Qualitative Impact Assessment of Land Management Interventions on Ecosystem Services ("QEIA")

Report-3 Theme-3: Soils

30-June-2023

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Citation

How to cite (long)

Newell Price, J.P., Williams, A.P., Bentley L. & Williams, J.R. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-3: Soils. (Defra ECM_62324/UKCEH 08044)

How to cite (short)

Newell-Price, J.P. et al (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-3: Soils. (Defra ECM_62324/UKCEH 08044)

This report is one of a set of reviews by theme:

Braban, C.F., Nemitz, E., Drewer, J. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA").* Report-3 Theme-1: Air Quality (Defra ECM_62324/UKCEH 08044)

Birnie, J., Magowan, E., Law, R., Lucas, O.T., Hassin, A.E.J. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA").* Report-3 Theme-2: Greenhouse Gases (GHG) (Defra ECM_62324/UKCEH 08044)

Newell Price, J.P., Williams, A.P., Bentley L. & Williams, J.R. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-3: Soils (Defra ECM_62324/UKCEH 08044)

Williams, J.R., Newell Price, J.P., Williams, A.P., Bowes, M.J., Hutchins, M.G. & Qu, Y. et al. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3, Theme-4: Water (Defra ECM_62324/UKCEH 08044)

Staley, J.T., Botham, M.S., Broughton, R.K., Carvell, C., Pywell, R.F., Wagner, M. & Woodcock, B.A. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-5A: Biodiversity - Cropland (Defra ECM_62324/UKCEH 08044)

Keenleyside, C.B. & Costa Domingo, G. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-5B: Biodiversity - Grassland (Defra ECM_62324/UKCEH 08044)

Maskell, L. & Norton, L. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-5C: Biodiversity - Semi-Natural Habitats (Defra ECM_62324/UKCEH 08044)

Siriwardena, G.M. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-5D: Biodiversity - Integrated System-Based Actions (Defra ECM_62324/UKCEH 08044)

Bentley, L., Feeney, C., Matthews, R., Evans, C.D., Garbutt, R.A., Thomson, A. & Emmett, B.A. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-6: Carbon Sequestration (Defra ECM_62324/UKCEH 08044)

Short, C., Dwyer, J., Fletcher, D., Gaskell P., Goodenough, A., Urquhart, J., McGowan, A.J., Jones, L. & Emmett, B.A. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3.7: Cultural Services (Defra ECM_62324/UKCEH 08044)

A list of all references used in the reports is also available as a separate database.

Foreword

The focus of this project was to provide a rapid qualitative assessment of land management interventions on Ecosystem Services (ES) proposed for inclusion in Environmental Land Management (ELM) schemes. This involved a review of the current evidence base by ten expert teams drawn from the independent research community in a consistent series of ten Evidence Reviews. These reviews were undertaken rapidly at Defra's request and together captured more than 2000 individual sources of evidence. These reviews were then used to inform an Integrated Assessment (IA) to provide a more accessible summary of these evidence reviews with a focus on capturing the actions with the greatest potential magnitude of change for the intended ES and their potential co-benefits and trade-offs across the Ecosystem Services and Ecosystem Services Indicators.

The final IA table captured scores for 741 actions across 8 Themes, 33 ES and 53 ES-indicators. This produced a total possible matrix of 39,273 scores. It should be noted that this piece of work is just one element of the wider underpinning work Defra has commissioned to support the development of the ELM schemes. The project was carried out in two phases with the environmental and provisioning services commissioned in Phase 1 and cultural and regulatory services in a follow-on Phase 2.

Due to the urgency of the need for these evidence reviews, there was insufficient time for systematic reviews and therefore the reviews relied on the knowledge of the team of the peer reviewed and grey literature with some rapid additional checking of recent reports and papers. This limitation of the review process was clearly explained and understood by Defra. The review presented here is one of the ten evidence reviews which informed the IA.

Acknowledgments

This project work and the resultant reports and databases were made possible by funding from the Department of Environment, Food and Rural Affairs, under contract ECM_62324. UKCEH and all the project participants are very grateful for the support we have received from DEFRA colleagues. In particular we would like to thank Tracie Evans, Hayden Martin, Daryl Hughes, Chris Beedie and Catherine Klein for their support and constructive inputs to the exercise. We would also like to thank our numerous external contributors and reviewers, some of whom have chosen to remain behind the scenes, and we are very grateful for the expansive and meticulous body of peer-reviewed evidence our authors have been able to refer to and make use of.

Contents

INDEX OF ACTION CODES IN THIS REPORT

1 INTRODUCTION

Defra have commissioned a UKCEH-led consortium to assess the evidence base to inform the priority actions which should be considered for future land management policy. This work provides the logic and evidence to support land management actions using a rapid, expert approach.

The specific objectives of this short project were to provide a rapid expert assessment of the impact of land management actions, currently under consideration for inclusion in Environmental Land Management (ELM) schemes on ecosystem services and to highlight key considerations which are important for determining which actions should be included in future land management schemes (e.g. displacement risk, spatial variables, etc.).

This report focuses on actions that were considered by Defra to have a positive benefit for soil conservation (extent of soil erosion - principally by water, but wind erosion is also considered) and soil health (increased soil organic matter, reduced soil contamination, increased soil biodiversity and improved soil structure, including less soil compaction). Soi structure is defined as the size, shape, and stability of soil units (called aggregates, blocks or peds) and soil pores.

Full assessments, including considerations such as causality, magnitude of effect, climate constraints, displacement issues and barriers for uptake were caried out for a short list of actions in section 3. The soil conservation and soil health co-benefits and trade-offs for a longer list of measures is considered in section 4. Sections 5 and 6 will summarise key action gaps and evidence gaps for future research (to be completed). Section 4 will provide recommendations, based on expert judgement, on the key land management actions which are fundamental for reversing soil degradation (and therefore should be considered for inclusion in ELM schemes). This data will feed into the development of farm 'standards' within the Sustainable Farming Incentive scheme; option development for the Local Nature Recovery scheme and project selection for the Landscape Recovery scheme.

Any action that provides soil surface cover at times of intense and/or prolonged rainfall, particularly when soils are 'wet' in autumn to early spring, will protect soil from water erosion. Vegetation and residue covers of 30-40% in autumn can have a significant impact in reducing soil erosion rates by 20-80% (Chambers et al., 2000), while higher covers of >60-70% can reduce the erosion rate by 50-90% (Niziolomski, 2014). They can also protect soil from wind erosion. Soil erosion can also be associated with soil carbon loss, although the fate of carbon stocks that are lost to erosion is variable (Quinton et al., 2010).

Actions that improve soil structure, infiltration and soil water storage can further reduce erosion risk. Growing a crop of any kind, whether that be a cash crop, cover crop, catch crop, green manure or grass ley can also contribute towards sequestering carbon (C) from the atmosphere and storing it in the soil. The longer the period of leaf growth, root growth and photosynthetic activity, the greater the C sequestration and storage potential and the greater the likelihood that the vegetation will also improve soil structure and potentially increase soil biodiversity. Increasing soil organic C contents through such sustainable soil management (SSM) practices can improve soil health, the efficiency of food production and the delivery of multiple public goods and services.

These are some of the principles that can guide action selection.

Actions are assessed in terms of whether they have major, moderate or limited benefits to soil erosion control and soil health. A major benefit signifies that the action can make a significant contribution to service provision (as measured using environmental indicators) towards the top of the range in terms of what is possible using land management practices. A moderate benefit signifies that the impact is typically in the mid-range of what is possible through changing land management or land use. This could be represented by the 25th to 75th percentile. A limited benefit means that a clear positive benefit can be detected or modelled, but that the effect is small and in the lower quartile of what is possible using land management practices. In some of the co-benefit sections, which describe the impact of actions on other ecosystem services and outcomes, cross references to other reports are provided, e.g. "TOCB Report-3-5D Systems **ECCM-021**" refers to action ECCM-021 in report 3, theme 5D ['TOCB' is trade-off/co-benefit].

2 Outcomes

The soil-related outcomes covered in this report are listed in the table below.

Service	*Suggested indicator for services flow*
Soil Conservation	Extent of erosion
Soil health	Increased soil carbon (as an indicator of soil organic matter content)[1]
Soil health	Reduced soil contamination
Soil health	Increased soil biodiversity
Soil health	Improved soil structure, including compaction

[1] It has been customary to assume that soil organic matter (SOM) is 58% carbon (C), hence the conversion of C to SOM using a multiplication factor of 1.724. However, more recent work shows the C content of SOM is variable and 50% is a more accurate mean, hence the conversion factor is now generally accepted to be 'x 2'. See: Pribyl, D.W. (2010). A critical review of the conventional SOC to SOM conversion factor. Geoderma 156, 75– 83.

3 Management Bundles

The actions fully assessed in this report for their soil conservation and soil health benefits are presented grouped in the following management bundles and sub-bundles. Soil management and protection actions not fully assessed in this report are fully assessed in the "Water" report (Report 3; Theme 4) or the "Carbon" report (Report 3; Theme 6) or the "Biodiversity – Cropland" report (Report-3 Theme-5A):

1. Systems action

Restoration, management and enhancement /Cropland	**ECCM-021A** - Farm perennial crops (conversion of annual crops to perennial crops) **ECCM-021B** - Farm perennial crops (maintain farm perennial crops) **ECPW-232** - Avoid growing crops with high risk of nutrient losses (e.g., field vegetables) in fields with high risk of soil erosion or close to sensitive sites

2. Soil management and protection

Tillage	**ECPW-242** - Use direct drilling into crop stubble or cover crops **ETPW-092** - Use minimum-tillage or no-tillage cultivation
Compaction management	**ETPW-223** - Assess soil structure and plan how to avoid and alleviate soil damage and compaction (soil management plan) **ECPW-003** - Avoid cultivation and trafficking on wet soils **ECPW-255** - Reduce weight of field machinery **EHAZ-017** - Use low ground pressure tyres **EHAZ-031** - Use controlled traffic farming (CTF) **ECPW-249** - Reduce grazing and stocking rates when soils are wet to avoid soil compaction
Cover cropping	**ECPW-025** - Harvest and establish the following crop early in the autumn

	ECAR-044 - Ensure persistent continuous vegetation cover on land **ECCM-023** - Use green manures within the rotation **ECPW-279** - Use of cover crops as an alternative to plastic mulch - Soil-enriching cover crops may be grown over the winter in the same beds where a food crop is to be planted the following spring and used in place of mulch **ETPW-251** - Use grass waterways in crops with high risk of soil erosion and run off (e.g., field vegetables) **ECPW-028** - Enhanced management of maize including early harvest, use of early maturing varieties, early planting times and establishment of a cover crop **ECPW-005** - Use restorative vegetation cover following destoning or lifting of root crops **ETPW-270** - Re-seed grassland by slot-seeding or over-seeding
Manure and mulch management	**EHAZ-113** - Use mulches and organic matter to increase the water retention capacity of soil

3. Drainage, irrigation and wastewater

Drainage	**ECCM-005** - Restore or enhance land drainage on mineral soils

4. Fertiliser, nutrient and manure management

Spatially test soils	**ECPW-299** - Spatially test soils within field for any or all the following: N, P, K, Mg, pH, micronutrients, potentially toxic elements and organic matter.

5. Litter and plastic waste

Use of biodegradable materials	**ECPW-281** - Use of biodegradable silage, crop cover mulches and planting trays to meet recognised compostable standard EN17033

3.1 Systems Actions

Three Systems actions are covered in the report; all three actions concern the "Restoration, management and enhancement" of land:

- **ECCM-021A** - Farm perennial crops (conversion of annual crops to perennial crops)
- **ECCM-021B** - Farm perennial crops (maintain farm perennial crops)
- **ECPW-232** - Avoid growing crops with high risk of nutrient losses (e.g. field vegetables) in fields with high risk of soil erosion or close to sensitive sites

3.1.1 Restoration, management and enhancement /Cropland
ECCM-021A - Farm perennial crops (conversion of annual crops to perennial crops)

This action covers the conversion of annual cropping to perennial cropping. This includes both food (fruit, nuts, horticultural crops and potentially novel grain crops like Kernza) and non-food crops such as short rotation coppice (SRC) and Miscanthus. For perennial food crops, Jaikumar et al. (2012) have assessed the agronomic potential of perennial rye and perennial wheat; and Curwen-McAdams and Jones (2017) have investigated the breeding of perennial grain crops based on wheat. However, yields to date have typically been low (50 to 73% of yields from annual grain crops) and perennial wheat requires further selection for allocation of biomass to grain and vigorous regrowth (Jaikumar et al., 2012), while perennial rye faces issues of winter survival and wed competition in cold temperate conditions (Daly et al., 2021).

3.1.1.1 Causality

Conversion from annual cropping to perennial crops that are established and maintained for at least 10 years can result in increases in topsoil and subsoil carbon (Ledo et al., 2020). This increase in SOC would be expected to translate into improvements in soil structure and function (Neal et al., 2020). However, it would depend on the perennial crop and how it is managed. For example, some horticultural perennial crops (e.g. asparagus) present significant risks for soil compaction, runoff and soil erosion (e.g. Niziolomski, 2014; AHDB CP 107C).

- The **extent of soil erosion** would most likely be reduced but it depends on which perennial crops are grown. Having a permanent vegetative cover, compared with periods of bare soil in late autumn, which is typical of some winter cereal land, can result in significant (> 50%) reductions in field-scale erosion rates and hence a reduction in erosion extent (e.g. Chambers et al., 2000).
- The action could result in a potential 20% **increase in SOC** at 0–30 cm over twenty years (Ledo et al., 2020).
- **Reduced soil contamination** – there is unlikely to be any change in soil contamination unless there is a change in use of plastic or other mulches. Some annual and perennial crops can benefit from the use of a plastic mulch. There may be opportunities to reduce the level of environmental pollutants in some agricultural soils through phytoremediation (Prabha et al., 2021).
- **Increased soil biodiversity** – soil biodiversity is likely to increase on the area converted to perennial crops, but consider displacement issues (see section 3.1.1.1.6), which could impact on biodiversity elsewhere.
- **Improved soil structure, including compaction –** soil structure is likely to be improved in line with SOC increases, with likely improvements in aggregate stability and associated pore connectivity (e.g. Kautz al., 2014). However, there could be some slight increases in soil bulk density (Ledo et al., 2020).

3.1.1.2 Co-Benefits and Trade-offs

The main consideration for a "perennialization strategy" is the balance of crop and food products that result from the transition as well as the yields and revenues achieved. It is important that the conversion to perennial crops does not result in displacement of annual crop production to less productive and/or suitable regions (with higher risks of soil degradation and potential loss of sensitive and vital habitats) or a reduction in crop yield.

Both consequences could have significant negative implications for food security and biodiversity. Nevertheless, an assessment of the FAO "perennialization strategy" by Ledo et al. (2020), using a harmonised global dataset, was mainly positive:

> "*a 20-year period encompassing a change from annual to perennial crops led to an average 20% increase in SOC at 0–30 cm (6.0 ± 4.6 Mg/ha gain) and a total 10% increase over the 0–100 cm soil profile (5.7 ± 10.9 Mg/ha). A change from natural pasture* (a natural ecosystem grazed by large herbivores) *to perennial crop decreased SOC stocks by 1% over 0–30 cm (−2.5 ± 4.2 Mg/ha) and 10% over 0–100 cm (−13.6 ± 8.9 Mg/ha)… Perennial crops generally accumulate SOC through time, especially woody crops; and* [air] *temperature was the main driver explaining differences in SOC dynamics, followed by crop age, soil bulk density, clay content, and depth. We present empirical evidence showing that the FAO perennialization strategy is reasonable, underscoring the role of perennial crops as a useful component of climate change mitigation strategies*." (Ledo et al., 2020)

[TOCB Report-3-5D Systems **ECCM-021**] Assuming that this refers to farming these crops instead of standard, annual, arable crops, there has been little or no relevant research, and insufficient roll-out to date for biodiversity effects to be detectable using monitoring data. From ecological principles, we would expect a combination of positive and negative effects on key species.

3.1.1.3 Magnitude

- Extent of erosion – a change from annual cropping to perennial could result in a > 50% reduction in soil erosion within the fields concerned, although this is only likely to be the case in perennial crops where vegetation cover is close to 100% throughout the year. This is supported by the crop (or 'C') of the Universal Soil Loss Equation (USLE - a ratio of soil loss under vegetation versus bare soil) which gives a reduction of >50% under this scenario (all other factors being equal; Wischmeier et al., 1978). Equally, a change from grassland to a perennial crop could increase the risk of erosion on the land in question. This is supported by comparative USLE C factors under grassland (C = 0.015), cultivated grass (C = 0.004 - 0.01) and vines (an example of a perennial crop; C = 0.15 - 0.6).
- Increased soil carbon – a change from annual to perennial cropping can typically result in a 20% increase in SOC at 0–30 cm depth and a total 10% increase over the 0–100 cm soil profile.
- Reduced soil contamination – any change (an increase or decrease) would relate to a change in the use of plastic or other mulches to enhance crop growth and control weeds.
- Increased soil biodiversity – cultivation can impact earthworm and fungal hyphae numbers (e.g. Kautz et al., 2014; Beare et al., 1993). A change from annual to perennial cropping is therefore likely to increase (potentially double) earthworm numbers (due to reduced soil disturbance and increased quantities of plant residue); increase the fungi to bacteria ratio and the complexity of the soil food web (De Vries & Wallenstein, 2017).
- Improved soil structure, including less soil compaction – 20% improvements in topsoil SOC and increases in pore connectivity are likely to be translated into improvements in soil functions such as regulating water and air flows into and within the soil (leading to better soil moisture status, water retention and drainage) and supporting plant growth (e.g. Neal et al., 2020), but the direction of change is entirely dependent on the associated change in management from annual to perennial cropping. Some perennial crops, such as asparagus can result in higher soil compaction risk if not carefully managed (Niziolomski, 2014).

3.1.1.4 Timescale

A change from annual to perennial cropping should result in measurable impacts associated with increases in SOC within twenty years (Ledo et al., 2020).

3.1.1.5 Spatial Issues

The action is broad scale in nature (i.e. it can potentially be applied in many circumstances at field scale, although land suitability (field scale) and land capability (regional scale) are both important factors), but should be targeted at perennial crops that replace the function and role (in the food system) of the associated annual crop without reducing yield or revenue per hectare. This is likely to require significant investment in research and co-development with farmers and advisers (i.e. a co-innovation approach).

3.1.1.6 Displacement

There are possible displacement and food security issues depending on the viability of perennial grain and other combinable crops. The most significant displacement issues concern the expansion of non-food perennial crops such as SRC and Miscanthus, particularly if grown on the best and most versatile land (Natural England, 2012).

3.1.1.7 Maintenance and Longevity

Given adequate support and advice, the change is likely to be permanent, provided that the cost-base for perennial cropping is equivalent to arable cropping and yields and gross margin are similar.

3.1.1.8 Climate Adaptation or Mitigation

Drought resistance of individual crops could be enhanced by a conversion from annual to perennial crops. Indeed, climate change could favour the production of some perennial crops in England (e.g. vineyards). However, if perennialization of annual crops results in a requirement to grow more of the annual type overseas (due to lower yield of the perennial type), the production of the imported annual crops could be impacted by climate change.

3.1.1.9 Climate Factors / Constraints

- A full land suitability assessment would be needed to determine soil type and climatic thresholds (e.g. ADAS, 2017).
- The action, where suitable, could contribute to climate change mitigation and adaptation, e.g. if more drought resistant crops can be grown.
- Future increased frequency of drought, flood and/or heat stress is a threat to all agricultural production, but perennial crops could have greater resilience to these threats than most (possibly all) annual crops, due to deeper rooting traits, greater permanence of root systems and higher soil organic matter contents.

3.1.1.10 Benefits and Trade-offs to Farmer/L-and manager

- Conversion costs for farmers could be significant, including land preparation, crop maintenance, harvest machinery and post-harvest storage facilities.
- New skills would be required in most cases and, in the early years of uptake, a ‘pioneering’ mindset.
- There could be an opportunity for premiums on the price of some perennial crop products during the early stages of overall adoption. However, in the longer term, if the perennial crop is to replace an annual crop, the base market price for the crop would need to provide an adequate margin over the variable and fixed costs of production.

3.1.1.11 Uptake

- Conversion costs and new skill requirements could be significant barriers to adoption.
- Short-term tenancy issues could also present difficulties for adoption.
- Short-term planning horizons can also be a constraint for land owners, due to the low gross margins associated with many farming businesses.
- For some perennial crops, the conversion would also involve a change in enterprise and associated knowledge and skills.

3.1.1.12 Other Notes

It would be straightforward to monitor the persistence and extent of perennial cropping through remote sensing (e.g. Simms et al. 2014).

More assessment is needed on the potential return on investment and economics of changing land use from annual to perennial cropping.

3.1.2 ECCM-021B - Farm perennial crops (maintain farm perennial crops)

This differs from **ECCM-021A** in that the action supports the maintenance of existing farm perennial crops. These include both food (fruit, nuts, horticultural) and non-food (SRC and Miscanthus) crops.

3.1.2.1 Causality

The principal benefit is in preserving and protecting the existing SOC store, as well as other ecosystem service benefits (supporting biodiversity etc.). See the Causality section for **ECCM-021A** above.

3.1.2.2 Co-Benefits and Trade-offs

Maintaining food and non-food perennial crops can have multiple ecosystem service benefits.

[TOCB Report-3-5D Systems **ECCM-021**] Assuming that this refers to farming these crops instead of standard, annual, arable crops, there has been little or no relevant research, and insufficient roll-out to date for biodiversity effects to be detectable using monitoring data. From ecological principles, we would expect a combination of positive and negative effects on key species.

3.1.2.3 Magnitude

This is an action that maintains the *status quo*, so will preserve existing levels of soil health and conservation. However, the longer the perennial crops have been in place, the more likely soils will be healthier and more resilient.

3.1.2.4 Timescale

Soil health and conservation benefits will be preserved as long as farm perennial crops are maintained. For newly established perennial crops, the increases in soil organic carbon (SOC) may continue for 100 years or more, although there will be a reduction in the rate of increase and levelling off as a new equilibrium is reached (Ledo et al., 2020).

3.1.2.5 Spatial Issues

Spatial targeting and prioritisation may be relevant as some perennial crops may deliver more ecosystem services than others due to their location and landscape position relative to other terrestrial and aquatic habitats (e.g. orchards could be used to buffer sensitive habitats from more intensively managed annual crops); and the habitat support they provide for specific valued species.

3.1.2.5.1 Displacement

There are unlikely to be any displacement effects from preserving perennial food crops. However, the growing of non-food perennial crops such as SRC and Miscanthus on the best and most versatile land (Natural England, 2012) would represent a lost opportunity for expanding production of fruit and vegetable crops. There may be opportunities to grow SRC, Miscanthus and other non-food perennial crops on former industrial sites as a means of rehabilitating the soils on such sites.

3.1.2.6 Maintenance and Longevity

The action would need to be maintained for at least 30-40 years for it to have the anticipated effects on carbon sequestration and soil health. A return to annual cropping would rapidly reverse many of the benefits gained from perennial cropping (Johnston et al., 2009).

3.1.2.7 Climate Adaptation or Mitigation

Many perennial cropping systems could be susceptible to an increased frequency and duration of waterlogged conditions and drought (Burton and Lim, 2005; Howden et al., 2007). However, well-managed perennial crops (including alleviating soil compaction prior to establishment, timely operations and controlling traffic to some degree) may have better resilience to climate change than many annual crops due to higher soil organic matter content, better soil structure and a more extensive root system.

3.1.2.8 Climate Factors / Constraints

Some perennial cropping systems may become less economically viable in the future due to a greater frequency of extreme conditions and weather events, such as greater frequency and intensity of drought that would require an increased need for irrigation (e.g. in apples or cherries; e.g. Roper & Frank, undated). However, other perennial crops such as vines may benefit from hotter, drier summers (Bindi & Howden, 2004; Jones & Davis, 2000).

3.1.2.9 Benefits and Trade-offs to Farmer/Land manager

The action allows the land manager to maintain the existing production system, so while a degree of adaptation to climate change may be necessary the associated enterprise should remain viable in many cases.

3.1.2.10 Uptake

Maintaining farm perennial crops requires stability and certainty in terms of land tenure and access to markets.

3.1.2.11 Other Notes

Perennial cropping farms would benefit from support and advice to help them adapt to climate change and access markets.

3.1.3 ECPW-232 - Avoid growing crops with high risk of nutrient losses (e.g. field vegetables) in fields with high risk of soil erosion or close to sensitive sites

The growing of some arable and horticultural crops on sloping land, particularly in plough-based cultivation systems and row crops, can result in the soil being left exposed to erosive rainfall. Late harvesting of crops can additionally result in compacted, bare soil in late autumn and early winter when soil erosion risk is very high. Avoiding the growing of such crops on sloping land can reduce the overall risk of soil erosion. Sandy and light silty soils are particularly erosion prone. Sensitive sites are taken to mean sites of high conservation status such as Sites of Special Scientific Interest (SSSIs) or Special Areas of Conservation (SACs).

The action focuses on controlling rill (small channel) rather than wash (rain splash and surface runoff that does not form channels) erosion. Wash erosion takes place a number of times in almost all sloping fields every year, while rill erosion occurs less frequently and is sporadic in time and space due to variations in soil type, rainfall and cropping from year to year (Evans et al., 2016). Between 14 and 48% of 'high risk' farmed landscapes erode to some extent each year (Evans et al., 2016). Most at risk fields erode only once every five years, even if the fields are growing a vulnerable/high risk crop such as vegetables or maize.

Crops with high rates of erosion include (Evans 2005, Evans et al., 2016):

- Field vegetables (especially row crops)
- Maize
- Newly established ley grasses
- Hops
- Sugar beet
- Potatoes

3.1.3.1 Causality

The action can have major, contextually dependent benefits and is likely to have the following impacts:

- **Extent of erosion** would most likely be reduced but depends on which crops are defined as high risk and lower risk. A change from field vegetables to winter cereals could result in similar extent and rates of erosion, although erosion risk is likely to be reduced (Evans et al., 2016). A land use change to permanent grassland or woodland would reduce erosion extent and rates but consider displacement issues (e.g. field vegetables tend to be grown on the best and most versatile land, which is often light- or medium-textured and limited in extent, and displacement could result in these crops being grown on imperfectly drained land that presents other soil degradation issues, such as compaction; or grown overseas).
- **Increased soil carbon** – there is unlikely to be any significant change in soil organic carbon (SOC) unless the land use is changed (e.g. permanent grassland or woodland). An increase in the amount of crop residue returned or period of vegetative cover could result in SOC increases over decades (Poeplau & Don, 2015; Ruis and Blanco-Canqui, 2017).

- **Reduced soil contamination** – there is unlikely to be any change in soil contamination unless plastics are used in field vegetable or maize production but there would be associated displacement issues in that contamination avoided on the land where high risk crops are not grown may occur on land that is required to grow the crop as a result of the displacement.
- **Increased soil biodiversity** – soil biodiversity is unlikely to change unless there is land use change or a reduction in tillage intensity (depth, degree and frequency of cultivation, e.g. Ernst & Emmerling, 2009), but consider displacement issues.
- **Improved soil structure, including compaction** – soil compaction would most likely be reduced in the medium term (5-10 years) with a change in land use (e.g. woodland or extensive grassland; Troldborg et al., 2013) and soil compaction risk would be reduced with a change from late harvested crops (e.g. maize, sugar beet, field vegetables) to combinable crops but consider displacement issues.

The management of high-risk crops results in low vegetation covers (for a significant part of their growth cycle; pre- and post-establishment and post-harvest) and, in many instances, soil compaction over winter. High risk crops such as field vegetables, maize and sugar beet tend to have low vegetation covers and fine seedbeds in the initial stages of crop development and are generally late harvested (in late autumn and, in the case of sugar beet and some field vegetables, over winter). The wetter soils at those times increase the risk of soil compaction and cause wheel ruts that can concentrate surface wash and overland flow on sloping land. Other crops, such as winter cereals are also at risk of erosion in autumn until *c*. 30% vegetation cover has been achieved (Chambers & Garwood, 2000), but because few field operations take place in late autumn and winter, they are less prone to soil compaction and erosion. However, the action does not define 'high risk crops' and does not propose that high risk fields are reverted to grassland.

