UNIVERSITY OF CAMBRIDGE
INSTITUTE FOR SUSTAINABILITY LEADERSHIP

Commercial gains from addressing natural capital challenges in the dairy sector

Technical report

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Publication details

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The principal investigators and authors of this report is Dr Jonathan Green of CISL.

This document is part of a series of 'Doing business with nature' publications; these identify challenges and opportunities for companies whose future growth depends on a healthy and sustained supply of nature's goods and its services, known as 'natural capital'. The rationale for investing in sustainable natural capital management is set out in Doing business with nature: Opportunities from natural capital and has been further developed through commodity-specific Action Research Collaboratories (ARCs) for Dairy in the UK and Ireland (described here) and for Cotton.

The authors would like to thank all members involved in this Action Research Collaboratory (ARC) for their input.

Reference
Please refer to this paper as *Commercial gains from addressing natural capital challenges in the dairy sector: Doing business with nature* (CISL, 2016).

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About this document

This document '*Commercial gains from addressing natural capital challenges in the dairy sector: Technical Report* ' was written by Jonathan Green, John Pharoah and Martin Roberts of University of Cambridge Institute for Sustainability Leadership (CISL). It is part of a series of 'Doing business with nature' publications that identify challenges and opportunities for companies whose future growth depends on a healthy and sustained supply of nature's goods and its services. The rationale for investing in sustainable natural capital management is set out in Doing business with nature: Opportunities from natural capital and has been further developed through commodity-specific Action Research Collaboratories (ARCs) for Cotton and for Dairy in the UK and Ireland, described in the following pages and in a Summary Report.

Collaboratory Members:

The authors would like to thank all members involved in this Dairy ARC for their input. As well as the six industry leaders who participated CISL would also like to thank the following for their insightful inputs: Sarah Bell (Openfield), Robert Craig (JRC Craig & Son, Dolphenby Farm, Cumbria), Rachael and Andrew Little (Row End Farm, Soulby, Cumbria) and Peter and Di Wastenage (Wastenage Farms, Budleigh Salterton, Devon).

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Overview

With a wide array of commitments to create a more sustainable dairy industry, farmers and others have sought clarity as to which approaches at the production level should be adopted that will deliver these commitments. Six leading companies partnered with the University of Cambridge Institute for Sustainability Leadership to make an important first step. Representing different perspectives upon the dairy value chain, each company recognised that more sustainable use of natural resources creates a more resilient dairy industry by providing opportunities for increasing productivity, reducing input costs and the mitigating risks. The companies shared a common commitment, therefore, to reduce barriers to the improvement of natural capital management in dairy production systems. Through this Action Research Collaboratory (ARC) existing approaches were evaluated to highlight those practical management interventions that could, if adopted at scale, help halt degradation of water, biodiversity and soil and deliver benefits to farmers and the public. By investing in evidence-based management interventions that enhance natural capital, companies would be better able to protect the long-term security of their supply chains, sustain commercial growth and create additional social benefits.

Setting the scene

There are a variety of management interventions or practices that may be adopted at the production stage of the dairy industry to, for example, improve yields, increase operational efficiency, address environmental issues or secure natural capital. The companies of the Dairy ARC submitted over 90 potential interventions, which were then prioritised to focus on ten for inclusion in this review. The purpose of this review was to study the evidence for natural capital impacts of management interventions that a business may be considering. The evidence would highlight whether those interventions had previously been successful in providing positive impacts on water, biodiversity or soil. For each of the ten interventions, therefore, a systematic review was conducted, which revealed 91 studies with evidence of the management interventions' effects on water, biodiversity or soil. As well as concerns around natural capital, the businesses involved identified that they also wanted to consider the cost and impact on yield of each intervention. By reviewing this evidence, companies will be able to identify a more optimal mix of cost-effective farm-level management interventions.

This report provides further information on the ten management interventions which were assessed in the Natural Capital for Dairy project. A summary of this can be accessed via CISL's webpages.

Compiling the evidence

The ten key interventions were researched through a systematic review, based on Sutherland's conservation evidence process (Figure 2). The systematic reviews presented here are detailed evaluations of the evidence for the impacts of specific management interventions on natural capital. This document synthesises the 91 studies that were reviewed to provide evidence on how the ten interventions impact on water, biodiversity and soil.

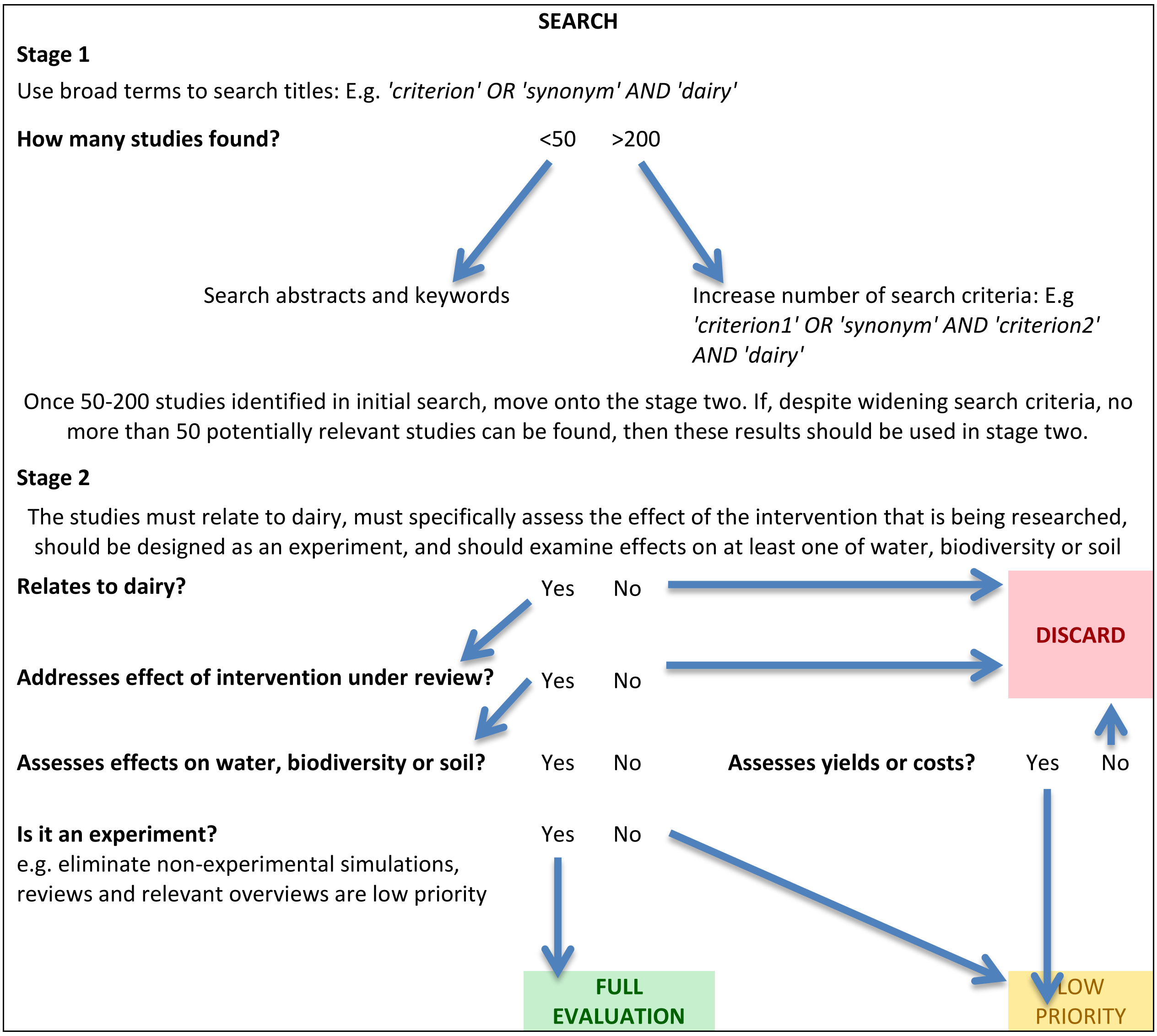

Figure 1: The evidence was reviewed and assessed according to a systematic search and filtering process.

Each chapter is devoted to the synthesis of evidence for one intervention and includes:

- a description of the intervention
- some quick facts
- a brief synthesis of evidence

The studies from which conclusions are drawn are also detailed individually. Impacts on soil, water and biodiversity are reported upon; impacts are categorised as *positive*, *likely positive, negative, likely negative, neutral* or *limited evidence.* Yield per unit area either *increases, decreases, stays the same* or there is *limited evidence.* Cost is assessed as *low*, *medium* or *high*. The key messages from the individual studies as well as their geographical regions of experimentation were underlined and the evidence was categorised according to the type of study.

