Interreg
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REVIEW OF CURRENT METHODS AND APPROACHES FOR SIMPLE ON FARM ENVIRONMENTAL MONITORING OF FAB SOLUTIONS

Activity 2 will identify user-friendly tools and methods to measure the environmental and socio-economic performance of FAB solutions

The aim of this report is to:

- Review methods to measure the environmental performance of FAB solutions. The focus is on biodiversity, soils and water quality.
- Identify scientific approaches that could be used at the farm level and implemented by farmers or extension workers.
- Determine if and potentially how these measurement approaches could feed into and support regional or national monitoring.

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1. INTRODUCTION

1.1 PROJECT BACKGROUND

The agricultural sector, the basis for the agro-food sector in North West Europe (NEW), is today heavily dependent on external inputs (fertilizers, pesticides, etc.) and creates a number of negative effects on the quality of natural resources (soil, water, biodiversity). Functional Agrobiodiversity (FAB) (targeted stimulation of biodiversity to deliver ecosystem services such as pest and disease control, pollination, soil and water quality) offers opportunities to drastically reduce the dependence on inputs, but the knowledge in this area is still highly fragmented and insufficiently embedded in agricultural practice, policy and society. FABulous Farmers aims to accelerate the implementation of FAB by farmers and other land managers in NWE, by collecting, deepening and sharing knowledge and practical experiences about FAB between farmers, scientists, citizens and policy makers in 12 pilot regions in NWE over 5 countries (FR, NL, UK, BE and LUX). 10 FAB solutions are developed in a region-oriented manner, tested and demonstrated across 315 farms and evaluated for ecological performance and economic profitability, with the aim of reducing the dependence on external inputs by an average of 30%. In each pilot region, a FAB learning network is set up in which farmers exchange knowledge and experiences and draw up a FAB action plan. In addition, we collaborate with local actors, citizens, policy makers and value chain partners to embed FAB more widely in society, policy and market, through the design and implementation of FAB landscape integration plans and the rollout of citizen science tools; development of policy papers (at EU and national / regional level), and 12 business cases for valorisation of FAB via the market. Finally, a long-term development plan is drawn up for the continuation and expansion of the FAB learning networks after the end of the project.

1.2 MAIN AIMS OF ACTIVITY 2 AND THIS REVIEW

Activity 2 will identify user-friendly tools and methods to measure the environmental and socio-economic performance of FAB solutions. NERC-CEH will focus on the environmental effects and their measurement (soil, water & ecology) the subject of this review Activity 2.1. ILVO and ZLTO (NL) on farmer costs and benefits (based on farmers needs in the pilot regions) Activity 2.3 and UvA on social costs and benefits of an exemplar Activity 2.5. They will work with all partners to determine what will work on the ground and balance the need for on farm efficiency with the need for scientific robustness to measure change and provide flying experts to aid on farm assessment by regional partners.

The aim of this report is to:

- Review methods to measure the environmental performance of FAB solutions. The focus is on biodiversity, soils and water quality.
- Identify scientific approaches that could be used at the farm level and implemented by farmers or extension workers.
- Determine if and potentially how these measurement approaches could feed into and support regional or national monitoring.

1.3 PROJECT CONTEXT AND OVERVIEW

Agriculture is a defining part of the agro-food cluster, which is of strategic importance in Europe (6% of EU's GVA, 24 million jobs) and in NWE in particular (agro-food cluster is part of most national/regional innovation strategies for smart specialisation). Almost half of the land in NWE is farmed (48% in EU, Eurostat) producing food, fuel and fibre for the agro-food sector and the bio-based economy and delivering public goods and services like water retention and landscape values. Agricultural land in NEW consists of 60% of arable land with crops and vegetables and 34% of permanent grassland.

Over the past five decades, the EU Common Agricultural Policy has encouraged farmers to modernize and intensify production. This led to a mainly "linear" production approach, resulting in farming becoming a resource intensive sector, dependent on many external inputs (fertilizers, pesticides, machinery,...) and natural resources (soil, water, biodiversity), maximising production at the cost of polluting the environment and reducing farmland biodiversity. Agriculture accounted for 51% of the total water use in EU in 2014. In 2012 more than 90% of the assessed River Basin Management Plans (RBMPs) indicated that agriculture was a significant pressure on water bodies. Since farming covers 48% of the land surface area of the EU, agriculture has an enormous influence over the soils resources (decline of soil organic matter, soil erosion, soil compaction), while also being heavily dependent on them (soil fertility and productivity). In a linear approach even more external inputs (fertilisers, pesticides, irrigation,…) are necessary to compensate for the loss of soil fertility further impairing the reuse of natural resources, biodiversity, human well-being and even long-term agricultural productivity.

There is an urgent need for increased resource efficiency in farming systems to make the transition to more circular agro-ecosystems, which depend less on external inputs and conserve natural resources (soil, water, biodiversity). A very promising concept in this regard is FAB. FAB refers to the application of farm management practices that enhance and exploit elements of biodiversity for their role in providing ecosystem services (e.g. pollination, biological pest control, soil erosion control, water retention,…) and supporting sustainable agricultural production. E.g. multi-annual research in UK and NL showed that field margin management could increase farm yields up to 30% while reducing the use of pesticides by 30% (REF).

Although a lot of research has been done through NWE, knowledge on FAB is still very fragmented and has not resulted in practical on-the-farm tools to assist farmers in their decision-making for implementation of FAB in their farming activities. Although agri-environment scheme options have been developed for most countries based on good research on what works on farms and increasingly knowledge about the potential hydrological/ecological impact of options on specific land parcels is used to help farmers make decisions about which options to take up –e.g Glastir (Wales), EFS (Northern Ireland).

Furthermore knowledge needs to be gathered on economically sound business models that make implementation of FAB principles possible in different agricultural sectors and environmental settings. There is a need for transnational development and demonstration of possible FAB solutions and improving accessibility of reliable on the farm decision-making tools (everything from knowledge exchange between farmers (talking and demonstrating) to apps or online resources) to meet these challenges. Some regions have more experience on certain FAB solutions and can act as an example for others to learn from (e.g. Hoeksche Waard (NL) on flower strips for natural pest control, Normandy (FR) on agroforestry for soil & water conservation and Upper Sûre (LUX) on increasing soil biodiversity by adding organic inputs). Also in terms of data and methods partners from different regions have complementary competences: e.g. CEH (UK) has a leading expertise in assessment tools for ecological monitoring, while Biobest (B) has a database of flower mixes for different ecosystem services and ILVO provides methodologies for network learning.

In this project knowledge on FAB will be made available with the aim of encouraging farmers to put this knowledge into practice in their daily work to realize the shift towards a more circular farming system, using external inputs in a rational way, ensuring reuse of natural resources and building on biological regulation where possible. This will contribute not only to a more resilient agro-food system, but will also enable rural areas to generate significant societal ecosystem services. Since 94% of NWE farmland consists of arable land with crops and vegetables and permanent grassland, we will focus on these 3 agricultural subsectors: field vegetables, arable and dairy farming. For these subsectors the project creates an innovative, holistic approach, in which resource efficiency, economic viability and provision of ecosystem services are tackled together at farm production business, landscape and food chain level.

The project will generate and exchange knowledge and practical experiences on FAB between farmers, scientists, citizens and policy makers to deliver an area-based approach in 12 pilot regions throughout the NWE region, representing the diversity in agricultural settings in NWE. Applied research organisations will cooperate with ecological and agro-innovation organizations to gather existing research data and good practice FAB solutions. In each pilot region area specific FAB solutions will be tailor-made for the specific environmental and agricultural characteristics resulting in a tailor-made collective FAB action plan for each pilot region. The FAB solutions will be jointly developed, tested and evaluated on ecological functioning and economic profitability. Farmers and farmer groups in a pilot region are encouraged and supported to implement the area specific FAB solutions on various scales: within farm plot, with adjacent plots and at a wider landscape scale to deliver multiple services and benefits for the agricultural sector and for society.

2.1 INTRODUCTION

'FABulous Farmers' aims to accelerate the uptake and implementation of Functional AgroBiodiversity (FAB) by farmers and land managers in NWE (BE, NL, LUX, UK, FR) as a nature-based solution to shift from a linear agro-system to a circular agro-ecosystem that is more robust to disturbances, optimizes reuse of natural resources (soil, water and biodiversity) and is less dependent on exhaustible external inputs whilst delivering benefits to farmers, society and the environment.

2.1.1. FAB solutions

The 10 FAB solutions are shown in Table 1 in relation to the ecosystem services they help deliver and farm management e.g. quantity of fertilisers and pesticides.

2.2 METHODOLOGY FOR THE REVIEW

We conducted a systematic literature survey (Batary et al. 2012, Torralba et al. 2015) using keyword searches in the ISI Web of Science database (until Sep 2019) to extract potential articles, then filtering by title and keywords, abstract and finally full publication content. Combinations of the following keywords were used for literature searches; reduced/conservation tillage, agroforestry, hedgerows, mixed crops/crop rotation, manure, sward diversity, field margins, pesticides, carbon storage. Studies from Europe were targeted but for some options evidence is more geographically specialised and other countries/continents were included.
We also utilised recent reviews of agri-environment options e.g. ERAMMP evidence pack, AGFORWARD project and searched the reference lists of previous syntheses on related topics.

Table 1 is a summary of the results from the review. Annex 1 provides a similar table with text describing the relationships. Annex 2 summarises the strength of evidence for each FAB option, weak (evidence only from a few studies or contextually limited e.g. geographically), intermediate (some evidence but not fully conclusive, contested, some contextual limitations), strong (large number of studies across range of contexts).
Annex 3 proposes potential interactions between options.

Table 1. Selected FAB solutions and their contribution to ecosystem service provision and farm management

FAB solutions	**Fertiliser**	**Pesticide**	**Pollination**	**Biodiversity**	**Soil quality & conservation**	**Soil organic carbon**	**GHG emissions**	**Water quality**	**Water conservation**	**Yield**	**other Costs (e.g. equipment)**
1. Reduced tillage techniques	↑	↑ ↓		↑ soil fauna	↑	↑ ↓	↓GHG↑ N_2O	↓	↑ moisture conservation	↓ short-term, (↑) long-term	↑ equipment cost & labour
2a. Mixed crops/crop rotations	↓	↓		↑	↑			↑			
2b. Sward diversity	↓ esp. with legumes	↓	↑	↑	↑ soil structure	↑	↓ GHG (C sequestration) ↑N_2O	↑	↑ drought resistance ↓ Flooding	↑ ↓	↑
3. Cover / catchcrops (incl legumes)	↓	↓		↑	↑	↑ mixed effects from legumes	↓ short-term, ↑ long-term	↑	↑ ↓ Cover crops require water but mulch retains moisture	↓ in high N soils, ↑ in low N soils	↑ seed and machinery costs
4. Organic matter input (plant residuals, wood chips, biochar,…)	↓	(↓) with biochar		↓ soil microbial community	↑ with plant residual return ↓ pollutants/ heavy metals could increase	↑	↓ with biochar but sometimes ↑	↓		↑	↑ transport cost
5. Modify manure quality and diversity (fresh manure, limit use of fertilizer)	↓			↑ soil microbial diversity	↑	↑	↓ GHG (less production inorganic fertilisers)↑ N_2O emissions	(↓) in the longer-term	↑	↑ or ↓ dependent on organic matter return	↑ transport and equipment cost & costs for manure treatments

FAB solutions	Fertiliser	Pesticide	Pollination	Biodiversity	Soil quality & conservation	Soil organic carbon	GHG emissions	Water quality	Water conservation	Yield	other Costs (e.g. equipment)
6. Agroforestry	↓	↑ ↓	↑	↑	↑quality, less erosion	↑ ↓	↑ ↓	↑	↓flooding, ↑ conservation for crops	↑ ↓	↑
7. Hedgerow management		↑ ↓	↑	↑	↑quality, less erosion	↑	↓	↑	↓flooding, ↑↓conservation for crops	↑ ↓	↑
8. Field margin management		↓	↑	↑		↑		↑	↑		
9. Reduction in the use of plant protection products		↓	↑	↑			↓(?)	↑		↓ (no PPPs), possibly no change with reductions in PPPs	
10. Semi-natural landscape elements (provide habitat)	↓	↑ ↓	↑	↑	↑quality, less erosion	↑ ↓	↑ ↓	↑	↓flooding, ↑ conservation for crops	↑ ↓	↑

2.3 MEASUREMENTS AND INDICATORS FOR FAB INTERVENTIONS

2.3.1. (1) Reduced tillage techniques (reduced soil disturbance and compaction)

Definition

Conventional tillage uses a moldboard plow and multiple trips across the field with other tillage tools (e.g. disks and field cultivators) to invert the soil. Reduced tillage (RT) replaces the moldboard plow with a lighter tillage implement like a chisel plow which disturbs less of the surface crop residue and often single passes with a disk and/or field cultivator. In Germany roto-tillers and other implements that limit soil disturbance to shallow depths are being used and there are different reduced tillage options e.g. reduction of mold plow tillage in rotation, reduction in tillage depth whilst maintaining inversion tillage and non-inversion tillage at shallow soil depths (Zikeli and Gruber 2017). In no-till (NT) a self-contained planting unit is used to plant the crop in a single pass with no seedbed preparation (Harper et al. 2018) and may be referred to as direct drilling or seeding (Vincent-Caboud et al. 2017). It requires leaving at least 30% of surface area covered by plant residues immediately after crop establishment, and crops are sown using machinery capable of placing seeds through plant residues from preceding crops (Heroldova et al. 2018).

Causality

Yield

No-till on its own reduces yields, yet this response is variable. When NT is combined with residue retention (cover crops) and crop rotation, its negative impacts are minimized particularly in rainfed dry climates, so may be an important climate-change adaptation strategy for ever-drier regions of the world (Pittelkow et al. 2015). In their review Pittelkow et al. (2015) could not determine whether initial yield reductions are caused by biophysical conditions (for example, soil structure, decomposition of residues on the soil surface) or sub-optimal management. Yield declines with NT in humid environments may be primarily caused by factors unrelated to these principles.

Biodiversity

No-till increases the ecological sustainability of agroecosystems by maintaining high populations of soil-ameliorating fauna and insect pest predators. This may increase the small mammal density and diversity, including those of insectivores, as has previously been confirmed in set-aside fields (Heroldova et al. 2018)

Pest & weed control

Although RT may increase beneficial pest predators and so control arthropod pests (Schipanskia et al. 2017, Heroldova et al. 2018), the lack of soil inversion usually increases weed infestations and changes the composition and functional attributes of the weed community (Carmona et al. 2015, Armengot et al. 2016, Weber et al. 2017). Although this does not always impact yield (Armengot et al. 2016) there may be a need for increased herbicide use which can lead to herbicide resistance (Harper at al. 2018). The NT management system may also intensify crop infestation by the common vole (Heroldova et al. 2018). Using crop rotations and cover crops with RT can help to control weeds (Weber et al. 2017, Carr 2017, Creamer et al. 2002)

Soil quality and conservation

Increased SOC in the topsoil changes the soil structure, enhances soil quality and reduces soil erosion but this change does not necessarily link to increased yields. Min-till may have other beneficial effects including reduced energy usage, soil structure improvement, better aggregation and improved water infiltration.

Carbon (C) sequestration and greenhouse gas (GHG) emission reduction

Tillage of soil is a major driver of reduction in soil organic carbon (SOC) on agricultural land, so NT management has been recommended for C sequestration (Lal 2004). Physical disturbance during tillage disaggregates and aerates the soil, accelerating SOC decomposition (Mikha and Rice 2014), and RT is thought to prevent this.

The effects of NT and RT management on SOC have been scrutinised in recent years. After considering bulk density and SOC distribution with depth, the evidence for SOC increases in NT systems is reduced (Angers and Eriksen-Hamel 2008, Baker et al. 2007). Specifically, RT was shown to lead to changes in the distribution of C with depth (Angers and Eriksen-Hamel, 2008, Luoet al. 2010, Dimassi et al. 2014). For the above reasons a review to inform the LULUCF inventory concluded that RT is not a reliable option to increase the SOC of UK soils (Buckingham et al. 2013) or globally (Luo et al. 2010).

In fact, if tillage increases the distribution of SOC with depth, there may be positive effects in terms of reduced C decomposition. Deeper mineral soil horizons tend to contain less C (Jobbagy and Jackson 2000). Furthermore, organic matter that is incorporated to deeper parts of the soil may be degraded more slowly, or readily adsorbed onto fine mineral particles which may be less saturated than at the surface (Buckingham et al. 2013). For this reason deep ploughing to bury SOC-rich topsoil has been considered as an SOC storage intervention, while vertical redistribution of C by anecic earthworms is also of interest (Chenu et al. 2019).

The positive effects of NT management on SOC may have been overstated (Powlson et al. 2014), and factors other than tillage greatly affect C declines on arable land – e.g. conversion to annual crops, periods of bare soil and drainage (Baker et al. 2007), and number of crops and cropping cycle (Luo et al. 2010). Regardless, there is considerable uncertainty about the effects of RT for SOC. Snyder et al. (2009) suggest that SOC increases may only occur if crop productivity can be maintained or increased. The effects of conservation tillage are also dependent on soil type and temperature (Luo et al. 2010).

Water quality and conservation

Van den Putte et al. (2010) reported that under European conditions the moisture conservation of NT was most important under drier clay and sandy soils.

The higher herbicide use in RT increases the risk of groundwater contamination, if leaching occurs, and of adverse effects on human health (Carmona et al. 2015, Alleto et al. 2010; Gasnier et al. 2009).

Co-benefits and trade-offs

Co-benefits of RT include reduced costs and GHG emissions associated with fuel consumption (Buckingham et al. 2013, Govaerts et al. 2009). Buckingham et al. (2013) report variable effects of NT management on crop production, but there may be positive effects on soil moisture (Freibauer et al. 2004) and soil structure (Powlson et al. 2014).

Trade-offs include a risk of increased N_2O emissions in poorly aerated soils, often found in NW Europe, which is concerning due to the increased global warming potential of N_2O (Freibauer et al. 2004, Rochette 2008); the mitigation potential of RT could be reduced by 50-60% after consideration of increased N_2O emissions (Freibauer et al. 2004). Increased herbicide usage may be required under RT, which may be expensive and can have negative environmental consequences such as herbicide resistant species and run off of herbicide into water courses (Buckingham et al., 2013, Powlson et al. 2014, Carmona et al. 2015). There are also possibilities of crop failure in RT systems (Freibauer et al. 2004).

Option interactions

Conservation tillage is often associated with cover cropping (Chenu et al. 2019) and crop rotation which have been shown to increase SOC (Bai et al. 2019) and could help to increase beneficial arthropods, improve soil quality and control pests (Schipanski et al. 2017, van der Putte et al. 2010). Combining the NT approach with crop rotation and residual input is likely to offset negative effects of NT practice on yields in dry climates probably because of improved water infiltration and greater soil moisture conservation but may not increase yields in humid climates (Pittelkow et al. 2015).

Magnitude

A review to inform LULUCF inventories suggested changes of -2.2 to 8.1 t C ha^{-1} when moving to from conventional tillage to RT (Buckingham et al. 2013). A recent review in the UK suggested increases of -0.23 to 1.37 t C ha^{-1} y^{-1}, but studies considered only soil sampled to 30 cm depth, assuming consistent bulk density (Powlson et al., 2012). Freibauer et al. (2004) reported a range of 0.3 to 0.4 t C ha^{-1} yr^{-1} for NT or RT managements in Europe. Globally, Powlson et al. (2014) estimated a potential additional C sequestration and

climate mitigation potential of 0.4 to 0.6 Gt CO_2e yr^{-1} for NT compared to conventional systems. The variability in observed C sequestration rates arises from differences in amounts of crop C returned to the soil, which depends on yields under till and NT management, but is also independent on texture and climate (Virto et al. 2012, Dimassi et al. 2014).
A potential increase in SOC sequestration after conversion from conventional to NT practice is not infinite (Powlson et al. 2014) and non-monotonic (Dimassi et al. 2014). Potential positive or negative effects of NT or RT depends on the baseline SOC stock. For example a high C-rich soil is more likely to lose more C than a C-poor soil (Govaerts et al. 2009).

Timescale

Powlson et al. (2012) report mixed to positive effects of NT on SOC (to 30 cm depth) within 5-23 years. A meta-analysis showed that the benefits of NT compared to conventional tillage in reducing the global warming potential is only evident in the long-term (> 10 years) (Six et al. 2004).

Spatial issues

Trade-offs include a risk of increased N_2O emissions in poorly aerated soils, often found in NW Europe (Rochette 2008).

Displacement

If RT corresponds to a reduction in yield, it could be argued that more intensive farming is required elsewhere to meet demands for food.

Longevity

If RT or NT soils are ploughed occasionally for e.g. pest and weed control, the potentially sequestered C in the topsoil will be partly or completely lost (Powlson et al. 2014).

Climate interactions

A recent meta-analysis highlighted that conservation tillage increases SOC by ~5%, with more positive effects of NT management in regions characterised by warm climates (Bai et al. 2019).

Social and economic barriers

A change from conventional to RT or NT requires different farm equipment and infrastructure, which will be particularly challenging for small farm holders. A change from conventional to RT may not increase farm income in the short-term, representing a problem especially for small farm holders (Powlson et al. 2014).

Metrics and verification

Yield

There are questions about the impact of RT on yield; thus a measurement of yield would be desirable.

Biodiversity

It is believed that soil invertebrate abundance and diversity increase with RT; thus this should be tested (pitfall traps, soil samples).

Pest & Disease control

Lack of soil inversion tends to increase weed abundance and composition although this can be managed if other options such as cover crops are included. Weed distribution and abundance should be measured. Heroldova et al. (2018) describe the measurement of vole density based on counts of active burrow entrances showing evidence of habitation according to the presence of food, fresh faeces around a tunnel entrance, vegetation eaten around the hole, burrowing activity and a smooth tunnel opening).

Soil quality and conservation

RT may improve soil quality and structure and this should be tested.

Carbon (C) and Greenhouse Gas emissions (GHG)

RT is intended to increase SOC but the evidence is mixed and there is considerable uncertainty about the results. This should be measured (g or t C yr^{-1}) both in the plough layer and below the plough layer (= C content and bulk density).

The risk of increased N_2O emissions in poorly aerated soils makes it desirable to measure.

Water quality
RT may affect water quality through increased inputs of herbicides to control weeds no longer managed mechanically; thus water quality should be measured, however, it should be noted that it can be difficult to link water quality results to field or farm level management practices.

Water conservation/ flooding
Water infiltration may be improved through improvements in soil structure, NT may also influence water conservation particularly in certain soil types. Field experimentation e.g. soil moisture, soil infiltration and catchment modelling should be undertaken.