Changing land use or cropping on erodible land can be effective in reducing soil erosion risk, as illustrated in the following quotes:

- "…in a locality where land use is unchanging there is a 'core' of fields that erodes; other fields do not suffer from rill erosion, presumably because they have a permanent vegetation cover or they are flat, or nearly so, with no breaks of slope… a change in land use may be more likely to determine if soil erosion becomes more extensive and severe. A switch from autumn-sown to spring-sown cereals may have little impact, but a further extension of maize could have a serious impact on both soil and water quality." (Evans et al., 2016).
- "Similarly, if more vegetables or other root crops are grown, the consequences for soil loss are likely to be significant as these crops have a high risk of erosion compared to combinable crops. If grass leys are introduced into the crop rotation to curtail erosion, precautions will need to be taken at time of drilling, for though ley grassland is at very low risk of erosion, when it does erode, erosion can be severe."

3.1.3.2 Co-Benefits and Trade-offs

Associated co-benefits would be expected at the field scale for:

- Water quality
- Soil carbon

[TOCB Report-3-6 *Carbon* **ECPW-232**] Soil erosion is associated with the loss of soil carbon stocks (see section 3.12 in QEIA Report -3-6 *Carbon*), therefore reducing soil erosion will protect below ground carbon stocks, both by reducing losses in any eroded material and by reducing exposure of otherwise buried SOC (e.g. Lal, R., 2005). The Countryside Survey reports a consistent loss of soil organic carbon (by 5.3 t ha^{-1}, from 0-15cm) from arable land between 1978 and 2007 (Emmett et al., 2010). However, carbon being lost via agricultural soil erosion may be being deposited in other habitats resulting in long term sequestration (Quinton et al., 2010).

3.1.3.3 Magnitude

Based on rates of rill erosion in arable fields from SSEW - monitored transects 1982-1986, erosion rates could be reduced by 20-80% (mean = 2.0 t/ha cf. 4.8 t/ha) at the field scale.

Where the change results in increased duration and amount of vegetation and crop residue cover, associated improvements in soil carbon (20-30 years), soil biodiversity (1-5 years) and soil structure (1-5 years) would be expected (e.g. Popelau & Don, 2015).

3.1.3.4 Timescale

Measurable soil erosion control impacts of the action would be expected in 0-5 years. The soil erosion control effect from increasing vegetation and residue cover would be immediate while the effects from improving soil structure (avoiding and alleviating soil compaction) could take up to 5 years.

3.1.3.5 Spatial Issues

The following quotes from Evans et al. (2016) inform how the action should be spatially targeted:

- "*If the principal aim of a policy instrument or management strategy is to curtail runoff and erosion, it will be best to concentrate on those soil landscapes known to be most at risk of soil erosion by water (Evans, 1990), especially in the context of the need for improved spatial targeting of on-farm mitigation measures to help deliver value for money… Best estimates of amounts of soil eroded across soil landscapes indicate that 50 % of the total volume of soil eroded in lowland England and Wales originates from just 14 of 196 soil associations*"
- "*Thirty soil associations account for 79 % of the estimated total volume of soil eroded in lowland England and Wales.*" They "*grow a wide range of crops many of which have inherent risk associated with the timings of bare tilled ground and subsequent harvesting, and the type of crop grown (e.g. high-risk maize, potatoes and salad crops)*."
- "*Techniques to mitigate soil erosion by water… should be targeted at landscapes more at risk of erosion or at fields growing high risk crops, (e.g. root crops, maize, field vegetables) and outdoor pigs*".

Consideration should also be given to the status and sensitivity of local waterbodies, including coastal systems.

The scale at which high risk crops are not grown could also be considered. Soil erosion can be initiated at certain especially vulnerable sites within a landscape, field or group of fields (Najafi et al., 2021). So local surveying to identify such runoff generating and sediment contributing areas could help target actions to particularly sensitive parts of fields.

3.1.3.6 Displacement

There could be displacement issues associated with not growing field vegetables and other high value crops on the best and most versatile land. The issues could be within farms (growing on land less suited to the high value crop), between farms (not growing on high-risk land could make the farm enterprise unviable) or globally (most likely movement of high value crop production overseas where, in some cases, production may be less efficient and pressure on soil and water resources may be higher).

3.1.3.7 Maintenance and Longevity

The new cropping system or land would need to be maintained. Soil conservation effects could be seen within the year of transition or within a few years and would persist as long as the new system is maintained. If the change was from one arable or horticultural system to another the transition may involve commitment to new supply chains and markets so is unlikely to be reversed within a few years unless the transition proved to be uneconomic or impractical.

3.1.3.8 Climate Adaptation or Mitigation

If storms become more intense, more frequent and of longer duration in future (Martel et al., 2021; Seneviratne et al., 2021), a change from a high risk to a lower risk cropping system could result in relatively little change in overall erosion rate and extent (MacLeod et al, 2012). The cropping systems themselves may also be at risk in some parts of the country due to hotter and drier summers and greater need for irrigation (Keay & Hannam, 2020).

3.1.3.9 Climate Factors / Constraints

Cropping systems may be at risk in some parts of the country due to hotter and drier summers in the future and greater need for irrigation, which may make some systems prohibitively expensive or practically unviable (Keay & Hannam, 2020).

3.1.3.10 Benefits and Trade-offs to Farmer/Land-manager

Where the amount of lower erosion risk land is limited on a farm (i.e. the farm only has higher risk land), not growing high value crops on high-risk land could mean that the growing of such a crop, which is at the same time profitable and erosion prone, is not possible at all on the farm. The farmer may then be prevented from running one of the few enterprises that could make the farm financially viable.

3.1.3.11 Uptake

Farmer mind-set, tenancy issues, path dependencies (e.g. previous investments, such as in harvesting or irrigation machinery), land availability and the high value of high-risk crops are all potential barriers to uptake.

3.1.3.12 Other Notes

n/a

3.2 Soil Management & Protection

This section covers seventeen “soil management and protection” actions that concern tillage systems, soil compaction management, cover cropping and manure and mulch management. The actions aim to protect the soil surface from raindrop impact, enhance soil organic matter and improve soil structure, thereby providing potential major benefits for soil erosion control and soil health:

- Tillage
  - **ECPW-242** - Use direct drilling into crop stubble or cover crops
  - **ETPW-092** - Use minimum-tillage or no-tillage cultivation
- Compaction management
  - **ETPW-223** - Assess soil structure and plan how to avoid and alleviate soil damage and compaction (soil management plan)
  - **ECPW-003** - Avoid cultivation and trafficking on wet soils
  - **ECPW-255** - Reduce weight of field machinery
  - **EHAZ-017** - Use low ground pressure tyres
  - **EHAZ-031** - Use controlled traffic farming (CTF)
  - **ECPW-249** - Reduce grazing and stocking rates when soils are wet to avoid soil compaction
- Cover cropping
  - **ECPW-025** - Harvest and establish the following crop early in the autumn
  - **ECAR-044** - Ensure persistent continuous vegetation cover on land
  - **ECCM-023** - Use green manures within the rotation
  - **ECPW-279** - Use of cover crops as an alternative to plastic mulch - Soil-enriching cover crops may be grown over the winter in the same beds where a food crop is to be planted the following spring and used in place of mulch

    - **ETPW-251** - Use grass waterways in crops with high risk of soil erosion and run off (e.g., field vegetables)
    - **ECPW-028** - Enhance management of maize including early harvest, use of early maturing varieties, early planting times and establishment of a cover crop
    - **ECPW-005** - Use restorative vegetation cover following destoning or lifting of root crops
    - **ETPW-270** - Re-seed grassland by slot-seeding or over-seeding
- Manure and mulch management
    - **EHAZ-113** - Use mulches and organic matter to increase the water retention capacity of soil

3.2.1 Soil management & protection – Tillage Actions ECPW-242 & ETPW-092

- **ECPW-242** - Use direct drilling into crop stubble or cover crops
- **ETPW-092** - Use minimum-tillage or no-tillage cultivation

Actions **ECPW-242** and **ETPW-092** involve adopting reduced cultivations (in terms of intensity, i.e. depth and degree of disturbance and inversion), either using discs, chisels or tines rather than ploughing (aka inversion tillage), to cultivate the soil surface as the primary cultivation in seedbed preparation (typically 10-15 cm cultivation depth) or direct drilling or broadcasting of seed into the soil (i.e. no-till). Reduced/no-till cultivations (rather than inversion ploughing) can retain soil surface organic matter, protect soil biology and preserve good soil structure, with the resulting soil conditions improving water infiltration and retention rates (at least in part through increased earthworm populations) while also reducing soil erosion risks; large reductions in surface runoff can be achieved where a mulch of crop residues is left on the surface (Defra PE0206).

3.2.1.1 Causality

It is generally well accepted that a change from inversion tillage (ploughing) to reduced cultivation systems can have major benefits for soil conservation and soil health, i.e. resulting in reduced soil erosion, a gradual increase in soil carbon, (Cooper et al., 2021; Dawson & Smith, 2007), increased soil biodiversity (e.g. earthworms, springtails and mites) (e.g. Ernst & Emmerling, 2009; George et al., 2017) and an increase in soil strength and aggregate stability, both associated with soil resistance to erosion (e.g. Bartoli et al., 2016; Nciizah & Wakindiki, 2015: Schjønning & Rasmussen, 1989).

- **Extent of erosion** – reduced cultivation can result in a reduction in surface runoff and erosion (e.g. Withers et al., 2007; Deasy et al., 2010). Direct drilling into crop stubble or cover crops can result in a further reduction in erosion, compared with the use of discs or tines to surface cultivate the soil, due to the vegetation and residue cover afforded by the crop stubble and cover crop (e.g. Defra project WQ0127; Deasy et al., 2010).
- **Increased soil carbon** – cultivation can result in losses of SOC due to the disruption of soil aggregates and the exposure of organic matter to oxidation (e.g. Liu et al., 2006). Reduced cultivation systems can therefore result in gradual increases in soil carbon (Cooper et al., 2021; Dawson & Smith, 2007), although there is some evidence to suggest that the main factor determining differences between systems is carbon input differences (i.e. the balance between photosynthesis and respiration that is largely determined by the annual duration of vegetation cover), which is not necessarily influenced by the cultivation system (e.g. Virto et al., 2012). Conversion to a minimum or no-tillage system is also characterised by changes in the depth distribution of SOM, with more OM concentrated near the surface and deposited near the base of the (former) plough layer in reduced till systems (Angers & Eriksen-Hamel, 2008; Powlson et al., 2012).
- **Reduced soil contamination** – there is unlikely to be any change in soil contamination due to minimum-tillage or no-tillage cultivation.
- **Increased soil biodiversity** – a reduction in tillage intensity can result in increases in earthworm numbers and may also increase numbers of soil mesofauna (e.g. springtails and mites) (e.g. Ernst & Emmerling, 2009; George et al., 2017).

- **Improved soil structure, including less compaction** – Long-term reduced cultivation generally results in an increase in soil strength and aggregate stability (Schjønning & Rasmussen, 1989).

3.2.1.2 Co-Benefits and Trade-offs

The actions can result in co-benefits for the following outcomes:

- Air quality – due to lower particulate emissions from reduced diesel use.
- Greenhouse gas (GHG) emissions - only for ECPW-242 associated with the use of a cover crop resulting in lower nitrate leaching losses and associated reduction in indirect nitrous oxide emissions.
- Water quality - large reductions in surface runoff can be achieved where a mulch of crop residues is left on the surface. Nitrate leaching is generally decreased as there is less soil disturbance and hence less organic matter mineralisation.

3.2.1.3 Magnitude

- **Extent of erosion** – compared to conventional inversion tillage, reductions in sediment and associated particulate P loss can be up to 60% on medium/heavy soils and as high as 90% on light soils (Defra project WQ0127; Deasy et al., 2010; Newell Price et al. 2011). Minimum tillage techniques that leave crop residue on the soil surface have been shown to be particularly effective in reducing erosion according to Chambers et al. (2000).
- **Increased soil carbon** – changes in soil carbon due to the introduction of reduced tillage systems have been estimated at:
    - -1.0 - + 0.4 t C/ha/yr (No till: 0.39 t C/ha/yr) (Dawson & Smith, 2007)
    - -0.14 to + 760 t C/ha/yr (mean 0.31 t C/ha/yr) (Powlson et al., 2012)
    - 0.22 t C/ha/yr (Virto et al. 2012)
    - 0 t C/ha/yr (Dimassi et al., 2014)
    - 0.14 t C/ha/yr (Du et al. 2017)
    - 0.23 t C/ha/yr (Meurer et al., 2018)
- **Increased soil biodiversity** – a two- to six-fold increase in the mass of deep-burrowing earthworms after ten years of reduced tillage compared with ploughing. (e.g. Ernst & Emmerling, 2009; Stroud et al., 2023).
- **Improved soil structure, including less compaction** – compared with conventional tillage, no-till with residue retention can increase mean weight diameter of aggregates by 52% and proportion of water-stable aggregates by 55% (264 studies; Li et al., 2019). No-till can also increase saturated hydraulic conductivity by 25% and increase soil available water capacity (AWC), with residue retention having an additional 10% increase in AWC compared with no-till (Li et al., 2019).

3.2.1.4 Timescale

- Erosion risk is related to vegetation, residue covers, soil structure and root traits, so effects could be seen in the season of conversion (0-5 years).
- Changes in earthworm numbers and soil structure could be detected within 5-10 years (Ernst & Emmerling, 2009; Li et al., 2019).
- Changes in soil carbon could be detected after 10-20 years although some studies have measured no change after 40 years (Dimassi et al., 2014).

3.2.1.5 Spatial Issues

The actions are widely applicable but require a degree of communication, knowledge exchange and targeting to select the right cultivation system for each farm, soil type, farmer mindset etc. (e.g. AHDB, 2020).

3.2.1.6 Displacement

Reduced tillage has been attributed to reduced yields in some situations (Withers et al, 2007). The technique requires a reasonable level of skill to be implemented effectively and at the most appropriate time for soil and weather conditions to be effective. However, in Defra project SP1605B, reduced cultivations were not found to necessarily reduce crop yields, and, in some cases, yields can even be increased (HGCA, 1988; Davies and Finney, 2002). Over a 10-20-year period, reduced tillage often has no effect on crop yields (e.g. Dimassi et al., 2014).

3.2.1.7 Maintenance and Longevity

While the land remains in arable production, the reduced tillage system should be retained as the dominant system in perpetuity. Occasional subsoiling may be necessary when the less cultivated soil becomes 'tight'; and weed burden and seasonally ‘wet’ soil conditions may necessitate occasional ploughing. This should not impact on the overall effect of a reduced cultivation system in the long-term but may have short-term impacts on soil health.

3.2.1.8 Climate Adaptation or Mitigation

Reduced cultivation systems are generally better at conserving moisture than plough-based systems, so would be favoured where springs and summers are drier. However, wetter autumns may make it more difficult in some years to establish crops using reduced cultivation techniques (Keay & Hannam, 2020).

3.2.1.9 Climate Factors / Constraints

Climate change is likely to result in a greater frequency of extreme events such as sustained periods of waterlogged soils in autumn and winter. This could compromise the ability to implement a reduced cultivation system year after year: “*Wetter regions, especially with shorter growing seasons, limit opportunities for the natural tilth-making actions that are needed in the absence of tillage*” (AHDB, 2020)

3.2.1.10 Benefits and Trade-offs to Farmer/L-and manager

There are potential significant economic benefits in terms of lower establishment costs within no-till or reduced tillage systems, but each farmer needs to consider if a reduced cultivation system will work for them (AHDB, 2020).

3.2.1.11 Uptake

Adopting a reduced tillage or no-till system is a long-term decision, partly due to the investment costs associated with purchasing new cultivation equipment, so tenancy is an important factor. The decision would be farmer- or land manager-led, often with support from an adviser. Uptake is increasing from a relatively low baseline of around 40% of arable land cultivated using reduced (or minimum) tillage, and around 4% of arable land ‘cultivated’ using zero tillage (Defra, 2010).

3.2.1.12 Other Notes

A selection of soil quality indicators could be used to monitor the benefits from direct drilling and reduced tillage cultivation systems (e.g. Stockdale et al., 2021). There are a number of scoring systems that use different weightings and minimum datasets:

- Weighting / scoring systems (Wienhold et al., 2009)
- Logical Sieves (e.g. Corstanje et al., 2017)
- Score cards (AHDB/ BBRO: https://ahdb.org.uk/soil-health-scorecard ; https://www.agricology.co.uk/resources/testing-soil-health-scorecard-farm-soil-monitoring-2018%E2%80%932019 ; Romig, Garlynd and Harris, 1997; https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/assessment/?cid=nrcs142p2_053871)
- Dashboards (Frontier: https://www.frontierag.co.uk/images/CropNutritionAdvice/Soil-Life-Leaflet.PDF ; Agrii, Hutchinsons)
- Minimum data sets (e.g. Jiang et al., 2020; Raiesi, 2017)

3.2.2 Soil management & protection – Compaction management ETPW-223 - Assess soil structure and plan how to avoid and alleviate soil damage and compaction (soil management plan)

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following action:

- **ETPW-228** - Create a soil management plan to improve soil structure, soil biology and soil chemistry

Assessing soil structure is the first step towards improved soil management but does not determine what the management should be. It leads to a more considered approach to soil management and should aim to result in less soil compaction, reduced erosion and maintenance of soil organic matter levels. An effective soil management plan should assess soil erosion risk and the structural condition and depth of soil layers including in any compacted areas. This leads to spatial targeting of interventions in terms of the areal extent of any issues and the depth of any cultivations to alleviate compaction. The timing of field operations should also be considered to avoid compaction and ineffective or damaging cultivations when field conditions or the soil at working depth is 'wet' (i.e. when the soil moisture content is likely to result in compaction when significant pressure is applied; in the case of medium and heavy-textured soils, this is when the soil moisture content is above the plastic limit for that soil). When planning subsoiling operations it is also important to consider soil type and the crops to be grown in terms of the likely benefits to crop yield and the environment (Chamen et al., 2015; Defra project SP1605B; Marks & Soane, 1987).

Selecting early maturing varieties (e.g. early maturing maize to avoid late harvesting) and using cover crops and green manures can also form an important part of an effective soil management plan (e.g. the LEAF Soil Management Plan that forms part of the LEAF Marque Standard) and can contribute towards farm efficiency and resilience.

3.2.2.1 Causality

The action can benefit soil conservation and soil health if implemented well.
When soils are compacted, they can be susceptible to surface runoff. Improving or maintaining good soil structure can enhance water infiltration rates into the soil and reduce surface runoff volumes and erosion (Defra projects WQ0106 and BD5001).

3.2.2.2 Co-Benefits and Trade-offs

The action is likely to result in benefits to:

- Air quality
    - More rapid infiltration of slurries and digestate due to improved soil structure can reduce ammonia emissions
- Greenhouse gas emissions
    - There may be a small reduction in direct N_2O emissions, due to increased soil aeration.
- Water Quality
    - Sediment and associated particulate P loss reductions would typically be in the range 10 to 50%.
- Aquatic biodiversity
    - Impacts on nitrate leaching are negligible and therefore there would be limited impact on surface, ground and coastal waters.
    - By contrast, reductions in P and sediment losses should benefit freshwater environments.
- Food production
    - Improved soil structure can result in generally higher crop yields and/or improved root growth leading to increased nutrient use efficiency.

3.2.2.3 Magnitude

- Extent of erosion – if implemented well, erosion rates on sloping fields could be reduced by 10 to 50% (Defra WQ0106).
- Increased soil carbon – small increases in soil carbon due to increased crop yields may be possible but are unlikely to be measurable (Roe et al., 2021). If the soil management plan includes incorporation of grass leys, green manures or cover crops, carbon sequestration rates of around 0.3 t C/ha/yr are possible (Poeplau & Don, 2015). However, cover crops cannot be grown every year in all situations. Under UK/European conditions, winter cover crops are only grown prior to a spring-sown crop. In many UK situations farmers grow a succession of autumn-sown crops. It is unclear how frequently cover crops were grown in the cases that Poeplau & Don (2015) reviewed. In addition, growth of cover crops is highly dependent on weather and local conditions: in some years growth can be excellent, while in others it is poor. Some caution is required in assigning a SOC rate of increase to cover crops. They can contribute to C sequestration over time, but are not a panacea.
- Improved soil structure, including less compaction – targeted subsoiling of compacted soil layers in late summer or early autumn can improve soil structure and result in a seven- to ten-fold increase in water infiltration rates in the following winter, although this is not advised on sandy soils, which can be susceptible to slumping (Defra BD5001).

3.2.2.4 Timescale

It can take 0-5 years to achieve measurable benefits to soil structure. Some soils with poor structure or compacted layers may take a few years to recover and restructure. Subsoil compaction may persist for many years (>10 years), particularly in light sandy soils (Håkansson and Reeder, 1994).

The rate of response in local watercourses to reduced sediment and phosphorus loads is complex and uncertain but given the potential for remobilisation of nutrients and sediments, particularly within streams and rivers, it is likely to be >10 years before ecological benefits can be detected (Collins et al. 2010, 2013).

3.2.2.5 Spatial Issues

All farms can benefit from a soil management plan (e.g. the LEAF Soil Management Plan that forms part of the LEAF Marque Standard). However, changes in practice would be most effective, and measurable off-site impacts most easily detected, in catchments with a phosphorus or sediment issue.

3.2.2.6 Displacement

There are no displacement effects associated with this action.

3.2.2.7 Maintenance and Longevity

The action needs to be maintained indefinitely for the benefits to persist. The same benefits can be easily reversed with poor soil management.

3.2.2.8 Climate Adaptation or Mitigation

The action should help farmers adapt to climate change by allowing them to monitor how farm practices affect soil health and associated functions and services. Compaction alleviation is very important in the context of more extreme rainfall events (intensity, frequency and duration) predicted with climate change.

3.2.2.9 Climate Factors / Constraints

The action will contribute to climate change adaptation and (to a small extent – see 3.2.2.1.2 above) mitigation. Climate change may have implications for the viability of a particular farming system in some locations, but it will not diminish the need for a soil management plan.

3.2.2.10 Benefits and Trade-offs to Farmer/Land manager

Assessing soil structure is time consuming but many practitioners consider it to be time well spent (e.g. Defra, 2013). Visual Evaluation of Soil Structure (VESS) is a simple method of soil structure assessment that can be linked to management interventions (Guimaraes et al., 2013).

3.2.2.11 Uptake

Uptake of soil structure assessment is moderate but increasing. In 2012, based on responses from 2,880 farms, 47% of farmers dug a hole to assess soil structure (Defra, 2013). Based on responses from 2,266 farms that had taken action to reduce soil compaction, 32% undertook a subsequent visual assessment to evaluate the success of the action (Defra, 2013). Visual soil evaluation has been promoted within the farming community since the 2012 farm practices survey (e.g. AHDB, 2018a; AHDB, 2018b; AHDB, 2020).

3.2.2.12 Other Notes

None.

3.2.3 ECPW-003 - Avoid cultivation and trafficking on wet soils

This relates to a previous cross compliance requirement of farmers to avoid trafficking and working wet soils (Defra, 2009) and a current cross compliance requirement (RPA, 2022). In the Soil Protection Review 2010 (SPR10), previous restrictions on access to waterlogged land were replaced with a requirement to record access to waterlogged areas and remedial actions undertaken to mitigate soil damage (Defra, 2009). In the 2022 cross compliance guidance, farmers are required to minimise surface runoff and soil erosion (GAEC 5) and advised to avoid high risk practices, such as harvesting “crops late in the year when conditions are wet”, where possible.

3.2.3.1 Causality

The action can have major benefits for soil conservation and soil health if done well. Defra project SP1316 concluded that “*Working waterlogged land can have a significant impact on crop productivity, water quality (particularly sediment and associated phosphorus losses), flood risk (due to increase surface runoff), carbon storage (mainly related to erosional losses) and nutrient cycling (mineralisation rates and crop uptake can be reduced, and nitrous oxide emissions increased). Any measure that helps avoid working or trafficking waterlogged land will help prevent soil degradation and reduce the duration of waterlogging through maintaining better soil structure and good drainage*”.

Wet soils are sensitive to degradation from farming operations through compaction and erosion:

- In medium and heavy soils the main risks occur when the soil is in a plastic state and there is an increased risk of aggregate dispersion (puddling) and spreading of soil by sliding pressure (smear). In England and Wales, approximately 45% of winter sown crops are grown on slowly permeable soils that require field drainage to maximise opportunities for field work in the autumn, winter and spring.
- Sandy and light silty soils are more susceptible to compaction through compression, partly due to their inability to re-structure through shrink-swell processes.
- Soils naturally ‘wet up’ in the autumn as day length shortens and rainfall exceeds evapotranspiration. Late autumn harvesting and establishment of crops is therefore associated with structural degradation due to the likelihood of working soils when ‘wet’ or in a plastic state.
- Working wet soils can lead to compaction, reduced water infiltration and increased surface runoff and erosion which in turn can lead to adverse impacts on soil ecosystem services. Crop yield can be reduced due to restricted rooting and impacts on the ability of crops to sustain growth and take up water and nutrients, particularly in a wet late winter/spring or dry spring/summer. Reduced macroporosity and the development of platy structure rather than vertical fissures reduces water infiltration rates and can both increase soil erosion rates and flooding risk, thereby impacting on water quality. Accelerated soil erosion can also impact on soil carbon storage. Finally, the soil structural degradation resulting from working wet soils can also affect nutrient cycling in terms of the rate of organic matter mineralisation and uptake of soil nutrients.

- Working wet soils and associated degradation of soil structure may also have impacts on soil biodiversity (e.g. nematodes, spring tails, mites and earthworms) due to reduced pore continuity reducing opportunities for exploration and inducing anaerobic conditions.

3.2.3.2 Co-Benefits and Trade-offs

Avoiding cultivation and trafficking on wet soils can have significant co-benefits for:

- Crop productivity
- Greenhouse gas emissions
- Air quality (better soil structure results in more rapid infiltration of slurries and a reduction in associated ammonia emissions)
- Water quality
- Regulating water flows
- Soil carbon storage

3.2.3.3 Magnitude

Working 'wet' land usually involves ploughing (on a 'wetting front' in autumn, the soil is wet near the surface, at tine or disc working depth, and can be drier at plough depth), which not only increases runoff and soil erosion risk due to induced compaction and low infiltration rates, but can also increase loss of SOM through mineralisation (Bhogal et al., 2009). Restricted rooting depth due to soil compaction can reduce crop yield and impact upon subsoil carbon storage levels (Carter and Gregorich, 2010). Reduced plant growth over many years can lead to a decline in OM returned to the soil which may cause a net loss of soil carbon as the existing carbon stores are mineralised (Defra project SP1601).

3.2.3.4 Timescale

It can take 0-5 years to achieve measurable benefits to soil structure. Some soils with poor structure or compacted layers may take a few more years (5-10 years) to recover and restructure through natural processes such as freeze/thaw, wetting/drying and biological activity. Subsoil compaction may persist for many years (>10 years), particularly in light sandy soils (Håkansson and Reeder, 1994).

3.2.3.5 Spatial Issues

The action is broad scale in nature although some land is at higher risk from surface runoff and soil erosion (Defra, 2005) and some soils are more prone to waterlogging than others (MAFF, 1988).

3.2.3.6 Displacement

As a voluntary measure, there are no displacement effects associated with this action, as growers do not tend to voluntarily breach supply contracts. However, if strictly applied through regulation and inspection, it could result in displacement of the production of some late harvested crops such as field vegetables and root crops; potentially removing significant UK areas from production of crops with high economic value.

3.2.3.7 Maintenance and Longevity

The action needs to be maintained indefinitely for the benefits to persist. The same benefits can be easily reversed with poor soil management.

3.2.3.8 Climate Adaptation or Mitigation

Climate change is likely to result in a reduction in the overall duration of waterlogging in most parts of England, due to hotter, drier summers and higher evapotranspiration rates going into the autumn (Figure 1; Defra SP1316). However, it is possible that projected increases in winter rainfall in future could increase the severity of waterlogging (when it does happen) due to larger rainfall volumes overwhelming drainage systems (Defra SP1316).

