the environmental impacts of agricultural tools, the literature often focuses upon one environmental issue at a time, with limited syntheses undertaken to assess and compare a wide range of environmental impacts. Furthermore, to meet ambitious timelines required to take practical on-farm action, rapid evidence gathering is often required to provide the latest guidance to farmers to inform their decision making. Evidence reviews in an applied context must adopt strategic methodologies that enable resources to be utilised efficiently. The development of a cost-effective, rapid evidence review methodology to assess agricultural tools, which takes inspiration from a risk assessment style approach, would therefore help farmers, policymakers and authorities to make timely and informed decisions to meet their environmental goals in the practical field context.

Project aims and objectives

This project set out to develop a cost-effective evidence review methodology to explore the key environmental impacts of commonly used agricultural tools applied within a multi-faceted comparative framework. The primary aim was to review existing peer-reviewed literature to understand the positive and negative impacts (or no impacts) of non-chemical agricultural tools upon a set of defined environmental categories (see Methods section), with the findings able to complement the risk assessment perspective used in the evaluation of chemical tools.

Based on the available peer-reviewed scientific literature, a rapid evidence review methodology was developed which modified a rapid evidence assessment approach; a constrained number of sources (minimum of ten) were reviewed per environmental category to facilitate rapid evidence syntheses for a large number of tools across short time frames. It used the biotic (e.g., insects, earthworms) categories usually addressed within environmental risk assessment processes for plant protection products, as well as additional abiotic categories (e.g., soil, water, climate), to non-chemical agricultural tools that are commonly used within agricultural systems. We present this approach for assessing single agricultural tools (e.g., inversion tillage, crop rotation) here, using inversion tillage (i.e., ploughing) as a case study.

While the rapid evidence review methodology took inspiration from the categories used within environmental risk assessments for plant protection products, the approach was not intended to be comprehensive and used constrained search terms to identify key impacts, whereas in a formal regulatory risk assessment all aspects would have been considered in depth. Instead it aimed to facilitate evidence summaries that capture the key high-level environmental impacts for each agricultural tool, highlighting nuances in the research findings, as well as identifying potential data gaps that may inform further study.

Further objectives were set out to provide high-level comparisons of the severity of impacts between the different environmental categories. These included objectives to assess and estimate impact scale, likelihood and relevance from the reviewed literature. The project objectives followed are outlined below:

1. Identify existing evidence syntheses of environmental impacts and assess the quality of supporting evidence,
2. Ascertain whether impacts are direct or indirect, as well as their degree of selectivity,
3. Where available, identify and collate supporting quantitative details,
4. Estimate the scale and likelihood for each of the identified impacts,
5. Determine where there are knowledge gaps for specific environmental categories.

Methods

The research set out to understand, and where possible quantify, the scale and likelihood of the environmental impact, whether positive or negative, of a range of specific agricultural tools commonly used in cropping systems (e.g., inversion tillage/ploughing, crop rotation) to manage weed, pest and or disease pressure. A bottom–up rapid evidence assessment (REA) approach, which was modified for cost-effectiveness, was employed to review existing peer reviewed literature related to each specific agricultural tool. To offer a degree of comparability with the outputs from environmental risk assessments for plant protection products, the study aligned with a similar range of biotic impact categories in the analysis, which comprised of six categories for biodiversity (Table 1). This was complemented by four additional abiotic categories for soil, water, air quality and climate.

At the beginning of the study, five agricultural tools that are widely used within arable systems in Europe were selected to test the approach; inversion tillage, crop rotation, combine harvester use, fertiliser use and cover crops. While combinations of these tools are usually applied within agricultural systems, the aim of this assessment was to isolate the environmental impacts of each tool as much as permitted by the existing evidence and literature. This paper presents the findings from inversion tillage to demonstrate how the modified REA approach was applied.

Rapid evidence assessment

The research was conducted using a constrained version of a rapid evidence assessment (REA) approach to gather and analyze existing peer reviewed literature; the original REA methodology is presented in Collins et al. [14]. An REA applies similar methodological steps to a more comprehensive literature review, however, concessions are made regarding the breadth, depth, and comprehensiveness of the literature search. This enables REAs to be delivered efficiently within a relatively short period of time, whilst also providing a robust and systemic approach to provide an evidence summary that can inform practice. In this project, the REA approach was modified to constrain the number of sources reviewed

Table 1 The ten criteria used to assess each agricultural tool in the rapid evidence assessment

Impact category	Assessed environmental criteria
Abiotic	Effects on soil (structure, erosion)
	Effects on water quality (contamination)/ Water quantity (retention)
	Effects on air quality
	Effects on climate (Greenhouse gas emissions/Carbon sequestration/ Resilience)
Biotic	Effects on vertebrates
	Effects on aquatic organisms
	Effects on bees and other arthropods
	Effects on earthworms
	Effects on soil microorganisms
	Effects on terrestrial plants

(minimum of ten per environmental category). This decision was taken to facilitate the consistent review of a large number of agricultural tool environmental impact combinations in an efficient time frame. The REA process was refined using the first tool (inversion tillage) with the aim to enable key details to be collated efficiently and provide sufficient detail for further study.