2.3.2. (2) Mixed crops/crop rotations and sward diversity

(2.a) Mixed crops/crop rotations

Definition
This FAB intervention focuses on overcoming agricultural monoculture systems and includes the use of multiple crop species/varieties in a rotation, integration of short-term grass or other non-woody perennial leys into previously arable-only rotations, and alternating spring and winter crops to manage weeds (particularly used in no-till systems). A range of crop types is used to promote soil health by improving the diversity of root architecture and reduce disease/pest burdens (Defra 2018).

Causality
Yield
Crop rotation is used in association with reduced till and cover crops, and negative effects on yield often resulting in no-till systems can be reduced (Pittelkow 2015). More diverse crop rotations can mitigate the impacts of failing/poor performing crops and improve yield stability (Defra 2018).

Biodiversity
More diverse crop rotations can increase soil microbial richness and diversity (Venter et al. 2016), possibly by different organic matter inputs and changes in soil structure. Aboveground biodiversity can be enhanced by the crop species selected, which provide a range of habitats (Defra 2018).

Pollination
Differences in flowering times can attract a wider variety of pollinators (Defra 2018).

Pest & weed control
Crop rotations can disrupt pest and disease cycles (Smith et al. 2008b), potentially reducing the need for pesticide application. More diverse crop rotations can have lower weed densities (Schipanski et al. 2017, Cardina et al. 2009), particularly if legumes are incorporated into the rotations. Perennial forages were more effective than annual crops at suppressing annual weeds in the following crop and can shift the composition of weed communities over time (Schipanskia 2017, Entz et al. 2002). Perennial forages may also reduce the weed seedbank due to increased weed seed predation (Meiss et al. 2010). Crop rotations can be used against herbicide resistant weeds and can break the life-cycle of host specific pests and pathogens (Marcroft et al. 2004). Beneficial insect species also respond to previous cash or winter cover crops (Lundgren and Fergen 2010).

Soil conservation
Crop rotations can have a strong beneficial effect on soil quality (Schipanski et al. 2017, Defra 2018). In a case study crop rotations increased soil microbial biomass by 21% compared with monoculture (McDaniel et al.

2014). Including legumes in a crop rotation can improve long-term soil fertility and reduce fertiliser costs. Integrating perennial crops into the rotation, which typically have larger root systems than annuals, can also contribute to soil quality improvements by alleviating soil compaction, reducing soil erosion and helping drainage (Zan et al. 2001, Lynch and Wosciechowski 2015). Using crops with different root architecture and rooting depth allows access to immobile macro and micro nutrients in different parts of the soil profile and there is a potential reduction in nitrogen fertiliser use when introducing alternative species (Defra r2018).

Water quality

Potentially there may be a reduction in nitrate leaching from the soil, resulting from the varying ability of crops to reduce the pool size of nitrate and remove nitrate from different places in the soil profile, resulting from their different rooting depths and densities. Design of the rotation is a key factor in trying to match crop uptake with available N (Defra 2018).

Option interactions

Crop rotation is often used with conservation tillage and cover cropping (Chenu et al. 2019). It can be used to counter negative effects from reduced tillage such as increases in pest species and negative impacts on soil organic C stocks (Schipanski et al. 2017, van der Putte et al. 2010).

Social and economic barriers

Introducing new crops requires suitable machinery for sowing and harvest. There can also be knowledge gaps, resulting in the yield of a new crop being lower when grown for the first time (Defra 2018).

Metrics and verification

Yield

Crop rotation can positively influence yield and it would be good to measure this.

Biodiversity

Diverse crop rotations can increase soil microbial richness and diversity; thus there should be soil sampling and analysis of soil microbial communities of some sort.

Crop rotations may also influence soil invertebrate communities which has an impact on birds; thus methods for sampling invertebrates and birds should be included. Vegetation communities are also likely to vary by crop type so recording diversity and abundance of plant species in representable vegetation quadrats would be recommended.

Pollination

Pollinators should be influenced by different crop types; thus it would be useful to record presence and abundance of pollinators. This could be done using pollinator transects (Carvell et al. 2015), sweep nets and pit fall traps.

Pest & Disease control

Diverse crop rotations are thought to have beneficial effects on pest and weed abundance; thus this should be measured. The density and biomass of weeds in crops can be assessed in plots and transects along the field edge. The use of photographs might be useful. The abundance of beneficial insect predators and insect pests can be measured using pitfalls, soil cores, sweep netting/transects or pan traps.

Soil quality and conservation

Crop rotations can have a strong beneficial effect on soil quality particularly fertility so soil chemistry/nutrients (C, N, P, K, Ca, Mg, Na, pH) should be measured along with soil structure; soil aggregate stability, soil compaction, and soil erosion.

Water quality

It would be expected that a diverse crop rotation would improve water quality by decreasing nitrate leaching; water quality should be monitored although it Is difficult to attribute changes on individual farms or fields to changes in water quality. It may be better to focus on the level of pollutants in the soil which can be easily measured by each individual farmer.

2.3.1. (2.2b) Sward diversity

Definition

Increasing plant species diversity through the addition of grass, forb and legume species. This is normally carried out through field operations such as reseeding, oversowing or slot seeding but may also include introduction of plug plants or feeding animals with high quality hay containing seeds (from nearby sites). To maintain sward diversity it may also be necessary to reduce soil fertility which can be done by soil stripping or appropriate grazing or cutting management (Bullock et al. 2011). Diverse swards are likely to introduce N-fixing and deeper rooting species enabling reduction in manufactured N fertiliser use at the same level of production, and improved nutrient use efficiency (Meyer et al. 2018).

Causality

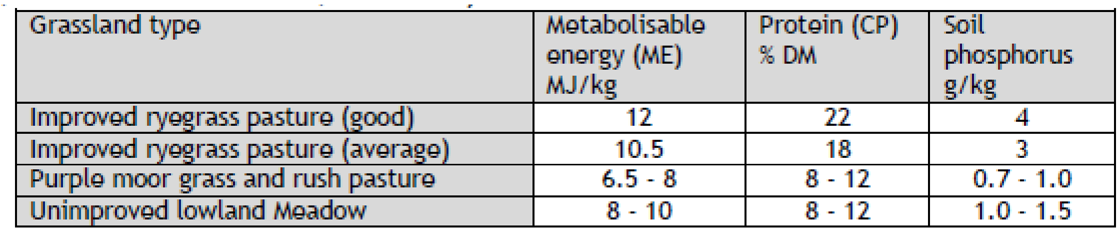
The evidence comes from mixed sources, some is for species rich leys where a few additional species have been added to an improved grassland, other is for less fertile, semi-natural species rich swards under different management conditions. There are likely to be different implications in implementing this FAB solution depending upon which type of grassland is already present.

Yield (Productivity and nutritional quality)

There is evidence that plant species diversity can be positively related to productivity. Newell-Price et al. (2019) cite evidence from the Jena experiment (Weisser et al. 2017) where the effect of plant species diversity on productivity at different levels of N addition was investigated. Grassland productivity increased with plant species richness, and the effects of diversity on productivity (average difference between monocultures and 16-species mixtures: 4.5 t ha^{-1} yr^{-1}) were stronger than the effect of manufactured N fertiliser (average difference between 0 and 200 kg N/ha: 3.2 t ha^{-1} yr^{-1}) (Weigelt et al. 2009). Other studies have also shown an enhanced yield with increased plant diversity in low to moderate input/output systems (Döring et al. 2012, Finn et al. 2013, Hector et al. 1999, Suter et al. 2015). This may be because more species lead to a greater efficiency in using energy and other resources and/or because a species-rich community is more likely to contain species which are highly productive (Bullock et al. 2011).

However, in a study using the dry matter yield of cut hay as a productivity measure, hay from species-rich grassland is between 2-8 t ha^{-1}, which is less than 30% of the dry matter that can be gathered from silage taken from agriculturally improved grasslands (Tallowin and Jefferson 1999, Bullock et al. 2011), although adding inorganic N fertiliser increases the output. There is a gradient from unimproved species rich grassland to agriculturally improved grassland and there is a trade off in productivity at a certain level of improvement and species richness.

It is not just the yield of the grassland that matters, but also the quality of the sward. The digestibility of the organic matter in the hay is a common measure of quality, Tallowin and Jefferson (1999) found that digestibility of forage cut from Lowland semi-natural grassland is about 20% below that of agriculturally improved grassland. Shellswell (2017) concludes that the metabolisable energy (ME) and crude protein (CP) of most species-rich grasslands is not equivalent to that of agriculturally improved grasslands citing figures from a number of sources (Table 1).



Grassland type	Metabolisable energy (ME) MJ/kg	Protein (CP) % DM	Soil phosphorus g/kg
Improved ryegrass pasture (good)	12	22	4
Improved ryegrass pasture (average)	10.5	18	3
Purple moor grass and rush pasture	6.5 - 8	8 - 12	0.7 - 1.0
Unimproved lowland Meadow	8 - 10	8 - 12	1.0 - 1.5

Table 1: Typical figures for the forage quality of different types of grassland (Scottish Natural heritage 2016, Tallowin and Jefferson 1999, Fisher 2013). Table taken from Shellswell (2017).

However, the herbal component of a grassland has been found to have more protein than the grass component, particularly legumes. A study of dairy cows grazing mixed species leys (containing perennial rye-grass *Lolium perenne*, white and red clover *Trifolium repens* and *T. pratense*, chicory *Cichorium intybus* and tall fescue *Festuca arundinacea*) were found to have increased milk production, milk solids and a higher dry matter intake per day compared with heifers grazing perennial rye-grass and clover leys (Roca-Fernández et al. 2016).

The breed of livestock is important and traditional breeds may be better adapted to less productive species rich grassland than faster growing commercial breeds. The season and livestock requirements are also important, in the spring and early summer species-rich grassland are most palatable and can provide the nutritional requirements for dry cows and ewes, but may not be good enough for finishing beef or lactating animals. Overall though stocking density will need to be lower in species rich grassland (Shellswell 2017).

The herbal component of a grassland/ ley has higher quantities of minerals/macronutrients than grass and legume sward components (Lindstrom et al. 2012, Pirhofer-Waltz et al. 2011, García-Ciudad et al. 1997). The use of species-rich grasslands within an agricultural system may reduce the need for mineral licks to maintain healthy livestock (Shellswell 2011). Soils are important in influencing the availability of nutrients in fodder although deep rooted plants are thought to be able to draw-up nutrients where they are unavailable in the topsoil. Herbaceous species (e.g. Chickweed- *Stellaria media*, *Dandelion-taraxacum officinale* agg., ribwort plantain-*Plantago lanceolata*, Yarrow-*Achillea millefolium*) have been found to contain higher quantities of the macronutrients phosphorous, magnesium, potassium and sulphur, and micronutrients zinc and boron than grasses and *Lolium perenne* in particular (Wilman and Derrick 2009, Pirhofer-Waltz et al. 2011). Grazing behaviour will influence the choice of species to consume in a species rich grassland, experience, learned behaviour from parents, age, and livestock type will all influence the choice of sward species and the impact that they have on physiology (Provenza et al. 2015).

Species rich grasslands may provide opportunities for livestock to use certain plant species that contain compounds to help prevent or reduce illness. For example, tannins present in bird's-foot-trefoil and sainfoin can alleviate bloat (although Newell-Price et al. (2019) suggest legumes can cause bloat), improve protein use, enhance immune response, increase reproductive efficiency, reduce methane and reduce intestinal parasites (Woodward et al. 2004), however this does all require further testing (Shellswell, 2017). Lambs grazing chicory *Cichorium intybus* or common bird's foot trefoil (Deane et al. 2002), were found to have lower mean nematode faecal egg counts suggesting that the active compounds in these plants could reduce endo-parasite burden (Marley et al. 2006). Ribwort plantain- Plantago lanceolata has been found to reduce endoparasites (Judson and Moorehead 2011). Yarrow *Achillea millefolium* contains two alkaloids, achillein and moschatin, that have medicinal qualities (Foster 1988).
More research on the mineral and medicinal properties of individual sward species and communities in different geographical locations on different soils, throughout the growing season and in relation to livestock consumption patterns is required.

Biodiversity
Successful diversification of grassland swards will increase plant species diversity and have implications for other above-ground and below-ground species including nectar plants and pollinators (Newell-Price et al. 2019, Scherber et al. 2010). There should be increases in the richness of associated soil- and foliage-dwelling species such as moths, spiders and beetles but there could be decreases in the abundance of species directly associated with the previously dominant plant species. Alison et al. (2017) demonstrated that created grasslands with a higher diversity of chalk grassland wildflowers, including key legumes such as *Lotus corniculatus*, supported a higher abundance of chalk grassland moths. Woodcock et al. (2013) showed that the introduction of simple seed mixtures into agriculturally improved grasslands could help support increased diversity of spiders and beetles; and while seed mixtures did not necessarily need to be of the highest diversity to achieve these benefits, the inclusion of legumes did appear to be crucial.
By contrast, Defra project BD5001 found that the introduction of deep-rooting herbs and legumes had no effect on earthworm biomass, earthworm numbers (Lees et al. 2016) or the foraging success/behaviour of starlings (*Sturnus vulgaris*). Weisser et al. (2017) also found that positive responses between plant diversity

and biodiversity were stronger in above ground taxa rather than below ground. Sward diversity is one factor that may influence the ability of habitats to support particular species, but there are many other habitat and non-habitat factors that will determine the success or failure of high biodiversity conservation projects (Newell-Price et al. 2019). For many species, the management and associated structure of grassland could be as important as plant species composition for high biodiversity goals. This particularly applies to vertebrate and soil-dwelling species, for which access to the soil surface and/or physical cover from vegetation (e.g. for nesting and protection from predators) are critical for the maximum resource benefits to be derived from swards. For example, grassland sward structure and management is a critical factor in providing suitable habitats for some bird species (e.g. Atkinson et al. 2005).

Diversification of sward structure can be achieved by changing grazing regimes or mowing, or creating fine-scale topography.

Pollination

Greater plant species diversity in grasslands could support and potentially increase the pollination role of grasslands (Defra 2018), although this will depend on grassland management, in particular whether plants are able to flower. A range of evidence shows that the greater the extent of low-intensity management and the closer such patches exist to a crop, the higher the numbers of pollinating insects in the vicinity (Whittingham 2014).

Pest & weed control

Mixing species with different properties gives higher density of crop cover and better weed control, reducing reliance on inputs (Defra 2018).

Soil quality & conservation

A more diverse sward may reduce soil compaction. A study that sowed both legumes and forbs was shown to reduce the force needed to penetrate soils (Carvell et al. 2007). As legumes and forbs are deeper rooted than grass species, they reduce soil compaction preventing runoff and associated nutrient loss to water bodies. Diverse swards can promote improved soil organic matter and soil fertility (Zaralis et al.2016), and improve bulk density and water infiltration rates (Doring et al. 2012b).

Carbon sequestration and greenhouse gas (GHG) emissions

Diverse swards could increase C sequestration in grasslands through increasing yields, introducing deeper rooting plant species (Dignac et al. 2017; Garcia-Pausas et al. 2008), deepening the topsoil layer and moving organic matter into the subsoil through biological pedoturbation (Newell-Price et al. 2019). There is evidence that increasing yields can increase soil organic C (e.g. Johnston et al. 2009). Therefore, if increasing sward diversity can result in increased productivity without an increase in N fertiliser use, then genuine C sequestration is achievable. Increases in soil organic C content with plant species richness increases have been found (Weisser et al. 2017, Fornara and Tilman 2008, Hungate et al. 2017). However, it is highly likely that soil C stocks in grasslands cannot increase indefinitely. Based on evidence from repeated soil surveys, long-term grassland experiments and simple mass balance calculations, Smith (2014) concluded that “it is untenable that grasslands act as a perpetual carbon sink, and the most likely explanation for observed grassland carbon sinks over short periods is legacy effects of land use and land management prior to the beginning of flux measurement periods”.

Where the addition of legumes to swards is effective in reducing N fertiliser use and in optimal soil and agro-climatic conditions, direct and indirect N_2O emissions could be reduced. However, where legumes are added to swards that did not previously receive N fertiliser, the additional fixed N can result in a net emission of N_2O, particularly on poorly draining waterlogged soils, or soils in wet regions (Garnett et al. 2017; Henderson et al. 2015).

Henderson et al. (2015) also note that the increases in grassland yields that arises from the addition of legumes enables higher ruminant numbers to be supported. As a result, methane emissions would also increase. However, enhanced livestock performance (i.e. higher growth rates and reduced finishing times) would result in reduced methane emissions per livestock unit relative to the baseline (Smith et al. 2014), i.e. “more GHG-efficient livestock production”. It is also important to take into account the effect of deep-rooting herb species in a diverse sward. If roots can penetrate deeper into the topsoil and upper subsoil, the C from the dead roots could be less prone to release due to lower decomposition rates deeper in the soil profile (Garnett et al. 2017).

Water quality and conservation

Reductions in manufactured fertiliser use from the introduction of legumes in diverse swards have the potential to reduce nitrate leaching losses by up to 20% at the field scale; and direct and indirect N_2O emissions by up to 50% (Cuttle and Scholefield 1995). However, this does depend on how this FAB solution is integrated with other FAB solutions, e.g. in a short-term herbal ley, N may be mineralised in preparation for arable cropping. It has also been suggested that a complex sward with high functional diversity may reduce the leaching of inorganic N (Scherer-Lorenzen et al. 2003; Phoenix et al. 2008). Deep-rooting species such as chicory can reduce nitrate leaching (Defra 2019).

Increasing sward diversity could potentially improve soil structure, impart greater resistance to soil compaction and increase water infiltration rates (Newell-Price et al. 2019), thereby lessening the risk of flooding. There is evidence of increased water infiltration rates with increasing plant species richness (Weisser et al. 2017), and resulting increased water-use efficiency. The establishment of deep-rooting herbs and legumes, and the resultant flood risk mitigation may be more effective 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 would result in greater runoff and flooding 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. Ultimately, the flooding risk associated with grass, grass/clover and diverse swards may be more closely related to how the sward is managed (e.g. stocking rates and amount of heavy machinery when soils are “wet”) than the nature of the sward itself (Defra project BD5001).

Co-benefits and trade-offs

The diversification of swards should be beneficial for a number of ecosystem services as seen in the above section. Higher sward diversity could improve soil quality, soil organic C and soil structure increasing C sequestration, increasing infiltration and reducing flood risk. Increases in cover of legumes and development of a more complex diverse sward should lead to reductions in N input, reducing costs and improving water quality. Increasing home-grown forage production (yield) also has the potential to reduce GHG emissions associated with feed purchased from elsewhere, leading to overall reductions in GHG emissions (Dickie et al. 2015).

Trade-offs could include a reduction in yield although there may also be increases with increased plant species richness, there could also be benefits from improvements in nutritional quality. Options for weed control from establishing and maintaining a higher sward diversity may be more limited (Newell-Price et al. 2019). It can be more difficult to maintain plant species richness within a grazing rather than a cutting system, although a combination of cutting and grazing can be optimal for managing multi-species swards at the field level and increasing diversity at the regional level (Natural England 2010a; Sebastià et al. 2011). Legumes can be difficult to store as silage or hay.

Magnitude

Biodiversity

Newell-Price et al. (2019) state that “for biodiversity, there are too many potential response variables to have meaningful measures of "magnitude of effect"”.

Carbon sequestration and greenhouse gas (GHG) emissions

The grasslands at nine European sites acted as a sink for C, with a measured flux of-2.4 ± 0.7 t C ha^{-1} yr^{-1} (Soussana et al. 2007). Diverse swards could, therefore, potentially increase this rate, in proportion to their ability to increase productivity, increase rooting depth or increase topsoil depth (Newell-Price et al. 2019). Smith *et al*. (2008) reported potential C sequestration rates of 0.22 t C ha^{-1} yr^{-1} in the cool-moist (temperate) bio-climatic region as a result of improved grassland management. The use of diverse swards may, be able to increase C sequestration close to rates measured by Soussana et al. (2007), particularly when moving from poor to optimal management or on previously degraded soils, but as mentioned above, it is unlikely to be possible to sequester C at these rates in the longer-term.

As also mentioned N_2O emissions can be an unwanted consequence of adding legumes to a sward. At a global scale, Henderson et al. (2015) estimated that on only 10% of the grazing land did C sequestration from legume addition exceed their effect on N_2O emissions. Legumes sown on these 'favourable', soils could sequester C at a rate of about 0.5 t C ha^{-1} yr^{-1}.

Henderson et al. (2015) also note that the increases in grassland productivity from the addition of legumes also enables higher ruminant numbers and hence methane emissions would also increase and would offset 26% of the global net soil C sequestration potential of legume sowing.

Water quality and conservation

The use of legumes has been estimated to reduce nitrate leaching losses by up to 20% where N inputs in manufactured fertiliser and organic manures are reduced to account for N fixed from the atmosphere (Newell-Price et al. 2011).

Timescale

Biodiversity

Timescales depend on scale and the response variable chosen. Measures of local animal abundance/activity/habitat use are likely to respond almost as quickly as the vegetation, but population-level responses will be slower and could take several years.

Plant species diversity should be improved in the year of implementation (if successful), with associated improvements at higher trophic levels taking longer, particularly where the introduction of diverse swards needs to be aligned with other changes in management as well as other changes at the landscape scale (5-10 years or >10 years).

Carbon sequestration and greenhouse gas (GHG) emissions

Detectable changes in soil C stocks is > 10 years.

GHG emission reduction through the introduction of legumes, where applicable, could occur in the first year of implementation particularly where legumes are substituting the use of manufactured N fertiliser.

Water quality and conservation

Reductions in nitrate leaching losses could occur in the winter following successful establishment of a diverse sward.

Reductions in flood risk could occur once deep-rooting herbs have become well established and soil structure has improved probably between 0 to 5 years.

Spatial issues

Biodiversity

Impacts of sward diversity on biodiversity can operate at the sub-field, field, farm or landscape level, depending on the species affected. Connectivity of smaller diverse patches can be critical in producing a larger effect on species richness and/or abundance.

Carbon sequestration and greenhouse gas (GHG) emissions

The introductions of diverse swards should be targeted on better drained soils where improvements in productivity are likely to be greater and nitrous oxide emissions lower.

Water quality

The improvements in water quality due to reduced nitrate leaching losses should be broad-scale in nature. Reduced flooding risk is most likely in catchments dominated by grassland and where soils have been in moderate to poor condition in the past. However, the introduction of diverse swards would need to be associated with changes in grassland management such as stocking rates and the timing of grazing, e.g. avoiding grazing at high stocking rates when soils are "wet".

Displacement

A reduction in yield from species rich grasslands could result in lower stocking densities in some areas, with displacement of higher stocking densities elsewhere to compensate (Bullock et al. 2011).

Longevity

A diverse sward can be short-lived, particularly if it is a seeded herbal ley that is returned to arable. To maintain sward diversity, regular management is required e.g. cutting, grazing and seeding.

Climate interactions

The potential for sequestration of C and mitigation of GHG emissions is discussed above, with some benefits from reduced nitrogen addition from adding legumes to a sward but potential release of N_2O. Theoretically a diverse sward should be more resilient and more able to adapt to changing climatic conditions.