Summary of evidence

Intervention	Impact					
	Soil		Water		Biodiversity	
	Structure	Fertility	Quality	Quantity	Diversity	Abundance
1. Loosening of compacted grassland soils	Beneficial	Limited Evidence	Mixed	Mixed	Limited Evidence	
2. Cereal-based whole-crop silage	Limited Evidence					Limited Evidence
3. Nitrification and urease inhibitors on pasture	Limited Evidence	Likely Beneficial	Beneficial		Likely No Effect	Likely No Effect
4. Fencing waterways	Likely Beneficial	Limited Evidence	Likely Beneficial	Likely Beneficial	Likely Beneficial	Likely Beneficial
5. Year-round housed dairy system	Limited Evidence		Limited Evidence		Limited Evidence	
6. Anaerobic digestion of on-farm dairy wastes	Limited Evidence	Mixed	Beneficial	Limited Evidence		
7. Precision agriculture on pastures	*Precision agriculture in pastures may offer significant benefits but requires extensive testing*					
8. Controlled traffic farming	Beneficial			Limited Evidence		Likely Beneficial
9. Tree shelterbelts		Limited Evidence		Limited Evidence	Limited Evidence	Limited Evidence
10. Fertilising pasture with selenium			No Effect			Limited Evidence

Table 1. Summary of each intervention and its effect on soil (structure and fertility), water (quality and quantity), and animals and plants (diversity and abundance).

1 Loosen Compacted Grassland Soil

Soil physical properties are improved by loosening but effects on pasture productivity are mixed

1.1 Description

Grassland soils can become compacted through trampling of cows or the impact of farm traffic, particularly when conditions are wet. Compaction can impede soil aeration, water percolation and root development. To alleviate the effects of compaction, mechanical loosening such as aeration (loosening to depths of around 270mm) or subsoiling/deep ripping (loosening to depths of around 500mm) has been proposed as a method to break up compacted soil layers and increase rainwater infiltration. Loosening may also allow faster incorporation of nutrients from manure into the soil, so reducing pollution concentration and volume in surface runoff.

1.2 Summary

The search revealed 61 studies, of which 13 assessed effects of loosening on soil, water or biodiversity. A further six studies were identified in secondary searches. The inclusion of one further study, because it was a highly cited study of yield effects in the UK[1], gave a total of 17 studies that were reviewed in detail.

		Soil		Water		Biodiversity		
Reference	**Country**	**Structure**	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	**Yield**
Douglas et al 1995	UK							Minimal Effect
Frost 1988a	UK	Positive						Mixed
Frost 1988b	UK	Positive						Negative
Butler et al 2008	USA			Mixed	Mixed			Mixed
Carter et al 1998	Canada	Positive						Negative
de Koff et al 2011	USA			Positive	Positive			No effect
DeLaune et al 2013	USA			Positive	Positive			
Franklin et al 2006	USA			No Effect	No Effect			
Franklin et al 2007	USA			Mixed	Mixed			
de Koff et al 2011	USA			Positive	Positive			No effect
Shah et al 2004	USA			Mixed				Negative
Wilcox et al 2012	USA				Positive			
Burgess et al 2000	New Zealand	Positive			Positive/No Effect	No Effect		No Effect
Curran Cournane et al 2011	New Zealand	Positive		No Effect	No Effect			
Drewry & Paton 2000	New Zealand	Positive						Mixed
Drewry et al 2000	New Zealand	Positive						Negative/No Effect
Harrison et al 1994	New Zealand	Positive			Mixed			Positive
You et al 2012	China	Positive	Positive		No effect			Positive

1.2.1 Soil

There were nine studies that investigated the effects of loosening on soil structure, with positive effects on soil physical properties[2-10]. Penetration resistance and bulk density were decreased by loosening but results lasted from less than 1 year[2,4,7,8] to over 2.5 years[3,5]. One of these also presented results showing that organic carbon and total nitrogen in soils was increased by aeration[10].

1.2.2 Water

The effects on water were less clear. Of seven studies that looked at water quality, two found positive effects of loosening[11,12], two found no effect[4,13], and three found variable effects[14-16]. Of those studies with variable effects, one study found that runoff water quality was decreased by aeration on poorly-drained soil while on well-drained soil there was either a positive effect or no effect on runoff water quality[15]. The other factor that resulted in mixed effects was whether the loosening treatment was conducted on manured fields or fields that had not received manure treatment. In the latter, aeration could increase pollutants and suspended solids in runoff, while in the former aeration generally improved the quality of runoff water.

Runoff water volume followed a similar pattern. Of ten studies, four showed at least some evidence of a positive effect (reduction) in runoff volume, while three showed no effect. The three remaining showed variable effects: one study found that aeration of a poorly-drained soil increased runoff volume while it was decreased or remained the same on well-drained soils[15], another found that no-till disk aeration increased runoff volume while other methods had no effect[14] and the final study found that subsoiled fields were significantly drier than controls, but aerated fields were not[9]. However, there was no significant difference in water use during the growing season and root length and growth rate was greater in loosened soils, which is expected to increase the ability of plants to obtain water in low moisture conditions[9].

1.2.3 Biodiversity

There were no studies that provided an in depth investigation into the effects of soil loosening on biodiversity. One study found no significant differences in botanical composition of aerated pasture compared to controls[2].

1.2.4 Yields

The majority of studies into the mechanical loosening of grassland soils were primarily concerned with effects on yields (12/17 studies). Only two studies reported positive effects on pasture yields[9,10] whilst four showed at least some negative effect[3,5,7,16] perhaps due to root damage[3] or because the soils were not sufficiently compacted to realise any yield benefits from loosening[5,16]. Of the three studies showing variable effects, the effect depended on the time of loosening and harvest[8], and the manure and aeration type[14]. Further, two of the studies were on soils that may have not have been sufficiently compacted to benefit from loosening[6,8]. One of the three studies showing no effect of loosening was conducted under dry conditions that may have resulted in increased root damage and greater wilting following aeration treatment.

1.2.5 Other considerations

The cost of loosening can be substantial and will require the use of specialist machinery. ADAS estimate the cost at approximately £40 per ha[17]. In addition to any soil, water and biodiversity effects, there are likely to be benefits through reduced losses of ammonia[17].

Soils are more vulnerable to compaction and erosion once mechanically loosened, so it should only be undertaken when a thorough inspection has confirmed the presence of over-compaction[18]. It may be possible to loosen specific areas such as around gateways [19]. Loosening of topsoil is ideally carried out in autumn; water stress is lower, which helps limit damage to grassland sward and subsequent yield losses, yet conditions are not too wet, which can cause further damage to soils[18]. Loosening of topsoil is not recommended for poorly drained soils[18].

Once complete, further steps should be taken to minimised or avoid over-compaction through, for example, avoiding farm traffic and intense grazing in wet conditions and this intervention can be combined with others that minimise compaction, such as use of controlled traffic systems (where appropriate), reduced stocking densities or use of low ground pressure tyres[18].

1.3 Literature review

1.3.1 Primary search

Source	Search terms (title/keyword/abstract)	Studies	*Relevant* studies	Search date
Web of Science	(loose* OR aerat* OR ripp*) AND compac* AND soil AND (pastur* OR grassland OR dairy)	61	13	16 Jul 2015

1.3.2 Secondary search

Source	Search terms	Relevant studies	Search date
Google Scholar	Alleviation of grassland compaction by mechanical soil loosening[17]	0	16 Jul 2015
Reference lists		5	16-31 Jul 2015
Total		**18**	

1.4 Literature

1.4.1 Europe

1.4.1.1 Traffic Systems and Soil Aerator Effects on Grassland for Silage Production[1]

Citation: Douglas et al 1995

Key message: Aeration had a minimal effect on grass yields

Location: Edinburgh, Scotland

Description: A study to investigate the effects of mechanical loosening to 100mm depth (among other treatments) on grass silage production. Soils had been compacted by farm traffic rather than by animal treading.

Did not assess ***soil***, ***water*** or ***biodiversity*** impacts. ***Yield:*** Found only minimal evidence of improvements in grass ***yield*** and ***nitrogen content***.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts							Minimal Effect

Study Type: Split-plot, replicated and controlled

1.4.1.2 Effects on Crop Yields of Machinery Traffic and Soil Loosening Part 1. Effects on Grass Yield of Traffic Frequency and Date of Loosening[8]

Citation: Frost 1988a

Key message: (1) Loosening decreased soil resistance, but soils re-compacted over the course of a year. (2) Yields were negatively affected by loosening in spring, but there was no effect on annual yields of loosening in autumn.

Location: Northern Ireland

Description: Experiments were carried out to test the effect of loosening (to a depth of 300-350mm) swards of perennial ryegrass for silage production. Two experiments were conducted. The first included an investigation into the effects of slurry spreading, whilst the second compared the effect of loosening in autumn and loosening in spring with controls (no loosening).

Soil: Cone ***penetrometer resistance*** was significantly reduced by loosening of soil but over the course of the year resistance reverted to values that were similar to unloosened soil. ***Yield:*** In the first experiment, ***yield*** was significantly (44 per cent) lower for loosened plots compared to controls in the first harvest after loosening and 10 per cent lower (although not statistically significant) in the following harvest. For the second experiment: ***yields*** were significantly lower (reduced by 20 per cent for autumn-loosened and 31 per cent for spring-loosened) for the first harvest following loosening. ***Yields*** were, however, significantly increased (9 per cent higher) for the second harvest of autumn-loosened areas, while in no effect was observed for spring-loosened areas. There was no significant effect from loosening at third harvest, but at fourth harvest average ***yields*** from the autumn and spring loosened areas were significantly greater than from unloosened areas (15 per cent and 11 per cent, respectively). ***Annual average yield*** from autumn-loosened areas was marginally, though not significantly greater than from unloosened areas, while spring-loosened areas had significantly lower ***annual average yields*** (8 per cent lower). ***Caveat:*** Despite extensive machinery use prior to commencement of the experiments there was no visible evidence of compaction in the soils and grass yields were considered typical of Northern Ireland.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive						Mixed

Study Type: Replicated, split-plot, controlled

1.4.1.3 Effects on Crop Yields of Machinery Traffic and Soil Loosening: Part 2, Effects on Grass Yield of Soil Compaction, Low Ground Pressure Tyres and Date of Loosening[7]

Citation: Frost 1988b

Key message: (1) Soil loosening in autumn or spring reduced subsequent grass harvest yields and gave no significant yield advantage over the following two seasons. (2) Soil resistance was decreased by loosening with effects lasting at least 8 months.