The scope of the study was set to only review peer-reviewed literature presented in the English language, with searches conducted using English search terms. Web of Science was selected as the database for the REA, as it focuses on peer-reviewed literature and allows advanced searches that provide consistent and replicable results. To improve the accuracy of the literature searches, the search terms utilized Boolean Operators (e.g., AND, OR), which were applied within the Web of Science's Advanced Search function. The search terms 'review' and 'meta-analysis' were included to target high quality literature where available. The REA was conducted for each of the ten environmental categories listed in Table 1. The REA was constrained by selecting the top ten relevant sources from each search, which were screened and recorded to determine if they should be included within the evaluation.

Ten sources were selected and reviewed for each category to extract all relevant information on the impacts (positive and negative), as well as being evaluated for their robustness (i.e., research quality, relevance of geographical region and context) in relation to the project aims; details of the associated scoring are outlined below. For each source, the relevant baseline for comparison (e.g., no-till) was also identified and recorded. Some sources featured details for several of the targeted categories, therefore, effort was made to capture all relevant information. This resulted in some categories having more than ten sources reviewed. The key conclusions from each source were summarized and documented in relation to the relevant categories, including quantitative details where these were available.

Research quality scoring

Each of the sources selected and reviewed within the REA process were also evaluated for their robustness (i.e., research quality, relevance of geographical region and context), with scoring criteria matched with the project aims. The principal aim was to gather extensive bodies of evidence quickly and efficiently, including quantitative details where possible, therefore, the highest scores for research quality were attributed to meta-analyses and review papers. The relevance of context for each source was also considered, favouring studies conducted from on-farm practice rather than laboratory based research. The project scope principally focused on arable systems in a European context, therefore, higher scores were given for geographical relevance to papers with this crop focus and in this region. Finally, an overall rating was given based on the quality and robustness of conclusions made and the credibility of evidence presented. The full details for the associated scoring are in Table 2.

Impact scoring

A scoring matrix was developed to provide a high-level estimate of the scale and likelihood for each of the identified environmental impacts (Tables 3, 4). To enable consistent scoring across the ten impact categories, the scoring criteria were kept deliberately broad as the use of indicator linked thresholds (e.g., tonnes of topsoil lost) would not be applicable across all environmental categories, therefore, resulting in non-applicable scoring. A high-level qualitative score was developed for determining the scale of the impacts identified from the reviewed sources (Table 4). This ranged across a five-point scale; − 2 (large negative impact), − 1 (small negative impact), 0 (no impact), + 1 (small positive impact), + 2 (large positive impact). To determine a score, the identified impact was compared against the equivalent baseline practice (e.g., no-till for inversion tillage), with scores guided by the conclusions identified in the reviewed literature. The likelihood of impact occurrence was scored on a five-point scale (Table 3); 1 (rare, i.e., occurs only in specific conditions/circumstances), 2 (low), 3 (medium), 4 (high) to 5 (very high, i.e., expected to occur most of the time, in all conditions/circumstances or reported in over 75% of cases). These combined output scores for the environmental impacts were intended to be used as a guide rather than directly compared with each other. This was due to there being no straightforward method of assigning weighting for the impacts, which would vary according to individual project goals and priorities.

Case study: inversion tillage

The review outputs from the first tool, inversion tillage, are presented as a case study. Inversion tillage, commonly known as ploughing or conventional tillage, is a principal agricultural tool that has been employed by farmers for centuries. While historically associated with advances in agricultural production [47], recent research has consistently highlighted some of the negative impacts that inversion tillage may have upon soil health [40, 75, 83]. In this structured review, inversion tillage was assessed for its impacts across each of the ten environmental categories (Table 1) to determine the various benefits and costs associated with employing this tool.