Social and economic barriers

There will be costs associated with seeds and establishment of a species rich swards and their maintenance, and possibly reduced productivity and livestock densities.

Interactions between options

Unlike some of the options, sward diversity does not depend on interactions between FAB measures to enable it to be viable. Increased plant species richness will benefit pollinators as does more semi-natural land, wildflower margins and agroforestry/hedgerows so these would all be complementary. A species rich sward is an FAB measure that is used in association with reduced tillage, a perennial ley can be used for weed suppression (Zikeli and Gruber 2017) and biodiversity benefits (see other sections on interactions).

Metrics and verification

Biodiversity

Diversification of the sward should increase above and belowground biodiversity and this should be measured within fields and also in adjacent land to understand the effects. Plant species diversity should increase and can be monitored using quadrats (Halbritter et al. 2019). The sward structure: height, management and fine-scaled topography should also be measured as this will impact upon other species. Invertebrates should benefit from increases in sward diversity and these can be measured using similar methods to pollinators. It has been suggested that earthworms would not necessarily increase with sward diversity and it would be useful to measure earthworms and other soil invertebrates (Halbritter et al. 2019). Invertebrate abundance and diversity will also influence bird species abundance and diversity and this should be measured using standardised repeatable methods.

Pollination

Nectar plants should increase in abundance and diversity within fields and the floral density of nectar plants should be measured alongside monitoring of the abundance and diversity of pollinators such as pollinator transects (Carvell et al. 2015), sweep nets and pit fall traps. This should be within fields and in areas surrounding the fields to understand the spatial extent of the effect.

Soil quality and conservation

Increases in legumes could increase soil nutrient status and this should be measured. There should be an improvement in soil structure, so soil compaction and soil erosion should be measured.

C sequestration and Greenhouse Gas (GHG) emissions

Diverse swards may sequester C, particularly when moving from poor to optimal management or on previously degraded soils, but it may not be possible to sequester C at these rates in the longer term so measurements of soil organic C should be taken over an extended time period e.g. in 5 year intervals. Deeper rooted plant species and increases in net primary productivity may increase soil organic matter and move it at depth, so SOC should be measured in top soil and subsoil (Ward et al. 2016).

Where the addition of legumes is effective in reducing manufactured N fertiliser use and in optimal soil and agro-climatic conditions, direct and indirect N_20 emissions could be reduced. However, where legumes are added to swards that did not previously receive manufactured N fertiliser, the additional fixed N can result in a net emission of nitrous oxide so if possible N_2O emissions should be measured.

Water quality

Increases in legumes should lead to a reduction in nitrate leaching, this should be verified through testing of water quality. However, as mentioned, it Is difficult to attribute changes on individual farms or fields to changes in water quality. It may be better to focus on the level of pollutants in the soil which can be easily measured by each individual farmer.

Water conservation/ flooding

Deeper rooting herbs should improve infiltration and it would be useful to measure soil moisture, soil infiltration and incorporate these into catchment modelling.

Yield

There is mixed evidence on the relationship between sward diversity, productivity and yield, further evidence is required. It can be measured as dry matter yield of cut hay.

Evidence also shows potential for improvements in sward quality with diversity, for instance, digestibility, metabolisable energy and crude protein, mineral content, micro and macro nutrients. Some of the plant species in a diverse sward may have medicinal properties and some measure of health/disease in livestock would be useful.

2.3.3 (3) Cover / catch-crops (including legumes)

Definition

Cover crops are fast maturing crops grown within a rotation (after harvest) to maintain soil cover during fallow periods (Defra report 2018), and are typically ploughed under as green manure, or killed with herbicides under no-till systems. Cover crops sequester C below ground through increased primary productivity and maintenance of organic input throughout the rotation. This option also includes the use of legumes (i.e. peas, beans or clover) in arable rotations. The legumes could be introduced to break a long arable run, or grown with the arable crop (intercropped or intersown).

Causality

Yield and productivity

Cover crops are used to improve the agro-ecosystem efficiency in using natural resources. To maximise resource use, crops should be grown whenever possible during the whole year, if resources are insufficient for continuous cash crops then cover crops are used to intercept radiation, maintain nutrient cycling, produce additional biomass and provide ecosystem services that can benefit the main crop. A review by Scopel et al. (2013) suggested that in Europe, overall crop productivity may not increase, although this was for systems employing both reduced tillage and cover crops not differentiating the effect of cover crops only. Increased yields have been found with N-fixing cover crops in low N soils, but decreased yields in intermediate or high N soils (Tonitto et al. 2006). Environmental variables (e.g. soil type, climate), crop type and management practices (e.g. sowing date of cover crop) will all be important.

Biodiversity

Cover crops can have a positive effect on biodiversity of many taxa especially invertebrates (Holland and Luff 2000, Lundgren and Fergen 2010). Soil biological activity and diversity are higher in systems with a surface mulch or cover crops (De Aquino et al. 2008). Legume crops can encourage on-farm biodiversity by providing a habitat for microorganisms and invertebrates (Veronesi et al. 2011). There may also be provision of winter seed and cover for birds.

Weed and pest control

The vegetative mulch that can be produced when cover crops are killed can be very effective at suppressing weeds when retained on the soil surface (Carr 2017, Dorn et al. 2015). In reduced tillage systems this enables better weed control. Most kill methods involve rolling or mowing, an effective "roller-crimper" was built and tested in the eastern USA and enabled cover crops to be grown profitably in the U.S. mid-Atlantic region without tillage (Moyer 2010). To support weed management it is best to use locally adapted cover crops that have rapid establishment, good soil coverage and high dry matter production (Dorn 2015). In some areas, weeds cannot be controlled by a vegetative mulch and it has been suggested that integration or re-introduction of grazing into the system would be more effective (Lehnhoff et al. 2017). Beneficial insect species that can control pest species respond to previous cover crops (Holland and Luff 2000; Lundgren and Fergen 2010). Predator abundance was greater in corn following an autumn-planted, spring-killed grass cover crop, , compared to corn without a preceding cover crop (Lundgren and Fergen 2010). Activity-densities of the carabid beetle were greater in conventionally-tilled corn following a pea/oat–cereal rye/hairy vetch cover crop system compared to treatments without a preceding cover crop (Shearin et al. 2008). Crop rotations should not have more than one occurrence of the following legume crops every five years: field beans, peas, green beans, vetches, broad beans and lupins, in order to avoid build-up of pests and diseases (e.g. pea and bean weevil (Defra 2018)).

Soil quality & conservation

Cover crops can be used to eliminate bare ground, potentially increasing soil nutrients and SOC by increasing productivity (especially if plant residues are returned to the soil), preventing erosion (Buckingham et al.,2013, Desjardins et al. 2005), improving soil structure through rooting systems (Scopel et al. 2013), or altering the soil bacterial diversity and composition to improve nutrient cycling (Alahmad 2017).

Bare soil tends to lose C and nutrients, at least in part due to soil erosion (Quinton et al. 2006).

Studies assessing the effect of no till on soil quality found that soil structural properties were often poorer from increased topsoil compaction, reduced porosity and high bulk density resulting in decreased water infiltration rates and lower hydraulic conductivity. Soil structure under no-till could be improved considerably by introducing cover crops, but the root and canopy characteristics of the cover crop are important (e.g. thick rooted cover crops beneficial to soil structural remediation can cause negative effects in soils sensitive to erosion) and should be considered carefully before implementation (Skaalsveen et al. 2019). Legumes improve soil fertility.

Carbon (C) sequestration and greenhouse gas (GHG) emissions

Perennial plants tend to increase soil C stocks at a faster rate than annuals, but the rate of soil C accumulation varies considerably with region, species, and management context (Guo and Gifford 2002, Schipanskia 2017). Bai et al. (2019) found that leguminous cover crops were associated with greater SOC sequestration than non-leguminous crops, whereas Poeplau and Don (2015) did not find a difference in C sequestration between legumes (n=61) and non-legumes (n=66). Even if N-fixing cover crops do increase C sequestration in agricultural soils, they may also lead to increased N_2O emissions. Emissions of N_2O from terrestrial ecosystems are a function of available mineral N, soil water content, the availability of electron donors (such as labile C), and soil physical properties (Basche et al. 2014). Cover crops can impact these processes, for example, a growing cover crop can decrease soil mineral N by incorporating it into its biomass, while a legume cover crop may increase soil mineral N via N fixation (Kaspar and Singer 2011). A cover crop may reduce GHG (N_2O) emissions, by reducing the application rate of synthetic N fertilisers, and the associated N_2O and CO_2 (from fertiliser manufacture) emissions. The mulching effect of cover crop residues on the soil surface may increase soil water and the potential for denitrification depending upon timing of precipitation (Dabney 1998). Additionally, decomposing cover crop residues can temporarily immobilize soil N and then later increase soil pools of labile C and inorganic N (Kaspar and Singer 2011, Steenwerth and Belina 2008), which will also impact dynamics of N_2O emissions (Basche et al. 2014).

There is no consensus in the literature on the impacts of cover crops on N_2O emissions. In their report to Defra (2018) the authors state that increasing the share of grain legumes/pulses in crop rotations is one of the most promising options for improving N Use Efficiency (NUE) and reducing N_2O emissions from agriculture due to replacement of manufactured N fertilisers and improvements in soil quality. Different factors such as the incorporation of residues within the soil, the species of cover crop and timing throughout the year all affect (N_2O) emissions (Basche et al. 2014).

Water quality and conservation

The presence of a permanent mulch of crop residue reduces surface runoff (Sun et al. 2015). It also reduces the amount of solar radiation reaching the surface and evaporating water, and soil moisture is more likely to be retained under cover crops (Scopel et al 2004). Infiltration may be improved by deep-rooting species such as legumes. Cover crops, particularly legumes, increase soil mineral N availability, allowing the reduction in use of chemical N fertilizers and lower the risk of nutrient leaching (Eory et al. 2015) however, if soil is left bare after a legume harvest, there is a risk of residual N being lost by leaching; although, most of the N should be taken off in the harvested bean/pea product (Defra 2018).

Co-benefits and trade-offs

The reduction of nutrient leaching could prevent water pollution and increase yield.
The use of cover crops can promote arbuscular mycorrhiza fungi (Bowles et al. 2017).

Magnitude of impact

A meta-analysis found that cover crops could increase SOC by 0.32 t C ha^{-1} yr^{-1} (Poeplau and Don 2015, Poeplau et al. 2018). Another meta-analysis highlighted that cover crops increase SOC by ~6%, comparing poorly with biochar application which increases SOC by ~39% (Bai et al. 2019). SOC sequestration under N-fixing cover crops may reach average cumulative SOC gains of 19.4 and 28.1 Mg CO_2e ha^{-1} by 2040 and 2100, respectively (Lugato et al. 2018).

Timescale

The timescales over which cover crops increase SOC are not clear. A global meta-analysis of which 73% of the sites were located in temperate regions modelled SOC stock after the introduction of cover crops (Poeplau and Don 2015). Based on experimental data and statistical modelling, soil C saturation using cover crops (if the cover crop was not removed from the soil) did not saturate and was estimated to occur after 155 years (but long-term studies were scarce with the longest study reporting data for up to 54 years, and only 8 plots exceeding 20 years of data).

Geographical issues

Cover crops can increase crop P nutrition, and may be more effective in areas with low available P (Hallama et al. 2019).

Displacement

It is unclear whether there are any displacement effects of cover cropping. However, initial C sequestration due to N-fixing cover crops may be offset by increased N_2O emissions in the long-term (Lugato et al. 2018).

Longevity

It is unclear how long SOC increases due to cover cropping will be maintained, particularly if cover crops are discontinued.

Climate interactions

Positive SOC impacts of cover crops are reported to be greater in regions characterised by warm climates (Bai et al. 2019), however, there are implications for water use from the use of cover crops (Lehnhoff et al. 2017), particularly in warmer climates. A study of European farmers found that fewer than 50% of southern European organic farmers used cover crops because of concerns that soil water deficits would result after cover crops were grown (Vincent-Caboud et al. 2017). In northern environments, humid conditions promote weed development throughout the cash crop production season if the residue biomass is inadequate to provide season-long weed suppression; with significant cover crop residue on the soil surface, the ability of farmers to employ mechanical methods of weed management is limited (Vincent-Caboud et al. 2017).

Social and economic barriers

Cover crops come at an immediate expense to the farmer in terms of seed and machinery costs and the long-term benefits of using cover crops such as fertility improvement and integrated weed management may not be sufficient motivation and there may need to be short-term returns (Scopel et al. 2013). Termination methods for cover crops in organic farming rely exclusively either on a mechanical solution or frost (Peigne et al. 2008). Cover crop regrowth due to inconsistent or incomplete termination may compete with the cash crop for nutrients and water resources (Vincent Caboud et al. 2017).

Metrics and verification

Biodiversity

Cover crops can influence invertebrates, and monitoring of the distribution and abundance of invertebrate species should be undertaken. Soil biological activity and diversity can be higher under cover crops than a ploughed field and this would be useful to measure.

Pest & disease control

Cover crops should reduce weed infestations (by the vegetative mulch used when cover crops are killed) so weed cover in fields should be monitored through vegetation plots and photographs to test this effect. The abundance of beneficial insect predators may be increased through the use of cover crops; this should be tested along with the abundance of insect pests using pitfalls, soil cores, sweep netting/transects or pan traps.

Soil quality and conservation

Cover crops can potentially increase soil nutrients (especially if plant residues are returned to the soil) so testing of soil nutrients should be carried out. They could also prevent erosion (Buckingham et al. 2013, Desjardins et al. 2005) and improve soil structure through rooting systems (Scopel et al. 2013) which suggests that soil erosion and soil structure should also be measured. Cover crops have also been found to alter the soil bacterial community diversity and composition to improve nutrient cycling so sampling and testing soil microbial diversity would be very useful. The use of cover crops can promote arbuscular mycorrhiza fungi, it would be very interesting to test this also.

Carbon (C) sequestration and greenhouse gas (GHG) emissions

Cover crops should increase SOC stock (g or t C yr^{-1}) and should be measured at least in the plough layer and preferably also below the plough layer. There is conflicting evidence about the impact of cover crops on N_2O emissions so it would be very useful to measure these.

Water quality

Cover crops, particularly legumes, should reduce the need for manufactured N fertilisers so should reduce nitrate leaching, testing water quality would therefore be useful. However, as mentioned already it is difficult to attribute changes on individual farms or fields to changes in water quality. It may be better to focus on the level of pollutants in the soil which can be easily measured by each individual farmer.

Water conservation/ flooding

The presence of a permanent mulch of crop residue should prevent runoff and retain soil moisture but this should be measured.

Yield

Cover crops may provide ecosystem services to benefit the main crop, so there could be an increase in yield. There is mixed evidence on the effects of cover crops on yield depending upon other factors such as whether reduced tillage is also included in the system, existing nutrient status and whether N-fixing crops are used. Measuring yield would be useful information.

2.3.4 (4) Organic matter input (plant residuals, wood chips, biochar)

Definition

Organic inputs, including compost, biosolids (recycled from sewage) and incorporation of crop residues. Biochar is another form of organic material that can be added to soil. Biochars are obtained by thermal treatment of organic material in low oxygen conditions (Qambrani et al. 2017) and can be a side-product of liquid biofuel production.

Causality

Carbon (C) sequestration and greenhouse gas (GHG) emissions

Organic inputs, have been demonstrated to have positive effects on SOC on cropland (Powlson et al. 2012, Wuest and Gollany 2012). The mechanisms for this are direct C inputs as well as increased productivity and C inputs from plant matter. However, organic inputs could cause a priming effect on microbial activity, which could result in SOC mineralisation and CO_2 efflux (Buckingham et al. 2013, Pascault et al. 2013). This priming effect is caused by a change in microbial community and C mineralization of different C sources applied (other than residual return) compared to native SOC (Zhu et al. 2017).

Processing of organic fertilizer may increase SOC storage. Chenu et al. (2019) highlight a number of studies suggesting greater long-term SOC storage from labile, easily degraded compounds than recalcitrant, lignin-rich material. This may be because labile compounds are processed with higher microbial C use efficiency, increasing SOC storage as microbial biomass. Another explanation is that soluble compounds migrate in soil between mineral surfaces, where they can be protected. However, it remains unclear whether “fresh” or “processed” organic matter will have the greatest benefits for SOC sequestration.

Biosolids, recycled from sewage, are produced in wastewater plants worldwide. In studies, SOC increased with biosolid application. Biochar constitutes a stable form of C in itself, but there is also inconclusive evidence that it might confer stability to existing fractions of organic matter in soil (Powlson et al. 2011). Most of the evidence base for biochar originates from outside Europe.

Soil quality & conservation

Biosolids contain organic matter, N and P, but the physicochemical composition depends on the origin (Sharma et al. 2017). Sharma et al. (2017) review that biosolids frequently contain toxic heavy metals, pesticides, insecticides, pharmaceuticals, steroid hormones and other toxic substances. After the application of biosolids to soils, humic acids, soil aggregate stability and water holding capacity had increased, whereas pH and bulk density had generally decreased. Unfortunately, lower pH is also associated with increased bioavailability of heavy metals. Long-term application of biosolids increases heavy metal concentrations and may reach critical values. However, Roig et al. (2012) applied aerobically digested biosolids for 16 years which resulted in improved C and N mineralization, organic matter content and increased enzyme activities.

Yield

Yields have been shown to frequently increase (Sharma et al. 2017, Agegnehu et al. 2017).

Co-benefits and trade-offs

N_2O emissions are a possible trade-off from manure, sewage sludge and urban compost, although emissions from production of inorganic fertilizers could be reduced by using organic fertilizers (Freibauer et al. 2004). Crop residues could increase N_2O emissions by placing a source of mineralisable N into the soil (Freibauer et al. 2004), especially when residues have a low C:N ratio (Baggs et al. 2000). N-leaching can also be an issue when applying manure (Buckingham et al. 2013).

Freibauer et al. (2004) identified that, if poorly regulated, sewage sludge could lead to build up of heavy metals and organic pollutants in the soil (see also Sharma et al. 2017). Urban compost could increase the availability of trace minerals in the soil. Heavy metals in biosolids may also interfere with microbial enzyme activities, interrupting the soil C and N cycles, and reducing respiratory C loss (Sharma et al. 2017). Biosolids itself contain enzymatic substrates, stimulating microbial growth and enzyme production; but enzyme production may be interrupted by Pb and Cu. However, increased C and N concentrations in biosolids and lower heavy metal concentrations increased microbial and enzyme activities (Sharma et al. 2017).

For biochar, a full life-cycle assessment is needed to understand the trade-offs and co-benefits. A review on biochar by Qambrani et al. (2017) concludes, based on biochar-life-cycle assessments, that more GHG are reduced than emitted in the process from plant material combustion to soil application. However, biochar originates from a variety of organic source materials with various economic and environmental consequences. Generally, biochar improves nutrient and water retention in soil, as well as crop growth (Powlson et al. 2011, Qambrani et al. 2017), reduces bulk density and increases crop yields (Agegnehu et al. 2017). This could reduce demand for N fertilizer, resulting in co-benefits in terms of GHG mitigation. Biochar was shown to reduce CO_2 emissions (by reducing the amount of labile C compounds in the soil), CH_4 emissions (by reducing anoxic microsites) and N_2O emissions (by binding labile N) (Qambrani et al. 2017). However, care must be taken as N_2O emissions have also been observed to increase after biochar application (reviewed in Al-Wabel et al. 2017). The GHG mitigation potential depends on biochar and pyrolysis types as well as soil type and pH (Laghari et al. 2016).

Magnitude

Powlson et al. (2012) reviewed SOC impacts of various biosolid inputs to arable soils, finding variable positive effects of farm manures in the region of 0.63 t C ha^{-1} y^{-1} (at the maximum permitted application rate in UK nitrate vulnerable zones). Other inputs such as sewage sludge and green compost had greater positive effects. Several studies suggest that C storage efficiency from cereal residues tends to be lower than from other biosolids, including manure (Powlson et al. 2012, Wuest and Gollany 2012). Smith et al. (1997) collated experimental data on SOC from EU countries and found that addition of animal manure, sewage sludge or straw had a lower C sequestration potential than extensification (a switch to ley-arable farming). A recent meta-analysis highlighted that cover crops increase SOC by ~6%, while biochar application increases SOC by ~39% (Bai et al. 2019).

Timescale

Getahun et al. (2018) found that soil loosening and straw slurry incorporation into arable soil increased SOC by >20 g kg^{-1} after just one year, with positive effects on grain yield. Powlson et al. (2012) demonstrated that increases in SOC due to organic inputs were greatest within the first 20 years of application, after which they diminished.

Spatial issues

One study suggests that SOC inputs from cereal residues or biosolids are contingent on suitable amounts of N, P and S (Kirkby et al. 2013). The amount of nutrients needed may be quite predictable, and if not already present might be supplemented using fertilizers. However, the implication in the case of incorporation of cereal residues may be to fertilize stubble, which is not recommended due to likely nitrate leaching (Buckingham et al. 2013). N-addition needs to be carefully targeted to minimise trade-offs. Indeed, improved agronomy and nutrient management consistently increased CO_2 mitigation potential in the review of Smith et al. (2008).

Displacement

Powlson et al. (2011) highlights the importance of the alternative fate of organic inputs, e.g. cereal straw. If the straw was burnt, it may be preferable to incorporate the C into the soil. However, burning cereal straw could also reduce fossil fuel combustion and help mitigate climate change (Powlson et al. 2008). Another pathway is for straw to be used as animal bedding, in which case it would largely end up incorporated in SOM elsewhere (Powlson et al. 2011).

Longevity

It is unclear whether increased SOC would persist after cessation of organic inputs. Effects on SOC tend to saturate with time (Powlson et al. 2012). Modelling scenarios for integrated crop residues and low soil disturbance suggest the formation of a new SOC equilibrium in Europe around 2050. Thereafter, N_2O emissions started to systematically increase, offsetting previous GHG emission reductions by 2100 (Lugato et al. 2018).

Climate interactions

Although most of the evidence on biochar comes from outside Europe, positive SOC impacts of biochar are reported to be greater in cool regions (Bai et al. 2019).

Social and economic barriers

The application dose of biochar and different biochar types for enhanced yield return and SOC sequestration needs to be soil and crop specific (Al-Wabel et al. 2017, Zhu et al. 2017), increasing the need of farmers interest and background research. The application of high quantities of biochar may not be feasible for small-farm holders. Laghari et al. (2016) stress the need for a comprehensive risk assessment of the biochar production process as human-toxic polycyclic aromatic hydrocarbons may be produced. Also, during the combustion process, harmful components in the biomass from combustion may be released, causing another health-related risk.