Location: Northern Ireland

Description: An experiment to assess whether compaction in soils under grass can be effectively ameliorated by soil loosening (to a depth of 350mm) without destroying the sward. In an earlier study soil loosening was found to reduce grass yields but this was partly attributed to lack of soil compaction prior to loosening[8]. Thus soils were compacted prior to experimental loosening treatments applied in autumn or in spring. Yield effects were measured at time of silage harvest in May, June and August.

Soil: The ***cone resistance*** of soils loosened in either autumn or spring was initially reduced significantly to depths of at least 280mm and effects persisted for at least 8 months following treatment. However, the effect of loosening on ***cone resistance*** declined over time and for autumn-loosened soils treatment effects were non-significant (although resistance remained generally lower) from 8 to 11 months after treatment. No residual effects on cone resistance were found in the year after soil loosening for either spring or autumn-loosened soil. ***Yield:*** At the first harvest after treatment, loosened soils had 11-12 per cent lower grass ***yields***. ***Annual yields*** in the year following loosening were 7 and 5 per cent lower from the autumn and spring loosened areas, respectively. ***Yields*** were generally not significantly different one year later.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive						Negative

Study Type: Randomised, replicated, controlled

1.4.2 North America

1.4.2.1 Evaluating Aeration Techniques for Decreasing Phosphorus Export from Grasslands Receiving Manure[14]

Citation: Butler et al 2008

Key message: (1) Core aeration has the greatest potential for reducing phosphorous losses after broiler litter manure has been applied. (2) Core and no-till disk aeration show potential for reduction of phosphorous export from dairy sludge manure.

Location: Georgia, USA

Description: This study reports on experiments to assess the effect of mechanical aeration of grasslands for reducing P transport by increasing infiltration of rainfall and binding of P with soil minerals. Three aeration treatments (aeration with cores, no-till disk aeration perpendicular to the slope, and slit aeration with tines, all applied to a depth of 80mm) were compared to a control (no aeration treatment) for their effect on the export of total suspended solids, total Kjeldahl P (TKP), total dissolved P (TDP), dissolved reactive P (DRP), and bioavailable P (BAP) in runoff from grasslands with three manure treatments (broiler litter, dairy slurry, and no manure). Tests using simulated rainfall were conducted after aeration of treated plots and again following compaction and aeration.

Water: Generally, differences in ***runoff volumes*** were not statistically significant between aerated plots and control. However, no-till disk aeration increased ***runoff volume*** by 59 per cent in the post-compaction test. After broiler litter or dairy slurry application, aeration did not significantly affect export of ***total suspended solids (TSS)***, although slit aeration resulted in non-significant reductions in ***TSS*** export of 23-28 per cent. When no manure is applied, ***TSS*** is significantly greater under core aeration than control. The effect of aeration on ***phosphorous*** export was mixed, but overall core aeration appeared to offer the greatest reduction in losses from fields applied with broiler litter. Both core aeration and no-till disk aeration showed potential for reducing ***phosphorous*** losses from fields applied with dairy slurry (for detail see below). ***Yield:*** Under broiler litter treatment, forage yields under core aeration were significantly greater than controls (2215kg ha^{-1} vs. 1633kg ha^{-1}, $p<0.1$). Under dairy slurry or no-manure treatments, aeration did not affect forage yields.

[***Phosphorous*** in detail: for broiler litter treatment, ***total Kjeldahl phosphorous (TKP)*** in pre-compaction tests was reduced by core (57 per cent lower), no-till disk (25 per cent lower) and slit (28 per cent lower) aeration. Post-compaction ***TKP*** was reduced by 50 per cent by core aeration, but this effect was not significant. Under dairy slurry, aeration did not affect ***TKP*** in pre-compaction tests, but reduced ***TKP*** export was found under core aeration (52 per cent lower) and no-till disk aeration (58 per cent lower) in post-compaction tests. With no manure application, aeration did not significantly affect ***TKP***. ***Total dissolved phosphorous (TDP)*** from broiler litter field was reduced by 27-66 per cent by aeration treatments prior in pre-compaction tests, but there was no effect for post-compaction tests. ***Dissolved reactive phosphorous (DRP)*** from broiler litter fields was reduced by 28-66 per cent by aeration. ***DRP*** from dairy slurry fields was reduced in post-compaction tests by 47 per cent and 55 per cent under core and no-till disk aeration, respectively. Slit aeration had no effect on ***DRP***. ***Bioavailable phosphorous (BAP)*** losses from fields applied with broiler litter was decreased by aeration in pre-compaction tests (particularly by core aeration), but ***BAP*** was greater in no-till disk aerated plots for post-compaction tests of fields applied with broiler litter. For dairy slurry fields, ***BAP*** was decreased in post-compaction tests by core and no-till disk aeration treatments.]

	Soil		**Water**		**Biodiversity**		**Yield**
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts			Mixed	Mixed			Mixed

Study Type: Randomised, replicated and **c**ontrolled

1.4.2.2 Influence of non-inversion loosening on permanent pasture productivity[3]

Citation: Carter et al 1998

Key message: (1) Loosening had positive impacts on the physical properties of soil that persisted for 3-4 years. (2) Pasture productivity was negatively affected by loosening, probably due to root disturbance.

Location: Prince Edward Island, Canada

Description: An experiment to test the effect of (non-inversion) soil loosening of compacted soil under a Kentucky bluegrass/white clover pasture at a depth of 200mm.

Soil: Prior to loosening, soils had ***dry bulk densities***, ***macropore volumes***, ***shear strength*** and ***penetrometer resistance*** values that indicated physical compaction of the soil to a degree that would be expected to limit root growth. Treatment resulted in significant loosening at 100-250mm depths with effects declining over time and lasting 3-4 years. ***Yield:*** Average (3-year) ***pasture productivity*** was lower in loosened fields than in controls probably due to root disturbance or injury caused by the mechanical loosening.

	Soil		**Water**		**Biodiversity**		**Yield**
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive						Negative

Study Type: Randomised, replicated and controlled experiment and measurements over 3 years

1.4.2.3 Effects of Pasture Renovation on Hydrology, Nutrient Runoff, and Forage Yield[11]

Citation: de Koff et al 2011

Key message: (1) Overall, beneficial impacts of renovation on nutrient losses and runoff lasted up to 3 months, which is the most critical period for nutrient runoff following manure application. (2) Effects on forage yields were mixed and always non-significant.

Location: Arkansas, USA

Description: Aeration (to 150mm depth) prior to swine slurry or poultry litter application was assessed for its effect on nutrient runoff and forage yield for three soil types: Pickwick, Taft and Captina.

Water*: Runoff volumes** were lower for seven out of eight aerated plots (reductions of 45 to 74 per cent) in the week following treatment, of which two of these effects were statistically significant. ***Runoff volumes were also lower for aerated plots compared to controls in the 13 months following treatment (18 of 20 measurements), but only significantly so for 1 rainfall simulation event, which was in Pickwick soil at 3 months after treatment for plots applied with swine slurry. ***Infiltration rates*** were generally increased by up to 87 per cent for aerated plots compared to controls. For Pickwick soils ***infiltration rates*** were always faster in aerated soils, and significantly so 3 months after aeration for fields with no manure and fields applied with swine slurry. Taft soils showed significantly increased ***infiltration rates*** for all manure/no manure treatments 1 day after aeration but measurements at 3 and 13 months show no significant differences for aeration. For Captina soil, aerated plots show significantly increased ***infiltration rates*** 1 week after aeration which persist for up to 12 months, although differences after 1 month are not significant. ***Dissolved reactive phosphorous (DRP)*** and ***total phosphorous (TP) loads*** (kg ha^{-1}) were lower for almost all aerated plots, compared to non-aerated controls and this decrease was significant for the plots that had received poultry litter. Aeration treatment effects for 3 to 13 months after aeration were mixed and not significant for any soil type or manure application. ***Total nitrogen (TN) load*** (kg ha^{-1}) was generally lower for up to 3 months after aeration and this effect was significant in the first week after aeration for Taft and Captina soils applied with poultry litter. The effect of aeration on ***TN load*** beyond 3 months after treatment was mixed and not statistically significant. ***Yield*:** Renovation did not result in any significant differences in forage yields.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive	Positive			No effect

Study Type: Replicated, controlled

1.4.2.4 Impact of soil aeration on runoff characteristics in dual-purpose no-till wheat systems[12]

Citation: DeLaune et al 2013

Key message: (1) Aeration is most effective in reducing runoff and nutrient losses within three weeks after implementation. (2) If aeration is implemented with nutrient applications, nutrient losses could be reduced by more than 4-fold compared to no-till.

Location: Texas, USA

Description: An experiment to test the effect on runoff of aeration (to 200mm depth and using roller angles of 0°, 5° and 10°) and conventional tillage against a no-till system.