The primary aim of inversion tillage is to disrupt weed, pest and disease life cycles by completely inverting the soil profile to provide a clean seed bed for crop

Table 2 Critical Appraisal for assessing the quality of each individual source

	Very high **5**	**High** **4**	**Moderate** **3**	**Low** **2**	**Very low** **1**
Quality of literature	An extensive body of high-quality evidence in review format	A developing body of high-quality evidence in review format	Studies of the highest quality (randomised control trial equivalent)	Studies using quasi-experimental methods	High quality observational studies only
Relevance of context	As level 4, but with excellent contextual and implementation insight drawn from high-quality studies and on-farm practice	Includes evidence generated in farming and growing businesses with farmers and growers testing the practice	Evidence generated in farming and growing businesses with the practice applied by professional researchers	Evidence generated in research centre farming and growing facilities	Evidence generated through laboratory research
Relevance of region (here in scope: arable systems in Europe)	European focused study and relevant crops	Global study which includes direct reference to relevant regions (i.e., Europe)	Global study which may be relevant to target regions, but this is not specific	Potentially irrelevant region for this context, e.g., China but includes useful findings	Irrelevant geographical context—i.e., tropical areas. Not included within the matrix
Overall	We can draw very strong conclusions about impact and be highly confident that the practice does/does not have an impact The body of evidence is very diverse and highly credible, with the findings convincing and stable	We can draw strong conclusions about impact and be confident that the practice does/does not have an impact The body of evidence is diverse and credible, with the findings convincing and stable	We can draw some conclusions about impact and have moderate confidence that the practice does/does not have an impact The design of the research allows contextual factors to be controlled for	We believe that the practice may/may not have an impact. The body of evidence displays significant shortcomings There are reasons to think that contextual differences may substantially affect practice outcomes	The body of evidence displays very significant shortcomings There are multiple reasons to think that contextual differences may unpredictably and substantially affect practice outcomes

Table 3 Scoring criteria to evaluate the likelihood of occurrence of the identified impact

	Very high 5	High 4	Medium 3	Low 2	Rare 1
Likelihood of occurrence	Expected to occur most of the time, in all conditions/circumstances. Reported in over 75% of cases	Often occurs in all conditions/circumstances OR expected to occur most of the time, but only in specific conditions/circumstances	Often occurs, but usually only in specific conditions/circumstances. Reported in at least 25% of cases	Occurs occasionally across various conditions/circumstances. Reported in less than 25% of cases	Rare, occurs only in specific conditions/circumstances. Only occasionally reported

Table 4 Scoring criteria to evaluate the scale of the identified impact compared to the observed baseline

	Large negative impact – 2	Small negative impact – 1	No impact 0	Small positive impact 1	Large positive impact 2
Qualitative score: Scale of impact (compared with baseline)	Significant impact determined by consensus	Negative impact detected	Within baseline variability	Positive impact detected	Significant impact determined by consensus

establishment [31]. This is achieved using a mouldboard plough, which takes the surface layer of the soil, including all vegetation, seeds and any other organisms present, and buries them at a depth of around 15–30 cm (dependent on plough setup) [56]. This agricultural tool is employed to loosen surface soil compaction [56, 57], reduce weed seed viability [56] and to incorporate organic matter (e.g., crop residues, weeds) prior to the planting of the following crop [8, 56].

The review findings demonstrated that inversion tillage has a variety of implications for the wider agricultural environment, which must be considered within any attempts to improve the sustainability of agricultural practices. Many of the reviewed studies centred around the environmental impacts of loosening upper soil layers to reduce soil compaction, where inversion tillage plays a central role.

Abiotic impacts

Soil

The reviewed literature primarily considered the negative impacts of inversion tillage on soil. While a primary aim of inversion tillage is to loosen the topsoil and reduce surface compaction [50], several studies revealed that cultivating the soil in this manner can increase subsoil compaction and negatively impact other physical aspects of the soil, such as soil organic matter and aggregate stability [2, 6, 56]. Half of the reviewed sources reported increases in soil erosion, as well as losses in topsoil from the use of inversion tillage practices [18, 29, 38, 50, 90], the typical baseline used for such comparisons was conservation tillage (i.e., reduced or no-till. These negative impacts were supported by a number of quantitative assessments within the reviewed literature. One experimental field study [71], referenced in Soane et al. [83], observed a mean loss of 2100 kg ha^{-1} of soil under inversion tillage, this represented a 268% increase in soil loss compared to the baseline grass ley treatment (570 kg ha^{-1}). By employing direct drilling instead of inversion tillage, another study [92] referenced in Soane et al. [83], showed reductions in particle erosion from clay soils by up to 79%. When considering impact scores (Tables 3, 4), the negative impacts identified for soil had the greatest severity (large negative impact in scale, high in likelihood) of all impacts identified in the inversion tillage review.