3.2.3.9 Climate Factors / Constraints

The action should help farms improve their resilience to climate change through improved soil structure (less compaction) and crop productivity. However, in some farming systems, growing late harvested crops on moderately well drained and imperfectly drained soils, the action could be incompatible with supply contracts, as some contracts require late harvesting even when the soil is wet or waterlogged.

3.2.3.10 Benefits and Trade-offs to Farmer/Land manager

Farmers could benefit from increased crop productivity but would need to assess their overall need to access wet soils to meet supply contracts.

3.2.3.11 Uptake

Previous controls (i.e. Soil Protection Review 2010) helped raise awareness of the issues associated with accessing waterlogged land and encouraged some farmers to change the way they accessed wet land. However, in a survey carried out in spring 2012 (Defra project SP1309), farmers did not acknowledge that land on their farm was ever worked (i.e. cultivated) when waterlogged. Furthermore, there was clear evidence of deficiencies in practice when remediating compacted soil as few farmers assessed the extent of the soil damage before acting. Improvements are needed in soil management, particularly in soil assessment (see **ETPW-223** - Assess soil structure and plan how to avoid and alleviate soil damage and compaction (soil management plan) to determine whether remediation is necessary.

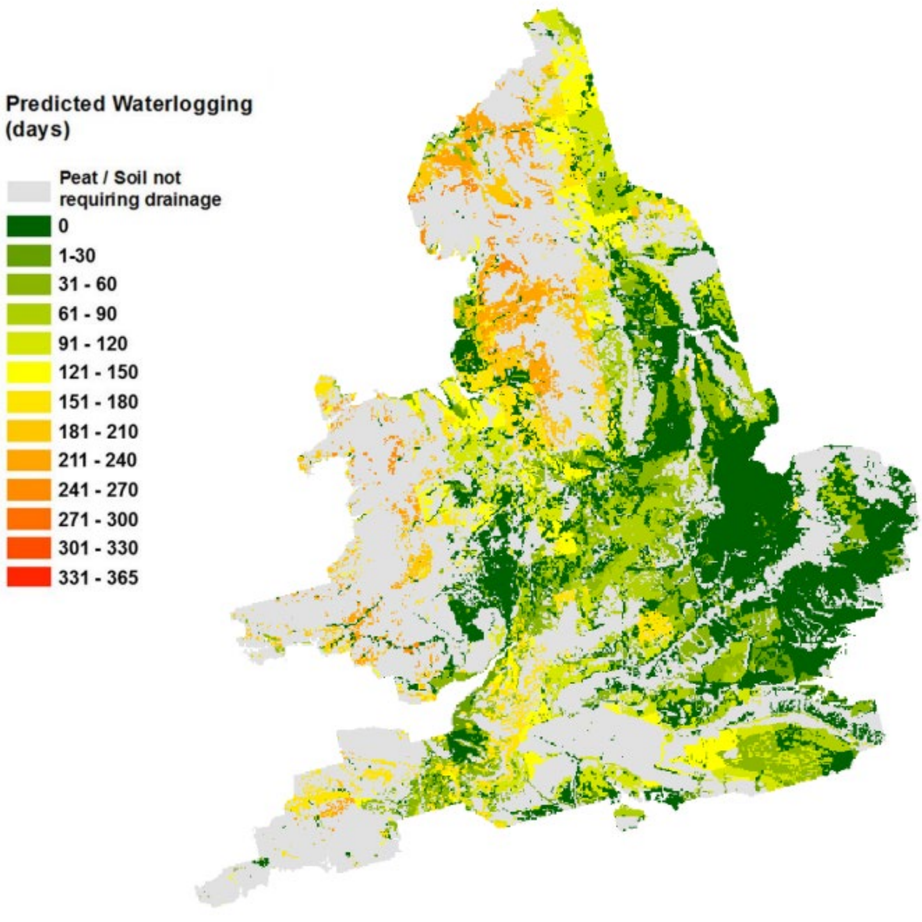

Figure 1. Predicted median days (per annum) of waterlogging for England and Wales; medium emissions scenario, 2050 (Defra project SP1316).

3.2.3.12 Other Notes

The action could be verified through a combination of farm advice, remote sensing and farm inspection.

3.2.4 ECPW-255 - Reduce weight of field machinery

Heavier machines allow more powerful and more rapid field operations but can result in soil structural degradation, including subsoil compaction that can persist for many years, particularly on light- and medium-textured soils (e.g. Håkansson and Reeder, 1994; Etana et al., 2013).

3.2.4.1 Causality

Reducing the weight of field machinery can potentially have major benefits for sol conservation and soil health. Damage to subsoil structure largely arises due to compaction resulting from vehicle field operations, particularly when soils are wet. There has been a general increase in the size of agricultural machinery and greater use of contractors for all field operations in the past few decades (Håkansson and Reeder, 1994; Batey, 2009). In the 1980's, wheel loads of 50 kN were considered to be high, but by 2001 the use of 90-120 kN wheel loads was commonplace (Van den Akker & Schjønning, 2004), although to deliver sufficient draft, mass per unit of horsepower has remained similar.

The use of heavy machinery with low ground pressure (LGP) tyres can allow fieldwork with high power requirement to be carried out in conditions that would not have been possible 30 years ago. Nevertheless, the increase in the size of machinery may give rise to soil compaction issues, particularly if tyre inflation pressures are higher than necessary and machinery is used when medium and heavy soils are in a plastic state or light sandy and silty soils are 'wet'. This needs to be taken into account when considering crop establishment using heavy machinery.

A particular concern is the occurrence and severity of subsoil compaction, which has a negative impact on soil functions such as water regulation, air regulation and crop yield (Keller et al., 2019) and can have serious on-site and off-site impacts. The extent of subsoil compaction is uncertain due to limited data but Brus and van den Akker (2018) have estimated that c. 40 % of European agricultural subsoils may be detrimentally compacted.

The one caveat to this is that the use of heavier, but more powerful machinery can allow more rapid progress with field operations allowing field operations to be completed before soils 'wet up' in the autumn. As long as heavy machinery is not used when the soil is 'wet' within 50 cm of the ground surface, the risks of soil structural damage are minimal. However, the mode of cultivation (e.g. tine vs power harrow cultivation) has implications for topsoil structural stability (NSRI, 2002).

3.2.4.2 Co-Benefits and Trade-offs

Reducing the weight of agricultural machinery could have co-benefits for:

- Air quality - better soil structure results in more rapid infiltration of slurries and a reduction in associated ammonia emissions. Lighter machinery may also result in reduced emissions of particulate matter.
- GHG emissions – better soil structure can also result in lower pore water volumes and reduced nitrous oxide emissions.
- Water quality – better soil structure can increase water infiltration rates thereby reducing surface runoff and erosion.
- Water regulation – better soil structure can increase water infiltration and retention.
- Food production – better soil structure can improve root proliferation and access to subsoil water.

[TOCB Report-3-5D Systems **ECPW-255**] Soil compaction is likely to have little effect on above-ground biodiversity, except via effects on soil-probing species, which may be affected by reduced earthworm abundance or accessibility (Wardle et al., 2004), but this is likely to have a very limited spatial footprint and so low impact, and reducing it will have a similarly small effect.

3.2.4.3 Magnitude

- Extent of erosion – Erosion risk is reduced when soil structure is improved, due to increased water infiltration rates and lower surface runoff volumes. Reducing the weight of agricultural machinery therefore has the potential to reduce runoff and erosion risk, although there is very limited direct evidence to support the action as an erosion mitigation option (Hallett et al., 2012). The effect would be greatest in arable and horticultural systems prone to erosion.
- Increased soil carbon – the action could potentially result in small increases in crop yield (and associated organic matter) and reduced erosional C losses. However, it is unlikely that the action would result in measurable increases in soil organic matter content (Kirk et al., 2012).
- Reduced soil contamination – no effect.
- Increased soil biodiversity – there may be reductions in earthworm abundance (Wardle et al., 2004).
- Improved soil structure, including less compaction – the action could result in potential yield increases of 1-3% across different crops and soils due to reductions in 'residual' or persistent compaction, most likely due to higher root length densities in the topsoil and subsoil (Munkholm et al., 2005; Chamen, 2011).

3.2.4.4 Timescale

Medium- and heavy-textured soils tend to undergo a degree of natural restructuring due to freeze-thaw activity and shrink-swell of clay particles as soils wet up and dry out. These soils can therefore naturally recover from the more severe consequences of subsoil compaction within 5 years. Persistent subsoil compaction is more common in light-textured soils, which may take more than 10 years to restructure even if managed well (Van den Akker & Schjønning, 2004).

3.2.4.5 Spatial Issues

The action is broad-scale in nature although preventing subsoil compaction may be more important on light-textured sandy and deep silty soils due to their lower capacity to restructure through natural processes compared with heavier soils (with higher clay content).

3.2.4.6 Displacement

The action could result in small increases in crop yield so could reduce the need for food imports by a small amount. However, in a wet autumn, a slower rate of operation with lighter machinery (cf. heavier, more powerful machinery) may result in fewer fields being established and a poorer seedbed in those that are established late, resulting in a reduction in crop yield overall.

3.2.4.7 Maintenance and Longevity

The action would need to be adopted indefinitely. A return to heavy machinery use would immediately increase the risk of subsoil compaction to former levels. However, investment in a new system and new machinery would result in path dependencies (processes where past events or decisions constrain later events or decisions) as farmers would want a return on the investment over time.

3.2.4.8 Climate Adaptation or Mitigation

The action should increase farm resilience to climate change by reducing soil compaction. Current climate change projections indicate that there could be a longer window of opportunity for autumn cultivations in most areas (Defra SP1316), which would reduce farmer reliance on heavy machinery with high field operation speeds.

3.2.4.9 Climate Factors / Constraints

The action should contribute to climate change mitigation and adaptation by reducing the extent and severity of subsoil compaction. Reduced compaction could lower the risk of nitrous oxide emissions (Hargreaves et al., 2013; Da Silva et al., 2014) and improve root length densities in the subsoil, thereby increasing crop resilience to drought conditions (Zhang et al., 2020).

3.2.4.10 Benefits and Trade-offs to Farmer/Land manager

The action requires new investment but could result in a more productive farming system if it results in better structured soils. However, there may be a trade-off between less compaction and slower work rates with lighter machinery.

3.2.4.11 Uptake

Farmer mind-set and path dependencies (e.g. previous investments) are barriers to uptake. However, an increasing number of farmers and growers are recognising the benefits of lighter machinery, particularly within a controlled traffic farming system (Munkholm et al., 2005; see 3.2.2.5 **EHAZ-031** - Use controlled traffic farming).

3.2.4.12 Other Notes

Reliable soil physical quality indicators would provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.2.5 EHAZ-017 - Use low ground pressure tyres

Low ground pressure (LGP) tyres are recommended for in-field use. Several manufacturers now provide tyres that can be adjusted for field and road use, although tyres of the 'VF' (very high flexion) type can run on the road at field inflation rates and hence do not require adjustments to be made for travelling from the farm to the field by road or farm track.

3.2.5.1 Causality

Using LGP tyres can have moderate benefit for soil conservation and soil health if implemented well. They can reduce the degree and depth of soil compaction and the risk of creating wheel ruts and therefore can reduce the extent of runoff and soil erosion on sloping land (e.g. Ren et al., 2019).

LGP tyres can be effective in reducing topsoil and subsoil compaction. They are generally wider than conventional tyres and work at lower pressures. Topsoil compaction from tyres is mainly determined by contact pressure, which is related to tyre pressure (Keller, 2005; Millington et al., 2016), whereas subsoil compaction is mainly determined by axle/wheel load (Lamandé and Schjønning, 2008; Batey, 2009).

LGP tyres can play a role in reducing soil degradation and if used appropriately (i.e. not when soils are 'wet'), can produce near optimal conditions (in terms of soil bulk density and porosity) for crop establishment and growth. At crop establishment and during the growing period, the action effect is limited to wheelings, while at harvest the action can affect the impact of trafficking across the whole field. LGP tyres can also reduce fuel use by limiting wheel slip and rolling resistance.

3.2.5.2 Co-Benefits and Trade-offs

Using LGP tyres can have co-benefits for:

- Air quality
    - Better soil structure results in more rapid infiltration of slurries and a reduction in associated ammonia emissions
- GHG emissions
    - There may be a small reduction in direct N_2O emissions, due to improved soil aeration
- Water quality
    - Particulate P and associated sediment losses would typically be reduced due to lower surface runoff volumes
- Water regulation
    - Due to improved water infiltration and soil water storage

- Food production
    - Due to improved root proliferation and access to water and nutrients

3.2.5.3 Magnitude

- Extent of erosion – There is some evidence that the use of LGP tyres can reduce soil erosion that is concentrated down tramlines. Stranks (2006) reported significant reductions in rolling resistance, rut depth and compaction depth as a result of using lower tyre pressure. 'Compacted' tramlines can act as concentrated flow pathways during periods of increased surface runoff, particularly if oriented up and down slope (Silgram et al., 2014).
- Increased soil carbon – The use of LGP tyres could potentially result in small increases in crop yield and reduced erosional losses, although it is unlikely to result in higher soil organic matter content (Kirk et al., 2012).
- Reduced soil contamination – no effect.
- Increased soil biodiversity – unknown, but some species could benefit from reduced levels of compaction (Wardle et al., 2004).
- Improved soil structure, including less compaction - Yield reductions due to topsoil compaction generally range from 5 to 25% across a range of crops from winter wheat to forage grass (e.g. Håkansson, 2005; Hallett et al., 2012).

3.2.5.4 Timescale

Improvements in soil erosion control and soil health are typically seen within 5 years, as soil compaction from high pressure tyres is focused in the topsoil, and can be effectively removed through a combination of cultivation and plant root activity.

3.2.5.5 Spatial Issues

The action is broad scale in nature but could be focused in catchments where surface runoff and sediment and phosphorus losses to water are significant issues.

3.2.5.6 Displacement

The action could result in small increases in crop yield so could reduce the need for food imports by a small amount.

3.2.5.7 Maintenance and Longevity

The action would need to be adopted indefinitely. Due to the higher cost of LGP tyres, on most farms considering replacing conventional tyres, LGP tyres would most likely be selected as an upgrade when a new machine is purchased rather than as a replacement of conventional tyres on existing machinery. However, once LGP tyres have been purchased farmers are likely to stick with them.

3.2.5.8 Climate Adaptation or Mitigation

The action should increase farm resilience to climate change by reducing soil compaction, with associated increases in crop root length density and decreases in surface runoff and soil erosion.

3.2.5.9 Climate Factors / Constraints

The action should contribute to climate change mitigation and adaptation by reducing the extent and severity of topsoil compaction.

3.2.5.10 Benefits and Trade-offs to Farmer/Land manager

The action requires new investment but could result in a more productive, profitable and resilient farming system. There could also be reductions in fuel use due to lower wheel slip and rolling resistance.

3.2.5.11 Uptake

Cost will be a barrier to uptake on many farms. Silgram et al. (2014) assumed that LGP tyres rather than standard radial tyres would be purchased for the whole wheeled machine inventory, which for a typical arable farm would cover two tractors, a trailed sprayer, a combine, two grain trailers and a drill. On a 200-ha farm the cost of replacing conventional tyres with LGP tyres would be around £9,000 (2022 prices).

On many farms, field operations and equipment (such as tyre type) are not generally changed or adapted because they are tried and tested. Divergence from the routine involves risks to both the business (monetary risks) and the farmer's reputation. Although the purchase of LGP tyres is generally cost effective, the initial investment cost and the uncertainty of benefits represent significant barriers to uptake and implementation for many farmers. The new 'VF' tyres are significantly more expensive than conventional radials and most farmers are not prepared to bear the investment cost unless they understand and have confidence in the potential to save on operational costs.

3.2.5.12 Other Notes

Reliable soil physical quality indicators would provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.2.6 EHAZ-031 - Use controlled traffic farming (CTF)

Controlled traffic farming (CTF) aims to reduce the proportion of each field area that is wheeled by machinery to avoid widespread soil compaction. CTF has been defined as "confining all vehicle traffic to the least possible area of permanent traffic lanes" (Chamen et al., 2015) and involves greater discipline in use of routeways and tramlines. The degree to which the trafficked area can be reduced depends on what crops are being grown and the dimensional characteristics of the machinery used to manage them. Minimising the tracked area involves matching up as closely as possible the track gauges (centre distance between wheels on an axle) and the operating widths of all machines running on the land. Direct multiples of the operating width can also be used, such as with sprayers and fertiliser spreaders. An effective CTF system can reduce the wheeled area from >100% to 20-40%.

3.2.6.1 Causality

CTF can have major benefits to soil health if implemented well. Adopting a complete or partial controlled traffic system can reduce the degree and depth and extent of trafficking over the field as a whole and associated soil compaction, helping to reduce the extent of surface runoff and erosion on sloping land (Chamen et al., 2015; Defra project SP1316; AHDB CP 107C).

The key benefits from CTF (as with other compaction avoidance technologies such as low ground pressure tyres or tracked tractors) include better soil structure where the soil is no longer trafficked; leading to fewer and less energy-intensive cultivations (McPhee et al., 2015); increased water infiltration rates/better drainage (Chyba et al., 2017); more machinery workdays; improved water and nutrient use efficiency; and increased yields in some years (Chamen et al., 2015).

Improvements in soil structure and porosity lead to other benefits; including improved workability, infiltration and aeration, which in turn influence drainage, the degree and duration of waterlogging, timeliness of field operations, droughtiness and crop yield. Improved drainage and shorter periods of standing water reduce disease risk.

3.2.6.2 Co-Benefits and Trade-offs

Adopting CTF systems can have co-benefits for:

- Air quality

  - Better soil structure results in more rapid infiltration of slurries and a reduction in associated ammonia emissions. The reduced cultivation associated with CTF systems is also likely to result in less fuel use and lower particulate emissions to the air.
- GHG emissions
  - There may be a small reduction in direct N_2O emissions, due to improved soil aeration.
- Water quality
  - Particulate P and associated sediment losses would typically be reduced due to lower surface runoff volumes.
- Water regulation
  - Due to improved water infiltration and soil water storage.
- Food production
  - Due to improved root proliferation and access to water and nutrients.

3.2.6.3 Magnitude

- Extent of erosion – Within CTF systems, there is some potential to create a concentrated flow of surface runoff down compacted tramlines that can enhance soil surface erosion. However, if the non-trafficked area has higher porosity (Lamers et al., 1986) and elevated water infiltration rates compared to conventionally trafficked soil, surface runoff generated on the tramlines may infiltrate in the un-trafficked 'bed' areas, especially if a convex camber is created on the tramlines to shed water into the cropped areas. Overall, erosion risk is therefore likely to be lower within a CTF system. Gasso et al. (2013) reported reductions in surface runoff of 27-42% in a CTF system, compared with conventional trafficking.
- Increased soil carbon – SOC content tends to increase with reduced cultivation/improved soil structure over time (Kirk et al., 2012); and so CTF systems, which have the potential to improve soil structure and crop yield across the whole field due to significantly fewer wheelings and reduced cultivation, might be expected to increase organic matter content over time. However, the requirement for rotational ploughing to reduce weed burden within some combinable cropping systems not only compromises the CTF system, but also reduces the likelihood of increasing SOM content.
- Reduced soil contamination – no effect.
- Increased soil biodiversity – CTF systems are associated with reduced cultivation, which can result in a two- to six-fold increase in the mass of deep-burrowing earthworms after ten years (e.g. Ernst & Emmerling, 2009) although benefits would be reduced if rotational ploughing is required to control weeds. The significant reduction in the number of wheelings (area trafficked) should also improve soil structure and benefit soil biodiversity (Wardle et al., 2004).
- Improved soil structure, including less compaction – the reduced cultivation associated with CTF systems can result in improved aggregate stability (see **ECPW-242** & **ETPW-092**). Saturated hydraulic conductivity can also be increased by 25% if a no-till system is adopted, with an additional 10% increase in AWC associated with residue retention (Li et al., 2019). The significant reduction in the number of wheelings (area trafficked) should also improve soil structure (Chamen et al., 2015).

3.2.6.4 Timescale

- Erosion risk is related to vegetation and residue covers, so effects could be seen in the season of conversion (0-5 years) where the land was ploughed before conversion to CTF. Effect from the significantly reduced area of wheelings could take significantly longer (at least 5-10 years).
- Changes in earthworm numbers and soil structure could be detected within 5-10 years (Ernst & Emmerling, 2009; Li et al., 2019).

3.2.6.5 Spatial Issues

The action is broad scale in nature, but CTF systems are more easily adopted within combinable cropping systems with simple crop rotations. Horticultural systems growing multiple crops with a variety of cultivation, drilling, planting and harvesting machines, many of which will be on different track gauges (width between wheels) are more challenging to adapt and may be more suited to a partial or seasonal CTF system.

3.2.6.6 Displacement

The action could result in small increases in crop yield due to improvements in soil structure across the whole field, so could reduce the need for food imports by a small amount.

3.2.6.7 Maintenance and Longevity

Adopting a CTF system requires significant investment, and so requires long-term commitment from the grower. The significant investment lends itself to a degree of permanence. Operational costs will be reduced but it may take 5-10 years or more before the full benefits of the system are seen (AHDB CP 107C, 2018).

3.2.6.8 Climate Adaptation or Mitigation

The action should increase farm resilience to climate change by reducing soil compaction in the field as a whole, increasing water infiltration rates, increasing opportunities to access the land and improving the soil as a plant growth medium.

3.2.6.9 Climate Factors / Constraints

The action should contribute to climate change mitigation and adaptation by reducing the extent and severity of soil compaction. Reduced compaction could lower the risk of nitrous oxide emissions (Hargreaves et al., 2013; Da Silva et al., 2014) and improve root length densities in the subsoil, thereby increasing crop resilience to drought conditions (Zhang et al., 2020).

3.2.6.10 Benefits and Trade-offs to Farmer/Land manager

Chamen (2011) collected mean values of data from around the world and concluded that compared with conventional traffic, CTF on average increased yields by 19% on clay, 22% on loam, 8% on silt and 20% for root crops across a range of soil textures. The results indicate that yield increases are possible across a range of crops and situations. Furthermore, Godwin et al. (2017) reported a 15-16% improvement in winter wheat yield for ‘zero traffic’ over ‘random traffic’ at Morley, in Norfolk in 2008.

Conversion to CTF system can be achieved at relatively low cost over the natural replacement cycle for farm machinery. By contrast, converting the whole machinery fleet to CTF over a year or two requires significant investment amounting to a few hundred thousand pounds for smaller farms to upwards of £0.5 million for very large enterprises (e.g. > 6 full time equivalent workers). However, even in the latter case, the investment would include purchase of machinery that would be bought in any case as part of the replacement cycle. Furthermore, there are elements of a CTF system, such as satellite guidance, that should now be considered as best practice. The overall cost will depend on the number of machines and implements to be converted and the timescale of conversion to CTF. This must be weighed up against the potentially reduced running costs of the CTF system (lower power requirement due to improved soil structure and wider working width on some machinery reducing distances travelled) and the return in terms of sustained and potentially more even crop yields (Chamen et al., 2015).

3.2.6.11 Uptake

CTF requires a change in mindset by the grower and can be difficult to achieve on many farms due to the expense of converting machines or amending purchasing policy, and unsuitable infrastructure such as narrow tracks, bridge crossings and underpasses, lanes and the presence of trees and hedges. Nevertheless, CTF can be carried out on any soil type, but is most applicable to intensive arable cultivation systems (which has a limited range of machinery types cf. intensive horticulture for example).

3.2.6.12 Other Notes

Reliable soil physical quality indicators would provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.2.7 ECPW-249 - Reduce grazing and stocking rates when soils are wet to avoid soil compaction

Removing livestock when soils are 'wet', and having the infrastructure to do so, can reduce surface erosion and soil erosion and compaction extent, and can have a major positive benefit for soil structure (e.g. Rounsevell & Jones, 1993). Actions with a similar mode of action and associated benefits include:

- **ETPW-151** - Limit supplementary feeding to severe weather conditions
- **EBHE-219** - Install/ manage invisible fencing
- **EBHE-228** - Remove redundant fencing (replace with invisible fences if desirable)
- **ETPW-070** - Install/ maintain electric fencing
- **ETPW-071** - Install/ maintain permanent fencing
- **ETPW-078** - Install/ maintain gates
- **ETPW-151** - Reduce stocking density or remove livestock grazing where likely impacts on sensitive habitats and species (aquatic and terrestrial)
- **ETPW-104** - Reduce stocking rate (grazing) to restore structure and flowering, maintain ground cover, and reduce poaching
- **ETPW-142** - Off-winter livestock or reduce winter grazing on upland and mountain heath
- **EHAZ-028** - Restrict the grazing season where there is a risk of causing soil compaction, run-off and erosion
- **EHAZ-033** - Feed and water livestock in an appropriate location (move to avoid poaching or feed on hard bases)

3.2.7.1 Causality

Reducing grazing and stocking rates when soils are 'wet' can reduce surface runoff and soil erosion extent and can have a major positive benefit for soil structure (Kurz et al., 2006; Mulholland and Fullen, 1991).

Soils are most easily poached/compacted when they are 'wet'. Livestock poaching/compaction reduces soil water infiltration rates and increases the risk of surface runoff. Reducing livestock numbers or the duration of grazing when soils are 'wet' reduces poaching damage and the potential for runoff and sediment generation, and associated mobilisation and transport of pollutants to watercourses.

3.2.7.2 Co-Benefits and Trade-offs

Reducing grazing and stocking rates when soils are wet can have co-benefits for:

- Air quality
  - Better soil structure results in more rapid infiltration of urine and slurries and a reduction in associated ammonia emissions.
- GHG emissions
  - There may be a small reduction in direct N2O emissions, due to improved soil aeration.
- Soil carbon
  - There may be a small increase in soil C due to higher grass cover (less bare soil) and reduced soil (and associated soil C) losses.
- Water quality
  - Particulate P and associated sediment losses would typically be reduced due to lower surface runoff volumes.
- Water regulation
  - Due to improved water infiltration and soil water storage.
- Food production

- Improved grassland productivity and utilisation due to better grass covers and improved root proliferation enabling better access to water and nutrients.

[TOCB Report-3-6 Carbon **EHAZ-033**] Soil compaction and damage through poaching (the process of removing surface vegetation cover and compacting the soil by livestock trampling) is a common issue in British pasture. Analysis of survey squares as part of the Wales-wide Environment Rural Affairs Monitoring and Modelling Programme (ERAMMP)[1] demonstrates that several types of poaching features are visible from aerial and satellite imagery including (Robinson et al., 2021; Tye & Robinson, 2020):

- Poaching around feeding areas
- Poaching where animals congregate for shelter or socialising (e.g. behind hedges or walls)
- Poaching in fields, particularly around farmyard access (e.g. where animals are congregated prior or after milking or for animal maintenance)
- General field poaching, trampling by animals

Additionally, gateway damage (where vehicles or livestock approach the point of egress) and exacerbation of contour terracettes (hillslope ridges formed by repeated wetting and drying cycles causing soil to move very slowly downslope) make the issue of moving livestock while also avoiding poaching a particular challenge (Tye & Robinson, 2020). However, the effect of soil compaction due to livestock poaching on carbon sequestration and storage has not been quantified. Logic and expert opinion suggest that reduced soil compaction and erosion will protect soil carbon stocks and above ground vegetation. However, the fate of carbon stocks that are lost to erosion is variable (Quinton et al., 2010). More research is needed into the inception and evolution of poaching features, including recovery (Robinson et al., 2021; Tye & Robinson, 2020).

Recent analysis of aerial and satellite imagery in Wales indicates that soil erosion and soil damage associated with poaching, livestock feeders and gateway egress points are very common in agricultural land (Robinson et al., 2021). This could suggest there are significant barriers to uptake of control measures among farmers. Grazing is ultimately one of the ways in which farmers make money, so there will be economic barriers to interventions that restrict grazing. In upland areas, while incentives to reduce stocking rates may be readily taken up by some farmers, reducing stocking may run counter to some farmers' ideologies. Furthermore, hefting of sheep on common land may become harder over time with declines in sheep numbers, potentially resulting in potential abandonment of some upland areas (Alison et al., 2019). Elsewhere, farmers may be open to incentives for rotational grazing, for instance to enhance plant productivity, and by extension potentially increase SOC (Alison et al., 2019).