Metrics and verification

Soil quality and conservation

Biosolids from sewage frequently contain toxic heavy metals, pesticides, insecticides, pharmaceuticals, steroid hormones and other toxic substances. After the application of biosolids to soils, humic acids, soil aggregate stability and water holding capacity had increased, whereas pH and bulk density had generally decreased. Nutrient retention should also be affected by the application of biosolids and biochar. Unfortunately, lower pH is also associated with increased bioavailability of heavy metals. Standard measurements of soil should be undertaken such as pH, bulk density, and soil nutrients, however, it would also be useful for biosolid applications to measure heavy metal contents and enzyme activities.

Carbon (C) sequestration and Greenhouse gas (GHG) emissions

Organic inputs have positive effects on SOC on cropland (Powlson et al. 2012, Wuest and Gollany 2012) although organic inputs could cause a priming effect on microbial activity, which could result in SOC mineralisation and CO_2 efflux. N_2O emissions are a possible trade-off from manure, sewage sludge and urban compost. Improved nutrient retention could reduce the need for N fertilisers which should be considered in calculating GHG emissions. SOC should be measured and if possible N_2O emissions.

Water quality

N-leaching could increase from organic matter inputs particularly manure, application of biosolids can lead to build up of heavy metals and organic pollutants so monitoring water quality is important. However, as mentioned, it Is difficult to attribute changes on individual farms or fields to changes in water quality. It may be better to focus on the level of pollutants in the soil which can be easily measured by each individual farmer.

Yield

Yields should increase but measuring and recording yield would be useful.

2.3.5 (5) Modified manure management, quality and diversity (fresh manure, limited use of fertilizer)

Definition

Organic fertilizer (=manure) is mainly derived from cattle, pig and poultry farming with liquid manure (slurry) having a lower dry matter content than solid manure (Bernal et al. 2009). In general, slurry has lower concentrations (g kg^{-1} fresh weight) of C and N than solid manure, but pH stays largely unaffected. Poultry manure (solid or liquid) has generally a higher C and N concentrations than cattle and pig manure (Bernal et al. 2009). Green manure refers to residuals that are returned to the soil or cover crops which often are grown as green manure material (see section on Organic matter input).

Causality

Carbon (C) sequestration and greenhouse gas (GHG) emissions

Manures and composts can reduce reliance on N fertiliser, leading to lower GHG emissions from fertiliser manufactures (Smith et al. 2011). Similar to inorganic fertilizers, organic fertilizers are used to increase plant yields. This can increase C inputs to the soil through plant material and root exudates (Buckingham et al. 2013). The positive impacts of manure application on SOC exceeds the impacts of inorganic fertilizers because C is added to the soil with liquid or solid manure, but not with mineral fertilizers. Indeed, when Jones et al. (2006) applied a variety of manures, slurries and mineral fertilizers to cut grasslands in southern Scotland, they found that all manure treatments increased topsoil C concentration, while mineral fertilizers did not. Interestingly, SOC increases were observed despite increases in DOC and CO_2 losses.

Soussana et al. (2007) assessed GHG budgets of nine grassland sites and demonstrated that C storage was positively related to N fertilizer supply, but this represented a combination of inorganic and organic fertilizers. Chenu et al. (2019) highlight a number of studies suggesting greater long-term SOC storage from labile, easily degraded compounds than recalcitrant, lignin-rich material. This may be because labile compounds are processed with higher microbial C use efficiency, increasing SOC storage as microbial biomass. Another explanation is that soluble compounds migrate in soil between mineral surfaces, where they can be protected. However, it remains unclear whether "fresh" or "processed" organic matter will have the greatest benefits for soil C sequestration, especially given possible emissions while processing organic materials. Manure application, in particular slurry, increases N_2O emissions but this can be reduced by avoiding surface broadcasting (Misselbrook et al. 2002) and using more effective techniques like trailing shoe or injection.

Soil quality & conservation

Manures typically increase soil aggregation compared to fertiliser treatments (Blair et al. 2004). Freibauer et al. (2004) highlight that manure application can improve soil structure. Manure amendments can rebuild a depleted soil microbial community. A global meta-analysis shows that manure increased microbial C and N by 36% and 27% compared to mineral fertilizer applications respectively (Kallenbach and Grandy 2011). They also found that the C:N ratio of manure can differ, but microbial C:N averaged 8.6 across amendments, which can lead to nutrient accumulation in soils.

Water quality & conservation

In soils already high in P, addition of composts and manures carries with it a risk of P runoff. In a review of P management of organic manures, Smith et al. (1998*)* concluded that restricting topsoil extractable P levels to 70 mg L^{-1} should minimise the risks of unnecessary P enrichment and subsequent leaching. Manure application can be associated with nitrate leaching (Moxley et al. 2014), especially where application is excessive or poorly timed (Goulding et al. 2000, Powlson et al. 2011). Both nutrient use efficiency and losses will vary with manure and compost type. Freibauer et al. (2004) highlight that manure application can improve water holding capacity.

Yield

Increases in plant productivity and food production on farmland from organic matter application.

Co-benefits and trade-offs

Key trade-offs of manure application identified during a review to inform LULUCF inventories were nitrate leaching and N_2O emissions (Moxley et al. 2014). In fact, these trade-offs may be more severe per kg of N in manure as compared with inorganic fertilizer (Bergström and Goulding 2005). Jones et al. (2006) found that for some types of organic fertilizer (though not all) increases in SOC were outweighed by N_2O emissions, given the increased global warming potential of N_2O. However, this offset may be preventable by using appropriate manure application techniques (Misselbrook et al. 2002) and modified manure like acidified slurries (Fangueiro et al. 2015).

A clear co-benefit of increased organic fertilizer application are increases in plant productivity and food production on farmland. However, Soussana et al. (2007) found that SOC increases due to N fertilizer could be counterbalanced by herbage use through cutting and grazing. If organic fertilizer use is always associated with increased herbage use, SOC storage outcomes may be diminished. Nonetheless, Soussana et al. (2007) suggest that in the absence of N supply and herbage use, grasslands are net C sinks. In contrast, a review by Zavattaro et al. (2017) reports a reduction in yield under manure treatment compared to inorganic fertilizer application at the same rate, while SOC increased by 33%. This negative effect of manure application on yields was cancelled out by small additions of mineral N to farmyard manure, suggesting that the reduction in yield was connected to limited N availability and a disruption of the soil N cycle. This was confirmed by the finding that yield had an overall lower N content under manure compared to mineral fertilizer treatment whereas soil N content increased. However, with the addition of mineral N to manure, the positive effect on SOC was reduced. Organic fertilizer inputs may displace inputs of inorganic fertilizer, for example in organic farming systems. This could provide the co-benefit of reduced emissions from manufacture of inorganic fertilizers. Smith et al. (2011)

reviewed possible benefits of organic farming for SOC sequestration. While it was unclear whether a switch to organic farming would increase SOC on-site, potential benefits were identified in terms of reduced GHG emissions from fertilizer production. However, the effect of such emissions-reductions must be weighed up against on-site emissions from use of manure (Powlson et al. 2011).

Freibauer et al. (2004) suggest that the preferential use of manure on arable land could prevent trace gas emissions that are more pronounced when manure is applied to grassland.

Magnitude

Evidence suggests that manure additions cause greater C storage per unit N than inorganic fertilizer (Buckingham et al. 2013). Furthermore, C storage efficiency from biosolids, including manure, may exceed that from cereal residues (Powlson et al. 2012; Wuest and Gollany 2012).

Estimates of change in soil C stocks caused by manure application on croplands ranged from 5 to 18 t C ha^{-1} in a review to inform the LULUCF inventory (Buckingham et al. 2013). This review (Buckingham et al. 2013) found positive changes in grassland SOC stocks brought about through slurry or manure applications (0.7 to 15 t C ha^{-1}). Jones et al. (2006) reported C storage of 15.7 to 48.3 t C ha^{-1} following application of manure for six years. Smith et al. (2008) report a CO_2 mitigation potential of -0.62 to 6.20 t CO_2 ha^{-1} y^{-1} for application of manure or biosolids in cool moist regions, although this includes both cropland and grassland. Manure application effects for SOC are sometimes presented in combination with other interventions. A meta-analysis by Conant et al. (2001) reports that fertilization in general (manures and inorganic fertilizers) can increase SOC by 0.3 t C ha^{-1} yr^{-1}.

Timescale

Increases in SOC can occur over short timescales. Jones et al. (2006) reported positive effects of manure application for SOC on cut grasslands within 6 years.

Spatial issues

Care should be taken not to generalise the effects of manure application to organic-rich soils. While there is strong support for positive effects of manure application for SOC on mineral soils, the review of Buckingham (2013) concluded that inputs to organic-rich pasture soils could lead to decreases in SOC.

N_2O emissions due to N fertilization could be more severe in areas which already have surplus N; yield-scaled N_2O emissions increase exponentially with N surplus, so adding N fertilizer in the wrong places will disproportionately increase N_2O emissions (van Groenigen et al. 2010). Furthermore, positive effects of manure for SOC can saturate, as demonstrated at the Broadbalk wheat experiment at Rothamsted (Powlson et al. 2012).

Displacement

Targeting organic fertilizer to build SOC stocks in one area could be offset by removal of C inputs elsewhere (Conant 2010). Manure application could be targeted to increase SOC on arable soils (which have low organic matter as a starting point) rather than on grasslands (Buckingham et al. 2013, Powlson et al. 2012, 2011). Such targeting could lead to net reductions in emissions, but local changes in SOC alone do not constitute climate change mitigation (Chenu et al. 2019).

Another aspect is the C:N:P ratio, macro- and micro-nutrient content of manures. Long-term input of nutrient ratios dissimilar to soil ratios can cause N and P accumulation in soils under which runoff of leached P and N may increase (Edmeades 2003). High nutrient concentrations then reach streams and potentially pollute systems downstream.

The alternative fate of other organic fertilizers, such as household green waste should also be considered. This would ensure that local increases in SOC are not offset by decreases in SOC or emissions elsewhere. Furthermore, redirecting organic fertilizers so that they are applied further from the point of production could increase gaseous emissions through transportation (Freibauer et al. 2004).

Longevity

As with inorganic fertilizers, all else being equal, cessation of manure application would be likely to reverse increases in SOC.

Climate interactions

Organic fertilizer effects on SOC may be diminished under increased drought conditions. Smith et al. (2008) report lower mean mitigation potential due to manure or biosolids application in dry areas as opposed to moist areas. Furthermore, Jones et al. (2006) found that increases in N_2O emissions after applying organic fertilizers were greater in a particularly wet year of their six-year study.

Lu et al. (2011) propose that under elevated CO_2, there may be increasing N limitation within ecosystems. The result might be that the positive effects of N fertilization on SOC and C sequestration are increased under elevated CO_2.

Social and economic barriers

Farmers are increasingly aware of the value of their organic fertilizer resources, and many already have the infrastructure to distribute them on their fields. However, manures and slurries do not tend to be shared between farms under different ownership (Farming Connect 2019, pers. comm.), not least because of potential issues regarding spread of diseases. As such there may be social and economic barriers to targeted redistribution of organic fertilizers e.g. storage and transportation. As the review of Buckingham et al. (2013) indicates, “even within a single farm, manure application is often unevenly distributed with the fields nearest the livestock buildings being the preferred sites of application”. Alternatively, manure can be transformed into other, stable and easier transportable products such as compost (Bernal et al. 2009). Composted manure reaches a high agricultural value if the organic matter content is high and the return of C and nutrients to the soil is optimal.

Hou et al. (2018) conducted a stakeholder survey investigating the applicability of manure treatment technologies in four European countries with different policies and incentives. Targeted stakeholder groups included livestock farmers, members of the board of farmers’ organizations, agricultural advisors, researchers and public authorities. The survey revealed that the top two incentives to use manure treatment techniques (to e.g. reduce N_2O emissions) are 1) increased pressure from policies and regulations and 2) facilitated farm manure export. The three main constraints for the application of manure treatments were economic factors: 1) lack of capital for investment, 2) high processing costs and 3) the long benefit of return. Hou et al. (2018) also show that technology preferences differ between farm types and countries, and that manure treatment will likely stay a regional, rather than an overall activity.

Metrics and verification

Soil quality and conservation

Manures typically increase soil aggregation compared to fertiliser treatments (Blair et al. 2004). Obviously they are intended to improve soil nutrient status so monitoring of soil chemistry (N, P, K, and pH) and structure (soil aggregate stability, bulk density) would be useful. Manure amendments have been shown to rebuild a depleted soil microbial community so if possibly soil microbial diversity should be monitored.

Carbon (C) sequestration and Greenhouse Gas (GHG) emissions

Manure application should increase SOC stock (g or t C yr^{-1}) and this should be measured at least in the plough layer and below the plough layer if possible (= C content and bulk density). It is possible that manure application can increase N_2O emissions so these should also be monitored.

Water quality & conservation

In soils already high in P, addition of composts and manures carries with it a risk of P runoff. There is a risk of nitrate leaching so water quality particularly water chemistry N and P should be monitored. However, as mentioned, it Is difficult to attribute changes on individual farms or fields to changes in water quality. It may be better to focus on the level of pollutants in the soil which can be easily measured by each individual farmer. Manure application can improve soil water holding capacity, soil moisture could be tested.

Other

It would be useful to measure the nutrient content of the manure – particularly slurry /dirty water, such measures would be very useful for understanding application rates. It would also be useful to know how farmers are applying manure, rates and methods.

2.3.6 (6) Agroforestry

This section builds on reviews from the AGFORWARD EU project, Keenleyside et al. 2019 and Alison et al. 2019.

Definition

Agroforestry is the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal production systems to benefit from the resulting ecological and economic interactions (Burgess et al. 2015, EU AGFORWARD project). The diversity of practices behind the term agroforestry is vast and includes silvoarable systems e.g. multispecies tree gardens, alley crops, forest farming, boundary planting (hedgerows and riparian buffer strips), improved fallow, intercropped and grazed orchards, silvopasture systems woody perennials combined with livestock serving as fodder for livestock around farmlands or as living fences or fodder hedges, including grazed forests, multipurpose trees, (including shelterbelts) (Burgess et al. 2015, Fagerholm et al. 2015) and agrosilvopastoral systems - a combination composed of woody perennials, agricultural species and livestock.
The AGFORWARD research project (January 2014-December 2017), field-tested a number of innovations for livestock and arable farmers e.g. combining poultry with fruit trees/ different understories, the feeding value of leaves from trees for ruminants (Hermansen et al. 2017), combining arable crops with short rotation coppice (hazel and willow), alley crops with tree species including poplar, black locust, sorb, wild cherry and crops including sugar beet, wheat, peas and maize (Kanzler et al. 2017). The width of the alleys varied widely depending upon the system, for instance organic systems tend to use narrower alleys, whilst conventional systems use wider ones to enable use of machinery and chemical application (Kanzler et al. 2017).

Causality

Yield

Agroforestry can increase land productivity, the combination of tree and crop systems leads to a more efficient capture of resources (such as solar radiation or water) than separated tree or crop systems (Graves et al. 2007, Jose 2009). Agroforestry was found to increase overall yields by up to 40% relative to monoculture arable and woodland systems (Graves et al. 2007).
The AGFORWARD project found some evidence of increased yields in alleys between trees compared with conventional fields (Kanzler and Mirck 2017, Vityi et al. 2017), however, in other studies declines in yields were reported for the arable crops planted in close proximity to the trees (possibly due to competition for solar radiation and water) (Gosme and Desclaux 2017, Arenas-Corraliza et al. 2017, Kanzler et al. 2017). A meta-analysis by Torralba et al. (2016) showed a decline in wood production and often food production depending upon landscape context.
In the UK, although data for all studied cereal crops indicated a decline in yield with greater proximity both to hedge (coppiced or standing) and tree rows, an exception of this trend was reported for oats, which benefited from proximity to a coppiced hedge (Smith et al. 2017a).

Biodiversity

A meta-analysis of publications on European agroforestry systems found that silvo-pastoral agroforestry has a significant positive effect on biodiversity compared to specialised agricultural and forestry systems, particularly the effect on birds (Torralba et al. 2016). In Sweden, Soderstrom et al. (2001) also found a positive effect on the species richness of birds from an increase in the proportion of pasture area covered by shrubs and trees. This was partially attributed to an increase in the abundance and diversity of invertebrates. There were positive relationships between increases in trees and shrubs and species richness of vascular plants, butterflies, bumble bees, ground beetles and dung beetles.
Agroforestry can provide food, shelter, resources and microclimate for a wide range of species. Torralba et al. (2016) found that in Atlantic and Continental Europe, integrating trees in arable systems can increase soil fertility and enhance biodiversity, not necessarily compromising productivity, however, variation is high and it is difficult to get data on all potential productivity components in an agroforestry system. Riparian buffer strips create interactions with terrestrial and aquatic environments, and are often characterised by high primary productivity, and plant and animal biodiversity. The meta-analysis also stresses the importance of promoting features and practices that act at a landscape scale, as in the case of hedgerows, which play an important role

in landscape-scale biodiversity conservation (Torralba et al. 2016). The type of forestry is important as landscape and biodiversity benefits will not be the same if a commercial monoculture is established.

Agroforestry elements can influence the presence and abundance of small mammal species (Graham et al. 2018). Small mammals avoid hedgerows with large gaps (> 3 m). Hedgerow width and length increase the total habitat area, indirectly increasing microhabitat complexity and refuge from predators (Gelling et al. 2007) for species including *Myodes glareolus* (bank vole) and *Apodemus flavicollis* (yellow necked mouse). *Muscardinus avellanarius* (dormouse), an arboreal species, uses hedgerows all year round, favouring large, dense, species rich hedgerows (Bright and MacPherson 2002).

Bats use hedgerows and other agroforestry features for feeding, shelter and navigation at a range of scales (Walsh and Harris 1996). Bats are macro-invertebrate feeders, so structural components, which increase the abundance of macro-invertebrates, may also benefit bats by increasing food availability. The activity of pipistrelle bats and bats with short to medium range echolocation are likely to be negatively affected by hedgerows with a heterogenous height profile as their manoeuvrability across the landscape is limited. A study comparing bat activity between organic and conventional farms found that bats were thought to prefer organic farms due to the presence of taller hedgerows, providing more shelter and greater food availability (Wickramasinghe et al. 2003). Dense basal vegetation of prickly species is thought to reduce hedgehog mortality (Graham et al. 2018).

Pollination

Agroforestry can provide habitat for pollinators. Wolton et al. (2014) found evidence that hedgerows, and other patches of non-cropped ground, are important in agricultural landscapes for the existence of healthy and diverse pollinator populations. Hedgerows can attract pollinators into intensive farmland (Haenke et al. 2014, Morandin and Kremen 2013) and export those pollinators into crops, increasing yield. See below for more evidence focused on hedgerows in particular.

Pest & disease control

Although the agroforestry component, e.g. tree rows in alley cropping, can act as a source of weeds or pests (Wartelle et al. 2017, Kanzler et al. 2017) agroforestry has been found to enhance populations of the natural enemies (predators and parasites) of crop pests (Pumarino et al. 2015, Jose et al. 2004) by providing a wide range of microhabitats, nectar and pollen resources, and larval development resources. See below for more on hedgerows specifically.

Soil quality & conservation

Agroforestry has been found to enhance and maintain long-term soil productivity and sustainability (Jose 2009). Agroforestry enhanced soil fertility, nutrient retention and nutrient cycling (Jäger 2017, Vityi 2017). Trees can enhance soil physical, chemical and biological properties by adding significant amount of above and belowground organic matter and releasing and recycling nutrients in agroforestry systems (Jose et al. 2004).

Agroforestry seems particularly useful in controlling soil erosion, significantly reducing the surface-runoff of soil (Torralba et al. 2016; Francia et al, 2006; Gómez et al. 2009; García-Ruiz et al. 2010, Jose 2009).

Carbon (C) sequestration and greenhouse gas (GHG) emissions

Woody vegetation is believed to lock-up C above- and below-ground over decades. Agroforestry may therefore be a potential way to store C in biomass and the soil, which may help mitigate climate change. Agroforestry can be established from different land uses, but the effects on C stocks vary greatly (de Stefano and Jacobson 2018).

The potential to sequester C depends upon the stage of the woodland cycle, age of trees, species composition, environment and management. In the years immediately after planting, afforestation leads to net GHG emissions as the loss of soil C is greater than the C sequestered by tree growth. A period of more rapid C sequestration takes place 10 to 40 years after planting, followed by slower sequestration as the trees mature (Eory et al. 2015).

De Stefano and Jacobson (2018) found that the introduction of woody species generally increases SOC stocks when the land use changes from less complex systems (such as agricultural systems) to agroforestry. Wiesmeier et al. (2019) suggest that “the storage of SOC increases in the order cropland < forest < grassland”, noting some exceptions between forest and grassland.

Previous work reports mixed effects of afforestation of grassland for SOC (Soussana et al. 2004) with different effects on SOC stocks with soil depth (de Stefano and Jacobson 2018). The conversion of pasture/grassland to agrisilvicultural systems in particular significantly reduced SOC stocks in the 0-100 cm soil profile. This reduction in SOC stock was related to the lack of perennial grasses which greatly contribute to organic matter turnover in the upper soil profile (de Stefano and Jacobson 2018). The conversion of agricultural systems was generally associated with increased SOC stocks (de Stefano and Jacobsen 2018, Li et al. 2012, Jose 2009). In Silvoarable systems the soil C levels within the uncultivated tree rows can be greater than within the cultivated alleys. Jäger (2017) estimated an additional 0.51 t of SOC ha^{-1} yr^{-1} in the topsoil 25 cm based on 22% of the area being allocated to trees.

Guo and Gifford (2002) report negative effects of converting pasture to plantation forest or secondary forest, although for secondary forests the effect was non-significant. In contrast, Li et al. (2012) report a positive effect of the conversion of pasture to agroforestry. Converting forests to agroforestry systems, especially agrisilviculture, reduced SOC stocks in the topsoil likely due to the lack of diversification, density, and structural complexity (de Stefano and Jacobson 2018). Notably, conversion from forest to pasture was found to increase SOC (Guo and Gifford 2002).

Planting trees together with N-fixing vegetation can increase C and N concentrations in the soil (Johnson and Curtis2001). If the use of agroforestry via increased natural pest regulation and improved nutrient efficiency reduces field operations (e.g. fertiliser, pesticide application), then reductions in fossil energy use to create and apply products will add further reductions to GHG emissions (Defra 2018).

Water quality & Conservation

Agroforestry leads to improvements in water retention. There is evidence of the importance of the location/position of woody features on hillslope (and also soil depth) for hydrological effects. In terms of runoff reduction, Chandler et al. (2018) compared soil saturated hydraulic conductivity between ungrazed farm woodland under contrasting tree species (Scots pine and sycamore), grazed silvopasture and upland pasture; this study showed that the coniferous farm woodland had the greatest saturated hydraulic conductivity but also that grazing negated beneficial effects of trees on water regulation. Xiong et al. (2018) carried out a meta-analysis comparing afforestation to other conservation techniques such as reduced tillage and engineering (e.g. terraces) and found that afforestation (and other biological techniques) reduced soil loss by 88% and runoff by 55%, and were generally more effective at reducing soil and water loss than the other methods.