Water

For the water category, which considered both water quality (i.e., contamination) and quantity (i.e., retention), the reviewed literature primarily discussed how inversion tillage negatively affects this latter category. The key findings centred around the reduced ability of tilled soil to retain water, with several studies demonstrating that soil moisture and water content decreased as a result of inversion tillage [2, 8, 40, 83]. One field study [12], referenced in Strudley, Green, and Ascough [87] found that soil water content was 8% lower under inversion tillage compared to no-till, which was attributed to the retention of crop residues on the soil surface and subsequently lower evaporation rates under no-till. The burial or removal of crop residues under inversion tillage was also found to contribute to increased surface run-off of water, resulting in negative implications for local water quality [8, 56, 83]. One study conducted in Italy [10], referenced by Soane et al. [83], revealed that annual run-off was 94 mm for fields under inversion tillage, compared to 57 mm for no-till sites. The reviewed literature did reveal one positive impact, as inversion tillage aerates the soil by breaking up surface compaction, this can increase water infiltration [8, 57, 62, 76]. However, this effect appears to be temporary, at least in certain soil types. In a 4-year field study [30] that measured infiltration after different tillage treatments (on sandy clay loam), it was observed that while pre-inversion tillage water infiltration rates were at 68%, increasing to 83% immediately post-till, after 2 weeks the infiltration rate had dropped significantly to 26%. By contrast, under a no-till treatment, water infiltration rates were 84%, 77% and 62% for pre-, post- and 2 weeks post-inversion tillage, respectively [30].

Air quality

The reviewed literature primarily demonstrated the negative impacts of inversion tillage on air quality when applied in semi-arid climates or under dry conditions. The direct impacts on air quality relates to the disturbance of the soil caused by inversion tillage which can result in an increase in dust and particulate matter (PM) emissions [32, 44, 54, 65, 79], especially when soils are dry [37, 44]. Inversion tillage creates a bare soil surface with little crop residue which increases the risk of wind erosion, resulting in greater sediment fluxes during strong winds [79]. A study conducted in a semi-arid region of northern Spain found that the wind-erodible fraction of the soil surface was observed to be 41 and 50% for chiselling and mouldboard ploughing, respectively [51]. Sediment and PM flux decrease with a reduction in tillage intensity, as soil that has not undergone inversion tillage promotes the aggregation of fine particles, thereby leading to lower concentrations of PM [32, 79]. While this demonstrates a negative effect of inversion tillage, the reviewed literature also indicated a positive impact on air quality. The literature discussed how in cases where organic manures are applied to the soil surface, ploughing enables the incorporation of manures into the soil, thereby reducing associated ammonia emissions, ammonia volatilisation losses occur when manure is exposed to air. The study by Webb et al. [95] indicated that using immediate incorporation of cattle, pig, or chicken (broiler and layer) manures into the soil via inversion tillage can reduce ammonia emissions by up to 95%. However, as ammonia losses begin as soon as the manure is applied, any delays to incorporation enable these losses to occur. For instance, incorporating manures a week after they have been applied results in only a 5–10% reduction in ammonia emissions [95].

Climate

Aspects considered under the climate category included greenhouse gas (GHG) emissions, carbon sequestration and climate resilience. While direct impacts of inversion tillage on GHG emissions and carbon sequestration were identified, the reviewed literature did not reveal any substantial evidence to determine whether inversion tillage has any direct impact on climate resilience. Indirect impacts on climate resilience associated with drought or flooding could be explored through consideration of water holding capacity or run-off (see water above), however, these indirect impacts were not featured within the reviewed literature. Nevertheless, the most severe negative impact (considering both scale and likelihood) was found to relate to soil organic carbon (SOC), with lower SOC being observed in fields under inversion tillage compared to those employing reduced or no-till methods [34, 52, 83]. One field study conducted over a period of 20 years in Germany [86] referenced in Ludwig et al. [52], demonstrated that SOC stocks were 5 t ha^{-1} lower under inversion tillage compared to reduced tillage. The loss of SOC due to inversion tillage consequently results in higher CO_2 emissions [83]. However, one positive impact of inversion tillage was found to be a reduction in N_2O emissions from soils that have undergone inversion tillage [22, 34, 39], with one meta-analysis [39] stating an increase of N_2O emissions by 10.4% under no-till methods compared to inversion tillage. Although, measurement of SOC, alongside other aspects such as N_2O emissions, can often be challenging and inconsistent which has led to highly variable results (see climate section in discussion below).

Biotic impacts

The effect of inversion tillage on six different biotic categories were assessed: vertebrates, aquatic organisms, bees and arthropods, earthworms, soil microorganisms and terrestrial plants. The review identified that inversion tillage can negatively impact all of the biotic categories evaluated, with most categories scoring very highly for likelihood and also having the most severe negative rating for scale of impact (i.e., − 2).