3.2.7.3 Magnitude

- Extent of erosion – On a 'typical' grazing livestock farm, sediment losses due to soil erosion could be reduced by up to 10% at the farm scale (Newell Price et al., 2011).
- Increased soil carbon – Avoiding poaching can increase vegetative cover resulting in potential increases in soil carbon, particularly on ley grass that forms part of an arable rotation. In this context, carbon sequestration rates of around 0.3 t C/ha/yr are possible (Poeplau & Don, 2015).
- Reduced soil contamination – not applicable.
- Increased soil biodiversity – no evidence of an effect in this specific context.
- Improved soil structure, including less compaction – the action has direct benefits for soil structure (e.g. Kurz et al., 2006).

[1] www.erammp.wales

3.2.7.4 Timescale

0-5 years: measurable impacts on the extent and rate of erosion could be achieved within the year of implementation. Soil compaction is also avoided in the year of implementation and existing poor structure could be improved within a few years through root exploration, earthworm activity and drying and wetting cycles.

Any increases in soil carbon would be due to having a more persistent vegetative cover (similar to having a winter cover crop on an arable field prior to a spring-sown crop) and would take more than 10 years (Johnston et al., 2009).

3.2.7.5 Spatial Issues

The action is broad scale in nature but is most applicable to light- and medium-textured soils on which extended grazing is possible. It could also be particularly targeted on sloping grasslands next to sensitive aquatic habitats. Where the issue is related to water quality (i.e. soil erosion associated with poaching), collaborative action initiatives would in many cases be needed to have an impact at the catchment scale. Poaching by livestock can impact on the quality of coastal waters, with ‘removing livestock when soils are wet’ one of several effective mitigation measures, particularly in small coastal catchments (e.g. Kay et al, 2007).

3.2.7.6 Displacement

On farms that do not have access to drier land, removing livestock when soils are wet could increase reliance on conserved forage and purchased feed, which can have their own environmental impacts. However, in many cases the reduction in grazed grass intake will be minimal (e.g. when the wet spell is short lived, but not during prolonged wet periods, e.g. very wet winters that delay turning out livestock) and could be recovered by increased grass productivity when soils are not waterlogged. On farms that cannot house livestock, the action could result in a need for lower stocking rates, which could also result in displacement of production to elsewhere.

3.2.7.7 Maintenance and Longevity

The action needs to be implemented permanently for the beneficial effects on soil quality to persist. Farms with grazing livestock will need to maintain livestock housing and manure management infrastructure to carry it out. Any investment in such infrastructure will lend itself to permanence.

3.2.7.8 Climate Adaptation or Mitigation

The action could form part of an effective climate adaptation strategy on some farms. Climate change may result in a reduction in the overall duration of waterlogging in most parts of England (Defra SP1316). However, it is possible that projected increases in winter rainfall in future could increase the severity of waterlogging (when it does happen), particularly on drained land, due to larger rainfall volumes overwhelming drainage systems (Defra SP1316).

3.2.7.9 Climate Factors / Constraints

The action could contribute to climate change adaptation and mitigation, through improving vegetation covers and reducing soil compaction, which should improve the resilience of the whole systems to extreme weather events through improved productivity ad higher soil water storage potential and infiltration rates.

3.2.7.10 Benefits and Trade-offs to Farmer/Land manager

Many farmers favour extended grazing of livestock as it reduces housing costs (mainly feed and manure management costs) and can improve animal health (housed livestock can be susceptible to respiratory disease). Reducing livestock grazing times could have an economic impact on the business as grazed grass is the cheapest form of forage available to a farmer. However, leaving livestock out to graze when soils are wet can also have an impact on the business through reduced grassland productivity and utilisation (e.g. delayed spring turn out dates due to compaction delaying soil drainage).

3.2.7.11 Uptake

Some livestock farmers plan to extend grazing into the autumn/winter in an attempt to reduce housing costs. This is only possible on better draining land without causing significant soil damage, although poaching can also occur on lighter land if livestock are grazed at higher stocking rates when soils are wet. The ability to take up the action will depend on the availability of better drained land or livestock housing and manure management infrastructure. Many farmers will need financial incentive to house livestock for longer periods.

3.2.7.12 Other Notes

Reliable soil physical quality indicators would provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.2.8 Soil management & protection – Cover cropping ECPW-025 - Harvest and establish the following crop early in the autumn

This action involves harvesting usually late-harvested crops such as potatoes and maize early (e.g. in September rather than October); and establishing autumn sown crops earlier (i.e. early October or sooner).

3.2.8.1 Causality

Earlier harvesting of crops, especially those that are traditionally harvested late, would enable field access by harvesting machinery when soil conditions are drier, reducing (severe) compaction and soil structural damage risks, and associated sediment and nutrient losses in surface runoff. Establishment of autumn drilled combinable crops by early October would enable the crop to provide good vegetation cover (at least 25 to 30%) over the winter months to protect the soil from rainfall, surface runoff and associated erosion (Chambers et al., 2000).

When soils are compacted and there is no growing vegetation to intercept rainfall or take up nutrients, the land is very susceptible to the generation of surface runoff and associated soil erosion (Withers and Bailey, 2003). By harvesting/ establishing crops early, compaction at harvest can be reduced.

In summary, effective implementation of the action could result in a moderate reduction in the extent of soil erosion (Chambers et al., 2000) and have a major positive benefit on soil structure and quality (Defra project WQ0140).

3.2.8.2 Co-Benefits and Trade-offs

Earlier harvesting of ‘late-harvested’ crops and establishing winter cereals earlier in the autumn can have co-benefits for:

- Water quality
- Water regulation (particularly lower risk of muddy flow events from sloping land; e.g. Boardman et al., 2003)

[TOCB Report-3-5D Systems **ECPW-025**] Assuming that this applies to crops that are winter-sown, this will have small negatives for granivorous bird habitat from destroying a short-lived crop-stubble a little earlier. If this replaces a spring crop, it will have very large negatives, as spring cropping, especially following a fallow stubble over-winter, provides critical, high-quality habitat for many priority farmland species.

3.2.8.3 Magnitude

- Extent of erosion – Compared with late harvested land, soil erosion rates could typically be reduced by 20-50% on early harvested land (Newell Price et al., 2011).
- Increased soil carbon – negligible effect.

- Reduced soil contamination – no effect.
- Increased soil biodiversity – no evidence of an effect, although avoiding compaction from late harvesting of maize and root crops could provide some benefits (e.g. Wardle et al., 2004).
- Improved soil structure, including less compaction - the action has direct benefits for soil structure (Defra SP0404 - Erosion Control in Maize Fields).

3.2.8.4 Timescale

Measurable soil structure and erosion control impacts of the action would be expected in 0-5 years. The soil erosion control effect from increasing vegetation and residue cover would be immediate while the effects from improving soil structure (avoiding and soil compaction) could take 5-10 years.

3.2.8.5 Spatial Issues

The action is broad scale in nature but should be targeted at farms growing late-harvested crops in sensitive catchments.

3.2.8.6 Displacement

If action implementation is targeted on sloping land it could result in displacement of late harvested crop production (e.g. potatoes, sugar beet and maize) onto other, less well drained land that may be less suited to late harvesting from a land access and soil compaction perspective. Potato and sugar production could be displaced globally.

3.2.8.7 Maintenance and Longevity

To deliver optimal results, the action would need to be implemented indefinitely. Where it concerns late harvested crops, there would need to be a change in cropping to earlier maturing varieties or earlier harvested crops such as peas, oilseed rape and cereals. Early establishment of cereals is only relevant to first winter wheats and is dependent on weather and agronomic factors such as weed control. There are a number of reasons why the measure could not be adopted for all autumn-sown crops. It is logistically impossible to drill all autumn-sown crops one month early due to the workload on farm. Oilseed rape and first winter wheats are prioritised for early drilling if weather/soil conditions allow. Other autumn-sown crops are delayed by harvest of the previous crop, weather/soil conditions, or due to workload in the autumn period, when harvest, cultivation, seed bed preparation and drilling have to be carried out across the whole of the autumn-sown arable area. Secondly, there are practical limitations to early drilling for some crops. For example, disease risk (e.g. take-all) in second to fourth wheats can be increased through early drilling (Spink et al., 2002).

3.2.8.8 Climate Adaptation or Mitigation

While climate change is likely to result in a reduction in the overall duration of waterlogging in most parts of England (Defra SP1316), in some areas, projected increases in winter rainfall could result in more intense waterlogging events making late harvesting unviable or at least incompatible with a commitment to managing soils sustainably.

3.2.8.9 Climate Factors / Constraints

The action may contribute to climate change adaptation within some systems and locations due to the avoidance of severe soil compaction and associated benefits for water regulation and crop root proliferation (ability to access subsoil water).

3.2.8.10 Benefits and Trade-offs to Farmer/Land manager

Restricting harvesting dates would eliminate some market options for many farmers and supply chains. Many farmers are contractually obliged to supply some vegetable and root crops at a time of year when harvesting is likely to result in some soil structural damage (e.g. potatoes, sugar beet, parsnips and Brussels sprouts).

Early establishment of cereals is possible following a break crop and when weed burden is not high. However, some situations such as the need to establish a stale seedbed (i.e. a seedbed in which weed germination has been controlled by a sequence of cultivation and 'spraying off' with herbicide) will dictate later establishment. The agronomic implications of not controlling arable weeds such as black-grass and sterile brome can be significant, with yield reductions of 10-15% not uncommon due to plant competition and crop lodging. Weed seeds can also contaminate the combine harvester and baled straw from the following crop, reducing the quality and value of both products and potentially spreading the problem across the farm or on to other farms.

3.2.8.11 Uptake

The main barriers to uptake are late harvesting of maize to optimise quality; contractual obligations to harvest field vegetable and root crops late; and an agronomic incentive to delay drilling of winter cereals in fields with high weed pressure, particularly in years with low black-grass dormancy. There is limited scope to increase uptake of drilling autumn-sown crops early, mainly due to practical limitations. For example, it is logistically impossible to drill all autumn-sown crops one month early due to the workload on farm; disease risk can be increased through early drilling of some crops; and where early drilling is favourable most farmers are already doing so to maximise yield potential, particularly for oilseed rape and first wheat crops (Kirk et al., 2012).

3.2.8.12 Other Notes

The action could be monitored using remote sensing. Reliable soil physical quality indicators would provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.2.9 ECAR-044 - Ensure persistent continuous vegetation cover on land

The action involves using a permanent vegetative cover (i.e. providing continuous vegetation cover on the cropped area, not simply growing a cover crop, temporary companion crop or retaining stubbles) to protect the soil surface from erosion, sequester carbon and, in the case of a permanent legume cover, fix atmospheric nitrogen. This can be challenging within arable systems, in which it is often necessary to carry out cultivations to control weeds, incorporate manures and residues and create a seedbed. Some arable crops such as maize, sugar beet and spring barley also suffer competition from a continuous vegetative cover, which can result in a yield penalty (e.g. Defra project WQ0140).

3.2.9.1 Causality

Persistent continuous vegetative covers protect the soil from rainfall induced surface runoff and soil erosion, and where successfully implemented can result in major benefits to soil erosion control. To be effective in reducing erosion risk the crop does not have to be alive (i.e. straw and crop residues can be effective), but the soil must be protected throughout the period when surface runoff can occur. Through root development, continuous vegetative covers can also provide major positive benefits for soil structure and have the potential to increase SOC levels, although there are many practical limitations to overcome, such as the persistent vegetation cover providing a 'green bridge' for crop diseases or competing with the cash crop for light, water and nutrients.

There is limited evidence to demonstrate the benefits of persistent continuous vegetative cover within arable rotations (e.g. Jez et al., 2021), but having vegetation and roots in place throughout the year can potentially have multiple benefits where practical limitations (e.g. weeds, competition between the permanent cover and the cash crop, effective establishment and persistence etc.) can be overcome. A number of projects are investigating this action along with other crop diversification strategies (e.g. Diverimpacts - DiverIMPACTS)

3.2.9.2 Co-Benefits and Trade-offs

Ensuring persistent continuous vegetation cover can have co-benefits for:

- Below ground C sequestration – due to the continuous vegetative cover providing photosynthetic activity (C input) for most of the year
- Water quality – lower nitrate leaching losses due to uptake of N in early autumn; lower particulate P and associated sediment losses due to soil surface protection and lower surface runoff volumes
- Water regulation (flow variability and flood protection) – due to better soil structure, vegetation cover and roots in the soil to improve water infiltration and soil water storage

3.2.9.3 Magnitude

- Extent of erosion – compared with bare soil, having a continuous vegetation cover and growing roots could reduce water erosion associated sediment losses by 20-80% (Newell Price et al., 2011; Defra project WQ0140). This is supported by the crop (or 'C') factor of the USLE (a ratio of soil loss under vegetation versus bare soil) all other factors being equal (Wischmeier & Smith, 1978).
- Increased soil carbon – rates of soil carbon increase would depend on the duration of vegetation cover before the action was implemented, but could be similar to some perennial cropping systems that can result in a 20% increase in SOC at 0–30 cm depth over a twenty-year timescale, depending on the starting SOC level (Ledo et al., 2020). The action is designed to provide continuous vegetative cover throughout the year.
- Reduced soil contamination – none
- Increased soil biodiversity – any improvements in soil biodiversity (e.g. earthworm numbers) would be associated with the effects of reduced or no cultivation and the increased availability of crop residues (e.g. Kautz et al., 2014).
- Improved soil structure, including less compaction - improvements in topsoil and increases in pore connectivity SOC are likely to be translated into improvements in soil structure and functions such as regulating water and air flows into and within the soil and supporting plant growth.

3.2.9.4 Timescale

Ensuring persistent continuous vegetative cover could result in measurable impacts associated with improvements in soil structure and potential increases in SOC within twenty years (Ledo et al., 2020). However, the timescale depends on the degree of change in terms of the annual period of vegetation cover and the frequency of cultivation.

3.2.9.5 Spatial Issues

The action is broad scale in nature but is likely to be spatially variable in its practical implementation. Some soil types, agroclimatic zones and agronomic situations will be more suitable to the practice than others, e.g. well-drained, light- and medium-textured soils in the east of the country with limited weed burden. Farmers are likely to benefit from sharing experiences with other local farmers that are experimenting with the action, particularly with respect to the cover species and establishment methods that are successful under local soil and climatic conditions.

3.2.9.6 Displacement

The main challenge associated with maintaining persistent covers within arable rotations is the potential impact on crop yield. When this occurs, there will be displacement issues.

3.2.9.7 Maintenance and Longevity

To be effective in terms of improving soil structure, soil biodiversity and SOC contents, the action needs to be implemented for several years at a time. Intermittent and well-timed cultivation (i.e. when soils are 'dry', e.g. flat lifting or strip tilling) should not have a significant impact, but regular cultivation is likely to undo any benefits gained.

The action could be discontinued at any time but investments in reduced tillage machinery will result in path dependencies as the farmers would want a return on investment over time. Where the persistent cover includes a legume, the saving on manufactured fertiliser would be a significant incentive to continue the practice.

3.2.9.8 Climate Adaptation or Mitigation

Climate change could have an impact on the ease of establishment and persistence of vegetative covers, particularly if the recent dry springs become a more typical part of UK weather patterns. Hotter, drier summers and more intense periods of waterlogging in winter could also have an impact on the establishment and persistence of some plant species (e.g. Real et al., 2008). Selection of suitable plant species or mixes, and when to establish them, is therefore an important consideration.

3.2.9.9 Climate Factors / Constraints

Persistent vegetative covers could contribute towards climate change adaptation and mitigation through providing some photosynthetic activity, root growth and soil surface protection through much of the year (potentially the entire year). Covers containing legumes will also fix atmospheric nitrogen, thereby reducing reliance on manufactured nitrogen fertiliser, although more research is needed to determine the degree to which the main cash crop benefits from the nitrogen fixed.

3.2.9.10 Benefits and Trade-offs to Farmer/Land manager

There are clear environmental benefits to establishing and retaining vegetative covers, which can also help reduce production costs and inputs. However, adoption does require a significant change in mind-set for many farmers as crop yield can be impacted and chemical, physical and cultural weed control options are reduced. The ability to adopt the option may be farm and individual field specific due to variation in soil type, climate, disease pressure and weed burden.

3.2.9.11 Uptake

The action requires a significant change in agronomic practice with a much-reduced reliance on cultivation and agro-chemicals to control weeds. A certain amount of 'trial and error' is also needed to determine the optimal species mix for the vegetative cover, to optimise establishment and persistence while reducing competition for water and nutrients with the cash crop. Farmer-led co-innovation groups are especially useful in this respect to share experiences. Any farmer embarking on this change in practice would need security of tenure for 10-15 years to provide confidence that the practice can be mastered, and benefits seen within the tenancy period.

3.2.9.12 Other Notes

The action could be easily monitored through remote sensing to assess the persistence of vegetative cover.

3.2.10 ECCM-023 - Use green manures within the rotation

Green manures are crops that are grown instead of a cash crop to improve soil structure, fix nitrogen (if legumes are in the mix), control weeds, suppress disease and add organic matter from incorporated crop residues. They tend to be incorporated while still green, with the specific intention of increasing soil organic matter. In many cases, the farmer sacrifices the revenue from growing a cash crop for the benefits of maintaining or enhancing soil organic matter levels and improving soil structure to potentially increase the productivity of following cash crops and to develop a more resilient system. They may be grown for the whole growing season or for part of the growing season between two cash crops.

3.2.10.1 Causality

Green manures protect the soil from rainfall induced surface runoff and soil erosion and can also provide major positive benefits for soil structure. As they tend to be grown in place of cash crops, they are normally in the ground for longer than autumn-sown catch or cover crops (that are in the ground between a summer/autumn harvested cash crop and a spring-sown cash crop) and when allowed to grow in spring and summer months have the opportunity to capture more solar radiation than a winter cover crop, and thereby have the potential to grow larger crops (summer green manure cf. winter cover crop) and sequester more carbon (e.g. Harrison & Peel, 1998; Sainju et al., 2002; Poeplau & Don, 2015).

The research evidence indicates that the longer the cover cropping or green manure period, the clearer the effects on soil structural condition. A review of studies on the use of cover crops and green manures to rectify soil structural damage found that changes in soil bulk density were only detected when green manures were established for nineteen months or more (Berdeni et al., 2021a). No effect was shown when green manures were established for 12 months or fewer, although Chen & Weil (2011) reported a change in bulk density after two consecutive winters of winter cover cropping. Jokela et al., (2009) considered that four or more years of cover crop growth are generally required for indicators of soil quality such as penetration resistance and bulk density to be improved.

Martlew (2021) also observed changes in topsoil and subsoil structure after thirteen years of growing a brassica green manure alternated annually with a winter wheat crop (compared with continuous winter wheat), although the most noticeable changes occurred when this was done in combination with reduced tillage. Indeed, the reduced tillage treatment provided the most significant benefits in terms of soil water retention, root morphology and soil pore characteristics. The combination of alternating green manure cropping and reduced tillage produced the most significant benefits to physical subsoil properties, and therefore the greatest potential to improve compacted subsoil.

3.2.10.2 Co-Benefits and Trade-offs

Using green manures within the rotation can have co-benefits for:

- Air quality – due to improved soil structure increasing the infiltration rate of slurries and other liquid manures.
- Biodiversity – due to the provision of a long term, flowering cover and potential to use a multi-species green manure seed mix.
- Pollination and seed dispersal – due to the presence of a vegetation cover that can be retained until flowering and seeding.
- Soil carbon – due to provision of vegetation cover (photosynthetic activity) and incorporation of the green manure (bulky residues).
- Water quality – due to protection of the soil surface and uptake of nutrients to reduce erosional and leaching losses.

[TOCB Report-3-5D Systems **ECCM-023**] Assuming that refers to the use of green manures instead of mineral nitrogen, phosphorus and potassium, this is likely to have some positive effects on soil biodiversity and dependent species, but there is an absence of evidence.

3.2.10.3 Magnitude

- Extent of erosion – through avoiding or reducing the amount of bare soil while the green manure is in place, the local impact at the field scale can be as high as a 60-80% reduction in soil erosion rates (Newell Price et al., 2011).
- Increased soil carbon – where green manures are incorporated into crop rotations, carbon sequestration rates of around 0.3 t C/ha/yr are possible in the years when green manures are grown (Poeplau & Don, 2015). However, green manures cannot be grown every year as they take the place of a cash crop in the rotation. In addition, growth of green manures is highly dependent on weather and local conditions: in some years growth can be excellent, while in others it is poor. Some caution is required in assigning a SOC rate of increase to green manures. They can contribute to C sequestration over time, but are not a panacea.
- Reduced soil contamination – none

- Increased soil biodiversity – providing an increased quantity of soil residue is likely to increase the population of earthworms (e.g. Kautz et al., 2014) and associated soil flora and fauna.
- Improved soil structure, including compaction – improvements in soil structure indicated by visual soil evaluation (e.g. VESS score improvement of half a point: Storr et al., 2017) are possible within a year of establishing a green manure. Changes in penetration resistance and a 5-10% reduction in soil bulk density are rare but possible within 10-15 years of regular use of green manures (e.g. Demir & Işik, 2020). Changes in soil pore characteristics (e.g. total porosity, pore continuity and connectivity) and improvements in soil moisture retention and root morphology are also possible within this timescale (Martlew, 2021).

3.2.10.4 Timescale

- Provided that green manures establish well, some reduction in the extent of erosion would be expected in the year of implementation (0-5 years).
- Increases in soil carbon would only be measurable after >10 years.
- Increase in earthworm numbers and visual changes in soil structure are possible in 0-5 years, with measurable changes in soil bulk density and porosity taking considerably longer (5-10 or >10 years).

3.2.10.5 Spatial Issues

The action would be usefully employed on sloping land to reduce erosion risk. However, soil structural and soil carbon benefits are applicable to all soils. The use of green manures may be more applicable in crop rotations that incorporate high value crops such as field vegetables, salad crops and potatoes, as the high value of these crops over the rotation can compensate for the cost of establishing the green manure, and the use of green manures results in better structured soil and more freely draining land, thereby improving flexibility of access for field operations.

3.2.10.6 Displacement

Growing a green manure in place of a cash crop will decrease crop production in the year it is grown and almost certainly result in displacement of cash crop production to other areas (within the UK or overseas). However, using green manures may result in a more resilient and sustainable system as they can help to maintain or enhance soil organic matter levels and soil structure, which can result in better crop rooting and improved water and nutrient use efficiency.

3.2.10.7 Maintenance and Longevity

The action needs to be maintained for 10-20 years for most of the environmental and production benefits to be seen. Using green manures does not require much investment other than the cost of the seed and the know-how to establish and incorporate them. However, there is a cost incurred from not growing a cash crop. The minimal investment means that the action can be easily reversed, so to continue with the practice it is important that farmers and growers receive sufficient technical support and reassurance that it can be successful. Some financial support in the early years of adoption would be a useful incentive, and would be essential where there is resistance to uptake.

3.2.10.8 Climate Adaptation or Mitigation

Using green manures may make farm businesses more resilient to climate change through maintaining and enhancing SOC levels, improving soil structure and protecting the soil surface from intense rainfall. However, successful establishment may be impacted by dry conditions (soil moisture deficits > 5 mm) in autumn or spring.

3.2.10.9 Climate Factors / Constraints

Climate change within the next 20-30 years is unlikely to impact on the viability of growing green manures (Keay & Hannam, 2020). Indeed, the action could contribute to climate change adaptation and mitigation through improved soil structure, soil water retention, water infiltration rates and carbon sequestration. However, most of these benefits are not likely to be seen within ten years of adoption.

3.2.10.10 Benefits and Trade-offs to Farmer/Land manager

The main benefit to the farmer or grower is the greater resilience of the production system through potentially improved soil structure, rooting, weed control and pest and disease suppression (by disrupting the life cycles of various pests and diseases; e.g. Larkin and Griffin, 2007; Zou et al., 2015). The main trade-off is associated with growing a green manure in place of a cash crop and the associated reduction in revenue.

3.2.10.11 Uptake

It may take several years to see the benefits from using green manures, so security of tenure is a clear issue for growers. High market prices for cash crops may be a disincentive as establishing and retaining a green manure may be seen as a missed economic opportunity by some growers. However, an increasing number of growers acknowledge the benefits from growing green manures (AHDB CP 107c). The planning horizons of individual farmers is a key factor, including whether they can afford to consider the long-term benefits of such actions, so a financial incentive in the short term may encourage uptake.

3.2.10.12 Other Notes

The action could be monitored using remote sensing, and reliable soil physical quality indicators could provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.2.11 ECPW-279 - Use of cover crops as an alternative to plastic mulch - Soil-enriching cover crops may be grown over the winter in the same beds where a food crop is to be planted the following spring and used in place of mulch

Other methods with a similar of mode of action and range of benefits include:

- **EHAZ-007** - Use cover crops
- **ECPW-002** - Minimise bare soil to reduce soil loss e.g. cover crops, crop residues, trees coppice etc.
- **ECPW-095** - Maintain soil cover (e.g. grass, crop or geotextile), to reduce soil erosion and loss around field structures such as poly-tunnels, plastic sheeting /cloches or irrigation equipment used for horticultural crops.
- **ECPW-295** - Maintain soil cover (e.g. grass, crop or geotextile), to reduce soil erosion and loss around livestock shelters/feeders/troughs; e.g. for outdoor pigs.

Where land would otherwise be left 'bare' over-winter, cover crops should be established immediately post-harvest or, at the latest, by mid-September. Alternatively, spring crops can be under- or over-sown with a cover crop that would be in place to provide vegetation cover once the spring crop has been harvested. Ideally, to protect the soil surface throughout the period when surface runoff can occur, the cover crop should not be destroyed until the land is due to be prepared for the following crop.

Winter cover crops are typically established in late summer or early autumn and destroyed by early spring. They differ from green manures, which can be grown at any time of year and typically for a longer duration of time.

3.2.11.1 Causality

Cover crops help to protect the soil from raindrop impact and rainfall induced surface runoff and therefore can have major benefits in reducing the rate and extent of erosion (e.g. Morgan, 1985; Evans, 1990; Sharpley & Smith, 1992; Ulen, 1997; Collins and Davidson, 2009). If used within a crop rotation on a regular basis over multiple years, they can also have additional moderate benefits through improving soil structure (e.g. Chen and Weil, 2011) and enhancing soil organic matter levels (Poeplau & Don, 2015).

For soil structure improvements, there is a lack of evidence of a clear and consistent effect from cover cropping. Some evidence suggests that when integrated into reduced or no till cropping systems for multiple years, they can be of benefit to topsoil structure. However, there is a lack of longer terms studies (> 1.5 years) and studies that quantify changes to soil structure at depths > 30 cm (Berdeni et al., 2021a).

3.2.11.2 Co-Benefits and Trade-offs

Using cover crops can have co-benefits for:

- Air quality – due to improved soil structure increasing the infiltration rate of slurries and other liquid manures.
- Soil carbon – due to provision of vegetation cover (photosynthetic activity) and incorporation of the cover crop (bulky residues).
- Climate regulation/GHG emissions – due to improved soil structure and uptake of soil nitrate, both of which can reduce the potential for N_2O emissions.
- Water quality – due to protection of the soil surface and uptake of nutrients to reduce erosional and leaching losses.
- Water regulation – due to better soil structure, vegetation cover and roots in the soil to improve water infiltration and soil water storage

[TOCB Report-3-5D Systems **ECPW-002** - Minimise bare soil to reduce soil loss e.g. cover crops, crop residues, trees coppice etc.] This has not been reviewed for biodiversity as it is too general: the various options will have a range of negative and positive effects for different species, which will be variable across action-taxon (i.e. group of organisms) combinations.