Water: Aeration using 5° and 10° roller angles reduced ***runoff volume*** and increased ***infiltration rates*** compared to no-till in the three weeks after treatment. However, six weeks after treatment, no-till (i.e. control) runoff volumes were lower than all treatments except the 10° aeration and after 10 months of tillage implementation, infiltration was 10% to 52% greater on no-till plots compared to tilled treatments. Similarly, aeration using 5° and 10° roller angles reduced ***soluble reactive phosphorus (P)***, ***total P***, and ***ammonium-nitrogen (NH_4-N)*** loads compared to no-till in the three weeks after fertilizer application and aeration.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive	Positive			

Study Type: Randomised, replicated and controlled

1.4.2.5 Fertilizer source and soil aeration effects on runoff volume and quality[13]

Citation: Franklin et al 2006

Key message: Aeration of hay fields does not have a significant effect on runoff volumes or nutrient losses.

Location: Georgia, USA

Description: A study to investigate the effect of fertilizer source (inorganic fertiliser versus broiler litter) and aeration (to a depth of 90mm) on the volume and quality of runoff from grassed plots.

Water: This experiment found no significant effect of aeration on ***runoff volume***, although ***runoff volumes*** in aerated plots were on average 27 per cent lower (P=0.16). Aeration also had no statistically significant effect on time to ***initiation of runoff***. ***Dissolved reactive phosphorous***, ***total kjeldahl phosphorous and ammonium (NH_4N)*** losses were also found to be the same in aerated plots as in non-aerated plots. ***Caveats:*** aeration slits were parallel to the slope, rather than perpendicular, which may mean that they do not interrupt the flow of water across the soil surface so effectively. Also soils may not have been as compacted as would be found in a grazed pasture, rather than hay fields in which forage is harvested.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No effect	No effect			

Study Type: Randomised, replicated and controlled

1.4.2.6 Aerating Grasslands: Effects on Runoff and Phosphorus Losses from Applied Broiler Litter[15]

Citation: Franklin et al 2007

Key message: (1) Aeration had mixed effects for well-drained soils, reducing runoff volumes and nutrient losses in one case but having no effect in the second. (2) Runoff volumes and nutrient losses were increased by aeration in poorly drained soils.

Location: Georgia, USA

Description: A study to test the effect of slit aeration (to a depth of 100-120mm) on runoff and nutrient losses in a fescue/bermudagrass hay field fertilised with broiler litter. Separate experiments were conducted in well-drained soil and poorly-drained soil.

Water: The effect of aeration on ***runoff volume*** was mixed for well-drained soils, with a reduction of 35% in one pair and no effect in another. ***Runoff volume*** was, however, increased by aeration in a poorly-drained soil pair. Mass losses of ***dissolved reactive phosphorous (DRP)*** followed the same pattern, with mixed effects on well-drained soils (significantly reduced by 35% in the first pair and no effect in the second pair) and an increase in mass ***DRP*** losses for poorly drained soils. There was no effect on ***total phosphorous (TP)*** in either of the well-drained soil pairs but TN was higher for the aerated field in poorly drained soil.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Mixed	Mixed			

Study Type: Paired sites (treated and control)

1.4.2.7 Influence of Aeration Implements, Phosphorus Fertilizers, and Soil Taxa on Phosphorus Losses from Grasslands[20]

Citation: Franklin et al 2011

Description: This paper summarises experiments reported in earlier papers[13-15]

1.4.2.8 Mechanic al aeration and liquid dairy manure application impacts on grassland runoff water quality and yield[16]

Citation: Shah et al 2004

Key message: (1) Aeration partially improved runoff water quality if grassland is manured but adversely affected crop yield and nutrient uptake. (2) There is a need for aerators that minimise surface soil disturbance to reduce total suspended solid losses.

Location: West Virginia, USA

Description: High spring rainfall and heavy soils in West Virginia can combine to reduce oxygen availability and depress grassland yields. An experiment was conducted to test the efficacy of applying liquid dairy manure and/or aerating soil (to ~150mm depth) to improve forage yields and improve runoff water quality for fields under orchard grass with 10-20 per cent alfalfa.

Water: In plots that were not treated with manure, nutrient concentrations in runoff ***water*** were unaffected by aeration compared to the control. However, in manured plots, aeration was observed to reduce losses of nutrients in simulated events (loadings of individual nutrients were reduced by >26% by aeration of manured plots) but no effect was observed for a single natural rainfall event. Higher total suspended solids were observed under simulated rainfall for aerated plots, but not under the natural rainfall event. ***Yield:*** Aeration led to a reduction in ***yield*** for manured plots. Relatively weak evidence that aeration reduced soil impedance, and overall aeration was found to reduce crop nutrient uptake, probably due to root damage. ***Caveat:*** the grassland had not been heavily grazed, so the baseline was not a compacted soil.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Mixed				Negative

Study Type: Randomised, controlled and replicated

1.4.2.9 Contour ripping is more beneficial than composted manure for restoring degraded rangelands in Central Texas[21]

Citation: Wilcox et al 2012

Key message: Contour ripping is effective for increasing infiltration rates and reducing runoff

Location: Central Texas, USA

Description: A study to assess the effect on compacted soils of applying composted dairy manure and contour ripping (to an average depth of 380mm) on soil infiltrability, amount of runoff, and nutrient concentrations in runoff.

Water: ***Runoff*** in treated plots was almost half (~ 30 per cent of rainfall) that from the control (~ 60 per cent of rainfall). ***Caveats:*** The effect of contour ripping cannot be assessed entirely independently of the effect of applying compost.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts				Positive			

Study Type: Repeated measures over time, control plots used but insufficient to attribute effects entirely to contour ripping treatment.

1.4.3 Australasia

1.4.3.1 Shallow mechanical loosening of a soil under dairy cattle grazing: Effects on soil and pasture[2]

Citation: Burgess et al 2000

Key messages: (1) Aeration significantly improved soil physical properties for water and air movement, and is a useful method for ameliorating compacted soil supporting permanent pasture on dairy farms. (2) Improvements in soil physical properties decline with time and aeration may have to be repeated annually. (3) Aeration should be completed when soil and atmospheric conditions (rainfall and evaporation) are best for mechanical loosening of soil.

Location: Hamilton, New Zealand

Description: This study investigated the effectiveness of mechanical loosening to 220mm depth for ameliorating soil damage by cattle in a ryegrass/white clover pasture grazed for > 20 years under an intensive dairy farming system. Soil physical properties, pasture yield, botanical composition, ground cover, and root activity were monitored and the longevity of effects assessed over a 40-week period.

Soil: Aeration significantly reduced ***penetration resistance***, ***degree of packing*** and ***bulk density*** and significantly increased ***porosity***, ***hydraulic conductivity*** and ***proportion of smaller aggregates***. During a 40-week study, physical conditions reverted to those of the control plots, although significant differences remained in ***degree of packing*** and ***macroporosity***. Aerated plots had more ***bare ground*** than controls at 3 weeks after treatment, but less ***bare ground*** 46 weeks after aeration. ***Water:*** No differences in ***soil moisture content*** were found between aerated and control soils. ***Root length*** and ***root dry weight*** (which are expected to increase the ability of plants to obtain water in low moisture conditions) were greater in aerated versus control plots, but not significantly so. ***Biodiversity:*** There were no significant differences in ***botanical composition*** of aerated pasture compared to controls. ***Yield:*** There were no significant differences in ***herbage dry matter yield*** between aerated and control plots except for one measurement four weeks after treatment, in which ***yields*** were lower in aerated plots (probably due to initial root damage). Subsequently higher ***yields*** in the aerated plots (compared to controls) resulted in no significant difference in annual ***herbage dry matter yields***. ***Caveats:*** The authors note that dry conditions during aeration may have caused irregular disturbance of the soil, resulting in root damage, whilst dry conditions immediately after aeration resulted in plant wilting, which resulted in the reduced herbage yields reported shortly after treatment. They also note that other studies find significant differences in aerated (versus control) plots only after 52 weeks, with effects becoming stronger at 60 weeks. Therefore, this study may have been too short to record all of the significant differences arising from aeration.

	Soil		**Water**		**Biodiversity**		**Yield**
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive			No Effect or weakly Positive	No Effect		No Effect

Study Type: Randomised, replicated and controlled

1.4.3.2 Is mechanical soil aeration a strategy to alleviate soil compaction and decrease phosphorus and suspended sediment losses from irrigated and rain-fed cattle-grazed pastures?[4]

Citation: Curran Cournane et al 2011

Key message: (1) Aeration did not improve soil physical properties compared to control plots. (2) Aeration did not reduce losses of phosphorous or suspended sediment in surface runoff.

Location: North Otago, New Zealand

Description: A study to assess the impact of aeration (to 200mm depth) of an irrigated ryegrass/white clover pasture grazed by sheep and cattle.

Soil: Seven days after treatment, aerated plots showed significantly increased macroporosity (28 per cent versus 11 per cent v/v) and decreased bulk density (1.05 versus 1.39 g/cm^3). However, no significant differences were observed 6 months after treatment, indicating rapid resettling of the poorly-structured soil. ***Water:*** No significant effect was observed for the volume of water runoff (measured 6 months after aeration, when soil physical properties were not significantly different from controls) or for losses of phosphorous and suspended solids.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive		No effect	No effect			

Study Type: Randomised, replicated and controlled

1.4.3.3 Effect of subsoiling on soil physical properties and dry matter production on a Brown Soil in Southland, New Zealand[6]

Citation: Drewry & Paton 2000

Key message: Subsoiling improves soil physical conditions, which persist for up to 22 months.