Vertebrates

The negative impacts identified for vertebrates were linked to limited food resources as a direct result of inversion tillage. The abundance of birds and small mammal species was found to be reduced in fields under inversion tillage, due to a lack of food resources and habitat disruption from the burial of seeds and crop debris [15, 28, 84, 97]. In one field study in northern France [7] it was observed that wheat and oilseed rape fields managed under conservation tillage (i.e., reduced or no-till), when combined with a cover crop, saw increases in the abundance of five bird species with 2.3–4.1 times more individuals compared with fields managed with inversion tillage. However, when herbicides were applied instead of cover crops in the conservation tillage systems, different results emerged with increases in abundance not consistent across all bird species. In this second comparison, there were both positive and negative abundance findings, with two species recorded with higher abundance by 2.1–2.2 times in fields managed with inversion tillage compared with conservation tillage [7]. In a further study focused on semi-natural habitat loss [36], populations of owls and other predatory birds were shown to decline because of lowered prey species availability under inversion tillage. These findings suggest that inversion tillage can have a negative effect across the food chain of vertebrate species.

Aquatic organisms

The literature did not identify any direct impacts to aquatic organisms from inversion tillage practices, mostly because aquatic organisms are not present where inversion tillage occurs. However, aquatic organisms are indirectly affected by run-off into nearby waterways, associated with inversion tillage (see water category above) [78, 83]. However, the literature suggested that different forms of inversion tillage can impact the extent of run-off in different ways, affecting the impacts on aquatic organisms. Chisel ploughing has been shown to incorporate organic manures more comprehensively into the soil than manure applied to the soil surface in a no-till system, reducing the direct runoff of phosphorous immediately after application [59]. However, as inversion tillage causes soil erosion over the long term (see soil category above), sediment becomes a component of agricultural runoff, which can lead to increased levels of phosphorous entering watercourses [4, 72, 78, 91]. Increased levels of phosphorous lead to eutrophication and associated negative impacts on aquatic organisms [72, 78].

Bees and other arthropods

Overall, inversion tillage was found to have an adverse effect on bees and other arthropods [3, 9, 15, 16, 35, 41, 48, 69, 89, 96]. The soil is heavily disturbed by inversion tillage which can destroy habitats and directly injure or kill arthropods in the soil [3]. Nest location was identified as a key factor for negative impacts on bees, with species that nest above-ground in agricultural fields found to be 9 times more negatively impacted by inversion tillage than species which do not nest in these areas [96]. Furthermore, arthropods unable to fly or those which undergo a larval stage in the soil are significantly negatively impacted, with one study [16] reporting a 50% reduction in sawfly emergence under inversion tillage due to the larval stage being directly affected by soil disturbance. Some selectivity in the impacts were able to be identified. While populations of larger beetles and other arthropod species, such as spiders and centipedes, were negatively impacted by inversion tillage [41, 46, 69], small carabid beetles were found to increase in abundance [9, 35, 46]. This was supported by further studies suggesting that smaller carabid beetles are able to tolerate inversion tillage events and can even thrive under these conditions [35, 69].

Earthworms

The impacts on earthworms varied greatly according to the specific species considered. Epigeic earthworm species that live within organic matter in the topsoil layer, which are small and do not burrow, were found to benefit from inversion tillage due to increased incorporation of surface debris [21, 75]. However, the larger burrowing anecic earthworm species were found to be detrimentally affected by inversion tillage, with greater anecic earthworm biomass identified under no-till or reduced tillage [16, 21, 60, 66, 68, 75]. Anecic earthworms can suffer injuries and death from direct contact with the mouldboard plough during inversion tillage, while their burrows can be destroyed during the process [21, 60, 66, 68]. Indirect impacts on soil and water were also able to be linked to reductions of anecic earthworm biomass [20, 83]. Burrows from anecic earthworms create pores that improve hydrological processes, which allow water to move through the soil [68]. Therefore, a reduction in anecic biomass could lead to reduced soil porosity in the field, increasing the risk of surface runoff.

Soil microorganisms

In most cases, inversion tillage was found to have an adverse effect on soil microorganism populations, however, whether the impacts can be considered positive or negative depends on the specific microorganism (e.g., beneficial or harmful) in question, goals (e.g., pest reduction, biodiversity) and perspectives (i.e., farmer, ecologist). The high level of disturbance from inversion tillage leads to the disruption of the life cycles of certain pests and diseases [43, 56], which is beneficial to farmers as it provides an element of crop protection. However, this disturbance also impacts beneficial microorganisms, such as fungal and bacterial populations. From the review, 12 studies reported substantial reductions in microbial activity under ploughing [5, 6, 8, 11, 34, 49, 53, 64, 74, 80, 88, 94]. This can be detrimental to overall soil health, especially if the abundance of arbuscular mycorrhizal fungi or beneficial bacteria are reduced [74, 94]. A degree of selectivity was identified within the literature. One study by Shi et al. [80] demonstrated that effects of tillage on microbiota can vary throughout the year depending on other environmental conditions (e.g., moisture). Therefore, the aforementioned adverse effects on microorganisms may not remain constant during the year.