3.2.11.3 Magnitude

- Extent of erosion – using cover crops can reduce erosion and associated sediment losses by 20-80% at the field level (e.g. Collins & Davidson, 2009; Defra projects WQ0127 and WQ0140). The extent of erosion would be reduced in proportion to the area of cover crops grown. However, uncompacted cereal stubbles can also be effective in reducing soil erosion due to the soil protection afforded by the crop residue cover and volunteer weeds. Indeed, where cultivation is used to introduce a cover crop, late or poor establishment can result in more erosion than on uncompacted, uncultivated cereal stubbles (Defra projects WQ0127 and SP1315; Figure 2).
- Increased soil carbon – carbon sequestration rates of around 0.3 t C/ha/yr are possible in the years when cover crops are grown (Poeplau & Don, 2015). However, cover crops cannot be grown every year in all situations. Under UK/European conditions, winter cover crops are only grown prior to a spring-sown crop. In many UK situations farmers grow a succession of autumn-sown crops. It is unclear how frequently cover crops were grown in the cases that Poeplau & Don (2015) reviewed. In addition, growth of cover crops is highly dependent on weather and local conditions: in some years growth can be excellent, while in others it is poor. Some caution is required in assigning a SOC rate of increase to cover crops. They can contribute to C sequestration over time, but are not a panacea.
- Reduced soil contamination – where plastic mulch is replaced by cover crops, the plastic contamination will be reduced at source.
- Increased soil biodiversity – cover crops can increase earthworm numbers and associated soil flora and fauna, and if introduced in combination with reduced tillage can increase earthworm numbers by two-to three-fold (Storr, 2019).
- Improved soil structure, including compaction – improvements in topsoil structure indicated by visual soil evaluation (e.g. VESS score improvement of half a point: Storr et al., 2017) are possible within a year of using cover crops. However, when cover crops are grown in late autumn and winter months only, plant growth is limited by light and temperature, and while some visual changes in soil structure may be observed, changes to soil bulk density and porosity are far less common. Changes in penetration resistance and a 5-10% reduction in soil bulk density are rare but possible within 10-15 years of regular use of cover crops (e.g. Demir & Işik, 2020).

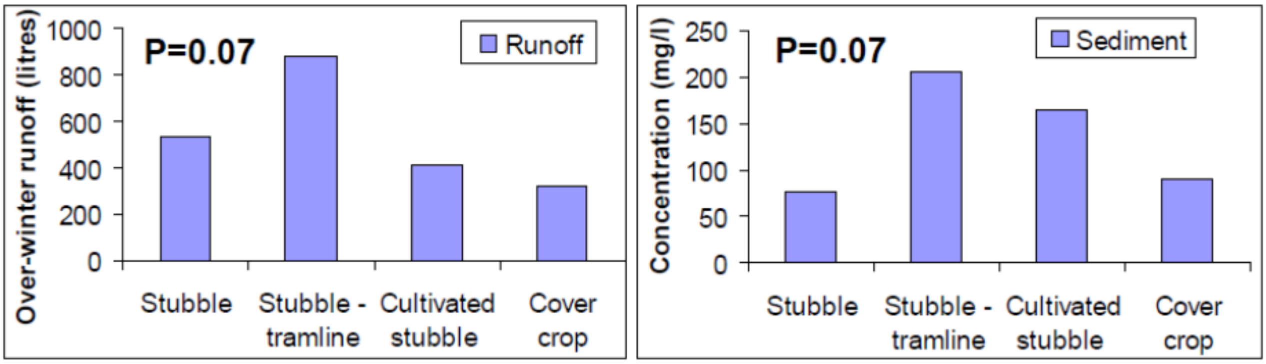

Figure 2. Treatment effects over the winter before potatoes. (Source: Defra project WQ0127).

3.2.11.4 Timescale

- Provided that cover crops establish well, small reductions in the extent of erosion (compared to cultivated stubbles) would be expected in the year of implementation (0-5 years).
- Increases in soil carbon would only be measurable after >10 years.
- An increase in earthworm numbers is possible in 0-5 years (Storr, 2019: Euteneuer et al., 2020).
- Cover crops generally need to be integrated into cropping systems for >1 year and sometimes for more than 10 years before clear benefits to soil structure and porosity are found (Blanco-Canqui et al., 2015).
- Discontinuing the use of plastic mulches will reduce plastic loading to soils. Microplastics can have a significant impact on soil properties (Qi et al., 2020). However, little is known about the timescale of these effects. Further interdisciplinary studies are needed to understand the medium- to long-term impacts of plastic debris on soil and agroecosystems (Qi et al., 2020).

3.2.11.5 Spatial Issues

Cover crops are particularly important within catchments that have a sediment loading issue (Collins and Davidson, 2009) and should be targeted on sloping land with sandy and light silty soils (Defra, 2005). Within sensitive catchments, the action will be more effective when farmers act collaboratively to protect the higher erosion risk land. Erosion losses from a few *critical source areas* for sediment could offset beneficial actions in other parts of a catchment (e.g. Strauss et al., 2007).

3.2.11.6 Displacement

The use of cover crops can sometimes result in a poor seedbed if the presence of the cover crops prevents timely seedbed preparation cultivations that would have been carried out in their absence, and can lead to yield impacts in the following crop (e.g. Bhogal et al., 2020). Some cover crops can also provide a ‘green bridge’ for pests and disease. This could result in a minor displacement issue due to the reduced crop yield. However, in the longer term, the improved soil structure and rooting, as well as the nutrients captured by the cover crop could result in a small yield increase and a more resilient production system (Stobart et al., 2015).

3.2.11.7 Maintenance and Longevity

The action needs to be maintained for 10-20 years for most of the environmental and production benefits to be seen. Using cover crops represents a cost (seed, establishment and destruction costs that typically exceed previous cultivation costs) to farmers and can present a yield risk to following crops due to the additional field operations required to destroy the cover crop. However, the cost may be similar to the use of plastic mulch that it is replacing in this action, and cover crops may not be as effective as plastic mulch in reducing the pressure from certain insect pests. The level of investment for cover cropping is not significant, but it is increasingly used in combination with reduced tillage, which does require an investment in machinery or the regular use of contractors. Farmers following this route will normally be committed to make it work and if the system is successful within the first few years of adoption the change is likely to be permanent (AHDB, 2020). Technical support and reassurance that cover crops can be a useful addition to the crop rotation will help confidence. Some financial support in the early years of adoption may also be a useful incentive.

3.2.11.8 Climate Adaptation or Mitigation

Using cover crops can help with climate change adaptation and mitigation. If adopted for several years, the likely improved soil structure could help with adaptation, while small increases in SOC and a likely small decrease in indirect nitrous oxide emissions (due to the avoided nitrate leaching losses) would help with mitigation (Newell Price et al., 2011). More frequent summer droughts would make cover crop establishment more challenging in some years and this could reduce their effectiveness in reducing erosion risk (lower vegetation covers in the critical autumn period), as well as reducing the amount of biomass and soil carbon accumulated (Harrison and Peel, 1998). Using cover crops instead of plastic mulch would also avoid the surface runoff and subsequent erosion associated with using plastic mulch on sloping land.

3.2.11.9 Climate Factors / Constraints

Cover crops are more suited to sandy and light silty soils (<18% clay in the topsoil) due to their ease of cultivation and their tendency to drain better and warm up more quickly in the spring. Growing cover crops on medium- and heavy-textured soils, and any soil that is imperfectly or poorly drained, is therefore more challenging but can be made to work with some patience and flexibility.

More frequent drought and more intense episodes of winter waterlogging (e.g. Villarini, 2011) could impact on the effectiveness of cover crops in reducing the extent of erosion and improving soil health, mainly due to the reduced biomass production.

3.2.11.10 Benefits and Trade-offs to Farmer/Land manager

Cover crops have numerous environmental benefits and can potentially be an advantage to the farming business due to improved soil structure, drainage, crop rooting, water retention and nutrient capture. However, in the early years of adoption there may be trade-offs associated with trialling seed mixes to determine the species that will be successful on a particular farm and the cover crop destruction methods that are most suited to the local soil and climate. Using cover crops may therefore be associated with yield impacts in early years and in future years when extreme weather event may impact their effectiveness. Nevertheless, the overall effect of cover crops should be positive on many farms, and will be significantly better for soil health and soil physical quality than plastic mulches (Qi et al., 2020).

3.2.11.11 Uptake

In a UK survey of arable farmers, Storr et al. (2019) found that the main barriers to using cover crops were cost, problems with incorporating the cover crop into the planned rotation and the difficulty of measuring cover crop benefit. Improved understanding of the benefits and limitations of using cover crops may improve farmer uptake and will help to guide best practice so that optimal agronomic and environmental benefits can be achieved. Furthermore, farmers using plastic mulches may not be convinced that cover crops can offer equivalent (plastic mulch associated) benefits such as increases in soil temperature, reduced weed pressure, moisture conservation, reduction of certain insect pests and higher crop yields (Kasirajan & Ngouajio, 2012).

3.2.11.12 Other Notes

The action could be monitored using remote sensing, and reliable soil physical quality indicators could provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.2.12 ETPW-251 - Use grass waterways in crops with high risk of soil erosion and run off (e.g. field vegetables)

A grassed waterway (GWW) is a purposefully constructed broad and shallow in-field channel with side slopes not exceeding a 1 in 2 gradient. They are used to trap sediment in-field and encourage infiltration of surface water, reducing the risk of runoff and off-site diffuse pollution and flooding. Geotextile materials can be laid down to provide immediate protection of the channel bed. The design takes into account soil, slope and rainfall and usually follows a natural drainage pathway to avoid excess field engineering. For more information see: GREATsoils: Engineering the landscape to secure asparagus production (AHDB)[2] [accessed: 16/02/2023]

Grass waterways can be established to protect the most vulnerable parts of agricultural fields from erosion and surface runoff. They are particularly effective where surface flows concentrate and have been used on high erosion risk land where perennial crops such as asparagus and nursery trees and shrubs are grown (Simmons and Truckell, 2013).

3.2.12.1 Causality

If implemented well, GWWs can be a major benefit to soil conservation and soil health. The grass cover protects the soil surface from the compacting and detaching energy of rain splash (Morgan, 2005) and imparts a degree of surface roughness thereby reducing entrainment and transport of sediment (Foster et al., 1982). It can also protect a soil surface from sealing (Assouline, 2004), maintain infiltration and reduce surface runoff velocity forcing deposition of entrained soil particles.

3.2.12.2 Co-Benefits and Trade-offs

Grass waterways can also provide co-benefits for:

- Air quality – due to conversion from arable/horticultural land to ungrazed grassland (Newell Price et al., 2011)
- Aquatic biodiversity – due to reduced diffuse pollution into local water courses
- Soil carbon – due to the establishment of a permanent vegetation cover and reduced surface runoff and erosion
- Climate regulation/GHG emissions – due to taking land out of arable/horticultural production (but see displacement section below)
- Water quality - due to reduced diffuse pollution into local water courses
- Water regulation – due to increased water infiltration and a reduction in rapid surface runoff, thereby reducing peak flow volumes

3.2.12.3 Magnitude

- Extent of erosion – local impact within the grass waterway can be significant with sediment losses reduced by around 50% (Newell Price et al., 2011). Impacts at the field scale could be similar due to the GWW targeting the higher risk sloping land. Grassed waterways will not prevent surface runoff and soil erosion in the rest of the field. However, it will curb movement of sediment off the field.
- Increased soil carbon – where grass waterways are a permanent feature, increases in SOC (on the area of GWW, which is converted from arable/horticultural land to unfertilised and ungrazed grass) are likely to initially be in the range 0.5 to 1.9 t C/ha/year (Dawson & Smith, 2007). The actual value will depend on the current SOC level, soil type, previous land management and climate, and rates will slow and eventually cease when a new equilibrium of soil C is reached (estimated to be after 50-100 years).
- Reduced soil contamination – none
- Increased soil biodiversity – Soil biodiversity would benefit from the lack of soil disturbance and permanent vegetation cover and associated residue with earthworm numbers potentially doubling within a few years (Storr, 2019).

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[2] GREATsoils: Engineering the landscape to secure asparagus production | AHDB

- Improved soil structure, including compaction – Provided that the GWW is not used as a track, soil structure is likely to improve with a 5-10% reduction in soil bulk density possible within 5-10 years (e.g. Berdeni et al., 2021b).

3.2.12.4 Timescale

- Extent of erosion – if well implemented, benefits to soil erosion control could be seen in the year of establishment (i.e. 0-5 years for measurable impact). However, there is a period of high erosion risk as the GWW establishes. Biodegradable geotextiles can be used to protect the soil during this time. Synthetic geotextiles can also offer synergistic effects with the vegetation in the longer term, as they can increase the maximum permissible velocities of flow before erosion occurs in the GWW (Simmons & Truckell, 2013).
- Increased soil carbon – increases in SOC could occur for up to 20 years with rates slowing and eventually ceasing when a new equilibrium of soil C is reached after around 50-100 years (i.e. >10 years for measurable impact; Dawson & Smith, 2007).
- Reduced soil contamination – none
- Increased soil biodiversity – changes in soil biodiversity can be seen within a few years (e.g. Storr, 2019), i.e. 2-5 years for measurable impact.
- Improved soil structure, including compaction – improvements in soil structure can be measured within 5-10 years.

3.2.12.5 Spatial Issues

The action should be targeted at the higher erosion risk land where surface runoff pathways concentrate. This targeting can be critical in reducing erosion rates and reducing off-site impacts from rapid surface runoff (Simmons and Truckell, 2013), although siting and implementation can be challenging in fields with complex slopes and multiple fall lines. Strictly speaking, a GWW should not be trafficked (due to the risk of soil compaction in wetter areas), so there may be issues with access and operations within the field.

3.2.12.6 Displacement

Establishing permanent grass waterways in arable and horticulture fields will inevitably result in some displacement of production. Depending on the width of the GWW, the percentage land take/loss can be 10-20% of productive land (USDA. 2020). However, it can result in a more resilient and sustainable production system for the farm in question. The area of a field occupied by a GWW depends on the predicted volume of water flowing onto the waterway at a predetermined level of risk, e.g. to receive and channel the surface runoff from a 1 in 30-year storm event.

3.2.12.7 Maintenance and Longevity

To be effective, the action needs to become a permanent feature of the field. Once implemented, and a land manager has seen the benefits in terms of reduced crop damage (due to fewer 'muddy flows' onto a growing crop), increased ease of access for field operations (wetter areas are occupied by the GWW) and reduced off-site impacts, they tend to retain the features. However, the change could be easily reversed through cultivation.

3.2.12.8 Climate Adaptation or Mitigation

Grass waterways should not be impacted by climate change or at risk from future climate scenarios unless prolonged drought becomes more common. In this case, it would be necessary to reseed parts of the grass waterway when grasses die back. In addition, if the GWW is designed with a return period in mind (i.e. GWW width, extent and plant species used) and the severity of events increases, it may need to be redesigned. Some GWW could require a geotextile to increase the maximum permissible surface runoff velocity before erosion of the GWW occurs.

3.2.12.9 Climate Factors / Constraints

Grass waterways are one way for farmers and growers to adapt to climate change as they increase a farm's resilience to intense rainfall. The SOC sequestered in the grass waterway also contributes (to a small extent) towards climate change mitigation.

3.2.12.10 Benefits and Trade-offs to Farmer/Land manager

The main trade-off for farmers and growers is the crop production area lost to the grass waterway. However, the area can be used to increase farm resilience and there are also potential carbon and biodiversity gain benefits as well as a potential increase in natural predators that can help control crop pests and diseases within a more complex agroecosystem.

3.2.12.11 Uptake

Establishing a grass waterway is a long-term commitment so security of tenure is likely to be an issue for many farmers, particularly when land is rented on an annual basis to grow field vegetables. However, the landowner could decide that it is the right option for a field and make grass waterway retention a requirement of the agricultural tenancy agreement. Grass waterways also need careful design to ensure that soil protection is optimised, and surface runoff volumes calculated (Simmons and Truckell, 2013).

3.2.12.12 Other Notes

The action could be monitored using remote sensing, and robust soil physical quality indicators could provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017). However, this is an example of an action that may be more beneficial to water resources than it is to soil.

3.2.13 ECPW-028 - Enhance management of maize including early harvest, use of early maturing varieties, early planting times and establishment of a cover crop

This action combines the protective effects of early harvest of maize in the autumn and the establishment of a cover crop and has been included as a management option within Countryside Stewardship (SW5: Enhanced management of maize crops) for several years[3]

3.2.13.1 Causality

Effective implementation of the action could result in major benefits for soil erosion control and moderate benefits for soil structure and quality. Forage maize is typically harvested in mid to late autumn using heavy machinery, which can cause compaction, reduce soil water infiltration and increase the risk of surface runoff and associated soil erosion (Withers and Bailey, 2003). The most common current practice is to retain maize stubbles over winter and cultivate them in early spring before establishment of an arable crop or grassland (SP1315). Surface runoff volumes from the highly trafficked, compacted maize stubbles can be significantly reduced through the use of a chisel plough (post-harvest) or over-sown rye-grass (Defra projects SP0404 and WQ0140). Over sowing a cover crop at the maize 6-8 leaf stage can be effective at providing vegetative cover after harvest and can result in significant reductions in surface runoff and erosion, but in some years this can result in a yield impact for the crop being grown or the following crop, mainly due to competition for water, nutrients and light (Defra project WQ0140).

3.2.13.2 Co-Benefits and Trade-offs

Enhanced management of maize can have co-benefits for:

[3] https://www.gov.uk/countryside-stewardship-grants/enhanced-management-of-maize-crops-sw5 [accessed 16/02/23]

- Air quality - due to improved soil structure increasing the infiltration rate of slurries and other liquid manures.
- Water quality - due to improved soi structure, protection of the soil surface and uptake of nutrients to reduce erosional and leaching losses.
- Water regulation - due to improved soil structure resulting in increased water infiltration, greater soil water storage capacity, and a reduction in rapid surface runoff, thereby reducing peak flow volumes.

[TOCB Report-3-5D Systems **ECPW-028**] Maize is a poor crop for biodiversity. The action is very unlikely to have positive effects as the crop provides low levels of biodiversity.

3.2.13.3 Magnitude

- Extent of erosion – where over-sown cover crops provide good ground cover after harvest of maize crops, sediment losses can be reduced by between 20 and 80% compared with bare ground (Kwaad and van Mulligen, 1991; Lal et al., 1991; Newell Price et al., 2015; Defra project WQ0140). However, the success of cover establishment will depend on the type of cover crop grown, establishment method and soil and weather conditions at the time of drilling. Good establishment of the cover crop is dependent on adequate summer rainfall (Defra project WQ0140). The effectiveness of the cover crop in reducing the extent of erosion is also dependent on no or limited soil damage through trafficking during maize harvest.
- Increased soil carbon – increases in SOC stocks of up 0.3 t C/ha/year are possible but only when the cover crop is retained for several months. Winter cover crops will accumulate significantly less SOC depending on the establishment date, the establishment success and the destruction date (Poeplau & Don 2015). Furthermore, within livestock production systems, maize and the associated cover crop will only be grown in part of a rotation. It is unclear how frequently cover crops were grown in the cases that Poeplau & Don (2015) reviewed. Cover crop establishment and growth is highly dependent on weather and local conditions, and is particularly challenging following a maize crop: in some years growth can be excellent, while in others it is poor. Some caution is required in assigning a SOC rate of increase to cover crops. They can contribute to C sequestration over time, but are not a panacea.
- Reduced soil contamination – none, unless the cover crop replaces the use of a plastic mulch (see "**ECPW-279** - Use of cover crops as an alternative to plastic mulch" and "**ECPW-281** - Use of biodegradable silage, crop cover mulches and planting trays to meet recognised compostable standard EN17033").
- Increased soil biodiversity – increased amounts of crop residue from the cover crop may result in an increase in earthworm numbers and biomass. Where cover cropping is combined with reduced tillage, earthworm numbers have been known to double within a few years (e.g. Storr, 2019).
- Improved soil structure, including compaction - the action has direct benefits for soil structure within the year of implementation (associated with early harvesting and field traffic when soils are not too wet), although these benefits are implied from measurements of surface runoff volumes and erosion losses (Defra SP0404 - Erosion Control in Maize Fields).

3.2.13.4 Timescale

- Extent of erosion – reductions in the rate and extent of erosion could be seen in the year of adoption and in each year that the action is successfully implemented (Stobart and Morris, 2013).
- Increased soil carbon – increases in SOC stocks from the cover cropping component of the action could potentially be detectable after 10-20 years (Poeplau & Don 2015).
- Reduced soil contamination – where the cover crop replaces the use of a plastic mulch the reduction in soil contamination would be instantaneous, although there would be residual effects from previous plastic mulch use.
- Increased soil biodiversity – where the cover cropping component is combined with reduced tillage, earthworm numbers have been known to double within a few years (e.g. Storr, 2019).

- Improved soil structure, including less compaction – soil structural benefits are likely in the year of implementation, although within a cultivated arable rotation these benefits could be ephemeral (0-5 years). Benefits are likely to persist for longer when the action is adopted as part of a reduced tillage system (Martlew, 2021).

3.2.13.5 Spatial Issues

The action is particularly applicable on sloping maize land with light/medium soils. However, the benefits from reduced soil compaction are applicable to all soils. Over sowing of cover crops on heavy soils can be problematic, mainly due to difficulties with establishing crops in the following spring, following destruction of the cover crop.

3.2.13.6 Displacement

There may be displacement issues where the maize yield is impacted by early harvesting or the use of a cover crop, particularly if lower maize yields do not meet livestock energy requirements and the farmer decides to purchase additional feed to fill the deficit. Where the maize is grown for anaerobic digestion this will already be causing some displacement of food production.

3.2.13.7 Maintenance and Longevity

The action is highly ephemeral in nature and could be reversed easily by returning to growing a later maturing variety and not growing a cover crop. However, where benefits have been seen from the action in terms of reduced soil compaction and erosion (Defra project WQ0140), and there is no impact on maize yields, farmers are likely to retain these practices. Benefits for soil erosion control and soil structure could be seen in the year of adoption, but the cover cropping component of the action would need to be retained for a decade or more for increases in SOC to be detected.

3.2.13.8 Climate Adaptation or Mitigation

Earlier harvesting of maize would be a form of climate change adaptation, particularly given projected hotter, drier summers (accelerating crop maturity) and warmer and wetter winters (increasing compaction, runoff and erosion risks) (Defra project SP0571; Keay, 2020). The growing of a cover crop could also make a small contribution towards climate change mitigation through C sequestration and storage, and reduced C losses via soil erosion.

3.2.13.9 Climate Factors / Constraints

When over-sowing a cover crop, good establishment is dependent on adequate summer rainfall (Defra WQ0140), so hotter, drier summers would be a threat to the success of the action.

3.2.13.10 Benefits and Trade-offs to Farmer/Land manager

It is important that the cover crop is over-sown after the maize has established to minimise the risks of competition by the cover crop, which can reduce maize yields (Stobart and Morris, 2014). Nevertheless, even if over-sowing is delayed, maize yields can be negatively impacted in some years (Defra project WQ0140). A potential economic benefit is that well established cover crops (e.g. rye grass over-sown in maize) can produce income for farmers by providing over winter grazing or a silage cut before the establishment of the next spring crop.

3.2.13.11 Uptake

The action has not been popular within agri-environment schemes, partly due to restrictions on when maize can be harvested and the need to under- or over-sow a cover crop or sow one “within 2 weeks of harvesting and no later than 15 October”. Where farmers are reliant on contractors to harvest maize, they will be reluctant to adopt the action as they may not be in control of the harvest date. The fear of losing maize yield due to competition from a cover crop and harvesting early may be another barrier to adoption.

3.2.13.12 Other Notes

The early harvesting component of the action could be monitored using remote sensing, and reliable soil physical quality indicators could provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.2.14 ECPW-005 - Use restorative vegetation cover following destoning or lifting of root crops

This action involves the growing of a cover crop or green manure following the harvesting of root crops in an attempt to restore soil structure. Destoning and the late harvesting of root crops can cause severe soil compaction, particularly if carried out when soils are beyond their plastic limit (i.e. 'wet'). Cover crops can improve soil structure with root growth improving soil drainage and infiltration, evapotranspiration reducing the risk of waterlogging and associated saturation-excess runoff over winter and crop residue returns increasing soil organic matter content.

3.2.14.1 Causality

The action can have moderate positive benefits for soil erosion control and soil health, but the benefits will be contextually dependent and require targeting (e.g. on lighter land and earlier harvested crops) to be effective. Late establishment of cover crops or green manures on heavy soils is likely to be difficult. It is not practical to over-sow in root crops such as sugar beet and potatoes as the cover crop will be destroyed during the harvest operation. In many situations, sugar beet is harvested too late to establish an effective winter cover crop and winter wheat is seen as the most economically viable option. Cover crops and green manures are therefore rarely established after sugar beet. Establishing cover crops, particularly on medium to heavy soil, from around mid-September onwards is exceedingly difficult due to reduced day length and lowering soil temperatures.

3.2.14.2 Co-Benefits and Trade-offs

The action, where feasible, could have co-benefits for:

- Soil carbon - (sequestered and stored by the restorative vegetation) see "ECCM-023 - Use green manures within the rotation".
- Water quality - (reduced sediment to water courses) see "ECCM-023 - Use green manures within the rotation".
- Water regulation - due to improved soil structure resulting in increased water infiltration, greater soil water storage capacity, and a reduction in rapid surface runoff, thereby reducing peak flow volumes.

[TOCB Report-3-5D Systems **ECPW-005**] This is assumed probably to replace imminent ploughing and/or winter crops, so will have negligible effect on biodiversity.

3.2.14.3 Magnitude

- Extent of erosion – where green manures provide good ground cover after harvest of root crops, sediment losses could be reduced by between 20 and 80% compared with bare ground (Kwaad and van Mulligen, 1991; Lal et al., 1991; Newell Price et al., 2015; Defra project WQ0140). However, there are very few types of cover crop that will provide an effective cover over winter when drilled late (e.g. oats and ryegrass are most likely to establish well) and soil and growing conditions are rarely suited for good crop growth (Newell Price et al., 2015). In addition, there may be significant erosion losses during the harvest period and before a cover crop is established.
- Increased soil carbon – increases in SOC stocks of up 0.4 t C/ha/year are possible but only when the green manure is retained for several months (Poeplau & Don 2015). However, green manures cannot be grown every year. In addition, growth of green manures is highly dependent on weather and local conditions: in some years growth can be excellent, while in others it is poor. Some caution is required

in assigning a SOC rate of increase to green manures. They can contribute to C sequestration over time, but are not a panacea.
- Reduced soil contamination – none.
- Increased soil biodiversity – increases in soil biodiversity are unlikely unless some form of reduced tillage can be adopted (e.g. Ernst & Emmerling, 2009), although this will depend on the restorative vegetation species selected.
- Improved soil structure, including less compaction - improvements in soil structure indicated by visual soil evaluation (e.g. VESS score improvement of half a point: Storr et al., 2017) are possible within a year of establishing a green manure. Changes in penetration resistance and a 5-10% reduction in soil bulk density are rare but possible within 10-15 years of regular use (e.g. Demir & Işik, 2020). Changes in soil pore characteristics (e.g. total porosity, pore continuity and connectivity) and improvements in soil moisture retention and root morphology are also possible within this timescale (Martlew, 2021).

3.2.14.4 Timescale

- Provided that green manures establish well, small reductions in the extent of erosion could be possible in the year of implementation (0-5 years).
- Increases in soil carbon would only be measurable after >10 years, but it depends on how often root crops are grown and the frequency and duration of growing the restorative vegetation cover.
- Visual changes in soil structure are possible in 0-5 years, with measurable changes in soil bulk density and porosity taking considerably longer (5-10 or >10 years).

3.2.14.5 Spatial Issues

The action, if feasible, is most likely to be adopted on light/medium soils suitable for root crop production and on which late autumn establishment of oats or rye is more feasible. It would be most usefully targeted in catchments with issues of surface runoff, sediment and/or phosphorus loading.

3.2.14.6 Displacement

If the restorative vegetation cover replaces a winter cereal food crop or a spring food crop there would be displacement issues. However, the action could form part of a more resilient and sustainable production system over the rotation as a whole.