There is also potential for silvopastoral agroforestry to act as riparian buffer strips. They provide benefits for water quality downstream i.e. via uptake and assimilation of nutrients from groundwater and surface water, reduce runoff rates thereby promoting infiltration, sediment deposition, and nutrient retention. They promote stream bank stability and erosion control and space for flood water storage resulting in improved flood defence downstream (Alison et al. 2019, Naiman and Décamps 1997, Sabater et al. 2003, Wharton and Gilvear 2007). Several studies have shown that agroforestry vegetative buffers reduce nonpoint source pollution from row crop agriculture (Nair 2007). Where nutrients have been leached below the rooting zone of crops, trees with deep roots can utilise excess nutrients (Jose 2009). Agroforestry systems also have the potential to mitigate movement of harmful bacteria such as *Escherichia coli* into water sources (Dougherty et al. 2009).

Co-benefits and trade-offs

As mentioned, C sequestration can be a benefit associated with agroforestry. Globally, deforestation is a major threat to forests with great impact on terrestrial C losses to the atmosphere and their feedback to climate change. Nair (2007) states “assuming that one hectare of agroforestry could save five hectares from deforestation” C emission from deforestation can greatly be reduced by implementing agroforestry systems.

Depending on the type of woodland restored, there may be other co-benefits such as recreation and timber production (Alison et al. 2019), coppicing or fruit production (Smith et al. 2017).

Silvopastoral and silvoarable agroforestry can provide shelter and shade for livestock and crops, improve nutrient cycling, improve air quality through pollutant capture, provide habitat for pollinators and other wildlife and improve water retention (Jose 2009, Smith 2010). Depending on the crops, silvoarable agroforestry can also increase total yields and profitability, but often does not (Torralba et al. 2016). The foliage from the trees may represent a significant feed resource depending on tree species, in particular in terms of energy, protein and micronutrients for cattle for instance, white mulberry (*Morus alba*) and common ash (*Fraxinus excelsior*) (Hermansen et al. 2017).

Some socio-economic co-benefits include co-benefits of diversified income from trees, including high value tree and fruit crops in agroforestry systems and improved biosecurity from hedgerows reducing transmission between stock in adjacent fields. However, wide hedgerows can also provide habitat for alleged secondary vectors (badgers) (Keenleyside et al. 2019).

Silvoarable systems require fewer N inputs, both because the area of crop is reduced and because the greater litter input and more extensive root systems fix N in the soil (Keenleyside et al. 2019). Notable trade-offs include a reduction in agricultural productivity although there is mixed evidence on whether yield and productivity is better or worse in an agroforestry system (see above).

In some agroforestry systems land can be "locked up" for forestry for decades. This is less of an issue for hedgerows, and shelterbelts trees along ditches. There may be conflict between two competing land uses e.g. mixing stock with fruit production creates issues around biosecurity and use of chemicals (Hermansen et al. 2017).

Magnitude

There is a potentially significant impact if action is taken to improve the biodiversity management of existing hedgerows and trees on farmland, and to create more diverse types, species and structures in agroforestry systems in a way that secures long-term multiple benefits for habitat function, climate adaptation and C sequestration and storage.

Soussana et al. (2004) propose a small increase in C following afforestation of grassland of 0.1 t C ha^{-1} y^{-1}, with a high degree of uncertainty. Upson (2014) calculated that a poplar system at 10 m × 6.4 m spacing in the UK would sequester 2.7–2.9 t C (ha^{-1} $year^{-1}$ in trees, but arable crop production would not be profitable for 12 years after tree planting. Aertsens et al. (2013) estimated a theoretical annual C sequestration from agroforestry of 1.56 Pg C in the EU27, if it was introduced on 90 million ha of arable land and 50 million ha of pasture land. However, the proposed system would lead to decreases in agricultural production.

Lorenz and Lal (2014) summarize the global C storage potential for agroforestry systems to range between 1.1 and 2.2 Pg C yr^{-1} for the top 1 m over a 50-year period with temperate agroforestry systems contributing relatively little compared to tropical systems.

In temperate regions, the C sequestration potential was highly variable ranging between 15 and 198 Mg C ha^{-1}, with a mode of 34 Mg C ha^{-1} (Dixon et al 1994), likely linked to differences in vegetation and soil properties (Lorenz and Lal 2014). Laganiere et al. (2009) suggest that broadleaf species have a greater capacity to accumulate SOC than conifers (see also Torralba et al. 2016) due to their deeper root system and higher ratio of root biomass-to-aboveground biomass. Furthermore, C sequestration or loss rates were different for soil organic and mineral layers (Laganiere et al. 2009, Li et al. 2012). Lorenz and Lal (2014) conclude that "it remains to be studied whether agroforestry systems can be specifically designed and managed to maximize the belowground C sequestration in soil […]".

Timescale

Biodiversity and other benefits would begin to appear in years 0-5, for example from replacing diseased trees, natural regeneration of hedgerow trees and development of agroforestry systems, and continue to develop over many years as the trees mature (Keenleyside et al. 2019). Timescales for effects of afforestation on SOC are unclear (Alison et al. 2019). A meta-analysis by Li et al. (2012) suggests that soil C and N stocks significantly increase after 30 and 50 years of afforestation respectively; before that, soil C and N stocks decreased or remained unchanged.

Spatial issues

Many agroforestry systems are linear and there is potential for agroforestry systems to deliver biodiversity benefits (and public goods) if proper landscape design and planning occurs to maximise range of environmental benefits (Keenleyside et al. 2019). Soussana et al. (2004) and Laganiere et al. (2009) highlight positive SOC impacts of afforestation on clay or calcareous soils in a mountain climate, but negative effects in warmer climates on sandy or acidic soils. There are also effects on the depth distribution of C in the different agroforestry systems (de Stefano and Jacobson 2018).

Displacement

Planting trees on agricultural land can lead to a reduction in agricultural output and a consequent displacement of production and GHG emissions (Eory et al. 2015). However, displacement effects may be alleviated by planting on degraded cropland which is unproductive (Powlson et al. 2011), or by establishing agrosilvopastoral systems instead of agrisilvicultural or silvopastoral systems.

Longevity

Afforestation is likely to achieve permanence due to the mechanical difficulties of reversing this process, and legal protection of woodlands.

Climate interactions

There is emerging evidence on the potential climate mitigation and adaptation benefits of agroforestry systems. It certainly has a significant role in decarbonisation, with sequestration benefits dependent upon the type of system and the soil (Keenleyside et al. 2019). Kay et al (2019) show that strategic and spatially targeted establishment of agroforestry systems could provide an effective means of meeting objectives on GHG emissions whilst providing a range of other important benefits. Climate change mitigation will involve the use of innovative tree varieties adapted to different climatic conditions.

Agroforestry contributes to the adaptation of the countryside to a changing climate, through micro-climatic effects within the habitat and on surrounding land. Tree lines can act as windbreaks to reduce wind speed and soil erosion and improve microclimate (Kanzler et al. 2017). The use of trees in alley cropping can improve soil moisture for shallow-rooted crops (e.g. cereals and vegetables) and also reduce the extreme changes in soil temperature during periods of drought, associated with high temperatures or in extreme cold weather conditions (Vityi et al. 2017).

Climate change is likely to increase the risk of pests and diseases especially in the absence of effective quarantine controls. The local climate will affect the type of forest that it is suitable to restore (Alison et al. 2019). Higher temperature increased the rate of SOC loss for this transition in a meta-analysis (Alison et al. 2019, Poeplau et al. 2011).

Social and economic barriers

Major barriers to implementation of agroforestry are expertise, knowledge, technical skills and time to manage woodland, and possibly unwillingness to invest capital in non-agricultural land management, particularly as this is a decision for the long term (Keenleyside et al. 2019). Farmers are not generally aware of the positive benefits of trees on farms, and culturally there is a perception amongst some farmers that trees get in the way of farming and concerns about the extent of competition with pasture/crop species (Keenleyside et al. 2019). Smaller areas of land providing wood chip and/or shelter may be of greater interest or creation of hedgerows (Alison et al. 2019).

Agroforestry can have significant costs at establishment particularly in pastoral systems, due to the need for protective fencing and loss of crop area (Hernandez Morcillo 2018). Many arable agricultural practices are adapted to large fields and the use of large machinery and it would be challenging to reintroduce field boundaries and consequently smaller fields. However, alley cropping has been successfully applied in some European countries and an initial focus on planting shelterbelts along existing field boundaries might also be a successful approach (Kanzler et al. 2017).

The policy framework may also be a barrier; currently agroforestry falls in the gap between forestry, environmental stewardship and agriculture and funding options are unclear. Other barriers are the limitations on long-term business planning and capital investment imposed by short-term tenancies. Investment and management support could enable farmers to restore existing agroforestry systems (e.g. hedgerow trees, shelter systems) and to develop new combinations of tree crops with existing arable and pasture systems, which may involve restructuring the farm business model. Targeted public support would ensure that these are designed (in terms of choice of species and systems) and located in the farmed landscape to maximise the long-term delivery of environmental public goods and climate adaptation benefits for the sector (Keenleyside et al. 2019).

Metrics and verification

There are methodological challenges linked to sample collection, analysis and data reporting, but also, the variability of effects across the different types of agroforestry limit the evaluation of agroforestry benefits (de Stefano and Jacobson 2018).

Biodiversity

Positive relationships have been found between increases in trees and shrubs and species richness of vascular plants, birds, butterflies, bumble bees, ground beetles and dung beetles. These should all be monitored and measured. Birds can be monitored using standardised methodologies e.g Breeding Bird Survey (Harris et al. 2018). Invertebrates can be surveyed using pitfall traps, sweep nets and transects (see pollinators). Plant species richness and abundance can be measured in quadrats (Halbritter et al. 2019), the size depends upon the context and there will be different contexts, for example within crops associated with agroforestry at varying distances from the agroforestry feature (2 m x 2 m), along hedgerows and woody linear features (linear plots e.g. 1 m x 10 m), within woodland (larger plots e.g. 10 m x 10 m). Vegetation plot data can be used to calculate metrics indicating eutrophication (e.g. Ellenberg fertility score, Grime CSR scores), whether species are generalists or woodland specialists. The composition of the agroforestry element in terms of woody diversity, non-native species should also be measured.

Vegetation structural characteristics have important effects on biodiversity so as well as biodiversity there are other measurements of the agroforestry element that may also be taken.
Structural condition criteria include:

- Height,
- Width (and resultant cross-sectional area),
- Crown and growing period,
- Tree biomass yield,
- Dates of bud break and leaf fall,
- Measurement of tree growth rates and stem form,
- Height of hedge base (indicative of effective management),
- Width of margins (width of perennial vegetation >1 m and distance from the centre to the edge of the plough > 2 m).

There should also be measurement and monitoring of landscape-scale biodiversity. This would include determining the extent, quality and connectivity of habitats in the landscape surrounding each agroforestry type. This could be through field survey (particularly for quality) or remote sensing for extent and connectivity.

Pest & disease control

Weed abundance has been shown to increase under silvoarable agroforestry. Weed abundance can be assessed in quadrats (1 m^2) at different distances from the trees in crops, and by taking photos. The impact of wildlife on trees can also be assessed using photos or scoring. Evidence suggests that agroforestry increases the abundance of beneficial insect predators although insect pests could also increase. These can be measured using pitfalls, soil cores, sweep netting/transects or pan traps.

Pollination

Agroforestry should increase pollinator diversity and abundance. Monitoring should include pollinator transects (Carvell et al. 2015), counted in appropriate weather conditions (dry weather temp > 17^{o}C, wind speeds up to 5 on Beaufort windscale). The plant species visited should be noted and the distribution and abundance of nectar plants along a transect including floral density by scoring flower abundance.

Soil quality and conservation

Agroforestry can increase nutrient retention, soil structure, and nutrient cycling so soil nutrient status, soil aggregate stability should be measured. However, changes in soil N (and soil C) have been found to take place over long time scales after afforestation and should be kept in mind. Agroforestry can also reduce soil erosion so measurement of soil erosion should be carried out.

Carbon (C) sequestration and Greenhouse Gas (GHG) emissions

Agroforestry can sequester C in biomass and soil however it can be variable, going from simple systems such as arable to woodland can increase SOC. However, afforestation of grassland can reduce SOC. SOC stock (g or t C yr^{-1}) is an important component to measure in the topsoil and at depth. Aboveground C can be estimated if sufficient structural measurements are taken.

Water quality & water conservation

Agroforestry is thought to improve nutrient retention and to reduce run off of nitrate fertilisers and pollutants. Water quality should be monitored. However, as mentioned, it is difficult to attribute changes on individual farms or fields to changes in water quality. It may be better to focus on the level of pollutants in the soil which can be easily measured by each individual farmer. Agroforestry can improve water retention, infiltration capacity and soil moisture can be measured.

Climate

As mentioned above trees can provide climatic benefits, trees can act as windbreaks to reduce wind speed, improve microclimate (Kanzler et al. 2017) and reduce extreme changes in soil temperature (Vityi et al. 2017). Measurements would include soil temperatures, air temperatures, wind speeds and light penetration.

Yield

Although there is evidence that agroforestry can lead to increased yields there is also evidence contradicting this so it would be desirable to measure yield in agroforestry systems. This could involve monitoring a number of different components e.g. forage yield, crops: yield and quality of crops at progressive distances from trees, fruit yield, the nutritive value of trees and scrubs for ruminants and stocking density.

2.3.7 (7) Hedgerow management

Definition

Hedgerows are a component of Agroforestry so a lot of the above section on agroforestry applies to hedgerows. Hedgerows are linear features over 20 m long and <5 m wide within farmed landscapes that incorporate a shrub component, hedgerow trees (where present) and associated ground flora. A hedgerow may also encompass not just the lines of trees or shrubs, but the base of the hedge which may be an earth bank, an associated ditch and permanent herbaceous margins where the management is influenced by the presence of shrubs or trees (Wolton et al. 2014).

Hedgerow management options could include a) “gapping up” (planting regionally relevant new hedgerow plants in gaps at an appropriate spacing and density- this could be a response to loss of trees through tree disease); b) rejuvenation through hedge laying or coppicing and other locally relevant (traditional) management practices and fencing on both sides to restrict livestock access during establishment and regeneration, and c) improvement of ground flora by limiting stock access, stopping application of fertilizer or it may require more extreme measures such as turf stripping or adding seeds and propagules.

Once hedges are restored or rejuvenated they need to be kept in a management cycle to ensure that they continue to form effective hedges and produce associated ecosystem services. Potentially, management may incorporate harvesting of wood as fuel, either as part of the regular cutting cycle (2-3 years) or the longer-term laying/coppicing cycle. Management of ground flora will require a fertilizer/pesticide free margin adjacent to the hedge (of at least 2 m from hedge center and 1 m from the edge of the extent of canopy - in accordance with cross compliance requirements) (Dickie et al. 2015). Hedge bottom, ditch sides and margins should be managed to promote a diversity of herbs and to allow their flowering, to provide pollen and nectar for pollinators. Hedge shrubs should not be cut more often than once every three years to ensure a reasonable amount of flowers (Staley et al. 2012). Larger, denser hedgerows will benefit wildlife by providing a greater habitat area linked to the presence of small mammals, bats and birds (Graham et al. 2018).

Causality

Wolton et al. (2014) carried out an extensive review of regulatory services delivered by hedges. They examined and consolidated existing reviews, reviewed the literature and contacted people from key organisations and networks, a lot of this material is used here.

Yield

There have been shown to be mixed effects on crop yield in Silvoarable systems. In Canada, in low rainfall years, crop yields fell immediately adjacent to a shelterbelt due to competition for water but were slightly higher in the next band outwards into the crop (Kowalchuk and Jong 1995). As above for agroforestry systems, there is evidence of increased yields in alleys between trees compared with conventional fields (Kanzler and Mirck 2017, Vityi et al. 2017). However, in other studies declines in yields were reported for the arable crops planted in close proximity to the trees (possibly due to competition for solar radiation and water) (Gosme and Desclaux 2017, Arenas-Corraliza et al. 2017, Kanzler et al. 2017).

In the UK, although data for all studied cereal crops indicated a decline in yield with greater proximity both to hedge (coppiced or standing) and tree rows, an exception of this trend was reported for oats, which benefited from proximity to a coppiced hedge (Smith et al. 2017a).

Biodiversity

Hedgerows positively affect the richness and abundance of flora, invertebrates and birds (Boatman (ed) 1994, and Hinsley and Bellamy 2000), and there is good evidence that the structure and form of a hedgerow and its management, in terms of differences in width, height, fenced buffer strips, frequency of cutting etc., has a big effect on biodiversity (Keenleyside et al. 2019). Management variability and resulting structural attribute variability have a greater influence on biodiversity than hedgerow habitat spatial configuration and landscape context (Graham et al. 2018, Deckers et al. 2004). Management that affects light levels, temperature and disturbance within a hedgerow is important for ground flora due to the hedgerow's similarity to a woodland edge (McCollin et al. 2000). Staley et al. (2013)found a trend towards taxonomic homogenisation of hedgerow ground flora driven by a decline in traditional hedgerow management techniques applied by hand, and increased eutrophication over time (from excess soil enrichment). Generalist herbaceous species benefit from management practices that open up the canopy such as coppicing. However, this may be at the expense of shade loving plant species such as ancient woodland indicators (Staley et al. 2013). Dense hedgerows may also limit drift of agri-chemicals into hedgerow basal flora (Tsiourus and Marshall 1998).

The vegetation structure and hedgerow dimensions are critical to the presence and abundance of small mammal species (Graham et al. 2018). Small mammals avoid hedgerows with large gaps (> 3 m). Hedgerow width and length increase the total habitat area, indirectly increasing microhabitat complexity and refuge from predators (Gelling et al. 2007) for species including *Myodes glareolus* (bank vole) and *Apodemus flavicollis* (yellow necked mouse). *Muscardinus avellanarius* (dormouse), an arboreal species, uses hedgerows all year round, favouring large, dense, species rich hedgerows (Bright and MacPherson 2002).

Bats fly along hedgerows (Downs and Racey 2006) and use them for feeding, shelter and navigation at a range of scales (Walsh and Harris 1996). Bats are macro-invertebrate feeders, and structural components of the hedgerow, which increase the abundance of macro-invertebrates, may also benefit bats by increasing food availability. The activity of pipistrelle bats and bats with short to medium range echolocation are likely to be negatively affected by hedgerows with a heterogenous height profile as their manoeuvrability across the landscape is limited. A study comparing bat activity between organic and conventional farms found that bats were thought to prefer organic farms due to the presence of taller hedgerows, providing more shelter and greater food availability (Wickramasinghe et al. 2003). Dense basal vegetation of prickly species is thought to reduce hedgehog mortality (Graham et al. 2018).

Hedgerow management under agri-environment schemes is associated with greater use by hedgerow bird species (Davey et al. 2010, Redhead et al. 2013) but there is only limited evidence for benefits to species' population growth rates at a national scale (Baker et al. 2012) probably because this management benefits breeding productivity, but most species are limited by over-winter survival. Hedgerow structure affects bird species in different ways (Graham et al. 2018). Tall hedgerows support species such as robin, song thrush, willow warbler and woodland species such as common chaffinch. Wide hedgerows are associated with greenfinch, goldfinch, wren, and common blackbird (Green et al. 1994). Shorter hedgerows may be preferred by the Linnet and yellowhammer (Green et al. 1994).

The predation rate of song bird nests by corvids is higher where nest sites are open and more accessible (Dunn et al. 2016). Nest site selection favours dense vegetation, which results in higher chick survival. This cover is better provided by hedgerows within a cutting cycle, rather than recently coppiced or remnant hedgerows (Graham et al. 2018). Ground nesting species need denser basal vegetation to be protected from predation (Hinsley and Bellamy 2000). Species composition and the age structure of the hedgerow is important. Dominance by individual woody or herbaceous plant species is associated with a significant difference in the percentage incidence of some bird species e.g. Whitethroat-elm dominant hedgerows (11.6% incidence) compared to hawthorn dominant hedgerows (4.5% incidence), Blackbird-parsley family ground flora dominant hedgerow (39.9% incidence) compared to Dog's mercury dominant hedgerows (16.7% incidence) (Green et al. 1994). The incidence of farmland bird species is positively associated with woody species rich hedgerows (30 m long plots) (Green et al. 1994) and with a greater percentage of hawthorn and bramble (Walker et al 2005).

Hedgerows have higher invertebrate diversity than other parts of the agri-environment structures (Maudsley 2000) and can affect beetle numbers even up to 1 km away (Holland and Fahrig 2000). Hedgerows that are larger and more structurally complex, with different strata of vegetation have higher invertebrate diversity (Maudsley 2000, Maudsley et al. 2002) because of a greater amount of niche space, greater resource availability, microclimate and shelter (Weibull and Ostman 2003, Langellotto and Denno 2004). Species associated with relict and remnant hedgerows tended to have low dispersal ability (Griffiths et al. 2007), a wider hedge base is beneficial for Staphylinidae by reducing habitat disturbance and edge effect (Maudsley et al. 2002), an established shrub layer can provide important forage for *Apoidea* (bees) and other pollinator species (Hannon and Sisk 2009), especially where the abundance and diversity of floral resources has been enhanced by management (Morandin and Kremen 2013, M'Gonigle et al. 2015). Cutting of hedgerows impacts on invertebrates: inappropriate timing of cutting results in loss of invertebrates. For instance it has been suggested that annual cutting regimes led to lower brown hairstreak (*T. betulae*) egg abundance, compared with hedgerows cut in less frequent rotations (Staley et al. 2017). The dominance of autumn cutting outside of environmental stewardship schemes can kill, injure or disturb species still active beyond September (Maudsley 2000). Cutting can also reduce the floral resource which can impact on nectar dependent species such as Lepidoptera (Staley et al. 2012). However, regular cutting also stimulates new growth which may be beneficial for other invertebrates (Maudsley 2000).

Hedgerows managed using hedge-laying approaches had greater abundance of detritivores, herbivores and predators than circular saw (Amy et al. 2015). Many invertebrate groups benefit from mature growth hedgerows because they provide a range of flowers, cavity nesting spaces and dead material for a variety of pollinators, (Kremen and M'Gonigle 2015). Hedgerow species composition is also important, the existence of individual woody species or combination of species within a hedgerow could favour particular invertebrate assemblages over others (Butler et al. 2012).

Heterogeneity in hedgerow structural condition is important because no single set of hedgerow characteristics were found to benefit all taxa and, if uniform hedgerow management is overprescribed, some species are likely to be negatively affected by a loss of suitable habitat or resource decline (Graham et al. 2018). A report for Defra (Wolton et al 2014)., focused on hedgerow priority species and those listed as Biodiversity 2020 Farmland Indicators, presents evidence of the importance of the inter-relationship of the five structural components of hedges (trees, shrubs, hedge base, field margins and ditches). Overall, of the 107 species studied, the majority (65%) are dependent on more than one hedge component, and over a third of them (35%) are dependent on three or more components (Wolton et al 2014).