Terrestrial plants

When assessing the impacts of inversion tillage on terrestrial plants, the most frequently cited benefit within the reviewed literature was the reduced weed burden as a result of the burial of weed seeds preventing germination [26, 38, 56]. In a 3-year comparative field study, the quantity of weed seeds within the 0–20 cm topsoil layer was found to be 68% lower under inversion tillage compared to no-till [26]. Inversion tillage can be used to provide a clean seed bed to assist in successful crop establishment, with reduced seed return further reducing the spread of weed seeds from mature plants via wind or animal transmission, ultimately lowering the weed burden [38]. From a farmer's perspective, this impact is significantly beneficial for weed control and is considered to be one of the main merits of inversion tillage [13, 58], however from an ecological perspective this may be a negative impact because it is reducing the plant species diversity in the field.

Discussion

When examining inversion tillage using the modified REA approach, at least ten papers were reviewed for all of the assessed environmental categories. Overall, the quality of literature (see Table 2) reviewed was scored as high, with meta-analyses able to be identified for all environmental categories except for terrestrial plants. However, despite the abundance of relevant literature and high quality of research, a number of genuine data gaps were identified, most notably in relation to aquatic organisms. This reflected cases where inversion tillage only had indirect impacts associated with a category, which in some instances needed to be inferred from the available evidence. For example, the observation of increased runoff from the use of inversion tillage leading to increased risk of eutrophication in nearby waterways [83]. It should be noted that the selection of just ten papers per category also meant there was a risk of gaps not being addressed due to the rapid nature of the process.

Abiotic impacts

Soil and water

The REA approach identified research that overlapped the different environmental categories, with changes to soil structure often directly affecting water quality and quantity. Several of the papers identified for the water category did not focus primarily on the direct impacts that inversion tillage has on water quantity or quality, instead these were discussed indirectly as a result of soil changes. For example, Indoria et al. [40] reviewed the impacts of conservation tillage, which aims to minimise soil disturbance, and identified that this results in increased soil aeration and porosity, which subsequently improves soil water infiltration and reduces surface runoff, compared to inversion tillage. Other papers supported this finding, with inversion tillage resulting in 2 mm h^{-1} lower hydraulic conductivity compared to no-till [87], with average annual run-off also being 37 mm higher under inversion tillage [83].

The REA approach was particularly effective for assessing the soil category, primarily due to the extensive number of papers that have been published over many years on the impact of inversion tillage on soil. As a result, all of the papers reviewed for soil were of high or very high quality, with no observed data gaps. For the water category, the quality of the literature reviewed was also scored as high. However, due to the generally lower context relevance and geographical applicability (i.e., global application rather than European specific) of the sources reviewed, the overall research quality score was scored as moderate. Sufficient information on the effects of inversion tillage upon water quality was able to be collected, with only one knowledge gap identified, which concerned the impacts of agro-chemical run-off as a result of inversion tillage on water quality. A more detailed review would be required to target and fully assess the impacts of this data gap, such as accessing grey literature and government advice programs. The results of the REA also suggested that climatic conditions (e.g., arid) can influence the extent of soil water retention from different tillage approaches [40], however, the papers identified did not provide any further insight into how this occurs. In this instance, additional, targeted searches with more specific search terms would have benefitted the approach and filled this knowledge gap.

Air quality

The REA approach demonstrated some overlap between the air quality and soil categories. There were several studies identified in the review process for the soil category which indicated that inversion tillage increases the risk of soil erosion by loosening the topsoil layer [18, 19, 38, 50]. While for air quality, increased soil erosion from the mechanical disturbance of the soil was attributed to increases in sediment fluxes and particulate matter emissions [44, 51, 79].

For the air quality category, the overall quality of the ten papers was scored as moderate. This is primarily due to lower geographical applicability as the majority of the studies were situated in semi-arid or arid regions. The overall research quality was also scored as moderate, as only two review papers were identified. Nevertheless, suitable information was found relating to the impacts of inversion tillage on air quality, with only limited data gaps identified. The focus of the studies on arid regions indicated that there is a data gap concerning the effects of inversion tillage on air quality in the temperate regions of Northern Europe. This is especially important as the results of the REA indicated that arid conditions contribute to increased PM and dust emissions due to reduced soil moisture [37, 44]. Additionally, none of the papers identified in this REA discussed the implications of emissions from tillage machinery and subsequent fuel consumption on air quality. To address these knowledge gaps, the review would benefit from additional targeted searches.