3.2.14.7 Maintenance and Longevity

The action needs to be maintained for several years for soil health benefits to be seen. However, it is ephemeral in nature, can be easily reversed (e.g. leave the harvested land bare or grow a cereal crop over winter rather than establishing a green manure) and does not require significant investment. If establishment of a green manure following root crops is found to be unreliable, farmers will not persist with it. However, if successful it can improve the resilience of the farming system over the rotation as a whole.

3.2.14.8 Climate Adaptation or Mitigation

Using restorative vegetation covers that are established and retained for at least six months before the cover is destroyed (Berdeni et al., 2021a) may make farm businesses more resilient to climate change through maintaining and enhancing SOC levels, improving soil structure and protecting the soil surface from intense rainfall. The action could contribute to climate change adaptation and mitigation through improved soil structure, soil water retention, water infiltration rates and carbon sequestration. However, these benefits are not likely to be seen within ten years of adoption, as the action only relates to one or two crops within the rotation.

3.2.14.9 Climate Factors / Constraints

Successful establishment may be impacted by wet conditions (prolonged waterlogging) in autumn. The action may only therefore be suitable on well-drained, medium- and light-textured soils.

3.2.14.10 Benefits and Trade-offs to Farmer/Land manager

The main trade-off for farmers is the growing of restorative vegetation covers rather than a cash crop. In many situations, potatoes and sugar beet can be harvested too late to establish an effective winter cover crop and the choice is therefore between a green manure or a winter cereal that will be in the ground for several months. The winter cereal is often seen as the most economically viable option. The main benefit of this action (ECPW-005) to the farmer or grower is the greater resilience of the production system through potentially improved soil structure, rooting, weed control and pest and disease suppression (e.g. Larkin and Griffin, 2007; Zou et al., 2015).

3.2.14.11 Uptake

It may take several years to see the benefits from using restorative vegetation covers, so security of tenure will affect adoption and maintenance for some growers. High market prices for cash crops may be a disincentive as establishing and retaining vegetation covers may be seen as a missed economic opportunity. However, an increasing number of farmers acknowledge the benefits from growing green manures.

3.2.14.12 Other Notes

The action could be monitored using remote sensing (i.e. to detect the presence of a restorative vegetation cover post-harvest), and reliable soil physical quality indicators could provide suitable metrics to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.2.15 ETPW-270 - Re-seed grassland by over-seeding or slot-seeding

Another action with similar outcomes for soil erosion control and soil health is:

- **ECPW-237EMx** - Create wildflower/legume rich swards

3.2.15.1 Causality

Where grasslands have become unproductive, re-seeding by over-seeding or slot-seeding (as opposed to a full re-seed which requires cultivations to prepare the seedbed) can have major positive benefits for soil erosion control and limited benefits for soil health due to the avoided cultivation in those cases where ploughing would otherwise have been part of the reseeding operation (but there is no change in land use).

Over-seeding is typically carried out on old, unproductive swards, as a ‘quick fix’ to boost grass productivity. There are two methods: 1) the existing pasture would typically be grazed hard (mostly with sheep, to open up an stunt the re-growth of the old sward) and the field sown thereafter, with grazing of the existing sward continuing until the new seeds start to germinate; 2) over-seeding performed immediately following harvesting the existing sward for silage or hay, with the existing sward being cut to a lower level than would typically be done (to stunt its regrowth). A variation on method two is to destroy the existing sward beforehand with glyphosate and then sow following adequate senescence of the existing pasture, leading to the establishment of a completely new sward. In all cases, it is suggested that the land be extensively scarified first to remove any dead material prior to sowing and to facilitate seed-to-soil contact. The species most typically sown for over-seeding are short-term, predominantly triploid *L. multiflorum* (Italian ryegrass), as they have the vigour to out-compete existing swards. However, other grass, legume and herb species can be used. The aim is to establish a new, vigorous cover as soon as possible, thereby providing adequate soil protection quickly and effectively.

Slot-seeding is typically done following destruction of the existing sward (and its roots) with glyphosate. Where glyphosate is used, competition with the existing sward is considerably reduced, meaning that the species sown do not need to be as competitive, and are therefore likely to persist for longer.

There has been little research on the use of over-seeding and slot-seeding to establish multi-species swards, but the need for vigorous seeds for successful establishment is likely to hinder their potential in this regard. Where a full re-seed is desired (as opposed to where new seeds are sown into an existing sward), both techniques are reliant on glyphosate (more so than when ploughing is used to bury weeds). Slot-seeding can also be more prone to slug damage, which may increase the need for chemicals for slug control.

3.2.15.2 Co-Benefits and Trade-offs

Over-seeding or slot-seeding rather than a full re-seed could have co-benefits for:

- Soil biodiversity – due to the reduced degree of cultivation required for overseeding compared with a full reseed. Over-seeding and slot-seeding can also be used specifically for increasing the botanical diversity (mainly the wildflower component) of species-poor grassland. Success is dependent on multiple factors, such as soil conditions (lower fertility and no weed burden), the choice of species sown, and management thereafter.
- Soil carbon – due to reduced cultivation (cf. a full reseed), the shorter period of time without a growing sward and the avoided erosional losses that are likely to be lower than for a full reseed.
- Water quality – due to the retained grass and herb cover providing greater soil surface protection and uptake of nutrients (cf. a full reseed).
- Water regulation – due to the typically lower surface runoff volumes associated with overseeding (cf. a full reseed).
- Resilience to drought – if the seed mix includes deep rooting herbs (e.g. plantain and chicory) thereby increasing sward diversity compared with the original sward.

3.2.15.3 Magnitude

- Extent of erosion – The establishment of a new grass, grass-clover or multi-species sward may be more effective (in terms of the establishment and persistence of the sown species) where swards are reseeded rather than overseeded, due to a more effective establishment and cover of the sown species. However, such reseeding operations on sloping land can result in greater runoff and erosion risk during the reseeding phase, particularly if the reseeding operations result in soil being exposed to raindrop impact and surface runoff in the early stages of establishment (Chambers et al., 2000; Evans, 1990). Using an analogy of 'early establishment of crops in the autumn', erosion rates could typically be reduced by 20-50% (Newell Price et al., 2011). More erosion control is provided if the existing sward (no matter what quality) is kept and oversown, as this will a) avoid significant soil disturbance (as would be the case for new seedbed preparation) and b) utilise any existing above- and below ground vegetation to protect the soil surface and control erosion.
- Increased soil carbon – Smith et al. (2008) reported potential C sequestration rates of 0.22 t C/ha/yr in the cool-moist (temperate) bio-climatic region as a result of improved grassland management. However, simply using slot-seeding or over-seeding rather than a full reseed will not achieve this unless they also entail a change in management, such as rotational grazing or adding legumes to the sward. Avoiding erosional losses associated with a full re-seed may result in some saving in SOC, but there is also evidence that in many fields this may simply result in a redistribution of soil C, with C addition in depositional areas and recovery of soil microbial biomass C in the eroded areas (Dungait et al., 2013). However, this assumes that the fine sediment with the highest concentration of C does not leave the field and enter a watercourse. Where introducing clover or deep-rooting herbs and legumes represents true additionality when over- or slot-seeding, this may help increase productivity and the depth of rooting, and thereby increase C sequestration rates by a small amount, but this could be offset by increased nitrous oxide emissions from the legumes and, if ruminant livestock numbers are increased, methane emissions (Garnett et al., 2017; Newell Price et al., 2019).
- Reduced soil contamination – none.
- Increased soil biodiversity – limited effect, as soil biodiversity is likely to recover rapidly from most reseeding operations (Lees et al., 2016).

- Improved soil structure, including less compaction – the action may result in a reduced risk of compaction due to the lack of cultivation compared with a full reseed. However, evidence of a persistent positive effect on soil structure is limited.

3.2.15.4 Timescale

Soil erosion control and soil compaction benefits would be seen in the week or months following over- or slot-seeding. Other soil health benefits may be seen after >10 years.

3.2.15.5 Spatial Issues

The action is applicable to many types of permanent grassland but is most relevant to sensitive catchments with sloping land and erodible soils.

3.2.15.6 Displacement

Raising the productivity of grassland, while also reducing reliance on manufactured nitrogen fertiliser, may reduce the need for purchasing of feed grown elsewhere, and may also lead to improved livestock performance, thereby reducing the carbon intensity of livestock products.

3.2.15.7 Maintenance and Longevity

Reseeding is an episodic practice, carried out every 3 to 10 years or more, so the effects of over-seeding (cf. a full reseed) could be minimal in the longer term. Any effects are likely to be seen in the few weeks or months following the seeding operation. Erosion and compaction benefits relate to the reseeding period itself with erosion risk reducing after about six weeks once vegetation cover is 30% or more (Chambers et al., 2000). Short-term soil carbon benefits are associated with the reduced erosion risk but in the longer-term may relate more to the species introduced to the sward than the reseeding technique itself. In many cases, the technique will need to be carried out every 3 to 5 years depending on the persistence of the desired species.

3.2.15.8 Climate Adaptation or Mitigation

Both techniques use considerably less fuel than a full re-seeding approach involving significant cultivation (where soil is ploughed and/or harrowed and can be rolled numerous times). However, where glyphosate is used GHG emissions (principally microbial respiration, but also associated with the herbicide manufacture) may be as a high as for a full re-seed. Losses of soil carbon from re-seeding will also be part-compensated by elevated growth from a productive ley relative to an old sward with lower annual yield (Barneze et al, 2020; Ostle et al., 2009; Carswell et al., 2019). Enhancing land productivity through re-seeding may also mean that (less productive) land elsewhere can be managed specifically for carbon sequestration (Soteriades et al., 2018; Grass et al., 2019; Clay et al., 2020).

3.2.15.9 Climate Factors / Constraints

Over-seeding and slot-seeding techniques are better at conserving soil moisture than a full reseed involving intensive seed bed preparations such as inversion ploughing, pressing and rolling operations. They may therefore be better adapted to future climatic conditions, particularly drier springs and summers.

3.2.15.10 Benefits and Trade-offs to Farmer/Land manager

The establishment of a new sward may be more effective where swards are reseeded rather than overseeded, due to more effective weed control and better establishment and cover of the sown species. This may convince some farmers to use a full re-seed rather than over-seeding or slot-seeding. However, for many farmers, the lower establishment costs associated with over- and slot-seeding will be a significant consideration.

3.2.15.11 Uptake

A number of manufacturers have developed drills specifically for grassland rejuvenation, as more farmers consider this approach, given that establishment costs are much less than a conventional re-seeding approach (due to savings on fuel and labour), fields are typically out of production for a shorter duration, and the risk of soil erosion (e.g. on steeper slopes and/or in high rainfall areas) is reduced as less of the soil is left bare. There also seems to be growing interest in using slot-seeding to introduce or enhance the proportion of clovers (*T. repens* and *T. pratense*) in the sward. This can be a way to reduce reliance on manufactured nitrogen fertilisers and to allow for easier weed management if clover is added to an existing sward (e.g., where docks are problematic).

3.2.15.12 Other Notes

The action could be most reliably monitored using remote sensing.

3.2.16 Manure and mulch management EHAZ-113 - Use mulches and organic matter to increase the water retention capacity of soil

3.2.16.1 Causality

Using (surface applied) mulches and organic matter to increase the water retention capacity of the soil can have limited positive benefits for soil erosion control and moderate benefits for soil health. Adding organic materials to soil can have a moderate effect in improving water retention capacity but the main advantage from using mulches, from soil erosion control perspective, is the protection they provide to the soil surface. Niziolomski (2014) found that a straw mulch, surface applied at 3-6 t/ha, and compost mulch at 8-10 t/ha significantly improved soil erosion mitigation in asparagus fields as measured by runoff initiation (volume and rate), total soil loss and sediment concentration. However caution is needed, given the observed variation in effectiveness and reliability of mulches, especially during 'extreme' rainfall events. In addition, the regular application of organic materials to agricultural land helps enhance and maintain soil organic matter levels, thereby preserving or improving soil structure and the ability of plant roots to access nutrients and water.

3.2.16.2 Co-Benefits and Trade-offs

The improved soil structure from using mulches and applying organic matter to agricultural land in the long run can have co-benefits for:

- Biodiversity – due to the organic matter providing a food source for soil fauna
- Soil carbon – due to the organic matter additions.
- Water regulation – due to improved water infiltration and soil water storage capacity.

However, organic materials are also a source of nutrients so can result in emissions of pollutants to air (principally ammonia and nitrous oxide) and water (e.g. ammonium, phosphorus and nitrate) following application.

[TOCB Report-3-5D Systems **EHAZ-113**] We would expect a negative effect on vegetation if fertility is increased (Tonn et al. 2010). The research in this area is on soil function and biodiversity only, and is generally confounded with organic management.

3.2.16.3 Magnitude

- Extent of erosion – surface application of a mulch at rates of 5-10 t/ha can reduce soil erosional losses at the field scale by 50-90%.
- Increased soil carbon – straw mulch applications can increase SOC by 50 kg C/ha/yr/t straw applied (with 95% CI in the range 20-80 kg C/ha/yr/t), based on measurements at 8 study sites in England (Bhogal et al., 2007). The application of livestock manures to agricultural soils in England has the potential to increase SOM by an average of 60 kg C/ha/yr per tonne of manure dry solids applied, with 95% confidence intervals in the range 16-102 kg C/ha/yr/t (Bhogal et al., 2007).

- Reduced soil contamination – use of compost mulches may increase the risk of soil contamination due to the presence of some physical contaminants (principally plastic and glass) in composts. Livestock manures can also be a source of contamination, e.g. heavy metals (Nicholson et al., 2006).
- Increased soil biodiversity – Any addition of organic materials is likely to increase soil biodiversity. Repeated applications of organic manures can result in a doubling of earthworm numbers within 5-15 years (Bhogal et al., 2009).
- Improved soil structure, including less compaction - materials high in organic C help to maintain soil structure and aggregate stability, which in turn can increase soil water retention and water infiltration rates (thereby reducing the risks of surface runoff and soil erosion) and improves plant nutrient uptake. A 2-3% increase in soil total porosity can be seen after 40-50 t/ha of C input (Bhogal et al., 2009), i.e. around ten applications of a typical cattle farmyard manure (FYM) at 40 t/ha per application (which would take at least ten years).

3.2.16.4 Timescale

- Reductions in soil erosion rate and extent can be seen in the first year of mulch use. Organic manures applied to the surface can have a similar effect, although there is a risk that surface applied material can itself be transported in surface runoff and pollute local watercourses.
- Measurable increases in SOC can be seen after 5-20 years (assuming regular and continuous applications), depending on the rate and frequency of mulch and manure application.
- Earthworm numbers can double within 5-15 years of farmyard manure or broiler litter application (Defra project SP0530). Compost and paper crumble had no effect.
- Measurable improvements in soil physical properties are possible after 10-20 years (i.e. 10-15 applications of bulky organic manure). These improvements can persist for at least 2 years following the cessation of applications (Defra project SP0530; Bhogal et al., 2009).

3.2.16.5 Spatial Issues

The action is broad scale in nature although light soils can benefit more than heavy soils in terms of improvements in soil water retention and available water capacity (Bhogal et al., 2009). Available water capacity (AWC) is defined as the amount of water (cm^3 water/100 cm^3 soil) retained in the soil between “field capacity” (FC) and the “permanent wilting point” (PWP). FC and PWP are defined as the volumetric fraction of water in the soil at soil water potentials of 10 to 33 kPa and 1500 kPa, respectively.

3.2.16.6 Displacement

There are no displacement issues associated with the use of mulches and organic matter.

3.2.16.7 Maintenance and Longevity

Once the action is implemented, farmers and growers tend to persist with the practice. However, the availability of organic materials is an issue for some farms and the cost of mulch application can be a disincentive. Benefits to soil erosion control can be seen in the year of adoption, while improvements to soil physical structure and increases in SOC may take 5-20 years.

3.2.16.8 Climate Adaptation or Mitigation

Using mulches and organic manures can help farmers and growers adapt to climate change through improving soil properties and protecting the soil surface from intense rainfall. There is no climate change mitigation effect as the C in mulches and manures has been imported from elsewhere. It is not additional carbon transferred from the atmosphere.

3.2.16.9 Climate Factors / Constraints

There are no climatic constraints to adopting the action, which can help with resilience to drought and potentially also reduce the risk and intensity of waterlogging.

3.2.16.10 Benefits and Trade-offs to Farmer/Land manager

The main trade-off for farmers is the cost of the mulch and the time and additional field operations required to apply it. However, on sloping sites in some years this will more than offset the on-site and off-site costs of soil erosion (Graves et al., 2011; Posthumus et al., 2015). Mulching materials can also be used for other (competing) purposes such as animal bedding or fuel, although in the case of animal breeding the resulting manure can be applied to land.

3.2.16.11 Uptake

Mulch use tends to be taken up by growers of high value horticulture crops such as asparagus, field grown herbs, sweetcorn, carrots, beans and onions (Niziolomski, 2014). By contrast, organic manures are sought after by many farmers and growers. However, there may be some reluctance to use mulches and organic materials if they increase the number of field operations required at busy times of the year.

3.2.16.12 Other Notes

The action could be monitored using a combination of remote sensing and field visits to observe mulch use. Soil physical quality indicators could also be used to assess the effectiveness of the action in improving soil health (Corstanje et al., 2017).

3.3 Drainage, Irrigation & Wastewater

This section covers the effect of field drainage systems on soil conservation and soil health along with potential co-benefits for air quality, biodiversity and flood protection and possible benefits and trade-offs for water quality.

Pressures and services impacted by the ‘Drainage, irrigation & wastewater’ management bundle:
‘F’= Full assessment of the bundle as this action has potentially important outcomes for the ‘Pressure’ and Ecosystem Services (ESs)
‘T or CB’ = As a Trade-off or minor Co-Benefit for the Pressures and ESs.

Pressure (Indicators are reduced emissions, inputs or area)	F/T/CB
Air pollution	CB
GHG emissions	
Food and fibre production	CB
Vulnerability to climate change	CB
Invasive Non-Native Species (INNS)	
Chemical pollutants/ pesticides	
Nutrient pollutants	T

Ecosystem Service - Biodiversity	F/T/CB
Protected and priority species	CB
SSSI’s	
Species	CB
Habitat condition	CB
Small feature habitats and habitat connectivity	
Habitat area	

Ecosystem Service (proposed indicators – may change)	F/T/CB
Flood protection (peak flows and coastal inundation)	CB
Resilience to Drought (low flows)	
Coastal erosion(sediment stabilisation)	

Water supply (increased supply)	CB
Water quality (purification)	T
Air quality (air pollutants removed)	CB
Soil conservation and protection (erosion)	F
Pollination and seed dispersal (Abundance, distribution and richness of species)	
Pest and disease control (abundance and spp. Richness)	
Global, regional and local climate regulation (C seq. and GHG fixed)	
Carcass disposal (spp. abundance?)	
Energy Use/renewables	

Ecosystem Service - Aggregated bundle (proposed indicators – may change)	F/T/CB
Water quality (pathogens and sediment) flood water and coastal	T
Water flow service (regulation of flow)	CB
Bio risks (AMR)	
Soil carbon	T
Soil health (contaminants, biodiversity, structure)	F

3.3.1 Drainage
ECCM-005 - Restore or enhance land drainage on mineral soils

A functioning drainage system ensures that water can move through the soil profile, allowing the soil to be maintained in a ‘well drained’ condition and extending the window of opportunity for machinery operations and livestock grazing, particularly in late autumn and early spring. Actively maintaining field drainage systems usually involves jetting, re-installation and renewed moling (using a ‘mole’ plough with a slim vertical leg to pull a ‘bullet’ and expander through the soil at 40 to 60 cm depth to create a drainage channel) every 5-7 years. These are costly operations, but they can help minimise the risk of waterlogging. which can lead to poaching and compaction. They also enable more flexible field working, providing insurance against very wet years (in which loss of production/profit can be total without a drainage system) and can mean the difference between operating a combinable cropping arable system and a less profitable extensive livestock grazing system.

3.3.1.1 Causality

Restoring or enhancing land drainage can have moderate benefits for the extent of erosion, limited benefits for soil structure and potential disbenefits for soil organic matter contents. Improving the effectiveness of agricultural drainage is likely to reduce the risk and extent of soil compaction and erosion as field operations are less likely to be carried out when soils are ‘wet’, tramlines will be less compacted and wheel ruts will be less likely to occur. However, improving land drainage is likely to reduce soil organic matter levels if sustained for the long term due to the improved drainage status of the soil resulting in generally drier conditions and higher rates of mineralisation and microbial respiration.

3.3.1.2 Co-Benefits and Trade-offs

Restoring or enhancing land drainage will have co-benefits for:

- Air quality – due to better drainage resulting in more rapid infiltration of slurries and other liquid manures.
- Biodiversity – in terms of the presence of some rare (red list) and priority farmland species.
- Water regulation – in terms of improving the regulation of the flow regime for peak events.

However, the higher organic matter mineralisation rates and preferential pathways afforded by drain flow can also result in higher losses of nitrate, phosphorus and sediment to water, although improved drainage may also result in lower surface runoff losses and a reduction in associated pollutants via the surface loss pathway. Higher rates of microbial respiration (cf. wetter, undrained soils) can result in higher losses of SOC to the air as carbon dioxide.

[TOCB Report-3-6 Carbon **ECCM-005**] It has been estimated via modelling using JulesDOCM that approximately 0.28 Gt C yr^{-1} is leached from mineral soils globally (Kwon et al., 2021). Research by (Sowerby et al., 2010) found that drought conditions (and hotter, drier soils) were associated with a large increase in the concentration of DOC lost per unit water, however the reduced drainage volume meant that drought conditions lead to an overall decrease in DOC lost. However, significant increase in the rate of soil respiration was also observed under drought conditions, causing an overall loss of +0.18 t C ha^{-1} yr^{-1}, whilst control plots sequestered -1.26 t C ha^{-1} yr^{-1}. There is a robust logic chain suggesting that increasing drainage on mineral soils will increase the rate of organic matter decomposition in soils.

3.3.1.3 Magnitude

- Extent of erosion – Maintaining field drainage systems reduces the risk of surface runoff and erosion. Erosion rates could be reduced by up to 10% (Defra project SP1316; Newell Price et al., 2011).
- Soil carbon – soil organic matter tends to reduce with improved drainage/aeration, particularly in organic mineral and peaty soils (Kirk et al., 2012; Figure 3). Peat shrinkage and subsidence following drainage has led to considerable SOM losses in lowland organic/peaty soils, such as the Fens and Lancashire Peat Mosses (Holden et al., 2007). Maintaining drainage systems can also reduce erosion–related losses of organic matter through reduced compaction and surface runoff (as associated with wetter, undrained soils), although in some circumstances soil erosion may be a sink for carbon due to re-deposition of carbon on lower slopes and storage of carbon through replacement by crop residue carbon in erosional slope positions (Dungait et al. (2013). However, this assumes that the fine sediment with the highest concentration of C does not leave the field and enter a watercourse. In Defra project SP1106A, predictions using the RothC model indicated that maintaining drainage would result in small reductions in SOC compared with a non-drained baseline (Figure 3). However, potentially off-setting this are (a) decreased erosion losses of SOC with better drainage; and (b) decreased N_2O emissions (due to drier soils).
- Reduced soil contamination – not applicable.
- Increased soil biodiversity – no known effect.
- Improved soil structure, including less compaction - maintaining field drainage systems reduces the period when soils are at risk from compaction and poaching, and could therefore help maintain good to moderate soil structure.

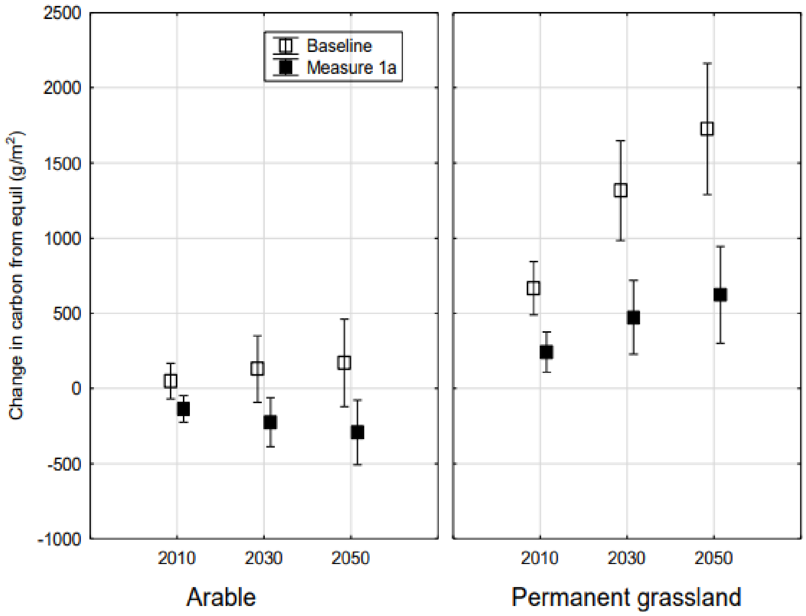

Figure 3. Effect of maintaining land drainage (Measure 1a) on SOC changes with time for arable land and permanent grassland (averaged for all England regions; Kirk et al., 2012). Error bars are 95% confidence intervals.

3.3.1.4 Timescale

The benefits and disbenefits (such as loss of SOC) from field drainage systems are likely to persist for as long as drains are maintained. Soil conservation benefits and water quality disbenefits from restoring and maintaining degraded drainage systems can be seen in the year following restoration. Indeed, risks to water quality from incidental losses of applied fertiliser and organic manures are likely to be higher in the 2 to 3 years following restoration. Benefits to soil structure may not be seen for >10 years, but could be sooner if drier soil results in reduced compaction risk.

3.3.1.5 Spatial Issues

The action is applicable to heavy soils (topsoil clay content >30%), any ‘naturally’ imperfectly drained or poorly drained soils and fields with high ground water tables.

3.3.1.6 Displacement

There are no displacement issues associated with the action. Evidence of yield increases is sparse, but almost all studies report some benefit with a large range of crop yield increases (e.g. Armstrong, 1977; Armstrong et al., 1988; Berryman, 1975; Cannell et al., 1986; Trafford, 1974).

3.3.1.7 Maintenance and Longevity

Drainage systems need to be maintained regularly for benefits (and disbenefits) to persist. Mole drainage should be carried out every 5-7 years and the drainage system renewed or maintained every 25-30 years (Defra project SP1316). Field drainage systems are one of the largest investments that a farmer or grower will make, so the investment will lend itself to permanence through path dependency.

3.3.1.8 Climate Adaptation or Mitigation

Maintaining drainage systems is an important consideration for climate change adaptation, particularly in parts of the country (mainly in the west) where episodes of more intense and prolonged rainfall and associated waterlogging can be expected.

3.3.1.9 Climate Factors / Constraints

More intense or prolonged periods of rainfall and associated waterlogging may require the capacity of some drainage systems to be increased (Defra project SP1316). This is an important consideration when drainage systems need to be renewed or maintained and may lead to some drainage systems being allowed to deteriorate (due to the high costs associated with maintaining drains) with associated changes in land management and use.

3.3.1.10 Benefits and Trade-offs to Farmer/Land manager

The benefits to the farmer or grower of restoring land drainage systems are significant. Well-maintained field drains can be the difference between running an economically sustainable farming enterprise and one that is not profitable without financial support. However, drainage installation at 20 m spacing between laterals and using permeable backfill costs £2,300-£3,400 per hectare; mole drainage costs around £70-£110 per hectare (Redman, 2019). Each farmer and grower therefore needs to consider whether the investment is economically justified on their land.

3.3.1.11 Uptake

Farmers with deteriorating drainage systems will need to consider whether further investment is justified on all or part of their land, or whether financial support through the Environment Land Management schemes (as an alternative to maintaining drains, i.e. allowing drains to deteriorate further) may be a better option from an economic and lifestyle perspective.

3.3.1.12 Other Notes

The action could be monitored through a combination of earth observation (drain lines can be viewed from the air and certain vegetation types, such as rushes, can be indicators of a deteriorating drainage system) and field inspection.

3.4 Fertiliser, nutrient, manure and mulch management

This section covers one action; the spatial testing of soils to improve nutrient use efficiency.