Location: Southland, New Zealand

Description: A 2.5-year study into the effect of subsoiling at 250-300mm depth using conventional and wing-shaped tines. Compacted soils were naturally well-drained and supported ryegrass/white clover sheep grazing pasture.

Soil: Soil physical properties were significantly improved by subsoiling. ***Macroporosity***, ***air permeability***, ***hydraulic conductivity*** (saturated and unsaturated) was increased one month after subsoiling with both conventional and winged tines and the effect was still present 22 months after treatment. Generally, the effects on ***soil physical qualities*** were similar for conventional and winged tines. ***Yield:*** Effects on ***yield*** were mixed. For winged-tine subsoiling, three of five seasons showed no significant difference in ***dry matter production***, one season exhibited increased ***yields*** compared to controls and one season exhibited decreased ***yields***. For conventional-tine subsoiling, three of five seasons showed no significant difference in ***dry matter yields***, whilst two showed lower ***dry matter yields*** than in control plots. ***Caveats:*** The soil in the study site may have been insufficiently compacted to exhibit a positive yield response to subsoiling.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive						Mixed

Study Type: Randomised, replicated and controlled

1.4.3.4 Effect of subsoiling on soil physical properties and pasture production on a Pallic Soil in Southland, New Zealand[5]

Citation: Drewry et al 2000

Key message: (1) Subsoiling significantly improves soil physical conditions, effects persisting for up to 2.5 years. (2) There was generally no effect on dry matter yields except during a dry summer when yields were 39 per cent lower in subsoiled plots.

Location: Southland, New Zealand

Description: A 2.5-year study into the effect of subsoiling at 250-300mm depth using conventional and wing-shaped tines. The study site was a ryegrass/white clover sheep grazing pasture.

Soil: Soil physical properties were significantly improved by subsoiling. Subsoiling with either conventional or winged tines increased ***macroporosity***, ***air permeability*** and ***saturated hydraulic conductivity***. Treatment effects decreased with time but were still significant at 180-240mm soil depths 2.5 years after treatment. There was little evidence that winged tines were more effective than conventional. ***Yield:*** For conventional subsoiling, there were no significant differences in ***dry matter yields***. Winged subsoiling generally resulted in lower ***dry matter yields*** but this was only significant (at the $P<0.01$ level) for one season out of five. ***Caveats:*** The soil in the study site may have been insufficiently compacted to exhibit a positive yield response to subsoiling.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive						Negative or No Effect

Study Type: Randomised, replicated and controlled

1.4.3.5 Effects of subsoil loosening on soil physical properties, plant root growth, and pasture yield[9]

Citation: Harrison et al 1994

Key message: (1) Physical properties of compacted soils can be significantly improved by aeration or subsoiling, leading to more extensive root systems and greater rates of root growth. (2) Dry matter yields in spring were significantly higher for pasture with loosened soils.

Location: Canterbury, New Zealand

Description: This study investigated the effects of aeration (soil loosening to 270mm) and subsoiling (loosening to 470mm) in a New Zealand ryegrass/white clover pasture grazed by sheep and cattle. The climate is dry, hot and windy causing it to be drought-prone in summer.

Soil: ***Soil bulk density*** was significantly reduced in both aerated and subsoiled treatments, compared to the control, particularly in the top 250mm of soil where compaction was identified as constricting grass root growth. Compared to the control, aerated fields had greater ***hydrological conductivity*** at 200-300mm depth. Subsoiled fields had greater ***hydrological conductivity*** at 200-400mm than either aerated or control fields. ***Water:*** Subsoiled (but not aerated) fields were significantly ***drier*** than controls (probably due to faster drainage and more water being retained in the control), but there was no significant difference in ***water use*** during the growing season. Pasture ***root growth*** rate (larger root systems increase the ability of plants to obtain water in low moisture conditions) was greater in loosened soils and, of the total ***root length***, 35% was below 250mm depth for subsoiled treatments, 28% for aerated treatments and 25% for control. ***Yield:*** Total ***dry matter yields*** were significantly higher in aerated and subsoiled fields than in controls during spring (Aug-Oct).

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive			Mixed			Positive

Study Type: Randomised, replicated, controlled

1.4.4 Asia

1.4.4.1 A device for mechanical remediation of degraded grasslands[10]

Citation: You et al 2012

Key message: The physical properties of compacted soils can be improved by aerating soils and substantially increased grass yields are observed in the following year

Location: Hebei Province, Northern China

Description: Using conventional tillage tools to improve degraded grasslands (*Leymus chinensis*) in arid and semi-arid regions of China has resulted in soil nutrition loss, severe soil erosion problems, and destruction of vegetation, interrupting livestock feed supply. Costs of replanting and forage purchasing are not affordable for most farmers here. To increase grass yields, soil conditions need to be amended with consideration of soil and water conservation. Therefore, soil-engaging tools with negligible soil disturbance, deep soil-penetrating and root-cutting functions are needed. A soil-engaging tool was designed to for root cutting and soil gashing at a depth of 150mm-200mm and its effect on severely compacted grassland soils was assessed.

Soil: No ***soil overturn*** was observed and roots were completely cut in the slits. ***Soil bulk density*** slightly (non-significant) lower in treated plots at 0-50mm and 100-150mm but significantly lower in treated plots at 200-250mm depth. ***Soil bulk density*** may be further reduced over the course of several years' worth of freeze thaw cycles, but this was not tested. Soil ***pH*** was reduced (improved) at 3 sampling depths, probably due to increased infiltration of alkaline elements from the surface and release of organic acids (lowering ***pH***) from dead roots. ***Soil organic carbon*** and ***total nitrogen*** were significantly increased at all depths, demonstrating improved soil nutrient circumstance (whereas conventional tillage will usually decrease soil organic carbon and nitrogen). ***Water: Soil moisture content*** was slightly lower in top soil of treated fields, but not significantly different at greater depths. ***Yield:*** The following year, grass ***yields*** increased significantly by 95 per cent.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive	Positive		No effect			Positive

Study Type: Randomised, replicated and controlled experiment

1.4.5 Review papers

1.4.5.1 The alleviation of grassland compaction by mechanical soil loosening[22]

Citation: Bhogal et al 2011

Key messages: (1) Where used in appropriate conditions, grassland looseners can alleviate compaction and where compaction is evident positive responses in ***herbage yields*** are likely. (2) Increased ***yields*** and improvements in ***soil physical properties*** may only persist up to 12 months. (3) Loosening can improve ***soil physical properties*** and reduce ***surface runoff*** and associated ***sediment and nutrient losses*** from grassland soils, although results have been variable. (4) Soil loosening devices should only be used when there is clear evidence of compaction. (5) The timing of operations is critical; use in conditions that are too wet will potentially lead to soil damage through smearing and wheel slip, and use in conditions that are too dry will most likely result in excessive soil surface heave and root damage leading to sward death. (6) Recently loosened soil is very sensitive to re-compaction and it is important to allow the newly loosened structure to be stabilised by root activity and natural soil processes before livestock are returned or machinery is used on the land. (7) There is a need to investigate the effects of modern topsoil loosening equipment on soil functions and ecosystem services at compacted soil sites in England and Wales.

2 Cereal-based whole-crop silage

There is limited evidence for potential benefits of CBWCS to soil structure and biodiversity

2.1 Description

The decline of arable cultivation in pastoral areas is thought to be a factor behind declining farmland birds. To reverse farmland bird declines, growing cereals such as wheat or barley for silage, as opposed to the more common alternatives of grass and maize, has been proposed for pastoral areas, where arable cultivation is increasingly scarce[23].

Wholecrop cereals are grown like grain but harvested earlier to make silage. Wheat is the most common cereal used, followed by barley, but there is increasing interest in triticale and rye. There are two primary types 1) fermented wholecrop, which is harvested earlier (at around 45 per cent dry matter) and 2) high dry matter wholecrop, which is harvested later (dry matter content around 55-60 per cent).

2.2 Summary

Only four relevant studies were found. However, of these, 3 reported on a single set of earlier experiments, so the number of original and relevant studies is just one.

		Soil		Water		Biodiversity		
Reference	Country	Structure	Fertility	Quality	Quantity	Diversity	Abundance	Yield
Defra 2007	UK	Positive*					Positive	No Effect

*Inferred: for more information see detail below

2.2.1 Soil

Effects on soil were not directly assessed. However, earlier harvesting of wheat and barley (compared to maize) reduces the need to work on fields when weather conditions are poor and reduces need for bare ground over winter (reduced ***soil compaction*** and ***erosion***)[24].

2.2.2 Water

Effects of CBWCS on water were not assessed. One study reported other potential (but not tested) water benefits: (1) high and predictable yields compared to grass, which is sensitive to drought (reduced vulnerability to ***water dependency***) and (2) the absence of the effluent problems associated with grass silage (reduced ***water impacts*** from pollution events).

2.2.3 Biodiversity

In the single study that investigated CBWCS, spring barley with only narrow spectrum herbicide applied was most effective at providing habitat and food resources for at-risk farmland birds. Forb abundance was also generally higher in barley field treatments, followed by maize and wheat and lowest in grass. Barley and wheat also showed greater larval abundance and, along with grass, greater abundance of adult invertebrates. Both were lowest in maize.

2.2.4 Yield

There was no evidence that CBWCS improved milk yield or quality compared to maize silage.