Establishing hedgerows in agricultural landscapes has the potential for creating wildlife corridors, allowing the movement of populations (Hilty et al. 2006) to places with better climate conditions. It is inherently hard to collect empirical evidence (and thus parameterise models) of causality about use of hedgerows by species as corridors (Davies and Pullin 2007). There is a lack of clear evidence of the positive benefits of hedgerows in increasing landscape connectivity for woodland-dependent taxa (Davies and Pullin 2006, 2007) although there is good evidence of benefits of hedgerows for a different set of species (broadly, described as "edge specialists").

Pollination

Some crop pest predators are also pollinators and may increase crop yield through improved pollination services. Wolton et al. 2014 found evidence that hedgerows, and other patches of non-cropped ground, are important in agricultural landscapes for the existence of healthy and diverse pollinator populations. Hedgerows can attract pollinators into intensive farmland (Haenke et al. 2014, Morandin and Kremen 2013) and export those pollinators into crops, increasing yield. Hedges provide breeding sites, food when crops are not in flower, shelter, protection and flight lines (Kells et al. 2001, Kells and Goulson 2003, Pywell et al. 2005). They are of particular importance for nesting bumblebees. Their value can be enhanced by the cultivation of nearby strips or patches of flowers grown for nectar and pollen. However, practically no research has been carried out on the cost effectiveness of hedges in increasing crop yields through boosting pollination. Such research needs to encompass the activities of insects other than bees and hoverflies, since these other taxa may be as important - for example, several other families of flies are frequent visitors to flowers in hedges and presumably crops.

Hedges benefit pollinators and other beneficial insects through increasing landscape connectivity in intensive agricultural landscapes. Hedges provide a microclimate which is frequently warmer and less windy than in open fields and so attractive to potential crop pollinators (Croxton et al. 2002, Lewis and Smith 1969).

Pest & weed control

Hedgerows can enhance populations of the natural enemies (predators and parasites) of crop pests by providing a wide range of microhabitats across the shrub layer, trees, banks, base, margins, ditches and soil, nectar and pollen resources, and larval development resources. Most research has been on ground dwelling arthropods such as carabid beetles, and to a lesser extent spiders (Maudsley et al. 2002). Evidence relating to the aerial dispersal of predators such as hoverflies from hedges into crops is much more limited. Research shows that the greater the structural and floristic diversity of hedges, the greater their invertebrate diversity (Peng et al. 1992). The number of arthropod species varies by the individual plant species. Kennedy and Southwood (1984) found that hawthorn *Crataegus monogyna* supported 209 invertebrate species, whilst holly *Ilex aquifolium* only supported ten species. The influence of the relationship between hedgerows, arthropod predators and crop pests remains unknown.

The pattern in the landscape may influence predator densities and species richness, as opposed to habitat quality alone. Pest species themselves may utilise the additional resources managed or created to benefit their natural enemies, with unknown effects on biological control (Wolton et al. 2014). For example, in one study grain aphids in arable crops we originated from adjacent hedges in some years (Vialatte et al. 2007). Hedges may also depress yield because they harbour pests such as carrot root fly *Psila rosae* (Pollard et al. 1974).

Bats also use hedgerows to feed and to navigate and in the US insect feeding bats have been shown to reduce crop pests, with economic value to the cotton industry (Boyles et al. 2011, Cleveland et al. 2012). Hedgerows can also act as a source of weeds.

Soil conservation

In their review, Wolton et al. 2014 found strong evidence that hedges can reduce soil loss from fields through intercepting water-borne sediment and reducing surface flow rate. Hedges can capture soil from fields above them and decrease the rate of water flow over fields below, so reducing soil loss (Follain et al. 2009). Hedges lying perpendicular to the slope increase the depth of the topsoil on their uphill side and can result in terrace formation over time (Kovar et al. 2011, Lenka et al. 2012, Pointereau and Colon-Solagro 2008), which further reduces soil movements. The hedge species planted can exert a considerable influence over the effectiveness of a hedge to reduce run-off and erosion: dense and structurally strong species such as hawthorn, hazel and oak have been shown to be the most effective barriers. Tall, moderately dense, hedges can serve as windbreaks to reduce soil erosion in flat, open, landscapes and those with light, for example sandy or peaty, soils (Farmer et al. 2008, Pointereau and Colon-Solagro 2008).

Carbon (C) sequestration and greenhouse gas (GHG) emissions

There is evidence that hedgerows provide climate change mitigation through the storage and accumulation of C above and below-ground (Nair 2007, Wolton et al. 2014). The above section on agroforestry in general suggested that there are mixed effects on C sequestration depending particularly upon the type of landuse change; afforestation of pasture tended to have negative effects on SOC. Benefits may be more likely for hedgerows which do not require changes in overall landuse. There is some evidence of (small) hedgerow co-benefits for soil C stocks (Ford et al. 2019) and also for net GHG emissions (Ford, H. et al. in prep (Multiland project)).

Through capturing eroding soil, hedges across slopes can increase SOC for up to 60 m uphill, although cultivation will reduce such accumulation substantially through facilitating oxidisation. Increased depth of the A-horizon was seen as the single most important factor for increase in SOC (Walter et al. 2003).

Water quality and conservation

Wolton et al. (2014) found strong evidence to show that buffer strips and hedges can be effective at preventing nutrients and other pollutants from reaching water bodies, particularly if placed along contours or beside water bodies (Benhamou 2013). The effect of the hedgerow structure was less well studied but evidence suggested that hedges more than 2 m wide and those with an underlying earth bank are most effective. Hedges act as a physical barrier to the movement of water and associated sediment, including pollutants (e.g. phosphates, pesticides (Borin 2010)), increasing rates of infiltration into the soil and percolation of nutrients through the roots of shrubs and trees, acting as a sink for nutrients (Grimaldi 2012). Because hedgerows are composed of multiple species, nutrients can be used efficiently at different times of the year according to species (Solagro 2000). However, there is also potential for a hedge to change from a nutrient sink to source in the dormant season and when leaf material decomposes (Ryszkowski and Kedziora 2007). Hedge location, orientation and network density are often cited as important factors in the hydrological effects of hedgerows. Wolton et al. (2014) also found strong evidence that individual hedges (and other forms of buffer strips) along contours or fringing water courses have the potential to reduce the volume of water reaching streams and rivers, and the speed with which it does so, following storms. Lines of shrubs or trees can greatly increase infiltration of water into the soil (Borin et al. 2010, Carroll et al. 2004, Kovar et al. 2011, Lenka et al. 2012, Marshall et al. 2009, 2013) by the greater root penetration of trees and shrubs, higher transpiration rates of hedgerow trees and shrubs, the evaporation of rainfall intercepted by the hedge canopy before it reaches the ground (Caubel et al. 2003, Ghazavi et al. 2008, 2011, Thomas et al. 2008, 2012), and creation of soil terraces. Hedges also reduce soil water levels in and beyond the hedge root zone during the summer, so it takes longer to become saturated during the autumn, providing a buffer against flooding events. Individual hedges can therefore, to some extent, reduce the risk of flooding lower down in the catchment. Hedgerows with gaps in them will be far less efficient at storing water so management is critical. Also if ditches are laid alongside hedgerows this will reduce the effectiveness of hedges at intercepting and impeding surface water flow.

Hedges can influence the availability of water to crops negatively and positively. Shrubs and trees may cause increases in net uptake and transpiration of water, creating a rain shadow and making it unavailable to the crop, however they can also help to retain moisture by intercepting rainfall and controlling water movement e.g. reducing water loss through evaporation and transpiration as a result of increased shading and wind shelter, facilitating the infiltration of surface water into the soil, removing excess water to facilitate crop growth (Wolton et al. 2014).

Co-benefits and trade-offs

Hedgerows increase C storage and C sequestration in woody growth aboveground and in roots, leaf litter and other SOM at and below ground level. Tree lines store more C than shrubby hedges: mature trees have greater above ground biomass than shrubs and input more C into the soil through higher leaf and small branch litter fall. There is evidence that hedges can be especially effective for interception of aerial pollutants, especially in urban/peri-urban environments and along roadsides (Morakinyo et al. 2016, Abhijith et al. 2017). Co-benefit of (wide) hedgerows for improving biosecurity against some livestock diseases by reducing transmission between stock in adjacent fields, but wide hedgerows can also provide habitat for alleged secondary vectors (badgers) (Keenleyside et al. 2019). Hedgerows make a contribution to the cultural landscape (Barr and Petit 2001). Hedges in floodplains can potentially increase flooding risk to downstream settlements by reducing storage capacity.

Magnitude

Carbon (C) sequestration and greenhouse gas (GHG) emissions

Aboveground, uncut shrubby hedges may accumulate around 0.5 t C ha^{-1} yr^{-1}, while tree lines may accumulate more than 3 t C ha^{-1} yr^{-1} (Wolton et al. 2012). Belowground, Robertson et al. (2012) conservatively estimated that new hedges could accumulate 0.54 t C ha^{-1} yr^{-} and old hedges 0.46 t C ha^{-1} yr^{-1}.

For established hedge networks, evidence from Britain, Germany and France, suggests that hedges may store roughly 100 t C ha^{-1} although this will vary considerably according to hedge structure, woody species and age.

The hedges within a particular Brittany landscape have been estimated (at a high hedge density of 200 m ha^{-1}) to contain as much as 38% of the total C stock across the local farmed landscape. Where the hedge density was 50 m ha^{-1} the hedge network contain 13% of the C stored in the biomass and soils of that landscape (Walter et al. 2003).

Water quality and conservation

Nitrate in groundwater was three times lower with hedges, with removal rates around 90% compared to 53% for the site without hedge (Caubel et al. 2001). Borin et al. (2010) in Italy found that a mature buffer strip could abate both nitrates and dissolved P concentrations by almost 100%, and by 60% and 90%, depending on the chemical and the time elapsed since application. A newly established 4 m wide buffer strip containing a line of trees and a grass strip reduced total run-off by 33%, losses of N by 44% and P by 50% compared to sites without buffer strips.

Modelling based on experimental results suggested that a banked hedge network in a 5 km^2 catchment in Brittany would result in a decline in N at the outflow of 3.3% (Benhamou et al. 2013). In Brittany a banked hedge network in a 32 ha catchment reduced peak and total flow within streams following storms by between a quarter and a half (Merot 1999). Contouring banked hedges can prevent up to 40% of catchment run-off. Further work in Brittany, based on modelling, suggested that even at the low hedge density of 27 m ha^{-1} annual stream flow would be reduced by 10%, and that in the particular landscape studied overall water interception by banked hedges was likely to reach its maximum at a density of 60 m h^{-1} (Viaud et al. 2005). In a study using a 4 m buffer strip planted at the beginning of the monitoring period with one line of trees (species not specified) and a strip of grass, total run-off over six years was reduced from 97 mm to 61 mm, a 33% reduction (Borin et al. 2010). At Pontbren, Carroll et al. (2004) report that strips of native trees (mainly birch and alder but with some blackthorn, oak and ash) can increase water infiltration compared to adjacent sheep grazed upland pasture by 60 times, when the trees are only six or seven years old (Wolton et al. 2014). Herbst et al. (2006) found that rainfall reaching the ground was reduced by 57% when the hedge they were studying was in leaf, and 49% when not in leaf.

Soil conservation

In seven study sites in Brittany soil accumulated near the hedge (Walter et al. 2003), soil thickness ranged from 30-60 cm near the top of the slopes, whereas down slope thickness increased to more than 1 m under the hedge. Bu et al. (2008) showed that a range of single-species shrub hedges in China were able to reduce run-off on sloping land by 17.2% - 70.8% and soil loss by 18.4% - 70%.

Climate

Hedges acting as windbreaks, if properly designed, are likely to reduce wind speed significantly over a distance of 12 times the height of a hedge on the downwind side, and 4 times on the upwind side. Thus, a hedge that has grown 6.25 m high may provide significant shelter over a distance of 100 m (Wolton et al. 2014). At a wider landscape scale evidence shows that networks of hedges can exert a significant influence on local climate, decreasing average wind speed by up to 60% (Pointereau and Colon-Solagro 2008), increasing daytime and decreasing night time temperatures, and increasing humidity.

Timescale

Hedgerow creation or restoration is a long-term process, with habitats likely to take decades to mature to provide their full biodiversity value (Keenleyside et al. 2019). Coppicing causes temporary but complete loss of the hedgerow habitat in the short-term, but has positive long-term effects on hedgerow biodiversity, including ground flora (Staley et al. 2013).

Biodiversity and other benefits would begin to appear in years 0-5, for example from replacing ash trees, natural regeneration of hedgerow trees and development of agroforestry systems, and continue to develop over many years as the trees mature. The effects of long-term management can remain evident in the composition of floral communities after 2 to12 years (Alignier and Baudry 2015).

Actions to increase the woody element of a hedge by laying or replanting are likely to take between 5 and 10 years to produce a hedge in structurally “good” condition. Recovery of associated ground flora may be rapid if interventionist action is taken (e.g. turf is stripped and flora sown into place), but will take considerably longer if reliant on natural recruitment from local species pools. Recovery of hedgerow trees depends on tree species and rate of growth, but will take decades (Dickie et al. 2015).

Spatial issues

Spatial configuration is a very important aspect of the contribution of hedgerows to ecosystem service provision. Contoured hedgerows may be particularly important for water regulating ecosystem services (Dickie et al. 2015).

Displacement

Hedgerows can add some of the benefits of agroforestry whilst not causing displacement of production elsewhere i.e. they can exist alongside production.

Longevity

Effects can be long term but to maintain all benefits management is required over the longer-term. While aboveground levels of C storage may reach equilibrium within a few decades even in uncut hedges, belowground this process may take many centuries. Robertson et al. 2012 suggested that based on data from British woodlands, hedges might continue to accumulate C for 700 or more years, before reaching a state of equilibrium.

Climate interactions

Strong evidence exists to prove that hedges managed as windbreaks or shelterbelts can improve crop yields. In particular, vegetables and fruits, along with broad-leaved crops like potatoes, sugar beet and beans (Wolton et al. 2014). Available information on likely net increases in yield suggests that for arable crops, such as cereals, this is likely to range from just a few percent to as much as 25% within the sheltered area. For vegetables and fruit, the yield increase may be much greater than this, perhaps as high as 75%. Crop type, local climate and soil, and hedge structure will all affect yields. Likewise, there is plentiful evidence to show that livestock such as sheep and cattle benefit from the protection from wind, driving rain and snow, which can be provided by hedges. The role of hedges in providing shade may be particularly important in temperate areas such as the British Isles, especially with climate change. Windbreaks can reduce livestock mortality (particularly of young animals) and heat stress, and increase growth rates, milk yield, disease resistance and fertility.

Social and economic barriers

Skills, expertise and costs in establishment and management may hinder the establishment and proper management of hedgerows.

Metrics and verification

Biodiversity

Hedgerows positively affect the richness and abundance of flora, mammals, invertebrates and birds. Plant diversity and abundance can be surveyed in quadrats along hedgerows and linear features (e.g. 1 m x 10 m plots). Metrics indicating whether there has been eutrophication can be calculated from the plot data (e.g. Ellenberg fertility score, Grime CSR scores). Analyses of species composition and characterisation of species as generalists or woodland indicators can be carried out. The composition of the hedgerow in terms of woody diversity and non-native species should also be measured.

Vegetation structural characteristics have important effects on biodiversity so as well as biodiversity there are other measurements of the hedgerow itself that should be taken.

Structural condition criteria include:

- Height,
- Width (and resultant cross-sectional area),
- Height of the hedge base (indicative of effective management),
- Width of associated margins (width of perennial vegetation >1 m and distance from the centre to the edge of the plough >2 m).

For birds standardised methodologies can be used e.g. Breeding Bird Survey (Harris et al. 2018). Mammals including hedgehogs, voles and bats. Invertebrate survey methods are described under pests & diseases and the same methods can apply to both pests and biodiversity.

There should also be measurement and monitoring of landscape-scale biodiversity. This would include determining the extent, quality and connectivity of habitats in the landscape surrounding each agri-environment option. This could be through field survey (particularly for quality) or remote sensing for extent and connectivity.

Pest & disease control

Evidence suggests that hedgerows increase the abundance of beneficial insect predators although insect pests could also increase. These can be measured using pitfalls, soil cores, sweep netting/transects or pan traps. Weed abundance may also increase with hedgerows acting a source for weeds. Weed abundance can be assessed in quadrats (1 m^2) at different distances from the hedgerow in crops and photos taken. The impact of wildlife on trees can also be assessed using photos or scoring.

Pollination

Hedgerows are important for pollinators and attract them to intensive farmed landscapes. They are important habitat for bees, however, often monitoring focuses solely on bees and hoverflies and other taxa should be considered e.g. flies as they may be very important. Monitoring should include pollinator transects (Carvell et al. 2015) and pollinators should be counted in appropriate weather conditions (dry weather temp > 17^{o}C, wind speeds up to 5 on Beaufort windscale). The plant species visited should be noted and the distribution as well as abundance of nectar plants along a transect including floral density by scoring flower abundance.

Soil quality and conservation

Hedgerows can increase nutrient retention, soil structure, and nutrient cycling so soil nutrient status, soil aggregate stability should be measured. Hedgerows can also reduce soil erosion and measurement of soil erosion should be carried out.

Carbon (C) sequestration and greenhouse gas (GHG) emissions

There is evidence that hedgerows provide climate change mitigation through the storage and accumulation of C above and belowground (Nair 2007, Wolton et al. 2014). Reduction of soil erosion also helps to retain SOC. SOC stock (g or t C yr^{-1}) is an important component to measure in the topsoil and at depth. Aboveground C can be estimated if sufficient structural measurements are taken.

Water quality & water conservation

Hedgerows have been found to improve nutrient retention and to reduce run off of N fertilisers and pollutants. Water quality should be monitored to confirm the magnitude of the impact. However, as mentioned, it Is difficult to attribute changes on individual farms or fields to changes in water quality. It may be better to focus on the level of pollutants in the soil which can be easily measured by each individual farmer. Hedgerows can improve water retention, infiltration capacity and soil moisture can be measured.

Climatic interactions

As mentioned above trees can provide climatic benefits, trees can act as wind-breaks to reduce wind speed, improve microclimate (Kanzler et al. 2017) and reduce extreme changes in soil temperature (Vityi et al. 2017). Measurements should include soil temperatures, air temperatures, wind speeds and light penetration.

Yield

There have been shown to be mixed effects of hedgerows on crop yield generally with distance and due to competitive interactions. Measurements of crop yield should be taken at progressive distances from hedgerows.

2.3.8 (8) Field margin management

Definition

Field margins can be managed to benefit biodiversity, pollination and pest control. Arable field margins are less productive than field centres due to many factors including weed competition and soil compaction so they are a good place to take some land out of production (Dickiet et al. 2015) to benefit other ecosystem services. They help to protect hedgerow flora and fauna from pollution and eutrophication from fertilisers and pesticides.

There are different types of field margin management that could be practiced; a conservation headland – crop remains in place, no spraying or fertilising, cutting and cultivating to 15 cm to allow natural regeneration, uncultivated margins- unsprayed refuges where natural enemies may reside, perennial grass strips around arable/pastoral fields ("beetle banks") or floral strips that could be planted with different mixtures, wild flowers, and bird food plants (Jonsson et al. 2015, Defra 2007).

Causality

Biodiversity

Creating field margins can significantly increase biodiversity, including vulnerable wild pollinator populations, beneficial invertebrate species (Dickie et al. 2015), plants and birds. In a study by Defra (2007) soil invertebrates and earthworms in particular were more abundant in the sown margins – indicative of improved soil condition (over the cropped land). There was evidence that the complexity and therefore the stability of invertebrate food webs are higher in the non-cropped margins, and particularly those sown with wildflowers. This will have important implications for the regulation of pest species and the strength of trophic cascades. Josefsson et al. (2015) found that fields with buffer strips supported on average 0.51 ± 0.26 more skylark territories ha^{-1} up to 100 m into the field and boosted invertebrate activity densities compared to fields without buffer strips. These effects were most apparent early in spring, but persisted throughout the sampling period, and were similar among spring and autumn sown fields.

Pest & weed control

Field margins, by reducing disturbances and providing resources that benefit natural enemies such as carabid and staphylinid beetles, that eat crop pests like aphids within or around agricultural fields, can support beneficial insects and pest predators and increase natural attack rates on pests so reducing their impact (Jonsson et al. 2015, Landis, Wratten and Gurr 2000). This can lead to reduced pesticide use (Firbank et al. 2011).

Jonsson et al. (2015) found that experimental provision of floral resources enhanced parasitism rates of two globally important crop pests in moderately simple landscapes but not in highly complex ones, and this translated into reduced pest abundances and increased crop yield. Wolton et al. (2014) found that in autumn and spring, grass margins that were either sown or established through natural regeneration were found to contain predatory beetles (Coleoptera: *Carabidae, Cantharidae, Coccinelidae* and *Staphylinidae*), harvestman (*Opiliones*), spiders (Araneae: *Lycosidae* and *Linyphiidae*) and bugs (Heteroptera: *Anthochoridae*) (Meek et al. 2002). In winter a diverse range of carabid and staphylinid species and spiders from the families *Lycosidae, Linyphiidae, Tetragnathidae* and *Clubionidae* were found (Pywell et al. 2005), as well as other beneficial species including woodlice (*Isopoda*) and earthworms (*Lumbricidae*) (Smith et al. 2008). Grass margins also support a diverse range of alternative prey including phytophagous invertebrates (Woodcock et al. 2008) and the hosts of parasitic wasps (Powell and Pickett 2003).

Pollination

Field margins, particularly if planted with wild flowers, have the ability to increase wild bee and pollinator abundance across a variety of agricultural landscapes (Williams et al. 2015, Scheper et al. 2013). Restoration of diverse floral habitats adjacent to high-value pollinator-dependent crops can increase pollination and pay for habitat installation in three to four years (Blaauw and Isaacs 2014). Studies across landscapes exhibiting a gradient of agricultural intensity to investigate the effects of sown flower mixtures and provision of floral resources showed that sown patches attracted higher densities of worker bees and males and queens (as an indicator of bee reproduction) than unsown controls response being strongest in the more intensively farmed landscapes (Carvell et al. 2011, 2015). In a study for Defra (2007) comparing different types of field margins, numbers of pollinators mirrored changes in flower numbers with the pollen and nectar flower and the wildflower mixes having highest numbers. Species richness of bees and butterflies followed similar patterns, although there were also within year effects dictated by the availability of key pollen sources throughout the spring/summer.

Carbon (C) sequestration and GHG emission

In an experiment topsoil C was enhanced by sown margins (Defra 2007).