Climate

Within the climate impact category different aspects were considered when reviewing the findings (GHG emissions, carbon sequestration, and resilience), but only ten sources were reviewed in total. The quality of the papers collected for this category was scored as moderate, with the relevance of context and geographical region being highly variable across the sources. In comparison to the other environmental categories, the papers reviewed for climate presented a greater amount of conflicting information. For instance, one of the positive impacts identified was a reduction in N_2O emissions; a review of four European field studies in Soane et al. [83] estimated lower N_2O emissions under inversion tillage (compared to no-till) in three out of four cases, with N_2O loss between 21 and 69% lower. This finding was supported by two other review papers, with this effect being attributed to lower soil moisture levels and a lack of crop residues on the soil surface [22, 39]. However, given the sensitivity of N_2O emissions to soil moisture and the variability in soil moisture under inversion tillage [39], these observations need to be treated with caution when viewed in isolation. In this instance, the REA approach did not provide sufficient breadth of information, collecting more than ten papers would have provided better scope for understanding more complex issues.

Similarly, there was some discourse surrounding the effect of inversion tillage on soil organic carbon (SOC) levels. A study by Feng et al. [27] suggested that deep inversion tillage can increase carbon sequestration and improve SOC stocks in the upper 20 cm of the soil, with another study demonstrating that CO_2 emissions from soils under inversion tillage can be up to 22% lower than no-till [83]. However, this was attributed to specific climatic conditions, with unusually high temperatures in Northern France increasing the rate of decomposition of crop debris on the soil surface [63] referenced in [83]. The majority of papers collected indicated that inversion tillage results in significantly reduced SOC levels compared to no-till methods [8, 34, 45, 52, 55, 57, 90]. For example, it was demonstrated by a 30-year study that inversion tillage can reduce SOC by up to 30% in dryland cropping systems [8]. Nevertheless, SOC levels and subsequent CO_2 emissions involve a range of complex interactions between different factors, such as rainfall, soil water content, temperature, crop residues, and soil organic matter [83]. Therefore, it is hard to determine from the restricted scope of this study what the short and long-term effects of inversion tillage (in isolation) are on CO_2 emissions.

In relation to climate resilience, there was a general knowledge gap in our findings. Only two papers mentioned the effects of inversion tillage on resilience in relation to drought tolerance, with one stating that resilience is improved by inversion tillage [76] and the other indicating that resilience is reduced [8]. The REA approach would need to be expanded and applied individually to the specific elements of climate to identify sufficient papers relating to resilience. Similar to this, another knowledge gap was identified about the fuel usage and GHG emissions of tillage equipment, which can also be attributed to the broad search terms used in the REA approach.

Biotic impacts

The quality of the papers collected for the biotic impact categories were scored as moderate or high in most cases, except for aquatic organisms, which was scored as low. This was due to some difficulty in collecting papers that had suitable relevance of context, as aquatic organisms are only indirectly affected by inversion tillage as a result of run-off into nearby waterways [78, 83]. However, the REA approach was still fairly effective for determining an overview of the environmental impacts, with sufficient data able to be extracted from the papers for all of the categories.

The REA approach demonstrated significant overlap between the soil microorganisms category and the soil category. Several studies indicated that inversion tillage significantly reduced soil microbial activity, with fewer bacterial and fungal species being present in the soil [5, 11, 49, 64, 74, 80, 88, 94]. Consequently, this is detrimental to soil health, as reduced fungal growth has negative implications for organic matter and aggregate stability in the soil [8], which were issues that were also identified under the soil category. The REA approach showed that certain categories, cannot easily be studied in isolation as one category often impacts, or is influenced, by another. The approach is, therefore, most effective when considering topics that already have a wide range of published literature spanning many years, with the approach useful for uncovering and summarising some of the more complex interactions between different environmental categories as a result of inversion tillage.

The review demonstrated that consideration of the benefits and trade-offs for biotic categories is highly dependent on the specific goals (e.g., pest reduction, biodiversity) and perspectives (i.e., farmer, ecologist) of the review. While the reduction of weed abundance could be considered a benefit to farmers, from an ecological perspective this could be a negative impact as the plant species diversity in the field has been reduced. These conflicting goals must be made clear when assessing the outputs of the REA approach.

Summary

The REA approach facilitated efficient compilation of the environmental implications of agricultural tools, highlighting nuances of these different impacts in relation to their direct or indirect effect and their selectivity. Due to the concessions in the amount of literature gathered and reviewed using this approach, a few data gaps were identified that would require additional research to address. Although, increasing the number of sources per category would have reduced the efficiency of the REA approach. The provision of extra time to find and evaluate more papers may yield more robust results and minimise data gaps, however, for the slightly more niche categories (e.g., aquatic organisms), the collection of additional papers relevant to the research question may not be possible due to genuine gaps in existing research.