3.4.1 Spatially test soils ECPW-299 - Spatially test soils within field for any or all of the following: N, P, K, Mg, pH, micronutrients, potentially toxic elements (PTEs) and organic matter

Spatially testing soils helps farmers to plan and target manufactured (i.e. 'synthetic' or 'chemical') fertiliser applications to all crops so that recommended rates are not exceeded. It also provides a baseline for soil organic matter contents so that the effects of management practice changes can be monitored over time. A number of methods can be used to spatially test soils from grid sampling to the use of management zones based on soil type or field history. Spatial testing of micronutrients is not worthwhile as most farmers are aware of any potential micronutrient deficiencies associated with their soils. Spatial testing for PTEs is already carried out on farms that receive biosolids under the Sludge (Use in Agriculture) Regulations (1989) or receive organic wastes under an Environment Agency deployment. Testing for PTEs outside these circumstances is unlikely to be beneficial unless very high soil concentrations are suspected.

3.4.1.1 Causality

Spatially testing soils to assess nutrient reserves and soil pH in combination with a recognised fertiliser recommendation system (e.g. RB209, PLANET and other supplementary guidance) can help farmers plan lime and manufactured fertiliser applications to all crops; and not exceed recommended rates. It will reduce the risk of applying more nutrients than the crop needs and will ensure that the necessary quantities of nutrients are available when required for uptake by the crop. By ensuring that the soil in every part of a farm or individual field is in a sufficiently fertile state to maximise the efficient use of nutrients in the soil or supplied by fertilisers and organic manures, the amount of excess nutrients in the soil is reduced to a minimum. Maintaining an appropriate balance between different nutrients (i.e. NPKS) is also important to maximise the efficient uptake of all nutrients and reduce environmental losses to a minimum. Reducing growth limiting factors and improving nitrogen use efficiency can also result in higher crop yields and can potentially increase rates of soil carbon sequestration (or reduce the rate of soil C loss) within some systems. Testing soils also allows farmers to monitor soil quality and assess the impact of any changes in land use or management practice. In turn these effects will reduce runoff and soil erosion, and improve soil health.

3.4.1.2 Co-Benefits and Trade-offs

Spatially testing soils, if implemented and acted upon effectively, can have co-benefits for:

- Air quality – due to nitrogen only being applied when its supply from all other sources is insufficient to meet crop requirements. As a result, the amount of fertiliser N applied to the soil surface is reduced to a minimum.
- Soil carbon – in theory due to reducing growth limiting factors resulting in higher crop yields.
- Reducing GHG emissions – due to reducing growth limiting factors and improving nitrogen use efficiency.
- Water quality – due to only applying fertiliser to meet crop and soil requirements, thereby reducing the amount of nutrient applied to the soil.

[TOCB Report-3-6 *Carbon* **ECPW-299**] Smith et al. (2020) reviewed methods of monitoring soil carbon and verifying soil carbon change, and emphasise the need for repeat soil surveys, supported by measurement/monitoring, reporting and verification platforms which can provide benchmarking and subsequently facilitate national reporting and emissions trading. Any impact will be dependent on appropriate actions being taken in response to assessment results. It is suggested that the maximum technical potential SOC sequestration in mineral soils in 2050 for UK land area is approximately -15.7 Mt CO_2 eq yr^{-1} (Net C uptake or sequestration is negative; Net carbon loss or flux is positive; Element Energy & UKCEH, 2021). Monitoring will be critical to efforts to achieving this potential.

3.4.1.3 Magnitude

- Reduced inputs of N and P – applications of manufactured N and P fertilisers could be reduced by a small amount, resulting in a 0-5% reduction in nitrate (plus ammonium and nitrite) leaching losses, and associated direct and indirect N_2O emissions, and NH_3 emissions; and a 0-5% reduction in P losses on the area where fertiliser is applied (Newell Price et al., 2011).
- Extent of erosion – no effect
- Increased soil carbon – small increases or slower rates of decline in SOC are possible due to increased productivity (Powlson et al., 2010; Ladha et al., 2011). This is also supported by carbon modelling outputs (Smith et al., 2008; Meena et al., 2020). However, the sequestration benefits from manufactured N fertiliser application are usually cancelled out by the release of CO_2 and nitrous oxide during manufacturing, transportation, storage, and application of fertilisers, unless the increased crop yield allows the destruction of ecologically valuable and carbon-rich habitats to be avoided, in which case there may be net carbon and biodiversity benefits (Cassmand & Grassini, 2020; Cassman et al, 2003).
- Reduced soil contamination – no effect
- Increased soil biodiversity – no effect
- Improved soil structure, including less compaction – no effect

3.4.1.4 Timescale

- Reduced N and P input effects could be seen in the year of adoption, although catchment scale impacts can take >10 years to take effect, particularly for P (Collins et al., 2018).
- Any changes in SOC would take >10 years and may not be detectable after 20 years (Lal, 2004).

3.4.1.5 Spatial Issues

The action is broad scale in nature.

3.4.1.6 Displacement

There are no displacement issues associated with the action. In fact, it is likely that productivity would be increased.

3.4.1.7 Maintenance and Longevity

The action requires regular testing of soils for soil pH and nutrients every 3-5 years. Testing for SOC could be done every 5-10 years (depending on field history and management practices) or every other year to build up a database and assess trends. Once farmers have set up soil management zones from which to take soil samples, they are likely to continue with the action as it allows them to adjust fertiliser application rates according to soil type and associated soil nutrient reserves. However, no capital investment is required, so if the results are thought to be unreliable for any reason, spatial testing of soils could be discontinued at any time.

3.4.1.8 Climate Adaptation or Mitigation

The action should help farmers and growers improve their nutrient use efficiency. Reductions in inputs of synthetic, manufactured fertilisers have clear climate change mitigation benefits.

3.4.1.9 Climate Factors / Constraints

Climate change impacts could result in crop yield constraints due to higher temperatures, wetter winters and a drier growing period, and so could have implications for the outcomes of the action (i.e. the improved nutrient use efficiency or higher yields anticipated through the action could be constrained by extreme weather events limiting yield potential). However, there are no climatic threshold or soil type constraints that would hinder the action itself.

3.4.1.10 Benefits and Trade-offs to Farmer/Land manager

For a small investment in time and analysis costs, farmers and growers would benefit from reduced overall costs (e.g. fertiliser inputs), greater efficiency of production and potentially higher crop yields.

3.4.1.11 Uptake

Soil testing is regulated under the Farming Rules for Water – the Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018, and requires soil testing to be carried out on cultivated land, at least every five years. Spatially testing soils represents the next level of nutrient management and is likely to increase where farmers are interested in greater spatial precision of nutrient applications. Variable rate application of fertiliser can lead to greater nutrient use efficiency and in some cases decreased N use. The main barrier to uptake is the increased cost associated with the greater number of samples taken and analysed and the time required for sampling and interpretation. However, for farmers interested in precision agriculture this is not a significant barrier to uptake.

3.4.1.12 Other Notes

The method could be monitored through inspection of farm nutrient management plans and records.

3.5 Litter and Plastic Waste

3.5.1 ECPW-281 - Use of biodegradable silage, crop cover mulches and planting trays to meet recognised compostable standard EN17033

Using degradable materials to manufacture plant transplant trays and containers, and to cover silage and protect the soil can reduce the amount of plastic use and plastic contamination in soils.

3.5.1.1 Causality

Soil-biodegradable silage wraps and mulches are a promising alternative to polyethylene products, but adoption has been slow, in part because of uncertainties about the silage fermentation effectiveness of biodegradable silage wraps and in-field degradation of biodegradable mulches (Griffin-LaHue et al., 2022). Boreani and Tabcco (2015) found that biodegradable silage wrap could produce silage of equivalent quality to that made using polyethylene wrap. Nevertheless, there are still some concerns that biodegradable plastic mulches and wraps, if incorporated into the soil have potential to alter soil microbial communities with further research needed to demonstrate their sustainability (Serrano-Ruiz et al., 2021).

3.5.1.2 Co-Benefits and Trade-offs

Using biodegradable silage wraps, mulches and planting trays has possible co-benefits for:

- Air quality – due to potentially reduced air particulate generation.
- Biodiversity – due to reduction in the amount of plastic added to soil; related to biodiversity adaptation.

- Soil carbon – due to the potential to enrich soil carbon stock, or may have a priming effect on rates of soil respiration (Sayer et al., 2011).

3.5.1.3 Magnitude

- Extent of erosion – biodegradable mulches are probably as effective as plastic mulches in protecting the soil surface and reducing surface runoff volumes. However, data on their effectiveness in the UK climate is limited (Kasirajan and Ngouajio, 2012). The rate of degradation and associated loss of soil protection effectiveness/performance are the key considerations.
- Increased soil carbon – increases in crop productivity from the use of plastic mulches (compared with no mulch; Lamont, 2005; Gao et al, 2019) may be associated with increases in SOC in the long term but there is no current evidence that biodegradable mulches would be any better or worse than plastic mulches.
- Reduced soil contamination – non-degradable plastic contamination would be reduced by 100% at source. However, modelling of field data predicts that 90% degradation (i.e. breaking down or decomposition) of biodegradable mulches takes ~21 to 58 months (Griffin-LaHue et al., 2022).
- Increased soil biodiversity – biodegradable mulches may have the potential to alter soil microbial communities, but further research is needed.
- Improved soil structure, including less compaction – the impact of microplastics on soi structure are largely unknown, although this is an emerging area of research (Lehmann et al., 2021).

3.5.1.4 Timescale

Reduced soil contamination – 90% degradation (i.e. breaking down or decomposition) of biodegradable mulches takes ~21 to 58 months. (Griffin-LaHue et al., 2022).

3.5.1.5 Spatial Issues

The action is broad scale in nature within the respective sectors: productive grassland for silage wrap; maize and horticulture for mulches and high value horticultural crops for planting trays.

3.5.1.6 Displacement

There are no displacement issues associated with the action. In fact, continued use of silage wrap, mulches and planting trays are likely to sustain high productivity levels and reduce the need to import animal feed and human edible crops.

3.5.1.7 Maintenance and Longevity

If biodegradable materials can be shown to be an effective, environmentally sustainable and cost-effective alternative to plastic silage wrap, mulches and planting trays, adoption should be rapid and sustained. However, the purchase/replacement cost of biodegradable plastics would need to compete with current practice whereby farmers can (and do) reuse nondegradable plastics repeatedly. There may also be significant manufacturing and transport footprints associated with biodegradable plastics. The challenge will be whether biodegradable plastics are effective over time, given the relatively slow rates of degradation.

3.5.1.8 Climate Adaptation or Mitigation

The action could contribute towards climate adaptation through sustaining or improving productivity and increasing drought resistance (Kasirajan and Ngouajio, 2012).

3.5.1.9 Climate Factors / Constraints

There are no known climatic or soil type constraints to adoption.

3.5.1.10 Benefits and Trade-offs to Farmer/Land manager

The action would allow farmers and growers to continue to benefit from the use of silage wrap, mulches and planting trays.

3.5.1.11 Uptake

Cost may be a significant barrier to the use of bio-based biodegradable film (and other buiodegradable plastics) to replace plastic. The effectiveness of materials for silage making may also be another barrier.

3.5.1.12 Other Notes

Monitoring of biodegradable plastic product use would be most effectively carried out through field inspections and checking of records.

4 ACTIONS WITH LIMITED ASSESSMENTS OR EVIDENCE

This section (and section 5) focuses on action co-benefits (for soil conservation and soil health) only. A full assessment (as in the above sections) of the following actions is provided in one of the other Qualitative impact reports that cover themes such as “Carbon Sequestration”, “Water” and “Biodiversity.”

4.1.1 ETPW-200 - **Provide nesting and roosting sites (e.g. nesting boxes, bat boxes, fallow plots/areas for ground nesting birds and invertebrates).**

4.1.1.1 Co-Benefits and Trade-offs for soil conservation and soil health

Actions that set aside uncropped cultivated areas in arable fields with late establishment of vegetative cover are likely to increase the risk of surface runoff and soil erosion on sloping land (Chambers et al., 2000), but will have benefits in terms of reduced nutrient inputs.

5 TRADES-OFFS & CO-BENEFITS (‘TOCB’)

Other actions that have co-benefits or trade-offs for soil conservation and soil health are described below.

5.1 SYSTEMS ACTION

5.1.1.1 ETPW-152 - Manage damaging rabbit populations

5.1.1.1.1 Co-Benefits and Trade-offs for soil conservation and soil health

Actions that maintain vegetative cover by reducing damaging grazing activities (which could leave soil bare), could reduce the extent of erosion (Thompson, 1953).

5.1.2 ECPW-247 - Use precision systems such as spot spraying and weed wiping when applying a pesticide

The co-benefits and trade-offs for soil health described below also concern the following actions, all of which are designed to reduce the amount or frequency of application (or runoff/leakage) to land of active substances or veterinary medicines:

- **ECPW-207** - Carry out detailed farm/field-scale pest and disease mapping and utilise this to minimise PPP application
- **ECPW-211** - Create/ maintain impermeable, bunded PPP filling/mixing/cleaning areas
- **ECPW-213** - Reduce routes of entry to water from pesticide use
- **ECPW-217** - Restrict preventative use of agrichemicals (including vet meds, e.g. prophylactics)

- **ECPW-231** - Apply Integrated Pest Management (IPM)
- **ECPW-240** - Use cultural approaches to pest control in place of chemical pesticides
- **ECPW-241** - Destroy cover crop using roller instead of spraying
- **ECPW-254** - Apply IPM principles to veterinary medicine use
- **ECPW-257** - Relocate sheep veterinary treatment areas and pens to appropriate locations
- **ECPW-259** - Install roofing over sprayer wash-down and loading areas
- **ECPW-260** - Use sheep dip drainage aprons and sumps
- **ECPW-262** - Store sprayer under cover
- **ECPW-269** - Use bio pesticides or biological control in place of chemical pesticides
- **ETPW-161** - Minimise the use of antihelminthics
- **ETPW-226** - Create and/or use lined biobeds and biofilters for the treatment of dilute PPP from pesticide handling facilities and sprayers
- **ETPW-236** - Develop, use and review an IPM Plan. To include a farm pest anti-resistance strategy
- **ETPW-254** - Use pest resistant / tolerant crop varieties to reduce the need for pesticides which have multiple pest resistance properties and have a high resistance rating
- **ETPW-258** - For pests with established thresholds: Only apply a pesticide if pest economic and/or environmental thresholds are exceeded

5.1.2.1 Co-Benefits and Trade-offs

Actions that limit the amount of pesticide applied to land can benefit soil health (Ahemad Munees, 2013; Pelosi et al., 2014), although there is limited evidence that soil organic matter and soil structure will be significantly enhanced.

5.1.3 ECPW-181 - Conversion to a more extensive system including reversion from high-risk forage to grass and whole crop and reduced inputs

5.1.3.1 Co-Benefits and Trade-offs

More extensive systems tend to result in lower nutrient inputs, lower stocking rates and more persistent vegetative covers. This can have positive benefits for soil conservation and soil health (e.g. Allan et al., 2015).

5.2 HABITAT CREATION

5.2.1 ETPW-205C - Create flower-rich and species rich grass margins, field corners, and plots

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions, although for some actions the impact is indirect rather than direct:

- **ECPW-022C** - Create species-rich grassland habitats
- **EHAZ-010X** - Create permanent grasslands
- **ECPW-157C** - Create buffer strips (including trees) around boreholes
- **EBHE-290** - Establish/ maintain a continuous grass sward/vegetation cover over Scheduled Monuments/ heritage assets on the SHINE database that are not Listed Buildings or Scheduled Monuments with no ground disturbance, bare patches or erosion with no ground disturbance, bare patches or erosion.
- **EBHE-292** - Exclude burrowing animals from Scheduled Monuments/ heritage assets on the SHINE database that are not Listed Buildings or Scheduled Monuments
- **EBHE-293** - Manage a permanent grassland for Scheduled Monuments/ heritage assets on the SHINE database that are not Listed Buildings or Scheduled Monuments
- **EBHE-295** - Prevent the use of vehicles around Scheduled Monuments/ heritage assets on the SHINE database that are not Listed Buildings or Scheduled Monuments

- **EBHE-080** - Create/ manage buffer strips around heritage assets on the shine database that are not Listed Buildings or Scheduled Monuments or around Scheduled Monuments (link boundary features) on cultivated land
- **EBHE-090** - Establish/ maintain a continuous grass sward in Registered Parks and Gardens
- **ECPW-157EM** - Enhance/ manage buffer strips (including trees) around boreholes
- **ETPW-091** - Restore/ enhance/ manage permanent grassland in coastal areas
- **ECCM-001** - Diversify arable rotations (including cover and catch crops, over and under sowing).
- **ETPW-205EM** - Enhance/ manage flower-rich and species rich grass margins, field corners, and plots
- **ETPW-229** - Enhanced overwinter stubble (This includes regrowth of vegetation and retention of "stubble and any subsequent regeneration until 31 July of the following year after harvest")
- **EHAZ-024** - Use grass or encourage natural regeneration where this can be efficiently incorporated into the rotation
- **ETPW-232** - Use grassland (grazed or ungrazed) in arable rotation as a break crop
- **ECPW-022EM** - Enhance or manage species-rich grassland habitats
- **ETPW-217** - Create areas of scrubby flower-rich grassland
- **ECCM-028** - Manage temporary grassland reseeding frequency (the benefits assume that reseeding frequency is reduced)
- **ECPW-032** - Use herbal and grass leys
- **EHAZ-010Y** - Enhance or manage permanent grasslands
- **ETPW-207** - Create/ enhance/ manage beetle banks
- **ETPW-143** - Where burning takes place, ensure small burns on a long rotation to create a varied age structure in dwarf shrub, including retaining mature and degenerate phases
- **ETPW-038** - Create/ manage/ enhance buffer strips
- **ECPW-042** - Create/ enhance/ manage riparian buffer strips
- **ECPW-291C** - Create riparian habitats
- **ECPW-291EM** - Enhance or manage riparian habitats
- **ETPW-233** - Establish trap crops to reduce pest prevalence (edge of field)
- **ETPW-271** - Create/ manage/ enhance buffer strips to encourage natural predators and species diversity
- **ECCA-024** - Create new areas of habitat adjacent to existing habitat patches to increase patch size and help sustain more viable species populations.

5.2.1.1 Co-Benefits and Trade-offs

Establishing vegetative cover (and creating structures that if orientated correctly can intercept and control runoff and associated erosion; e.g. ETPW-207 - Create/ enhance/ manage beetle banks) where there may have been no growing cover in previous circumstances or establishing more permanent vegetative covers is likely to reduce soil erosion extent and result in some positive benefit for soil organic matter and structure. Some of the above actions can also result in greater plant species diversity, which can also have benefits for soil health.

5.2.2 ETPW-116 - Provide a flower rich habitat for wild pollinators with a range of flowering times and flowering structures

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **ETPW-260** - Provide feeding areas to support the lifecycles of wild bird and pollinators (e.g. wild bird and pollinator seed mix)
- **ETPW-260x** - Provide feeding areas to support the lifecycles of wild birds (e.g. wild bird seed mix)
- **ETPW-260y** - Provide feeding areas to support the lifecycles of pollinators (e.g. pollinator seed mix)
- **ETPW-189** - Plant/ manage wildflowers

5.2.2.1 Co-Benefits and Trade-offs

Creating, enhancing or managing new habitat areas on arable land is likely to reduce nutrient inputs (assuming that nutrients would not be applied to new habitats) and improve vegetation cover, so reducing the extent of soil erosion while benefitting soil structure.

5.2.3 EBHE-214C - Create locally distinctive flower rich/hay meadows using traditional techniques

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **ECPW-176C** - Create heathland (including heathland mosaics)
- **ECPW-176EM** - Enhance or manage heathland (including heathland mosaics)
- **ECPW-245** - Graze and cut grass later when fibre content higher (to slow digestion in ruminants)
- **ETPW-081EMX** - Enhance / maintain coastal heath
- **ETPW-081EMY** - Enhance / manage coastal scrub
- **ETPW-101** - On meadows, make field- dried hay and minimise haylage and silage

5.2.3.1 Co-Benefits and Trade-offs

Creating flower-rich hay meadows or heathlands where grassland was previously managed more intensively (e.g. through multiple silage cuts or grazings) is likely to have limited positive benefits for soil structure. Plant species diversity can favour soil structural improvement through having a variety of rooting depths and traits. Diversity can also build in resilience of the vegetation and help maintain covers and roots to protect against soil degradation processes. Well-targeted creation of heathlands could also provide moderate positive benefits in terms of below ground carbon sequestration.

5.2.4 ECCM-025C - Plant hedgerows

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **ECCM-080C** - Plant hedgerows around point-source polluters
- **ECCM-025EM** - Enhance/ manage hedgerows
- **ECCM-080EM** - Enhance/ manage hedgerows around point-source polluters

5.2.4.1 Co-Benefits and Trade-offs

Planting hedgerows can have moderate positive benefits for soil erosion extent and soil health. Appropriate siting of hedgerows may intercept runoff to reduce soil erosion risk (e.g. if oriented across the slope, ideally on the contour). Hedgerows have been used to replace former field boundaries and the resulting smaller fields have less runoff and soil erosion risk. Increased soil organic matter from root development and seasonal leaf fall from the hedgerow may improve soil properties (e.g. Biffi et al., 2022; Van Den Berge et al., 2021). There may be major positive benefits for soil health under the hedgerows. Benefits from enhancing or managing hedgerows are less certain.

5.3 ACTIONS FOR HABITATS WITH SPECIFIC HYDROLOGICAL CHARACTERISTICS

5.3.1 ETPW-016C - Create water meadows

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions, although for some actions the impact is indirect rather than direct:

- **ETPW-036EM** - Enhance, manage floodplain meadows
- **EBHE-164C** - Create wetland habitats
- **EBHE-164EM** - Enhance/ manage wetland habitats
- **ECCA-007C** - Create wetland habitat mosaics, including creating the appropriate hydrological conditions

- **ECCA-007EM** - Enhance/ manage wetland habitat mosaics, including creating the appropriate hydrological conditions
- **ECCM-043C** - Create coastal wetland habitats
- **EBHE-084** - Restore/ maintain high water levels to protect heritage assets on the shine database that are not Listed Buildings or Scheduled Monuments
- **ECCM-042** - Create and enhance approaches to maintain water tables in coastal habitat and marshland
- **ECCA-006** - Re-naturalise river catchments by, for example, reconnecting rivers with their floodplain, restoring and realigning rivers, and restoring associated floodplain habitats.
- **ECPW-059** - Reconnect rivers with floodplains
- **EHAZ-051** - Remove constraints to river movement (e.g. remove bank protection and embankments to enable channel migration within the floodplain)
- **EHAZ-052** - Use land for temporary flood storage
- **ETPW-013** - Remove levees and flood banks

5.3.1.1 Co-Benefits and Trade-offs

[TOCB Report-3-3 Soil] Actions that create wetter lowland environments in which livestock graze can have potential limited disbenefits for the extent of soil erosion and soil structure due to exposure of bare soil and poaching. However, the level of risk will be highly context dependent (e.g. if a created wetland is fenced off to restrict livestock access, the risk to soil structure and erosion will be minimalised). In addition, the wetter environments are also likely to increase soil organic matter contents thereby benefitting below ground C sequestration and some aspects of soil health.

[TOCB Report-3-5B Improved grassland biodiversity]: Maintaining high water table levels will benefit existing wetland habitats and species. The effect of restoring high water table levels could provide new wetland habitats but where these replace well-established semi-natural vegetation the effect could be detrimental to some species.

5.3.2 EBHE-216 - Rewet moorland (including common land), e.g. through appropriate traditional grazing techniques

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions, although for some actions the impact is indirect rather than direct:

- **ECAR-041** - Reduce managed burning on non-SAC/SPA designated sites and on shallow peat
- **ECCM-030** - Restore/ manage upland and lowland peatlands including blanket bog and raised bog
- **ECCM-030B** - Raise water levels in areas of farmed peatland and adapt farming systems accordingly
- **ECCM-031** - Use controlled grazing (bogs and peatlands)
- **ECCM-032** - Manage hydrology in wetland habitats to restore functional processes
- **ECCM-033** - Restore peatland vegetation
- **ECCM-034** - Remove non-peat habitat vegetation
- **ECCM-035** - Use no-till cultivation on agricultural lowland peatland
- **ECCM-037** - Restrict root crops in agricultural peatlands
- **ECCM-038** - Raise water levels in areas of farmed peatland and adapt farming systems accordingly
- **ECCM-039** - Restore areas of farmed peatland to wetland
- **EHAZ-137** - Use paludiculture
- **EHAZ-129C** - Create fen
- **EHAZ-129EM** - Enhance or manage fen
- **ETPW-153** - Stabilise eroding peat through targeted restoration work
- **ETPW-155** - Remove grazing from recovering peatland, susceptible habitats and sensitive vegetation
- **ETPW-158** - Manage the dominance of graminoid or ericaceous species on bog by hydrological restoration, light summer grazing and cutting

- **EHAZ-134** - Restrict deep ploughing on agricultural lowland peatland
- **ECCM-065** - Switch to using peat alternatives in horticultural growing media
- **ECCM-046** - Use controlled grazing on intertidal, saline, salt marsh and coastal grassland habitats
- **ECPW-083** - Control grazing on sand dunes
- **EHAZ-067** - Control grazing on permanent coastal grassland

5.3.2.1 Co-Benefits and Trade-offs

In contrast to "**ETPW-016C** - Create water meadows", rewetting moorland, controlling grazing, protecting peatlands and reducing managed burning in uplands is likely to encourage peat stabilisation and development, and a lower risk of erosion. Raising water levels and reducing tillage on farmed lowland peatlands (without livestock) is also likely to benefit soil health overall and reduce the risk of wind erosion from peatlands.

5.3.3 EHAZ-063 - Block drains, ditches and grips

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **ECPW-158** - Install bioreactor (straw) into field drainage system
- **ECPW-168** - Create/ maintain leaky woody structures and woody debris in small water courses and their flood plains

5.3.3.1 Co-Benefits and Trade-offs

Reducing the effectiveness of agricultural drainage is likely to increase the risk of soil compaction and erosion. The one exception is the blocking of moorlands grips, which when combined with very low stocking rates can stabilise upland peats.

5.4 Drainage, Irrigation and Wastewater

5.4.1 ECPW-100 - Install/ maintain culverts in ditches to reduce sedimentation and bacteria levels in water bodies

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **ECPW-103** - Construct bridges for livestock and machinery crossing watercourses
- **EHAZ-075** - Create/ manage artificial water diversion (ditches, channels, pipes and earth banks)
- **EBHE-299** - Maintain necessary drainage works for Scheduled Monuments/ heritage assets on the SHINE database that are not Listed Buildings or Scheduled Monuments
- **ECPW-246** - Improve watercourse crossings to reduce sedimentation

5.4.1.1 Co-Benefits and Trade-offs

Improving the effectiveness of agricultural drainage and reducing livestock access to water courses and stream/riverbanks is likely to reduce the risk and extent of soil compaction and erosion. However, enhancing land drainage is likely to reduce soil organic matter levels if sustained for the long term (Auerswald & Fiener, 2019; Liu et al., 2021). Also, note that water diversions (EHAZ-075) can both increase (via runoff concentrations) and decrease (via runoff control) erosion risk, depending on how the outlets are managed. Action ECPW-246 (Improve watercourse crossings to reduce sedimentation) has more to do with erosion control than sedimentation control.

5.4.2 ECPW-238 - Cultivate and drill across the slope (where appropriate)

5.4.2.1 Co-Benefits and Trade-offs

Cultivating and drilling arable fields across the slope can reduce surface runoff and erosion in some circumstances. On fields with simple slope patterns, cultivating and drilling across the slope can reduce the risk of surface runoff and soil erosion being initiated and increase sediment re-deposition rates where surface runoff does occur.

The ridges created across the slope increase down-slope surface roughness and provide a barrier to surface runoff. As a result, the extent of soil erosion can be reduced (Defra SP1315). However, in fields with complex slope patterns, there is a risk that erosion can be increased where flow pathways converge at low spots.