2.2.5 Other considerations and notes on best practice

Using CBWCS should provide a relatively inexpensive option for dairy farmers, with cost per ton of dry matter for spring barley comparable to those of grass and maize. However, high dry matter wholecrop cannot be used in organic dairy production because of the additives needed to preserve the silage.

Defra[24] suggest that a key consideration is the flexibility as CBWCS can be fed to dairy cattle, beef cattle, young stock and sheep with other silage or it can provide 100 per cent of the livestock's dry matter intake. Moreover, the decision on how much whole-crop to harvest can be delayed until late in the cereal growth stage allowing the cereal crop to be harvested as grain if there is enough grass silage. Because of its high palatability, CBWCS can also give higher dry matter intake rates than grass silage alone and can improve cow welfare[25]. If needed, protein content can be increased by bi-cropping cereals with brassicas or legumes[25]. In pastoral areas, it is recommended that cereal stubbles from intensively managed crops should account for at least 10 per cent of the land area to ensure stability of skylark and yellowhammer populations[23]. Early harvesting of CBWCS could harm breeding attempts of late-nesting species (e.g. corn bunting and yellow wagtail), so where late-breeding species are likely to nest in CBWCS fields, harvesting should be delayed until most nesting attempts have been completed (e.g. until after 1st August in southern Britain)[24].

2.3 Literature review

2.3.1 Primary search

Source	Search terms (title)	Studies	*Relevant* studies	Search date
Web of Science	(cereal OR wholecrop OR whole-crop) AND (silag* OR forag*) AND (dairy OR pastoral OR grassland OR pasture)	51	3	09 Jul 2015

2.3.2 Secondary search

Source	Search terms	Relevant studies	Search date
Google Scholar	Cereal based whole crop silage dairy	0	09 Jul 2015
Reference lists		1	
Total		**4**	

2.4 Literature

2.4.1 Europe

2.4.1.1 New conservation measures for birds on grasslands and livestock farms[27]

Citation: Buckingham et al 2010

Description: <u>This paper summarises experiments reported in Defra (2007)[24]</u>

2.4.1.2 Cereal-based whole crop silages: a potential conservation mechanism for farmland birds in pastoral landscapes[24]

Citation: Defra 2007

Key message: Spring-sown barley provides substantially greater food resources than the other silage crops tested for red and amber-listed farmland birds of conservation concern.

Location: West Midlands, England

Description: A controlled experiment conducted on farms over 2 consecutive years (both winter and summer measurements taken) and replicated across 16 farms during a 3-year period. Cereal-based wholecrop silage (CBWCS) from winter wheat and spring barley (split field: all sprayed with narrow spectrum herbicide in spring and then half sprayed with broad spectrum herbicide in late spring/summer) were compared with more conventional silage from maize and grass for their effects on presence of seed-eating passerines (including red-listed Yellowhammer, Tree Sparrow and House Sparrow) and skylark in the fields where the crops are grown. All four treatments were grown in close proximity on each farm and monitored over two years.

Biodiversity: Spring barley with just a narrow spectrum herbicide applied was most effective at providing ***habitat*** and ***food resources*** to birds and was comparable in terms of costs per ton of dry matter (see Table 1 below). ***Forb abundance*** for the four most abundant species was generally greatest in the two barley field treatments (broad/narrow spectrum herbicide), followed by maize and wheat and lowest in grass. ***Larval abundance*** was generally highest in wheat or barley and lowest in maize, whilst ***adult invertebrates*** were more abundant in barley, wheat and grass than in maize. ***Soil:*** Overall, proportion of ***bare ground*** (which puts soils at increased risk of erosion) was lowest in grass, followed by barley and wheat and was highest in maize. During the winter, ***bare ground*** was lower in barley than in wheat fields. ***Yield:*** There is no evidence that CBWCS gives greater milk yields or improved milk quality over maize silage.

	Winter wheat	Maize	Spring barley: herbicide^{-}	Spring barley: herbicide^{+}	Grass
Bird benefits: summer	High	Low	High	High	Low
Bird benefits: winter	Low	Low	High	High	Low
Invert. abundance (summer)	High	Lowest (significant)	Highest	High	Medium/High
Production costs	£50 [£31-£34]/t DM	£52/t DM	£61 [£36]/t DM	£58/t DM	£77/t DM

Table 1. Summary of relative benefits to biodiversity and relative costs for farmers of producing silage from grass or maize in comparison to wholecrop cereal silage from winter wheat or spring barley (under two separate herbicide treatments). In square brackets are the production costs calculated including Entry Level Scheme payments if no broad spectrum herbicide is used and stubble is left *in situ* over winter.

	Soil		**Water**		**Biodiversity**		**Yield**
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive*					Positive	No Effect
*inferred due to decreased bare ground in barley and wheat fields compared to maize (*but not compared to grass*)							

Study Type: Replicated and controlled

2.4.1.3 *Cereal-based wholecrop silages: A potential conservation measure for farmland birds in pastoral landscapes*[28]

Citation: Peach et al 2011

Description: This paper summarises experiments reported Defra (2007)[24]

2.4.1.4 *Plant and invertebrate resources for farmland birds in pastoral landscapes*[26]

Citation: Westbury et al 2011

Description: This paper summarises experiments reported Defra (2007)[24]

3 Nitrification and urease inhibitors on pasture

Nitrification inhibitors offer benefits in the form of increased soil fertility, water quality and yields

3.1 Description

Losses of nitrogen to the environment through leaching of nitrate, gaseous losses of ammonia, nitrogen and nitrous oxide represent 30 to 40 per cent of the nitrogen entering pastures through nitrogen fixation and application of nitrogen fertilizers[29]. As well as representing inefficiency in the use of expensive fertiliser resources, these losses are also a significant contributor to global greenhouse gas emissions and also play a major role in degrading groundwater quality. High nitrate concentrations in pastures and forages also represent a health risk to grazing livestock and can be reduced to safe levels with nitrification inhibitors[30]. Lastly, some (although not all) studies report greater pasture yields when using nitrification inhibitors[e.g.31-34]. Nitrification and urease inhibitors are chemicals that are used to disrupt the chemical pathway that leads to these losses and there is considerable interest their use for agronomic, environmental and animal welfare concerns. Nitrification inhibitors restrict the conversion of ammonium to nitrate and to nitrous oxide, a potent greenhouse gas. Urease inhibitors act at an earlier stage of the cycle, preventing conversion of urea/urine to ammonium (thereby limiting production of nitrate and nitrous oxide)[29]. Common chemical used include nitrification inhibitors DCD (dicyandiamide) and DMPP (3, 4-dimethylpyrazole phosphate) and urease inhibitor nBPT (N-(n-butyl) thiophosphoric triamide).

3.2 Summary

The systematic search revealed 89 studies, of which 32 were determined to be relevant (they assessed effects of loosening on soil, water or biodiversity). One of these could not be accessed at all[35] and only the abstracts were available for a further five[36-40]. Two of the papers reported on the same experiment and were thus combined[41,42]. A further two studies were identified from google scholar and from the reference lists of other studies[43,44]. This gave a total of 32 studies that were reviewed (27 of these in detail). However, 30 of the 32 studies were conducted in New Zealand, where pastures tend to be free draining and have a longer growing season than the UK[45] and most are small-scale experimental studies. Much greater effort is needed to investigate the impacts of nitrification and urease inhibitors on soil, water and biodiversity under the climatic and biophysical conditions found in the UK and ROI, and under true grazing conditions at farm or pasture scales.

		Soil		Water		Biodiversity		
Reference	Country	Structure	Fertility	Quality	Quantity	Diversity	Abundance	Yield
Dennis et al 2012	Ireland			Positive				
Macadam et al 2003	Spain							Mixed
Cameron et al 2014	New Zealand			Positive				Positive
Cookson & Cornforth 2002	New Zealand		Positive	Positive				No Effect
Dai et al 2013	New Zealand						No Effect	
de Klein et al 2014	New Zealand			No Effect				No Effect
Di & Cameron 2002	New Zealand			Positive				Positive
Di & Cameron 2004a	New Zealand		No Effect					
Di & Cameron 2004b	New Zealand		Positive					
Di & Cameron 2004c	New Zealand		Positive	Positive				Positive
Di & Cameron 2005	New Zealand		Positive	Positive				Positive
Di & Cameron 2007	New Zealand			Positive				Positive
Di & Cameron 2012	New Zealand			Positive				
Di et al 2009	New Zealand			Positive				
Di et al 2011	New Zealand						No Effect	
Doole & Paragahawewa 2011	New Zealand			Positive				
Guo et al 2013	New Zealand		No Effect				No Effect	
Kim et al 2014	New Zealand		No Effect	Positive				Mixed
Ledgard et al 2014	New Zealand			Positive				Positive/No Effect
Menneer et al 2008a,b	New Zealand		Positive	Positive				Positive
Moir et al 2007	New Zealand		No Effect			No Effect		Positive
Moir et al 2012	New Zealand							Positive
Monaghan et al 2009	New Zealand			Positive		No Effect		Positive
O'Callaghan et al 2010a	New Zealand		Mixed	Positive		No Effect	No Effect	
O'Callaghan et al 2010b	New Zealand	Positive	Positive			Positive	Positive	
Robinson et al 2014	New Zealand		No Effect					
Singh et al 2009	New Zealand			Positive				No Effect
Sprosen et al 2009	New Zealand			Positive				Mixed
Welten et al 2014	New Zealand			Positive				
Williamson et al 1996	New Zealand		Positive	Positive				
Williamson et al 1998	New Zealand		No Effect	Positive				Positive
Zaman & Blennerhassett 2010	New Zealand			Positive				Positive

3.2.1 Soil

Although it was rarely the focus of the investigation, 14 studies reported the effects of nitrification or urease inhibitors on soil fertility, with mixed results. However, none of the studies reported negative effects and half reported positive effects[34,41,43,44,46-48]. The authors of one study also inferred positive effects on soil health due to the positive impacts on soil biota that were observed[44].