While the robustness of the literature identified varied between the different environmental categories with differing availability of meta-analyses and reviews, the overall quality of the papers was scored from moderate to high for nine out of ten categories. The exception, aquatic organisms, was scored as low as these are not present where inversion tillage occurs. Only two categories (water and climate) had ten papers that were all either meta-analyses or reviews (rather than individual articles) demonstrating that ten meta-analyses and reviews for each category is not always possible. Nevertheless, the REA approach worked effectively for the inversion tillage tool, as the desired total of 100 relevant papers (ten papers for each of the ten categories) were able to be reviewed. The approach could benefit from further disaggregation for the multi-faceted categories (e.g., climate, water) to ensure that sufficient findings and nuance can be collected from the review process for all aspects. The isolation of agricultural tools in the approach would also benefit from further holistic consideration where different questions are asked and thus, reveal a wider array of literature.

Further development

This initial phase of research is being complimented by a second phase of the project (not presented) that aims to explore the environmental implications and interactions of combinations of tools applied within production systems. The first system under consideration is conservation agriculture, with a focus on wheat production in temperate climates (e.g., comparable to Central Europe), to explore the environmental benefits and limitations of that specific system. It is expected that this two-phase literature review methodology can increase transparency around the environmental implications of production systems, disclosing both synergies and trade-offs. The assessment of the different tools across the same categories can finally support pathways to broadly increase the sustainability of cropping systems by informing cost–benefit frameworks.

Conclusion

The use of this modified REA approach to assess the environmental impacts of agricultural tools, which was inspired by the categories of environmental risk assessments of plant protection products, was highly effective at identifying a wide range of abiotic and biotic impacts in a resource efficient manner. It enabled rapid identification of the primary issues for environmental sustainability to guide further detailed study. The modified REA approach was able to demonstrate that inversion tillage has either direct or indirect impacts (or both), positive or negative (or both), for all of the abiotic and biotic categories assessed, as well as determining their degree of selectivity for different species or conditions where applicable.

A small number of positive impacts were observed, with inversion tillage offering effective weed control through the burial of weed seeds, which reduces the amount of herbicide required. By reducing topsoil compaction and incorporating crop residues, the practice creates a loose stale seedbed to sow crops. However, inversion tillage was identified to be particularly detrimental to physical soil health, especially in the long term. The negative effects of inversion tillage on soil structure, such as reduced soil organic matter, reduced aggregate stability and increased subsoil compaction, have negative implications for several other categories assessed both infield and outfield. Infield issues including greater levels of soil erosion and reduced water infiltration, which can negatively affect air quality as well as the quality of waterways outfield through increased nutrient leaching and sediment run-off, presenting further risks to aquatic organisms through eutrophication. The extensive disruption of biotic habitats from the mechanical process of inversion tillage can negatively affect several biotic categories directly infield and further impacts surrounding food chains through the reduction of food resources.

By isolating and evaluating various agricultural tools under this risk assessment categories-inspired REA, we were able to present a holistic approach to the identification of key environmental impacts that enables links between abiotic and biotic impacts to be quickly established. The consistent and balanced approach to the review of a wide range of environmental impact categories provided broad and nuanced perspectives to identify the most prominent opportunities and trade-offs. Providing a rapid screen of the evidence across a range of environmental categories for a range of agricultural tools can support the agriculture sector to identify the benefits and trade-offs when introducing new practices, such as shifting from conventional production to conservation tillage or regenerative practices. From these evidence reviews informed decisions can be made on the optimal practices to adopt to minimise negative environmental impacts in complex systems. While some data gaps were identified using the modified REA approach, the broad considerations of the approach can be used as the first step to provide rationale for subsequent detailed reviews or for commissioning further novel research.

In this paper, we have presented the first phase of a two-phase evidence review methodology, which aimed to isolate the environmental impacts of individual agricultural tools. This work will be supplemented by a second ongoing phase of work that considers the interactions of tool combinations typically applied within particular production systems (e.g., conservation agriculture). It is anticipated that through this combined approach, we will be able to build a better and more holistic understanding of the agronomic and environmental implications of different management options to enable farmers to make better informed decisions, as to both the effectiveness of the practice at managing weeds, pests or diseases, and the environmental implication of applying that tool. The modified REA methodology can also be used as starting point to inform and broaden the scope of more comprehensive environmental impact assessments performed to guide key policy decisions, with the aim to consider the environmental trade-offs of agricultural practices alongside those identified for chemical tool applications.

Abbreviations

GHG	Greenhouse gas
REA	Rapid evidence assessment
SOC	Soil organic carbon

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LG, SW and CB were responsible for the conception, design and editing of this work. LG, EW and EJ were responsible for data analysis and interpretation, as well as revisions of the work. All the authors have read and approved the final manuscript.

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Availability of data and materials

The data generated during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

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