Water conservation and water quality

Regulation of water flow and quality by field margins acting as buffer strips to retain water and sediments is dependent upon the location of pollinator strips in relation to topography and surrounding habitats (Dickie et al. 2015).

Co-benefits and trade-offs

Field margins can provide the above benefits without impacting significantly on yields without needing to remove land from production by being located on less fertile field edges. Although they can provide habitat for beneficial pest predators, they may also provide habitat for pests.

Magnitude

Two studies were conducted to determine whether beetle banks lead to more even predation across fields. When artificial prey were located across fields up to 60 m from the beetle bank, predation rates were even at all locations, although predation was highest on the bank itself (Thomas 1990). The impact on naturally occurring aphid infestations was evaluated within confined plots that excluded ground-dispersing predators. These were established at 8 m, 33 m, 58 m and 83 m from a beetle bank (Collins et al. 2002). The mean number of aphids and aphid peak was reduced up to 58 m from the beetle banks, but reductions were greatest at 8 m.

Timescale

Benefits can be seen quite quickly, planted strips will show results the same year.

Spatial issues

See section on semi-natural habitats.

Displacement

There will be some loss of productive land around the field edge but this should not result in significant displacement of production elsewhere.

Longevity

There is some uncertainty over the longevity of the beneficial impacts of pollinator strips based on the species sown, seed provenance and whether strips have a permanent location within fields (Dickie et al. 2015). Numbers of flowers were highest in the pollen and nectar and wildflower mixes in the first three years and then declined in the pollen nectar mix (though it remained highest in the wildflower mix compared to all other treatments) (Defra 2007).

Metrics and verification

Biodiversity

Field margins can significantly increase biodiversity, including beneficial invertebrate species (Dickie et al. 2015), plants and birds. Plant diversity and abundance could be surveyed in quadrats, 2 m x 2 m would be suggested for field margins and linear strips along arable field margin 1 m x 100 m. Bird species should increase with field margins, e.g. skylarks, they can be surveyed using standardised methodology e.g Breeding Bird Survey (Harris et al. 2018). Invertebrate survey methods are described under pests & diseases and the same methods can apply to both pests and biodiversity.

There should also be measurement and monitoring of landscape-scale biodiversity. This would include determining the extent, quality and connectivity of habitats in the landscape surrounding each agri-environment option. This could be through field survey (particularly for quality) or remote sensing for extent and connectivity.

Pest & disease control

Evidence suggests that field margins increase the abundance of beneficial insect predators although insect pests could also increase. Invertebrates can be measured using pitfalls, soil cores, sweep netting/transects or pan traps. A method for estimating the abundance of pests and predators (*P. xylostella* and aphids along transects) was proposed by Jonsson et al. (2015). Weed abundance may also increase, with field margins acting as a source for weeds. Weed abundance can be assessed in quadrats (1 m^2) at different distances from the margin in crops and photos taken.

Pollination

Field margins are important for pollinators and attract them to intensive farmed landscapes. Monitoring should include pollinator transects (Carvell et al. 2015) and pollinators should be counted in appropriate weather conditions (dry weather temp > 17°C, wind speeds up to 5 on Beaufort windscale). The plant species visited should be noted and the distribution and abundance of nectar plants along a transect including floral density by scoring flower abundance.

Water quality & water conservation

Field margins could improve nutrient retention and reduce run off of N fertilisers and pollutants. Water quality should be monitored to confirm the magnitude of the impact. However, as mentioned, it Is difficult to attribute changes on individual farms or fields to changes in water quality. It may be better to focus on the level of pollutants in the soil which can be easily measured by each individual farmer. Field margins could also improve water retention, infiltration capacity so soil moisture can be measured.

2.3.9 (9) Reduction in the use of plant protection products (PPPs)

Definition

Plant protection products (PPPs) are products that protect plants or plant products from harmful organisms during production and storage. They include herbicides, fungicides and insecticides. PPPs can be synthetic or natural ("biopesticides"), used in organic agriculture (Keulemans et al. 2019). Organic (sometimes called ecological) agriculture can be defined as farming systems where the use of pesticides, herbicides and chemical fertilizers is prohibited (Bengtsson et al. 2005). Organic systems use crop rotations, natural N fixation, biologically active soil, recycled farm manure and crop residues, and biological or mechanical weed and pest control (Soil Association 2003) to manage crop production. This is the extreme end of reduction in plant protection products, but it is also where a lot of the evidence on impacts comes from.

Integrated pest management which aims to reduce or minimise the effects of plant protection products to human health and the environment became compulsory In the EU in 2014. However, integrated pest management does not necessarily lead to reduced pesticide use (Keulemans et al. 2019). Decision-support systems to predict disease and pest outbreaks and precision agriculture could be used to reduce the use of PPPs.

Causality

Yield

Quantitative scientific studies on the effect of PPPs on yield quantity and quality are limited (Keulemans et al 2019). Without PPPs there are likely to be lower yields and crop losses from disease or damage. This will be dependent upon crop type, reductions in yield of between 20-40% (19%-wheat and 42%-potato) have been reported (Keulemans et al. 2019, Seufert et al. 2019) for organic systems. Although Ponisio et al. (2014) found that the yield gap between organic and conventional was 19.2%, very variable between crop type and that two agricultural diversification practices, multi-cropping and crop rotations, substantially reduce the yield gap (to 9% ± 4% and 8% ± 5%, respectively) when the methods were applied in only organic systems. However, an organic farming system can be very different to conventional with different objectives and farming practises (aside from the use of PPP's) so it can be difficult to directly compare them.

Whether PPPs can be reduced with no significant effect on yields is still under debate. Where application of PPPs is high there may be potential for reductions. In France a study of arable farms suggested that low PPP use would not reduce high productivity or high profitability of arable crops in 77% of the farms (Lechenet et al. 2014). Jacquet et al. (2010) suggested that a reduction of PPPs in French field crops is possible by 30% without reducing farmer's income. Pimentel et al. (1993) suggested that a reduction of PPPs by 50% in the US is achievable without crop losses.

Biodiversity

Organic farming was found to promote 30% higher species richness on average and a 50% higher abundance of organisms (Bengtsson et al. 2005). Organic farming is reported to increase diversity of carabid beetles (Bengtsson et al. 2005, Kromp 1989), vascular plants (Hyvönen and Salonen 2002, 2003) and birds (Freemark and Kirk 2001). Geiger et al. (2010) found that in particular the use of insecticides and fungicides had consistent negative effects on the species diversity of plants, carabids and ground-nesting farmland birds. In a study for Defra (SCARAB-2000) there were differences in arthropod abundance between a reduced pesticide input approach and current farm practice with current practise having long-term adverse effects. Pesticides reduce pest invertebrate species but may also reduce other non-pest beneficial predator species. There have been widespread concerns that neonicotinoid insecticides contribute to bee declines (Steinhauer 2018) - see section on pollination. Reduced use of pesticides can encourage soil biota, in particular allowing for increased earthworm numbers (Pelosi et al. 2014, Zwart et al. 1994). Herbicides reduce the abundance of weeds, and in doing so they also reduce species dependent on them e.g. invertebrates and birds (Chiverton and Sotherton 1991). Also, herbicides may not directly affect invertebrates but they can affect plant nutrient levels and hormone pathways used in defence, both of which may influence plant susceptibility to herbivores so host suitability changes (Egan, 2014).

Landscape context is also important, the extent and quality of semi-natural habitat, landscape structure and heterogeneity and farming practices at a wider scale. Landscape structure and heterogeneity may be more important than whether a farm is organic (Bengtsson et al. 2005, Weibull et al. 2000, Weibull et al. 2003, Keulemans et al. 2019) and reducing plant protection would be most effective in simplified agricultural landscapes. This is demonstrated when analysing the effect of scale, organic vs. conventional treatments were more significant at small scale (field) than landscape scale (Bengtsson et al. 2005). Geiger et al. (2010) did not find a positive relationship between organic farming and bird species diversity which they suggested could be due to the large spatial scale of the pollution associated with pesticide use across Europe, which inevitably leads to negative effects of pesticides – even in areas where the application of these substances has been reduced or terminated and this applies particularly to species operating at larger spatial scales such as birds. Keulemans et al. (2019) presents evidence that the increases in biodiversity are at the expense of the crop yield as they result from increased abundance of non-crop species that attract more invertebrate species (Gabriel et al. 2013, Rundhlof et al. 2016).

Pollination

Reduced plant protection is likely to increase floral resources for pollination and the abundance and diversity of pollinators. There have been increasing concerns about the impact of pesticides on pollinators, particularly bees. Exposure to neonicotinoids may not necessarily cause mortality but has been found to affect queen bees (Williams et al. 2015) and can cause colony failure. Pesticides also synergize with other risk factors such as nutritional stress, although these interactions have only been demonstrated at the individual bee level and not at the colony level (Tosi et al. 2017). Studies have also found that pesticides (such as pyrethroids, neonicotonoids and fungicides) whilst not individually impacting on pollinators can interact to have colony level effects (Sanchez-Bayo and Goka 2014).

Pest & disease control

Bengtsson et al. 2005 in a meta-analysis did not find evidence that insect pests are more abundant in organically managed fields probably because the abundance of beneficial pest predators was also enhanced by not using herbicides and pesticides. Geiger et al. (2010) in a study involving measuring the predation of aphids placed in the field found that use of pesticides, especially insecticides and fungicides, had the most consistent negative effect on the potential for biological pest control. The use of pesticides and herbicides may reduce the potential for biological control by removing pest predators. Krauss et al. (2011) proved that natural control by predators in organic farming had comparable effects on aphids as PPP control in conventional agriculture (Keuleman et al. 2019). There may however be trade-offs with yield.

It was found in a long term study (Defra 2000) that low input systems for weed control need to be carefully managed to avoid the build-up of high populations of problem weeds in the seedbank. Although high weed numbers in the crops were controlled in the continuation study after the initial trial, this was only achieved by the return to full-rate herbicide use. So short-term reductions in herbicide use could actually lead to higher use in the long-term.

Carbon (C) sequestration and greenhouse gas (GHG) emissions

Studies assessing impacts of organic farms vs. conventional farming on GHG emission and sequestration have had mixed results. Organic farming has been found to result in higher C storage (per unit area although not necessarily (per product unit), Tuomisto et al. 2012). Due to lower yields and increased nitrate leaching there may be similar or greater GHG emissions per tonne of organic crop compared with conventional systems, although studies which considered entire crop rotations and less-intensive modes of production, found much lower GHG emissions per tonne of organic crop (Nemecek et al. 2011). Disentangling the impact of reduction in PPP rather than the whole package of methods used in organic farming is difficult.

Water quality & conservation

Pesticides etc. can be transported off crop fields in surface or subsurface water flow (Patzold et al. 2007; Reichenberger et al. 2007, Wauchope et al. 2002). Reduced PPPs will result in lower levels of pesticides in water (Kreuger et al. 1999, Mäeder et al. 2002).

Displacement

If reducing PPPs causes a reduction in yield then either yield reductions will need to be accepted (possibly in association with measures to reduce food waste) or more land will be required to grow crops which may involve conversion of semi-natural habitat elsewhere (Keulemans et al. 2019).

Social and economic barriers

PPPs may be used by the farmer as an insurance policy rather than application based on need. There would be opportunities to reduce pesticide use more specifically targeted on likelihood of infection, however barriers include a lack of fundamental knowledge of the biology of the diseases or pests, the exact impact of local influencing circumstances (pest pressure, presence of natural enemies like predators and parasitoids, microclimate, cultivar sensitivity, …) and a reliable weather forecast for the next 2–3 weeks (Keulemans et al. 2019). There may be an issue that if products are not applied early in the season as insurance that application may be closer to harvest with more exposure to the consuming population (Keulemans et al. 2019). Reduced use of plant protection products may lead to products with more “imperfections” which may be off-putting to consumers.

Metrics and verification

Biodiversity

Reduced use of PPPs can significantly increase biodiversity, including beneficial invertebrate species, plants and birds. Plant diversity and abundance could be surveyed in quadrats, 2 m x 2 m would be suggested for field margins, within crops and linear strips along arable field margin 1 m x 100 m (Halbritter et al. 2019). Bird species can be surveyed using standardised methodology e.g. Breeding Bird Survey (Harris et al. 2018). Invertebrate survey methods are described under pests & diseases and the same methods can apply to both pests and biodiversity.

Pest & disease control

Evidence suggests that reduced PPPs will increase the abundance of beneficial insect predators although insect pests could also increase. Invertebrates can be measured using pitfalls, soil cores, sweep netting/transects or pan traps. A method for estimating the abundance of pests and predators (*P. xylostella* and aphids along transects) was proposed by Jonsson et al. (2015). Weed abundance may also increase and can be assessed in quadrats (1 m^2) at different distances from the margin in crops and photos taken.

Pollination

Reduced PPP is likely to increase floral resources for pollination and the abundance and diversity of pollinators. Bees are particularly important as they have been shown to respond negatively to various pesticides not just direct mortality but indirectly through behaviour and additive effects with other stressors. Monitoring should include pollinator transects (Carvell et al. 2015) and pollinators (particularly bees) should be counted in appropriate weather conditions (dry weather temp > 17°C, wind speeds up to 5 on Beaufort windscale). The plant species visited should be noted and the distribution and abundance of nectar plants along a transect including floral density by scoring flower abundance.

Water quality & water conservation

Reduced plant protection should reduce run off of pesticides. Water quality should be monitored to confirm the magnitude of the impact.

Yield

It is very important to measure whether reducing PPPs reduce yield. This will have knock on consequences for GHG emissions and displacement of food production.

2.3.10. (10) Semi-natural landscape elements (provide habitat)

Definition

Many of the above sections cover the use of selected semi-natural habitats in an agricultural landscape (e.g. agroforestry, hedgerows, and field margins). There are other semi-natural features that have not been considered e.g. ponds, ditches, or fallow land. Rather than focusing upon individual options, multivariate interactions between elements of semi-natural habitats across the landscape should also be considered (Benson et al. 2003). Restoration and creation are essential components of landscape-scale management of semi-natural habitats (Keenleyside et al. 2019). Benson et al. (2003) propose that a universal management objective should be the promotion of habitat heterogeneity. Heterogeneity affects species richness in different ways at different scales: within fields, between fields and at landscape scales.

The spatial configuration of semi-natural habitat is also important, particularly connectivity. Connectivity refers to the characteristics of the landscape that affect the movement of organisms, ecosystem functioning and resilience (Latham 2013). It is not solely linear connections between habitats of the same type but also involves consideration of habitat quality, landscape extent of semi-natural habitat and permeability of different habitat types (Lindenmayer 2008, Keenleyside et al. 2019). Where the differences between the habitat and the surrounding matrix are strong as in arable landscapes, corridors are more important, where the differences between the habitat and matrix are less strong as in grasslands then dispersal tends not to be confined to corridors and can be calculated by distance from semi-natural habitat (Concepcion et al. 2012).

Actions that can improve semi-natural landscape elements and contribute to wider landscape biodiversity and connectivity (Keenleyside et al. 2019) include:

- Improving site condition through good management to increase within-patch connectivity and fitness of populations;
- Increasing habitat patch size;
- Developing buffer zones around patches;
- Expanding habitats to join patches;
- Developing stepping stones between patches;
- Developing corridors;
- Improving the condition of land between habitat patches to increase permeability;
- Improving the extent and condition of landscape features such as hedgerows, field-margins and water courses;
- Developing networks of habitats;
- Encouraging large continuous areas of habitat at a landscape-scale.

There have been many studies looking at the impact of landscape context on the implementation of agri-environment scheme options. These options tend to be implemented at a local scale whereas the impacts of agricultural intensification operate at a range of scales including landscape and region (Concepcion et al. 2012). Species are sensitive to spatial and temporal scale, e.g. species with small area requirements can persist in highly fragmented habitat patches in agricultural landscapes too small to maintain species with larger ranges (Maskell et al. 2019). Local factors may be more important than regional ones as body size decreases (Gabriel et al. 2010n Concepcion and Diaz 2011). Many bird species are most influenced by spatial extents that are much larger than individual land-holdings (Pickett and Siriwardena 2011), and home ranges commonly extend beyond farm boundaries, even within a season (Siriwardena et al. 2006). This suggests that effective management needs to be coordinated at the landscape scale (Keenleyside et al. 2019).

A number of studies have looked at whether simple, intermediate or complex landscapes will be the most effective at improving biodiversity related measures (Batary et al. 2011, Jonsson et al. 2015, Concepcion et al. 2012). Tscharntke et al. (2005) refer to landscapes with less than 2% semi-natural habitats as “cleared” landscapes, where the effectiveness of conservation is limited by the basic absence of species sources. Landscapes with 2-20% semi-natural habitat in the matrix are referred to as “structurally simple” landscapes, where species sources are still present and conservation initiatives can achieve good results. In “complex” landscapes with more than 20% semi-natural habitats, the productive area is continually colonised by species from the surrounding species-rich landscape. Some ecologists regard a 20% proportion of semi-natural vegetation as a minimum threshold for maintaining biodiversity on farmland (Le Roux et al. 2008).

Causality

Yield

Semi-natural habitat can increase yield by providing habitat for pest predators, suppressing pest species, improving soil quality and providing habitat for pollinators (Lampkin et al. 2015, Pywell et al. 2015). Pywell et al. (2015) found no significant loss of yield per hectare for globally important arable crops when up to 8% of cropped land is removed from production for the creation of wildlife habitat (Defra 2018).

Biodiversity

Increased amounts of semi-natural habitat enhance biodiversity and species richness by providing habitat, food supply, microclimate and shelter. There are a number of studies that have analysed the relationship between landscape heterogeneity and species richness and generally found positive relationships across taxa (Stein et al. 2014, Jonsen and Fahrig 1997, Benson et al. 2003). Some authors have predicted and found that the effects of agri-environment options on species richness will be maximal in landscapes of intermediate complexity (Tscharntke et al. 2005), decreasing to zero in the simplest and the most complex landscapes (Concepcion et al. 2008, Concepcion et al. 2012). This is based on the assumption that relationships between landscape complexity and field scale species richness are non-linear and that these interact with local management effects (Concepcion et al. 2008, Concepcion et al. 2012).

Species number in agricultural fields increases from simple to complex landscapes because semi-natural landscapes contain more diverse resources and dispersal corridors (Concepcion et al. 2012, Benson et al. 2003). In simple landscapes there are low numbers of available species to colonise newly created habitat. As landscapes become more complex, local diversity is expected to increase until a saturation point is reached from where no further increases in species richness are expected. This saturation may be due to continuous recolonization filling all available niche space or to potential negative effects of semi-natural habitats on species requiring more open conditions (e.g. farmland birds) (Concepcion et al. 2012, Maskell et al. 2019). This hypothesis is not necessarily demonstrated in all landscapes. Batary et al. (2011) found that in croplands, species richness but not abundance was significantly enhanced in simple but not in complex landscapes. In grasslands, agri-environmental management effectively enhanced species richness and abundance regardless of landscape context. Pollinators were significantly enhanced by agri-environmental management in simple but not in complex landscapes in both croplands and grasslands. They concluded that agri-environmental management should be adapted to landscape structure and the species groups at which they are targeted.

An example of the impact of the surrounding landscape on restoration of hay meadow is given in Keenleyside et al. (2019). In the Elan Valley hay-meadows project (Hayes and Lowther 2014), opportunities were tested for patch expansion, restoration and linkage of species-rich grasslands by diversification of adjoining semi-improved swards. Monitoring of the restoration sites showed highly promising indications of developing species richness purely through natural re-colonisation by indigenous meadow species (Keenleyside et al. 2019). The presence of remnant populations of meadow species both within and adjacent to selected sites, together with suitable edaphic and climatic conditions meant that these sites could respond relatively rapidly to suitable restoration management.

Widespread conservation gains may be made by targeting interventions on larger areas of semi-natural grassland as habitat for a range of widespread but declining species, such as starling, yellow wagtail and lapwing (e.g. Hayes and Lowther 2014, Crofts and Jefferson 1999), rather than intensive restoration of fewer sites (Beaufoy and Jones 2011).

In the above section on hedgerows there is a lot of information on the benefits provided by hedgerows for biodiversity. There is a lack of clear evidence of the positive benefits of hedgerows in increasing landscape connectivity for woodland-dependent taxa (Davies et al. 2006, 2007) although there is good evidence of benefits of hedgerows for a different set of species (broadly, described as "edge specialists"). Hedgerow habitat and woody structures in open landscapes significantly increase the number of bird species, by increasing ecological niches, particularly benefiting generalist woodland birds (Aue et al. 2014, Hinsley and Bellamy 2000, Morelli et al. 2014). Some species, e.g. skylark and lapwing, are negatively influenced by hedgerows (Hinsley 2000).

At the landscape scale, there is good evidence for the importance of hedgerows to vertebrates, as navigational aids and for commuting between breeding and foraging sites (Keenleyside et al. 2019). There is, however, comparatively little evidence that connected hedges are important corridors for animal dispersal. This is particularly true for invertebrates, although they probably do have a facilitating role to play in this respect (Wolton et al. 2013), and hedgerows do contain more invertebrates than other elements of agricultural landscapes (Maudsley 2000).

Pollination

Distance from semi-natural habitat to crop has been shown to be important for the abundance of pollinators and crop pollination (Garibaldi et al. 2011, Ricketts et al. 2008, Kremen et al. 2004, Kohler et al. 2008). Pollination has been measured in a number of ways, flower visitor rate, seed set, fruit set in a variety of contexts i.e. different spatial scales, landscape types, crop types (Garibaldi et al. 2011, Ricketts et al. 2008, Kremen et al. 2004, Kohler et al. 2008). For most of these studies, distance from semi-natural habitat is the only metric used, but distance does not provide information on the quality of the habitat and may overlook smaller habitat patches such as where wildflower mixes of nectar rich species have been sown in field margins.

Pests & diseases

As mentioned above in the sections under field margins, agroforestry and hedgerows, the creation and maintenance of semi-natural habitats can encourage natural predators for pest control (Defra 2018) by providing a wide range of microhabitats, nectar and pollen resources, and larval development resources. However, there are also opportunities for increased numbers of pest species.

Soil quality & conservation

As mentioned in the above sections semi-natural habitats can reduce soil loss from fields through intercepting water-borne sediment and reducing surface flow rates. Semi-natural habitats enhance soil fertility, nutrient retention, nutrient cycling (Jäger 2017, Vityi 2017) and soil quality.

Carbon sequestration and greenhouse gas (GHG) emissions

As described above in the sections on agroforestry, hedgerows and field margins, increasing the amount of semi-natural land can increase C sequestration and reduce GHG emissions. Woody vegetation can lock-up C above- and below-ground over decades. De Stefano and Jacobson (2018) found that the introduction of woody species generally increases SOC stocks when the land use changes from less complex systems (such as agricultural systems) to agroforestry. Wiesmeier et al. (2019) suggest that "the storage of SOC increases in the order cropland < forest < grassland", noting some exceptions between forest and grassland. Previous work reports mixed effects of afforestation of grassland for SOC (Soussana et al. 2004) with different effects on SOC stocks with soil depth (de Stefano and Jacobson 2018).