5.4.3 ECPW-270 - Use cultivations / shaping of beds in potatoes and vegetable crops to direct water into beds and reduce run off e.g. angled tines, Creyke roller

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following action:

- **ECPW-271** - Use tied ridges (dammer dykes) in row crops

5.4.3.1 Co-Benefits and Trade-offs

Surface runoff, and associated soil erosion, can occur from ‘compacted’ tramlines/wheeled areas which act as concentrated flow pathways. The risk of runoff is greatest when soils are ‘wet’ during the winter. If tramlines are present, for example, as a result of the need to apply plant protection products during the autumn period, then tines can be used to disrupt the tramlines, which encourages water to infiltrate into the soil. Also, future tramlines can be drilled with the crop and then either wheeled over or sprayed off in spring. Using low ground-pressure vehicles (see also section 3.2.2.4 - EHAZ-017 - Use low ground pressure tyres) helps to limit soil compaction and maintain water infiltration rates (Defra PE0206, WQ0127).

5.4.4 ECPW-096 - Resurface gateways

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **ECPW-298** - Relocate gateways
- **ECPW-126** - Install/ maintain track drainage features such as sleeping policemen and guttering
- **ECPW-040** - Create/ maintain livestock tracks
- **ECPW-294** - Create/ maintain machinery tracks
- **ECPW-296** - Minimise trafficking and manage land to reduce soil erosion and loss around field structures such as poly-tunnels, plastic sheeting/ cloches or irrigation equipment used for horticultural crops.
- **ECPW-297** - Minimise trafficking and manage land to reduce soil erosion and loss around field structures such as livestock shelters /feeders/ troughs: e.g. for outdoor pigs.

5.4.4.1 Co-Benefits and Trade-offs

Resurfacing and relocating gateways and improving track drainage can reduce soil compaction and the extent of wheel ruts and livestock poaching around gateways and tracks, and also change flow pathways for control of surface runoff and erosion. There is a small risk that resurfacing gateways may increase runoff generation if the surface is impermeable. Although not an erosion problem there (the hard standing protects soil from erosion), increased surface runoff could initiate erosion adjacent to the hard surface.

For ECPW-126 (Install/ maintain track drainage features such as sleeping policemen and guttering), it is important to ensure they discharge runoff at safe volumes/velocities rather than allowing ponding and sudden release downslope. For ECPW-296 (Minimise trafficking and manage land to reduce soil erosion and loss around field structures such as poly-tunnels, plastic sheeting/ cloches or irrigation equipment used for horticultural crops), also see section 3.5.1 on “Use of biodegradable materials”.

5.4.4.2 ECPW-191 - Use more efficient spray irrigation equipment

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **ECPW-248** - Irrigate crops to improve yield and nutrient uptake (minimise soil damage from irrigation equipment)
- **EHAZ-110** - Use trickle or drip irrigation

5.4.4.3 Co-Benefits and Trade-offs

Using more targeted irrigation that reduces the amount and rate of irrigation water applied to land or reduces the amount of 'rain splash' impacting the soil surface can reduce the extent of surface runoff and erosion and the risk of causing soil compaction from agricultural machinery.

5.5 Climate Measures

5.5.1 ECCA-033EM - Manage/enhance coastal habitats to compensate for losses to climate change as part of a coastal management plan

This action relates to compensating for land losses due to natural coastal erosion processes exacerbated by climate change (e.g. extreme storm events, rising sea levels). Actions may include creation of intertidal habitat, seawalls and managed retreat.

5.5.1.1 Co-Benefits and Trade-offs

Manging and enhancing coastal and other habitats is likely to reduce soil erosion risk and result in moderate positive benefits for soil conservation in the location that is protected. Note that soil erosion risk at the coast relates to cliff and shoreline erosion, which involves different erosive processes from those operating in agricultural fields inland. It is unlikely that field erosion control measures will have any impact on mass movements involved in cliff retreat.

5.5.2 ECCA-026 - Plant a range of native species, including trees grown from locally adapted and genetically diverse seed sources, and from more southerly provenances

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions. Most actions are related to creating new tree or shrub cover, while ECCA-027 (Encourage diversification of the stand and continuity of canopy cover through natural regeneration of native species in semi-natural woodland) relates more to increasing the diversity of tree cover:

- **ECCM-074** - Plant, enhance or manage bioenergy crops (e.g. short rotation coppice)
- **ETPW-123** - Restock trees for resilience
- **EBHE-203C** - Create targeted scrub
- **ECCM-055** - Plant traditional orchards
- **ECCM-048** - Create woodland on a large scale
- **ECCM-051C** - Create buffer zones around ancient woodland (including through extension of existing woodland)
- **EBHE-209C** - Create traditional orchards with local varieties of fruit tree
- **EBHE-281** - Set up or engage with community tree planting projects
- **ECCA-018C** - Plant large-scale woodland in priority catchments
- **ECPW-044C** - Create targeted woodland
- **ECPW-071C** - Create floodplain woodland
- **ECCA-017C** - Plant trees to slow water, particularly cross-slope planting
- **ECCA-036** - Plant trees alongside water courses to provide shade and reduce water temperatures within rivers
- **EBHE-191** - Plant trees and shrubs around point-source polluters

- **EBHE-191** - Plant and establish appropriate species of field boundary trees
- **EBHE-205C** - Create wood pasture (e.g. through appropriate grazing)
- **ECAR-033C** - Create shelter belts (tree, woodland, scrub, and hedgerow) with appropriate species composition near sensitive habitats
- **ECAR-047** - Create/ enhance/ manage shelter belts (tree, woodland, scrub, and hedgerow) with appropriate species composition on hill slopes
- **ECCM-024EM** - Plant or manage trees outside of woodlands, including shelterbelts
- **ECPW-080C** - Create wind breaks
- **ECCA-017EM** - Manage trees to slow water, particularly cross-slope planting
- **EBHE-308** - Re-plant trees in Registered Parks and Gardens
- **ECCA-027** - Encourage diversification of the stand and continuity of canopy cover through natural regeneration of native species in semi-natural woodland
- **ECCM-049** - Create woodland through natural regeneration
- **ETPW-171** - Allow natural regeneration and extension of existing habitat (e.g. hedgerows, scrub, rough grassland)
- **ECCM-051EM** - Enhance or manage buffer zones around ancient woodland (including through extension of existing woodland)
- **EBHE-303** - Plant trees and hedges to mitigate the visual impact of polytunnels from the immediate view of neighbouring residential dwellings
- **EBHE-273** - Plant/ manage trees and shrubs to mitigate noise from transport and facilitate positive sound
- **ECCM-24C** - Plant trees outside of woodlands including shelterbelts
- **EBHE-104** - Create a woodland creation plan
- **EBHE-314** - Create a woodland management plan
- **ECCM-058** - Monitor health of trees

5.5.2.1 Co-Benefits and Trade-offs

Targeted introduction of trees, shrubs and scrub to the agricultural landscape is likely to result in an overall reduction in surface runoff and soil erosion risk and moderate to major positive benefits to soil quality in terms of increased soi organic matter and improved soil structure.

[TOCB Report-3-5B Grassland **EHBE-104**] Biodiversity benefits will depend on the existing land cover and management, and on the type of woodland that replaces it, and how this is managed. There could be significant benefit for a range of taxa and species if the plans follow the principle of maximising habitat value within the woodland and the landscape within which it is placed.

5.6 Restoration, management and enhancement

5.6.1 EBHE-203EM - Enhance / manage targeted scrub

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions, all of which aim to increase vegetation growth, thereby reducing surface runoff and erosion, and improving soil health:

- **ETPW-112** - Manage scrub to maintain, restore and enhance grassland condition and associated species populations, recognising its inherent value in providing shelter/structure/food and nesting resource
- **EBHE-140EM** - Enhance/ manage Ghyll woodland
- **EBHE-196** - Planted Ancient Woodland (PAWS) restoration
- **ECPW-071EM** - Enhance or manage floodplain woodland
- **EBHE-209EM** - Restore or manage traditional orchards with local varieties of fruit tree
- **ECCA-018EM** - Manage large-scale woodland in priority catchments
- **EBHE-307** - Retain mature and veteran standing trees in Registered Parks and Gardens
- **EBHE-198** - Restore/ manage ancient woodland with native broadleaf species
- **ECPW-04EM** - Manage or enhance targeted woodland

- **ECPW-156EM** - Enhance/ manage trees and shrubs around point-source polluters
- **ECAR-033EM** - Enhance/ manage shelter belts (tree, woodland, scrub, and hedgerow) with appropriate species composition near sensitive habitats
- **ECPW-080EM** - Enhance, manage, wind breaks
- **Carbon-01** - Conservation of long-established woodlands with existing high carbon stocks
- **Carbon-02** - Longer rotations in even-aged managed stands
- **Carbon-03** - Create and implement a woodland carbon plan
- **Carbon-04** - Enrichment of woodland growing stock for carbon sequestration

5.6.1.1 Co-Benefits and Trade-offs

Enhancing and managing woodlands and tree shelterbelts will help to control soil erosion, and provide soil health benefits. Actions such as Carbon-04 (Enrichment of woodland growing stock for carbon sequestration) that aim to increase SOC content are also likely to have positive benefits for soil health.

5.6.2 ECAR-042 - Create/ maintain fire breaks to minimise spread of wildfires

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **EHAZ-138** - Manage vegetation to reduce the risk of wildfires
- **ECCA-035** - Prepare and implement wildfire management plans

5.6.2.1 Co-Benefits and Trade-offs

Preventing wildfires will secure vegetation development and growth, so reducing runoff and soil erosion, and bringing soil conservation and soil health benefits.

5.6.3 Grassland-02 - Mob grazing

5.6.3.1 Co-Benefits and Trade-offs

Grazing at high field stocking rates for short periods and with long grazing intervals can increase soil organic matter in some circumstances (e.g. following several years of arable cultivation) but could result in soil compaction (Defra “mob” grazing project: impacts, benefits and trade-offs; started 2021; rapid evidence assessment, 2022, in draft).

5.6.4 ECCM-014 - Use low-intensity grazing systems using biodiverse sward mixtures

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **ETPW-105** - Use low intensity mixed livestock grazing
- **ETPW-150** - Manage localised grazing pressure
- **ETPW-157** - Create and use a grazing plan including stocking rates; monitor and adjust in line with grass productivity (especially where there are multiple graziers)
- **ETPW-243** - Reduce field stocking rates
- **ETPW-244** - Reduce livestock numbers

5.6.4.1 Co-Benefits and Trade-offs

Grazing at lower stocking rates and increasing the plant species diversity of grass swards (providing a variety of rooting depths and other root traits) could potentially have limited positive benefits for soil erosion and soil structure, although the evidence for this is limited. The timing and location of grazing can often be more important for poaching risk (and associated soil erosion and loss of soil health) than the stocking rate (Newell Price et al., 2013).

5.6.5 Arable-01 - Extended stubble - unharvested crop stubble followed by a one-year fallow

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **Arable-02** - Unvegetated, ploughed fallow (natural regeneration) for one year
- **ETPW-257** - Use vegetated fallow in arable rotations
- **Arable-03** - Annually cultivate headlands and leave unsown

5.6.5.1 Co-Benefits and Trade-offs

Leaving the land fallow (without a sown crop) can result in moderate positive benefits in terms of improved soil structure (natural restructuring on medium and heavy soils) and reduced erosion due to the vegetative and residue cover but can result in soil carbon losses due to the imbalance between (reduced) photosynthetic activity and soil microbial respiration. In the case of Arable-02 (Unvegetated, ploughed fallow (natural regeneration) for one year), ploughing is likely to have a negative impact on soil health (e.g. earthworm numbers).

5.6.6 ECPW-264 - Leave unharvested cereal headlands

5.6.6.1 Co-Benefits and Trade-offs

Retaining a crop residue cover can protect the soil surface and reduce the extent of erosion. Not cultivating and keeping roots intact may also help preserve good soil structure. However, any severe soil compaction on the headlands could be retained until the crop is removed and there is opportunity for subsoiling.

5.7 Maintenance, restoration of habitat features in Parks and Gardens

5.7.1 EBHE-310 - Protect existing trees to prevent damage from livestock and wild animals in Registered Parks and Gardens

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **EBHE-192** - Manage existing in-field trees situated within areas of cultivated land by reversion to permanent pasture to beyond extent of tree canopy to protect tree roots from cultivation and compaction
- **ECCM-056** - Manage veteran and ancient trees
- **ETPW-171** - Protect natural regeneration (e.g. through scrub management, protective fencing, invisible fencing)
- **Carbon_01** - Conservation of long-established woodlands with existing high carbon stocks
- **EBHE-309** - Maintain standing/fallen deadwood in Registered Parks and Gardens
- **ECCM-053** - Manage deadwood (where appropriate, remove diseased deadwood, leave healthy deadwood to contribute to carbon storage)
- **ECPW-237Cy** - Enhance/ manage in-field vegetation including grass, scrub, trees

5.7.1.1 Co-Benefits and Trade-offs

Retaining and protecting trees that may otherwise be removed or damaged has similar outcomes to planting trees (i.e. the benefits to soil conservation and health are sustained); and retaining deadwood can benefit soil biodiversity.

5.8 Create and enhance access and PROW

5.8.1 EBHE-006 - Create or dedicate new rights of way for footpaths, bridleways, cycle tracks, and restricted byways to make or complete community circuits of off-road routes, link to community places and spaces, public transport, waterways, access land, common land, National Trails and fill gaps in the off-road network or improve public safety

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **EBHE-015** - Create new permissive paths (any payment needs to be time bound after which landowner either dedicates as permanent or stops receiving payment, starting point 3 years)
- **EBHE-021** - Create public access (on foot, on horse or on bike) to open access land and common land
- **EBHE-026** - Dedicate land as access land
- **EBHE-044** - Create/ maintain safe access to beach schools sites
- **EBHE-154** - Create/ maintain controlled access to sand dunes
- **EBHE-265** - Dedicate new Byways Open to all Traffic
- **EBHE-282** - Create higher access rights on Open Access land (i.e. allow for activities currently restricted open access land by Schedule 2 of the CROW Act)
- **EBHE-284** - Create launch points for recreational activities by such as paddle sports, fishing, wild swimming, for able-bodied and disabled users
- **EBHE-300** - Coordinate new public access with adjacent land managers (to link to transport hubs and community spaces, access land, National Trails and other parts of the off-road and quiet road network)
- **EBHE-251** - Create/ enhance/ maintain access for caves or disused mines
- **EBHE-054** - Create places for geo-caching

5.8.1.1 Co-Benefits and Trade-offs

Actions that create new paths or byways for access can have potential limited disbenefits/trade-offs for the extent of erosion and soil quality. However, if the public were previously accessing the land (prior to path creation) and new paths are well designed and sited, erosion could be better controlled as a result of the path creation. Encouraging use of a single track (rather than spread over a larger area) should protect adjacent areas.

5.8.2 EBHE-008 - Create/ maintain infrastructure needed to mitigate the effects of access (boardwalks over wetlands, hedges and banks to hide walkers from birds, hedges to keep dogs from straying etc) where not already required by regulation

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **EBHE-022** & **EBHE-023** - Improve access infrastructure including path surfaces and widening on PRoW cycle tracks and informal paths on publicly accessible greenspace (including access land, common land and TVGs) so that they are accessible all year round for all legal users
- **EBHE-029** - Create/ maintain alternative routes on paths and greenspaces liable to inundation (flooding and erosion)
- **EBHE-031** - Create or dedicate new replacement routes of the same or higher status where inundation or erosion will be permanent

5.8.2.1 Co-Benefits and Trade-offs

Actions that mitigate the effects of public access (primarily footpaths) are likely to have limited positive benefits for the extent of soil erosion and soil quality. These actions specifically provide infrastructure or rerouting to mitigate the negative impacts of public access. They do not simply open up access to the public, which can result in increased trampling, compaction and surface runoff, as is the case for EBHE-006 above.

5.9 Soil management and protection

5.9.1 EHAZ-004 - Use under and over sowing

5.9.1.1 Co-Benefits and Trade-offs

Using under and over sowing to establish a following cover crop or grass/legume cover has similar benefits to a standard cover crop, with potential to reduce nutrient inputs (through use of legumes in the cover crop and the capture and release of nutrients from the cover crop itself), soil health and the extent of erosion (Defra project WQ0140; also see action **ECPW-028**).

5.9.2 EBHE-117 - Create/ enhance/ manage contour grass strips

5.9.2.1 Co-Benefits and Trade-offs

Creating contour grass strips has a similar mode of action and range of benefits to cultivating and drilling across the slope (**ECPW-238** - Cultivate and drill across the slope, where appropriate), although in fields with complex slopes there is a risk that convergent surface flow can breach the strips, making soil erosion worse (Defra SP1315). However, soil health will be increased due to arable reversion to grassland in the grass strips.

5.9.3 ECCM-071 - Use intercropping

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following action:

- **EHAZ-115** - Use intercropping systems with alternate irrigation

5.9.3.1 Co-Benefits and Trade-offs

There is limited evidence that intercropping may improve soil health due to a higher leaf area index (improved crop canopy structure for light capture), resulting in higher photosynthetic activity leading to increased labile C released by crop roots and associated improvements in soil physical quality. The soil health bioindicators affected can be labile soil C, microbial activity, microbial biomass and microbial structure (Bedoussac et al., 2015, Kremer, 2019; Kremer and Deichman (2016). Where one of the intercropped crops is a legume, this is likely to result in reduced nutrient (manufactured fertiliser) inputs. Indeed, in the UK intercropping is most commonly used in organic systems.

5.9.4 ECPW-039 - Aeration of soils in grassland situations to remove surface compaction / capping especially from sheep grazing

5.9.4.1 Co-Benefits and Trade-offs

Compacted soil layers reduce the infiltration of rainwater and slurry into the soil. Aerators and slitters can be used to alleviate compaction in the upper 10 cm of the topsoil. Disrupting these compacted layers allows more rapid percolation of rainwater/slurry into the soil and reduces the
risk of surface runoff and erosion (Defra project WQ0106).

"*Results from UK studies have been variable, with both yield increases and decreases measured. However, these results do suggest that mechanical soil loosening can be effective in improving soil structure and increasing grass yields where soil compaction has been positively identified and mechanical alleviation is effectively carried out. Where no compaction was identified at the outset of field trials/experiments, it appears that soil loosening improved soil physical properties (i.e. reduced penetration resistance), but rather than increasing productivity, resulted in a reduction in grass yield due to sward and root damage (e.g. Frost,* *1988a and 1988b). It is probably the case that where compaction cannot be identified through visual assessment (i.e. compaction assessed as a distinct coarsening and angularity of structures at some level in the topsoil), soil loosening is unlikely to have a positive effect on grass yield and the resulting sward and root damage is more likely to result in yield penalties (relative to the situation when mechanical loosening has not been carried out)*." From "The alleviation of grassland compaction by mechanical loosening" (Defra project BD5001).

5.9.5 ECAR-020 - Extend the grazing season for cattle

5.9.5.1 Co-Benefits and Trade-offs

Leaving livestock out to graze when soils are 'wet' can increase soil compaction, runoff generation and soil erosion extent and can have a major negative impact on soil structure (Defra SP1316; Newell Price et al., 2013).

5.9.6 ECPW-239 - Cultivate to create rough soil surface on bare land/stubble fields uncropped over winter

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following action:

- **EHAZ-018** - Leave autumn seedbeds rough (instead of finely tilled seedbeds)

5.9.6.1 Co-Benefits and Trade-offs

Actions that increase soil surface roughness are likely to have a limited positive benefit on the extent of erosion; and a limited positive benefit on soil structure compared with creating fine seedbeds. Chambers et al. (2000) found that the most effective step in controlling soil erosion by water was the process of identifying what soil and cropping factors led to erosion initiation at each site. Methods such as adopting minimum tillage, avoiding soil compaction where possible, creating rough seedbeds and timeliness of cultivations were all effective. According to Kay et al (2009), the success of soil management methods (in controlling soil erosion) in the post-harvest period is likely to be site specific due to factors such as crop type, soil type, slope and hydrology (particularly soil moisture conditions).

Unsown, fine seedbeds are very susceptible to soil erosion and compaction. It is therefore very important to establish an actively growing crop as soon as possible to reduce the risks of surface runoff and erosion. Rapid establishment of a following crop can reduce surface runoff by up to 75% relative to no tillage (Martin et al., 1999) and by even more relative to an unsown seedbed.

Surface water infiltration is improved with a rough surface, and ultimately will result in reduced risk of surface runoff, erosion and associated losses of sediment and particulate P (Newell Price et al., 2011). The aim of this post-harvest option is to reduce the risk of soil surface capping (as fine seedbeds are more prone to capping) and to enhance infiltration rates. The option can also help to reduce the occurrence of sheet wash and rill erosion as the rough surface impedes and helps break up any surface flow generated in rainfall events (Newell Price et al., 2011; Ulen, 1997). Cultivation by ploughing or tines can be particularly effective at reducing runoff volumes from compacted maize fields (Withers and Bailey, 2003; Defra project SP0404).

Compared with compacted, bare stubbles, creating a rough soil surface by ploughing or discing has been found to be a useful soil management method for reducing surface runoff volumes (Kay et al, 2009).

Deasy et al. (2010) suggest that incorporation of crop residues, or minimum tillage where residues and the stubble from the previous crop are left on the soil surface may be more effective in increasing surface roughness than ploughing. Deasy et al (2010) also recognise the benefits of creating a rough surface as it will reduce runoff velocity, erosion and transport capacity of sediment, along with promoting the deposition of material during transport. Chambers et al. (2000) highlighted the importance of avoiding fine, rolled seedbeds on erosion-susceptible soils as these will be most prone to slaking and capping and can lead to increased risks and rates of surface runoff generation. Currently there is only limited field evidence that the actions can reduce particulate P and associated sediment losses by up to 80% (Newell Price et al., 2011).

5.9.7 ECPW-243 - Drill double headlands in arable crops

5.9.7.1 Co-Benefits and Trade-offs

There is some evidence to suggest that changing the orientation of tramlines can reduce soil erosion extent (Defra SP1315). Drilling double headlands also creates additional lines of crop or stubble across the slope, thereby creating additional barriers to surface runoff.

5.9.8 ECCM-077 - Use of urease inhibitors with urea fertilisers

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **AQ-04** - Use fertiliser with urease and nitrification inhibitors

5.9.8.1 Co-Benefits and Trade-offs

There is limited evidence of the effect of urease and nitrification inhibitors on soil health, namely microbial diversity. Effects range from no effect to short-lived effects on target groups (e.g. Luchibia, 20201):

5.10 Litter and Plastic Waste

5.10.1 EBHE-278 - Remove waste plastics in an approved manner, wash, and segregate and store correctly and recycling. NB recycling scheme available locally required for compliance.

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following actions:

- **ECPW-277** - Reduce and reuse plastics in agriculture, forestry and horticulture
- **ECPW-288** - Clean plastic sheets to reduce contamination in order to facilitate recycling
- **ECPW-289** - Implement measures to stop visible plastics from entering manures and slurry storage e.g. baler string, ear tags, plastic enrichment toys and silage wrap
- **ECPW-293** - Reduce and reuse plastics

5.10.1.1 Co-Benefits and Trade-offs

Better management of waste plastic in farmyards and fields is likely to reduce the amount of plastic contamination in agricultural soils. For more information see section 3.5 on litter and plastic waste.

5.11 Livestock Management

5.11.1 LIVESTOCK MANAGEMENT- FEEDING STRATEGIES

5.11.1.1 AQ-01 - Free range poultry/pigs in woodland

5.11.1.1.1 Co-Benefits and Trade-offs

Introducing free range poultry and pigs into woodland could have benefits for soil biodiversity. However, the evidence for this is limited and there are likely to be disbenefits in terms of soil compaction and erosion, depending on the level, timing and duration of stocking.

5.12 Maintenance and Restoration of Cultural Heritage Sites

5.12.1 Maintenance and restoration of cultural heritage sites

5.12.1.1 EBHE-081 - Minimise cultivation on Scheduled Monuments/ heritage assets on the shine database that are not Listed Buildings or Scheduled Monuments

5.12.1.2 Co-Benefits and Trade-offs

Reduced cultivation systems can result in reduced soil erosion, a gradual increase in soil carbon, (Cooper et al., 2021; Dawson & Smith, 2007), increased biodiversity (e.g. earthworms, springtails and mites) (e.g. Ernst & Emmerling, 2009; George et al., 2017) and an increase in soil strength and aggregate stability (e.g. Schjønning & Rasmussen, 1989). For more information on reduced cultivation, see section 3.2.1.1 on minimum-tillage or no-tillage cultivation.

5.12.2 EBHE-287 - Do not harrow or roll Scheduled Monuments/ heritage assets on the SHINE database that are not Listed Buildings or Scheduled Monuments

The co-benefits and trade-offs for soil conservation and soil health described below also concern the following action:

- **EBHE-288** - Do not plough, sub-soil cultivate or re-seed across Scheduled Monuments/ heritage assets on the SHINE database that are not Listed Buildings or Scheduled Monuments

5.12.2.1 Co-Benefits and Trade-offs

Actions that avoid cultivation are also likely to result in moderate positive benefits for soil conservation and soil health (e.g. soil structure).

6 KEY ACTION & EVIDENCE GAPS

6.1 ACTION GAPS

All the main land management actions that contribute towards improved soil conservation and soil health have been included in the action list provided. Actions that increase the amount of soil surface cover at times of intense rainfall, particularly when soils are 'wet' in autumn to early spring, will benefit soil conservation. Similarly, actions that avoid cultivating or rolling the land when soils are 'wet' are likely to improve soil structure as well as soil water infiltration and storage. Growing plants of any kind, whether that be trees, shrubs, hedgerows, crops or a grass ley can contribute towards sequestering carbon (C) from the atmosphere. The longer the period of leaf growth, root growth and photosynthetic activity the greater the C sequestration potential and the greater the likelihood that the vegetation cover will also improve soil structure and potentially increase soil biodiversity. While in most cases total C sequestration rates are low (e.g. use of cover crops, green manures and grass leys within an arable rotation), the benefits for soil physical properties can be significant (e.g. Neal et al. 2020). Some high cost, technical actions, such as the use of tracked rather than wheeled machinery, have not been included, but these are significant business decisions that may be beyond the scope of an agri-environment scheme.

In the case of soil erosion, the focus in the report is on erosion by water (principally surface runoff/overland flow). However, wind erosion, tillage erosion and co-extraction of soil with root crops, machinery and vehicles are also important causes of soil loss (Owens et al., 2006). These can be locally very damaging e.g. in fenland soils and high value horticultural crops.

The report makes some reference to the economics of production. However, future reports could provide more detail on the costs and economics of specific actions, e.g. reduced cultivations have lower cost (fuel less draught as fewer, shallower and speedier operations; lower labour demand), so even if yields are reduced, economic margin can be unaffected or even improved for the farmer. The likely costs of some soil erosion control measures are available (e.g. Posthumus et al., 2015).

6.2 EVIDENCE GAPS

The impact of several land management actions on soil conservation and soil health remains uncertain. The activities that require further research include:

- The use of cover crops and green manures and their long-term effects on soil health.
- The practical integration and implementation of continuous vegetative covers (and associated roots) within arable and horticultural systems.
- The effect of machinery size and tyre/track type (including tyre inflation pressures) on soil health and conservation; in particular, the impact of operating such machinery in various soil moisture conditions and seasons (e.g. on a 'wetting front' in the autumn vs a 'drying front' in the spring).
- The effect of contrasting soil cultivation systems and crop rotations on soil health and soil carbon sequestration.
- The overall effect of overseeding with deep-rooting herbs and legumes (including the effect of the overseeding operation and establishment period) on soil health and soil carbon sequestration.
- The impact of grazing management (stocking density, grazing interval, grazing time, grazing timing etc.) on soil health and soil C sequestration.
- The impact of low intensity grazing systems and biodiverse swards on soil health, farm economics, productivity and other ecosystem services. What are the implications of widespread adoption at a regional, national and global scale?
- The overall impact of free-range poultry and pigs in woodland on soil health and soil conservation.
- The impact of herbicides, fungicides and pesticides on soil health.

- The impact of land drainage, maintaining land drainage systems and allowing drainage systems to deteriorate on soil health and soil conservation.
- The impact of intercropping and companion cropping systems on soil health, productivity, farm profitability and other ecosystem services.
- The impact of biodegradable materials on soil health, particularly microbial diversity.

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