3.2.2 Water

The effects on nitrate in water were clear: 21 of 22 studies found positive effects (lower levels of nitrate leaching)[31,33,34,36-38,40,41,43,47-58] and one found no effect[39]. Temperature[35,43], timing and rate of application[34,35,37,41,47,55,58], rainfall[51] and soil conditions[59,60] can all affect the efficacy of inhibitors and duration of effect.

Runoff water volume was not assessed and was not identified as something that might be influenced by nitrification/urease inhibitors.

3.2.3 Biodiversity

The majority of studies showed no effect of nitrification or urease inhibitors on biodiversity. DCD application of had no significant effect on non-target soil microorganism abundance[54,59,61,62] or diversity[44,54], although populations of targeted ammonium-oxidising bacteria were reduced[54]. Fewer studies investigated impacts on invertebrates, but one study found that earthworm populations were unaffected by DCD application and another Springtails (Collembola) populations were not affected when fields were treated with DCD alone, but were increased when applied with urine[44]. There was no consistently observed effect on sward botanical composition or clover content treatment[31,32].

3.2.4 Yields

Although the majority of studies showed increases in pasture growth and Herbage dry matter yields under DCD application[30,32-34,40,47,49,53,55,57,58], some showed no significant effect[31,36,37,39,48] and one showed decreased white clover yields under DCD[55,63], but not under DMPP treatment[63].

However, there are several important considerations. First, the amount applied may be important with two studies reporting greater yields at increased rates of DCD application[34,58], but another finding no significant effect[55]. Second, the type and form of inhibitor used – for example a mix of nBPT and DCD gave greater yields increases than DCD alone[58] – although liquid and granular forms were found to achieve similar results[41,42,55]. Last, timing was found to be important, with autumn application giving significantly increased dry matter yields compared to no effect of application only in winter[41,42].

3.2.5 Other considerations

Nitrification and urease inhibitors are best combined with other best management practices such as those around nutrient management[64]. Spraying of pastures is not expected to be as cost effective in the UK as in New Zealand, but targeted delivery (such as though a bolus, via drinking water or livestock-mounted systems) may prove viable[65]. Nevertheless, the cost of nitrification and urease inhibitors could be substantial (although partially offset by reduced fertiliser requirements)[45,64] and their application should therefore be carefully planned to maximise effectiveness. Nitrification inhibitors' effectiveness is highly dependent upon environmental and management factors. For example, the yield increases ascribed to treatment with nitrification inhibitors were greater for areas with high nitrogen inputs, such as pastures, and using nitrification inhibitors in irrigated or high rainfall areas with high levels of drainage is expected to give greater reductions in nitrate leaching than drier areas[66]. In addition, attention should be paid to the soil type. For instance, greater benefits to crop yields are expected in coarser textured and more acidic soils[66]. DMPP may be preferable due to recorded negative impacts of DCD on white clover yields and because it is effective at lower rates of application[64].

Note that in addition to any soil, water and biodiversity effects, the primary benefit is expected to be through significant reductions in nitrous oxide emissions[64].

3.3 Literature review

3.3.1 Primary search

Source	Search terms (within title)	Studies	Relevant studies	Date of search
Web of Science	(((nitrification OR urease) AND inhibit*) OR thiophosphoric triamide OR nitrapyrin OR dicyandiamide OR ammonium thiosulfate) AND (pastur* OR grassland OR dairy)	89	34	3 Aug 2015

3.3.2 Secondary search

Source	Search terms	Additional *relevant* studies	Date of search
Google Scholar	nitrification inhibitor pasture improve aquatic diversity	1	3 Aug 2015
Reference lists		1	3 Aug 2015
Total relevant studies		2	

3.4 Literature

3.4.1 Europe

3.4.1.1 Reducing Nitrate Losses from Simulated Grazing on Grassland Lysimeters in Ireland Using a Nitrification Inhibitor (Dicyandiamide)[38]

Citation: Dennis et al 2012

Key message: Dicyandiamide can significantly reduce nitrate losses in grazed pasture

Location: Wexford, Ireland

Description: A lysimeter study to determine the effectiveness of dicyandiamide (DCD) in reducing nitrate leaching.

Water: DCD treatment reduced ***total nitrate*** losses by 38-42 per cent and ***peak nitrate*** losses by over 50 per cent. ***Caveats:*** We were unable to access the full text, so the information presented is from the abstract.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Randomised, replicated and controlled

3.4.1.2 Dicyandiamide and 3,4-dimethyl pyrazole phosphate decrease N2O emissions from grassland but dicyandiamide produces deleterious effects in clover[63]

Citation: Macadam et al 2003

Key message: Dicyandiamide, but not 3,4-dimethyl pyrazole phosphate, was observed to be phytotoxic to white clover.

Location: Derio, Spain

Description: A study to investigate the effects of dicyandiamide (DCD) and 3,4-dimethyl pyrazole phosphate (DMPP) on nitrous oxide emissions and whether these nitrification inhibitors are toxic to clover.

Yield: DCD produced phytotoxic effects and yield reduction in white clover. DMPP had no such effect.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts							Mixed

Study Type: Randomised, replicated and controlled

3.4.2 Australasia

3.4.2.1 Dicyandiamide (DCD) effect on nitrous oxide emissions, nitrate leaching and pasture yield in Canterbury, New Zealand[40]

Citation: Cameron et al 2014

Key message: DCD consistently reduced nitrogen leaching losses from animal urine.

Location: Canterbury, New Zealand

Description: A 3-year study to assess the effect of dicyandiamide (DCD) on nitrous oxide emissions, nitrate leaching and pasture yields.

Water: DCD reduced ***nitrate leaching losses*** by 48%–69% from animal urine applied in April. ***Yield: Pasture yield*** responses to DCD application varied from 0%–17%. ***Caveats:*** We were unable to access the full text, so the information presented is from the abstract.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				Positive

Study Type: Unsure

3.4.2.2 Dicyandiamide slows nitrification in dairy cattle urine patches: effects on soil solution composition, soil pH and pasture yield[48]

Citation: Cookson & Cornforth 2002

Key message: Application of dicyandiamide reduced nitrate leaching losses

Location: Christchurch, New Zealand

Description: A study to evaluate the effect of a dicyandiamide nitrification inhibitor (DIDIN) on nitrate and ammonium production, soil pH and pasture yield.

Soil: Amending applied urine with DIDIN significantly increased soil ***pH*** relative to controls (which may therefore reduce acidification rate and lime requirements). ***Water:*** Decreases in maximum soil ***nitrate*** concentrations may translate to a up to 73 per cent reduction in peak soil nitrate concentrations reaching ground water from a urine patch. ***Yield:*** DIDIN treatment did not affect ***pasture yield***. ***Caveats:*** Very large amounts of nitrogen were applied, so adequate nitrate and ammonium remained available for optimum pasture growth, even when leaching was apparent (i.e. without treatment with nitrification inhibitors).

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Positive	Positive				No Effect

Study Type: Randomised, replicated and controlled

3.4.2.3 Effects of nitrogen application rate and a nitrification inhibitor dicyandiamide on methanotroph abundance and methane uptake in a grazed pasture soil[61]

Citation: Dai et al 2013

Key message: Application of dicyandiamide (DCD) does not significantly affect soil methanotroph abundance or daily CH_4 fluxes.

Location: Christchurch, New Zealand

Description: An experiment to determine the effect of nitrogen application rates and dicyandiamide (DCD) methanotroph abundance and methane flux in a grazed perennial ryegrass/white clover pasture soil.

Biodiversity: Application of DCD had no significant effect on methanotroph abundance.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts						No Effect	

Study Type: Randomised, replicated and controlled

3.4.2.4 Evaluating the effects of dicyandiamide (DCD) on nitrogen cycling and dry matter production in a 3-year trial on a dairy pasture in South Otago, New Zealand[39]

Citation: de Klein et al 2014

Key message: Nitrate concentrations were significantly reduced by DCD application

Location: South Otago, New Zealand

Description: A 3-year study into the effect of dicyandiamide on nitrate

Water: No effect of DCD application on ***nitrate*** concentration in drainage water was detected. ***Yield:*** There was no significant effect on annual ***dry matter yields*** under true pasture grazing conditions. ***Caveats:*** Nitrate concentration in drainage without DCD applications were low, limiting the potential for DCD to reduce concentration. We were unable to access the full text, so the information presented is from the abstract.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect				No Effect

Study Type: Unsure

3.4.2.5 The use of a nitrification inhibitor, dicyandiamide (DCD), to decrease nitrate leaching and nitrous oxide emissions in a simulated grazed and irrigated grassland[49]

Citation: Di & Cameron 2002

Key message: Dicyandiamide (DCD) has the potential to reduce nitrate leaching and simultaneously raise herbage yields.

Location: Canterbury, New Zealand

Description: A lysimeter study to assess the effect of dicyandiamide (DCD) on nitrate leaching and nitrous oxide emissions from urine patches on a grazed, free-draining and irrigated perennial ryegrass/white clover pasture.