There is some evidence of (small) hedgerow co-benefits for soil C stocks (Ford et al. 2019) and also for net GHG emissions (Ford, H. et al. in prep (Multiland project)). If semi-natural habitat leads to reductions in fertiliser and pesticide applications then reductions in fossil energy used to create and apply products will further reduce GHG emissions (Defra 2018).

Water quality & conservation

Semi-natural habitats can form buffer strips that significantly decrease pollution run-off (Joseffson et al. 2013) and provide benefits for water quality downstream i.e. via uptake and assimilation of nutrients from groundwater and surface water, sediment deposition, and nutrient retention. Reductions of 70-90% were reported for suspended solids, 60-98% for P and 70-95% for N in a study by Borin et al. (2010). Agroforestry systems have the potential to mitigate movement of harmful bacteria such as *Escherichia coli* into water sources (Dougherty et al. 2009).

Semi-natural habitats can regulate water flow, e.g. field margins act as buffer strips, hedgerows and trees reduce speed of flow and increase infiltration into the soil. See the sections on hedgerows, agroforestry and field margins.

Co-benefits and trade-offs

Increased semi-natural habitat contributes to supporting the farming system, including soil fertility building, crop protection and animal health maintenance (Lampkin et al. 2015).

Magnitude

Pollination

The size/magnitude of this relationship is likely to be substantial which is supported by national scale evidence for two European countries of large scale declines in functionally dependent plants and dependent pollinators.

Timescale

Timescales will vary according to the habitat type, landscape component and landscape context. In a study of hay meadows in the Elan valley (Hayes and Lowther 2014) where there were existing sources of indigenous meadow species that were able to naturally recolonise restoration sites, some sites are already showing levels of species richness starting to approach that of adjacent high quality meadows (Sites of Special Scientific Interest) -albeit without the presence of some rarer meadow species- within just 10 years of appropriate management; a situation that would be expected to take many decades in areas with more nutrient-rich, species-impoverished conditions. As mentioned previously, benefits from agroforestry and hedgerows will be longer-term, biodiversity and other benefits would begin to appear in years 0-5, for example from natural regeneration of hedgerow trees and development of agroforestry systems, and continue to develop over many years as the trees mature.

Spatial issues

Spatial configuration is extremely important for semi-natural habitat within farmland. The connectivity of the habitats and potential for wildlife corridors, the quality of the dispersal matrix for species, fragmentation of habitats are all important and included in the types of semi-natural interventions proposed in the opening paragraph of this section.

Displacement

There will be displacement of crops if semi-natural areas are introduced.

Longevity

Varies according to type, agroforestry effects are likely to be long-term as once established there are legal protections and difficulties associated with removal. Hedgerows also could be long-term but do require maintenance. Field margins could have shorter-term effects.

Climate interactions

Semi-natural land contributes to the adaptation of the countryside to a changing climate, through micro-climatic effects within the habitat and on surrounding land. Tree lines and hedgerows can act as wind-breaks to reduce wind speed and soil erosion and improve microclimate (Kanzler et al. 2017) including improving soil moisture and reducing extreme changes in temperature for crops. They can also act as shelterbelts for livestock.

Social and economic barriers

There may be a lack of knowledge, technical skills and time associated with the creation and management of semi-natural habitats. There may be a perception that semi-natural habitats will compete with pasture/crop species and reduce production. Some aspects of semi-natural habitat management may have associated costs e.g. establishment of agroforestry and protective fencing. Smaller areas of semi-natural habitat may be more acceptable as they provide benefits but are less impacting on production.

Metrics and verification

Metrics described in the above sections agroforestry, hedgerows, field margins could be used here (diversity of plants, invertebrates and birds, soil and water quality and conservation, GHG).In addition to local scale measurements there is a need to extend outside of the study area where the option is being implemented and collect data on landscape context, the extent, quality and connectivity of semi-natural habitats, habitat heterogeneity and landscape-scale biodiversity. This could be from field survey of the habitats surrounding an agri-environment option, and use of remotely sensed data or monitoring data collected for other purposes where appropriate. Metrics that could be calculated include the size of fields: length of boundaries around fields harbouring semi-natural vegetation (m), a measure of landscape connectivity calculating Euclidean or least cost-distance for different habitat types; habitat diversity, the length of water features such as rivers and streams and the proportion of area occupied by semi-natural land (Concepcion et al. 2012, Maskell et al. 2019).

2.4 INDICATORS

Accompanying this report we have produced an excel table for the 10 FAB solutions with proposed indicators that can be measured on farm to assess state and change. The table is a live document, meaning it will change through time being updated through the life of the project.

2.5 CAN ON FARM MEASUREMENTS BE USED TO UNDERSTAND STATE AND CHANGE AT THE REGIONAL OR NATIONAL SCALE?

In this project we seek to assess state and change through the use of indicators. We divide our indicators into national/regional and local/farm. The National indicators are robust measures that we can collect at the farm scale and benchmark for example against national or regional data collected in monitoring such as the EU LUCAS survey. An example would be soil organic matter concentration, where measurements from farmers' fields in the FAB project can be compared with regional data from LUCAS. Secondly there are local/farm indicators which may not be so robust and the goal of collecting them is to educate and inform the land owner with regard to particular practices used on the farm. The information provides the farmer with a way of understanding the benefit of a measure and tracking progress, but the measurement may not be comparable with scientific data sets. An example might be that the farmer keeps records of manure applied, (T/Ha) but there is no regional or national data set against which this measure can be compared.

The scale at which the measurement is taken is important. At local scales e.g. field, an option may have a more significant effect than at a landscape scale (Bengtsson et al. 2005), for biodiversity taxa operate at different spatial scales, and as the section on semi-natural habitat demonstrates landscape context is very important. This means that measurements and indicators should not just be at the field where an option has been implemented but across farm and landscape.

Annex 4 is provided as an excel table and consists of three tabs. A table cross checking the need for indicators for FAB options against criteria (Yield, Biodiversity, Pollination, Pests & weeds, Soil quality & Conservation, SOC, Water quality, Water conservation, Carbon sequestration and GHG, Other). A table listing all of the indicators regardless of option and a more complex table detailing indicator by option.

Annex 1 Selected FAB solutions and their contribution to ecosystem service provision and farm management (text to accompany arrows shown in table 1) part 1

FAB solution	**Fertiliser**	**Pesticide**	**Pollination**	**Biodiversity**	**Soil quality & conservation**	**SOC**
1. Reduced tillage techniques (reduced soil disturbance and compaction)	Needed to sustain yields (Pittelkow et al. 2015 in Field Crop Research)	Reduced tillage may increase beneficial pest predators and so control arthropod pests (Schipanskia et al. 2017), the lack of soil inversion usually increases weed infestations (Carmona et al. 2015, Armengot et al. 2016)		increases soil fauna and insect pest predators (Heroldova et al. 2016)	Soil quality goes up due to increased soil structure; positive effect easily offset by tillage	Mixed evidence for impact of reduced tillage on SOC (Powlson et al. 2014)
2a. Mixed crops/crop rotations	Crop rotations can have a strong beneficial effect on soil quality reducing need for fertilisers (Schipanski et al. 2017)	More diverse crop rotations can have lower weed densities (Schipanski et al. 2017, Cardina et al. 2009) and beneficial pest predators respond to cover crops		Increases biodiversity (Defra 2018)	promotes soil health by improving the diversity of root architecture and soil structure (Defra 2018)	
2b. Sward diversity	Effects of diversity on productivity stronger than the effect of manufactured N fertiliser (Weigelt et al. 2009)	Mixing species with different properties give higher density of crop cover and better weed control, reducing reliance on inputs (Defra 2018)	Increases in nectar plants and pollinators	Diversification of grassland swards should increase plant species and invertebrate diversity (Newell-Price et al. 2019, Scherber et al. 2010), Alison et al. 2017, Woodcock et al. 2013). Questions about impacts on below ground fauna	More diverse sward may reduce soil compaction	Increases in SOC content with plant species richness have been found (Weisser et al. 2017, Fornara and Tilman 2008, Hungate et al. 2017)

FAB solution	Fertiliser	Pesticide	Pollination	Biodiversity	Soil quality & conservation	SOC
3. Cover / catchcrops (incl. legumes)	Reduced N-leaching by avoiding times of bare soil (Tonitto et al. 2006) and increased crop P nutrition (Hallama et al. 2019)	Vegetative mulch can be very effective at suppressing weeds when retained on the soil surface (Carr 2017, Dorn et al. 2015); Beneficial insect species to control pest species respond to cover crops (Holland and Luff 2000, Lundgren and Fergen 2010)		A positive effect on biodiversity of many taxa especially invertebrates (Holland and Luff 2000, Lundgren and Fergen 2010)	Cover crops potentially increase soil quality by increasing productivity and preventing erosion (Buckingham et al. 2013, Desjardins et al. 2005), improving soil structure through rooting systems (Scopel et al. 2013) or improving nutrient cycling (Alahmad 2017)	Cover crops potentially increase soil SOC (Buckingham et al. 2013, Desjardins et al. 2005); Mixed evidence for effect of leguminous crops on SOC (Bai et al. 2019)
4. Organic matter input (plant residuals, wood chips, biochar, …)	Biochar in combination with organic or inorganic fertilizers increase nutrient use efficiency and reduce fertiliser needs (Al-Wabel et al. 2017); biosolids may decrease need for inorganic fertilization			Biochar has the capacity to bind toxic components (bioremediation) which may negatively affect/change the soil microbial community (Zhu et al. 2017)	Biochar improves nutrient and water retention in soil, (Powlson et al. 2011, Qambrani et al. 2017); Could be build-up of heavy metals and organic pollutants in the soil (Freibauer et al. (2004, Sharma et al. 2017)	Higher SOC stocks with plant residual return (Dimassi et al. 2014, Virto et al. 2012); Biochar application increases SOC by ~39% (Bai et al. 2019)
5. Modify manure quality and diversity (fresh manure, limit use of fertilizer)	A fertilizer in itself; instead of inorganic fertilizers or amended with small amounts of mineral N			Manure amendments can rebuild a depleted soil microbial community (Kallenbach and Grandy 2011)	Generally increased by improving soil structure (Freibauer et al. 2004)	Positive impacts of manure application on SOC (Jones et al. 2006)

FAB solution	Fertiliser	Pesticide	Pollination	Biodiversity	Soil quality & conservation	SOC
6. Agroforestry	Silvoarable systems require fewer N inputs, because area of crop is reduced and because greater litter input and more extensive root systems fix N in the soil (Keenleyside et al. 2019)	Beneficial if conversion from cropland (monoculture): higher abundance of natural predators, lower abundance of parasitic and non-parasitic weeds (Pumarino et al. 2015); However, can also provide habitat for pest species	Agroforestry can provide habitat for pollinators	Agroforestry has a significant positive effect on biodiversity compared to specialized agricultural and forestry systems (Nair 2007), particularly birds (Torralba et al. 2016, Hermansen et al. 2017, Soderstrom et al. 2001) possibly due to effect on invertebrates	Reduced soil erosion, especially in dry/Mediterranean areas (Torralba et al. 2016); Agroforestry enhanced soil fertility, nutrient retention and nutrient cycling (Jäger 2017, Vityi 2017)	Introduction of woody species generally increases SOC stocks when the land use changes from less complex systems to agroforestry (De Stefano and Jacobson 2018), C storage increases in the order cropland < forest < grassland (Wiesmeier et al. 2019)
7. Hedgerow management		Hedgerows can enhance populations of the natural enemies (predators and parasites) of crop pests by providing a wide range of microhabitats across the shrub layer, trees, banks, base, margins, ditches and soil, nectar and pollen resources, and larval development resources; Can also provide habitat for pest species	Hedgerows important in agricultural landscapes for healthy and diverse pollinator populations (Wolton et al. 2014, Haenke et al. 2014, Morandin and Kremen 2013) export pollinators into crops, increasing yield	Hedgerows positively affect the richness and abundance of flora, invertebrates and birds (Boatman (ed) 1994, De Snoo 1999, Hinsley and Bellamy 2000)	Hedges can reduce soil loss from fields through intercepting water-borne sediment and reducing surface flow rate (Wolton et al. 2014)	Through capturing eroding soil, hedges across slopes can increase SOC

FAB solution	Fertiliser	Pesticide	Pollination	Biodiversity	Soil quality & conservation	SOC
8. Field margin management		Reduction in pesticide use; Field margins reduce disturbances and provide resources that benefit pest predators and increase natural attack rates on pests so reducing their impact (Jonsson et al. 2015 ,Landis et al. 2000)	Field margins particularly if planted with wild flowers can increase wild bee and pollinator abundance across agricultural landscapes (Williams et al. 2015, Scheper et al. 2013)	Creating field margins can significantly increase biodiversity, invertebrate species (Dickie et al. 2015), plants and birds		In an experiment topsoil C was enhanced by sown margins (Defra 2007)
9. Reduction in the use of plant protection products (PPPs)		The objective of this option is to reduce pesticides. This should result in increased potential for biological pest control (Bentsson et al. 2005)	Negative impacts of pesticides, on pollinators directly and indirectly (e.g. combining with other stressors, behavioural impacts of neonicetinoids) (Williams et al. 2015, Tosi et al. 2017)	Use of pecticides had consistent negative effects on species diversity of plants, carabids and ground-nesting farmland birds (Geiger et al. 2010); Landscape context may be more important than reduction of PPPs though		
10. Semi-natural landscape elements (provide habitat)	Lower inputs, increased soil quality and nutrient cycling, less land in production	Semi-natural habitat can enhance populations of the natural enemies (predators and parasites) of crop pests by providing a wide range of microhabitats, nectar and pollen resources, and larval development resources; Can also provide habitat for pest species	Lots of evidence demonstrating positive relationships between distance from semi-natural habitat, abundance of pollinators and crop pollination (Garibaldi et al. 2011, Ricketts et al. 2008, Kremen et al. 2004, Kohler et al. 2008)	Evidence for positive relationships between habitat heterogeneity and biodiversity (Stein et al. 2014, Jonsen and Fahrig 1997, Benson et al. 2003); Evidence for relationship between semi-natural habitat and increases in biodiversity by introducing agri-environment options (Batary et al. 2011, Concepcion et al. 2012)	Semi-natural habitats can reduce soil loss from fields through intercepting water-borne sediment and reducing surface flow rate; Semi-natural habitats enhance soil fertility, nutrient retention, nutrient cycling (Jäger 2017, Vityi 2017) and soil quality	There may be mixed effects on SOC, afforestation of simple systems such as arable can result in increased SOC; Grasslands may store more C than forests, afforestation of grassland has shown mixed effects; Effect on SOC depends upon the type and quality of the semi-natural habitat

Annex 1 part 2

FAB solution	**C sequestration and GHG emissions**	**Water quality**	**Water conservation & flooding**	**Yield**	**other Costs (e.g. equipment)**
1. Reduced tillage techniques (reduced soil disturbance and compaction)	Reduced GHG emissions (Armengot et al.) or increased N_2O emissions	Higher herbicide use- unless used alongside other options such as mixed crops, cover crops (Carmona et al. 2015)	Negatively correlated with water balance (Dimassi et al. 2014); Moisture conservation of no-tillage important under drier clay and sandy soils (Van der Putte et al. 2010)	Negative effect on yield in the short-term, might be offset in the longer-term or by use with other options such as cover crops (Pittelkow et al. 2015, Six et al. 2004)	New equipment may be needed; labour time might go up (Powlsen et al. 2014)
2a. Mixed crops/crop rotations		Increases water quality			
2b. Sward diversity	Grasslands can act as a sink for C but it will not be possible to sequester C at the same rates in the longer-term (Newell-Price et al 2019, Smith 2014); Where legumes are added to swards that did not previously receive manufactured N fertiliser, the additional fixed N can result in a net emission of N_2O (Garnett et al. 2017; Henderson et al. 2015)	Reductions in manufactured fertiliser use have the potential to reduce nitrate leaching losses (Cuttle and Scholefield 1995)	Sward diversity could improve soil structure, reduce soil compaction and increase water infiltration rates (Newell-price et al. 2019), thereby lessening the risk of flooding (Weisser et al. 2017)	Mixed evidence of relationship between sward diversity and yield, some positive (Döring et al. 2012, Finn et al. 2013); Some negative (Tallowin and Jefferson 1999, Bullock et al. 2011); Frequently lower stocking densities in species rich swards	Minor costs associated with seeds and establishment of a species rich sward, and possibly reduced productivity

FAB solution	**C sequestration and GHG emissions**	**Water quality**	**Water conservation & flooding**	**Yield**	**other Costs (e.g. equipment)**
3. Cover / catchcrops (incl. legumes)	Cover crops may decrease N_2O emissions in the short term (Bosche et al. 2014), but increase them in the longer-term due to interactions with the C cycle (Lugato et al. 2018)	Cover crops, particularly legumes, increase soil mineral N availability, allowing the reduction in use of chemical N fertilizers and lower the risk of nutrient leaching (Eory et al. 2015)	Cover crops require water (Lehnhoff et al. 2017) permanent mulch of crop residue reduces surface runoff (Sun et al.2015) and the amount of solar radiation evaporating water, so soil moisture is more likely to be retained under cover crops (Scopel et al 2004)	Increased yield with N-fixing cover crops in low N soils, but decreased yields in intermediate or high N soils (Tonitto et al. 2006); Review by Scopel (2013) found no yield increase	Expense to farmer in seed and machinery costs
4. Organic matter input (plant residuals, wood chips, biochar, …)	Reductions in emissions as a function of amounts of biochar applied (Qambrani et al. 2017); N_2O emissions possible trade-off from manure, sewage sludge, crop residues and urban compost, although emissions from production of inorganic fertilizers could be reduced by organic fertilizers (Freibauer et al. 2004)	N-leaching can be an issue when applying manure (Buckingham et al. 2013)		Increases crop yields by ~20% with an application rate of about 10 t ha^{-1} biochar (Agegnehu et al. 2017, Jeffery et al. 2011); increased yields with biosolids (Sharma et al. 2017)	Transport of biochar offsets the positive effects of GHG mitigation; biosolids may need additional treatment before they can be applied to soils
5. Modify manure quality and diversity (fresh manure, limit use of fertilizer)	Increases N_2O emissions but can be reduced by avoiding surface broadcasting (Misselbrook et al. 2002); Increased C sequestration, reduced emissions from manufacture of inorganic fertilisers (Smith et al. 2011)	Can reduce water quality if applied long-term; Nitrate leaching (Moxley et al. 2014)	Manure application can improve water holding capacity (Freibauer et al. 2004)	Increased or decreased; Increases mainly when organic matter is returned to the soil or mineral N is added	New equipment may be needed when application method changes to reduce GHG emissions

FAB solutions	**C sequestration and GHG emissions**	**Water quality**	**Water conservation & flooding**	**Yield**	**other Costs (e.g. equipment)**
6. Agroforestry	After planting, afforestation leads to net GHG emissions as loss of SOC greater than C sequestered by tree growth; A period of more rapid C sequestration takes place 10 to 40 years after planting, followed by slower sequestration as the trees mature (Eory et al. 2015); If agroforestry reduces fertiliser and pesticide inputs then reduced emissions from manufacture and application	If used as bufferstrips in riparian zones, water quality is improved by reducing non-point source pollution (Nair 2007)	Agroforestry leads to improvements in water retention	Mixed evidence: Agroforestry increased yields by up to 40% (Graves et al. 2007) and increased yields in alleys between trees cf conventional fields (Kanzler and Mirck 2017, Vityi et al. 2017); Declines in yields for arable crops planted in close proximity to trees (possibly due to competition for solar radiation and water) (Gosme and Desclaux 2017, Arenas-Corraliza et al. 2017, Kanzler et al. 2017); Negative effects of agroforestry on yields (Torralba et al. 2016)	Agroforestry can have significant costs at establishment particularly in pastoral systems, due to the need for protective fencing and by taking land out of production
7. Hedgerow management	Hedgerows provide climate change mitigation through the storage and accumulation of C above and below-ground (Nair 2007, Wolton et al. 2014).	Hedges prevent nutrients and other pollutants from reaching water bodies, particularly if placed along contours or beside water bodies (Wolton et al. 2014), Benhamou 2013)	Hedgerows along contours or fringing water courses can reduce volume and speed of water reaching streams and rivers; Lines of shrubs or trees can greatly increase infiltration of water into the soil (Borin et al. 2010, Carroll et al. 2004, Kovar et al. 2011); Hedges can influence the availability of water to crops negatively and positively	Mixed effects on crop yield in Silvoarable systems; Evidence of increased yields in alleys between trees compared with conventional fields (Kanzler and Mirck 2017, Vityi et al. 2017); In other studies declines in yields were reported for the arable crops planted in close proximity to trees/hedges (Gosme and Desclaux 2017, Arenas-Corraliza et al. 2017, Kanzler et al. 2017)	Costs at establishment and management, woody structures and protective fencing

FAB solutions	**C sequestration and GHG emissions**	**Water quality**	**Water conservation & flooding**	**Yield**	**other Costs (e.g. equipment)**
8. Field margin management		Regulation of water quality by field margins acting as buffer strips to retain sediments- is dependent upon the location of pollinator strips in relation to topography and surrounding habitats (Dickie et al. 2015)	Regulation of water flow by field margins acting as buffer strips to retain water- dependent upon the location of pollinator strips in relation to topography and surrounding habitats (Dickie et al. 2015)		
9. Reduction in the use of plant protection products (PPPs)	GHG emission could increase due to losses in yield and subsequent displacement of food production (this is likely with no use of PPPs); There is evidence that there can be reductions in PPP with no loss of yield	Reduced plant protection will result in lower levels of pesticides in water (Kreuger et al. 1999, Mäeder et al . 2002)		Without plant protection products there are likely to be lower yields (Keulemans et al. 2019); Whether plant protection products can be reduced with no significant effect on yields is still under debate; Where application is high there may be potential for reductions. (Lechenet et al. 2014)	
10. Semi-natural landscape elements (provide habitat)	Increasing the amount of semi-natural land can increase C sequestration and reduce GHG emission	Semi-natural habitats can form buffer strips that significantly decrease pollution run-off (Joseffson et al. 2013)	Semi-natural habitats can regulate water flow, e.g. field margins act as buffer strips, hedgerows and trees reduce speed of flow and increase infiltration into the soil	Mixed effects: depends how much land is taken out of production and whether benefits outweigh loss of productive land; No significant loss of yield per hectare for globally important arable crops when up to 8% of cropped land is removed from production for the creation of wildlife habitat (Pywell et al. 2015, Defra 2018)	Can have costs at establishment, protective fencing for forestry, and taking land out of production

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