Water: Treatment with DCD reduced ***nitrate-N*** leaching by an average of 76 per cent for urine applied in the autumn, and by 42 per cent for urine applied in the spring. Further, weighted calculations for an average pasture suggest that DCD could reduce ***nitrate-N*** concentration in the drainage water from 19.7 to 7.7 mgN L^{-1}, which is within safe limits for drinking water. ***Yield:*** Annual herbage yields were increased by 33 per cent with application of DCD. Application of DCD was expected to increase average annual ***herbage yield*** of a grazed paddock over 30 per cent, from 11t ha^{-1} yr^{-1} to 15t ha^{-1} yr^{-1}.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				Positive

Study Type: Randomised, replicated and controlled

3.4.2.6 Effects of temperature and application rate of a nitrification inhibitor, dicyandiamide (DCD), on nitrification rate and microbial biomass in a grazed pasture soil[35]

Citation: Di & Cameron 2004a

Key message: (1) DCD is most effective in late autumn to early spring when soil temperatures are generally below 10°C and when drainage is high. (2) At 8°C, DCD was more stable, remaining in the soil for significantly longer than at 20°C (half lives of 111-116 days and 18-25 days, respectively).

Location: [Laboratory] New Zealand

Description: A study to investigate how temperature and application rate of DCD affects nitrification inhibition and soil microbial biomass.

Soil: Under DCD treatment, soil ***microbial biomass carbon*** and ***nitrogen*** did not differ significantly to controls.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		No Effect					

Study Type: Randomised, replicated and controlled

3.4.2.7 Effects of the nitrification inhibitor dicyandiamide on potassium, magnesium and calcium leaching in grazed grassland[46]

Citation: Di & Cameron 2004c

Key message: Cation nutrient leaching losses were reduced by 50 to 65 per cent for Ca^{2+}, K^{+} and Mg^{2+}.

Location: Canterbury, New Zealand

Description: A lysimeter study to investigate the effect of treatment with dicyandiamide (DCD) on calcium, magnesium and potassium cation loss for a free-draining perennial ryegrass/white clover pasture.

Soil: Peak concentrations of ***Ca^{2+}***, ***K^{+}*** and ***Mg^{2+}*** were significantly reduced by treatment with DCD. Calculated for a grazed pasture, DCD is expected to reduce ***Ca^{2+}*** leaching by 50 per cent (from 213 to 107kg Ca ha^{-1} yr^{-1}), potassium leaching by 65 per cent (from 48 to 17kg K ha^{-1} yr^{-1}), and magnesium leaching by 52 per cent (from 17 to 8kg Mg ha^{-1} yr^{-1}).

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Positive					

Study Type: Randomised, replicated and controlled

3.4.2.8 Treating grazed pasture soil with a nitrification inhibitor, eco-n™, to decrease nitrate leaching in a deep sandy soil under spray irrigation - a lysimeter study[47]

Citation: Di & Cameron 2004d

Key message: (1) Treating grazed pasture soil with DCD can reduce nitrate leaching. (2) DCD treatment can improve herbage dry matter yields.

Location: Canterbury, New Zealand

Description: A lysimeter study to assess the effectiveness of using dicyandiamide (DCD) to reduce nitrate leaching in a perennial ryegrass/white clover pasture. Losses of cations were also monitored.

Soil: Peak ***Ca^{2+}*** and ***Mg^{2+}*** concentrations were significantly reduced by treatment with DCD. There was no effect on ***K^{+}*** peak concentration. Treatment with DCD reduced annual losses for ***Ca^{2+}*** (38-56 per cent reduction, $P<0.05$) and losses were also lower, but not significantly, for ***Mg^{2+}*** (21-42 per cent reduction, $P>0.05$). There was no effect on annual ***K^{+}*** losses. ***Water:*** Treatment with DCD in autumn (after application of cow urine) significantly reduced peak ***nitrate concentration*** in leachate. A further DCD treatment in spring did not significantly reduce ***nitrate concentration*** further. Annual

nitrate losses were reduced 75 per cent by treatment with DCD in autumn but no extra benefit was gained from further treatment in spring. ***Yield: Dry matter yields*** were higher in DCD-treated plots and autumn plus spring treatment with DCD gave significant increases in ***yield*** of 15-33 per cent.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Positive	Positive				Positive

Study Type: Randomised, replicated and controlled

3.4.2.9 Reducing environmental impacts of agriculture by using a fine particle suspension nitrification inhibitor to decrease nitrate leaching from grazed pastures[34]

Citation: Di & Cameron 2005

Key message: (1) DCD applied as a fine particle suspension is highly effective at reducing nitrate leached from grazed pasture. (2) Application of DCD at 10kg ha^{-1} achieved similar reductions in nitrate leaching and increases in pasture production as at 15kg ha^{-1} but 5kg ha^{-1} was not high enough.

Location: Canterbury, New Zealand

Description: A lysimeter study to test the effectiveness of dicyandiamide as a fine particle suspension for reducing nitrate leaching losses in a perennial ryegrass/white clover pasture.

Soil: Application of DCD at 10kg ha^{-1} significantly reduced leaching of ***calcium*** and ***magnesium cations*** by 51 and 31 per cent, respectively. ***Water:*** Peak ***nitrate nitrogen concentrations*** were reduced from an annual average of 43mg L^{-1} to 38mg L^{-1} and 18mg L^{-1} under 5kg and 10kg DCD ha^{-1} treatments respectively. When DCD was applied at 5kg ha^{-1}, it reduced peak ***nitrate concentration***, but the effect was not always statistically significant. Application of DCD at 10 kg ha^{-1} significantly decreased ***total nitrate nitrogen leaching*** by 68 per cent, from 134kg N ha^{-1} year^{-1} to 43kg N ha^{-1} year^{-1}, while application at 5kg ha^{-1} reduced it to 116kg N ha^{-1} year^{-1}, an effect size which was not statistically significant. ***Yield:*** Herbage ***dry matter yields*** were increased by 33%, from 15.3t ha^{-1} year^{-1} to 20.3t ha^{-1} year^{-1} when DCD was applied at 10kg ha^{-1}. When DCD was applied at 5kg ha^{-1}, it had no effect on ***dry matter yields***.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Positive	Positive				Positive

Study Type: Randomised, replicated and controlled

3.4.2.10 Nitrate leaching losses and pasture yields as affected by different rates of animal urine nitrogen returns and application of a nitrification inhibitor - a lysimeter study[33]

Citation: Di & Cameron 2007

Key message: Dicyandiamide (DCD) is a valuable nitrogen management tool to mitigate nitrate leaching in pasture systems

Location: Canterbury, New Zealand

Description: A study into the effect of dicyandiamide (DCD) on nitrate losses and pasture productivity under different urine nitrogen loading rates: 0 (Control), 300, 700 and 1,000 kg N ha^{-1}. Pasture was a perennial ryegrass/white clover mix and the experiment was conducted using a lysimeter.

Water: Peak ***nitrate*** concentrations in leachate were significantly reduced by application of DCD under all urine treatments. In addition, for all urine loading rates the use of DCD significantly reduced ***total nitrate nitrogen leaching*** losses by 45-83 per cent (average of 63 per cent). ***Yield:*** Application of urine+DCD resulted in an 18-35 per cent (average 25 per cent) increase in pasture ***dry matter yield*** compared to controls (urine only).

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				Positive

Study Type: Randomised, replicated and controlled

3.4.2.11 How does the application of different nitrification inhibitors affect nitrous oxide emissions and nitrate leaching from cow urine in grazed pastures?[50]

Citation: Di & Cameron 2012

Key message: Both DCD and DMPP are effective at reducing nitrate leaching in grazed pasture soils

Location: Waikato, New Zealand

Description: An study of dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP) effectiveness for reducing nitrous oxide emissions and nitrate leaching in two grazed pasture soils.

Water: Peak ***nitrate nitrogen concentration*** in drainage water was significantly reduced from 320mg/L in the control (urine only) to 143mg/L (urine+DCD) and 163mg (urine+DMPP). ***Total nitrate nitrogen losses*** through leaching were reduced by 36 per cent and 28 per cent in the DCD and DMPP treatments respectively (from 628.6 kg ***nitrate nitrogen*** per ha in the control).

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Randomised, replicated and controlled

3.4.2.12 A lysimeter study of nitrate leaching from grazed grassland as affected by a nitrification inhibitor, dicyandiamide, and relationships with ammonia oxidizing bacteria and archaea[51]

Citation: Di et al 2009

Key message: DCD nitrification inhibitor was highly effective in decreasing nitrate leaching losses from all three soils under both rainfall conditions.

Location: New Zealand

Description: A study to determine the effectiveness of dicyandiamide (DCD) in reducing nitrate leaching in three different soils from different regions of New Zealand under two rainfall conditions.

Water*: Nitrate concentrations** were substantially reduced in DCD-treated plots for all soil types and for both rainfall scenarios, and this reduction was statistically significant in 4/5 results. Across three soil types and two rainfall scenarios ***total nitrate-nitrogen leaching was reduced by 59 per cent.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Replicated and controlled

3.4.2.13 Methanotroph abundance not affected by applications of animal urine and a nitrification inhibitor, dicyandiamide, in six grazed grassland soils[59]

Citation: Di et al 2011

Key message: Application of DCD did not affect non-target soil biota.

Location: New Zealand

Description: A laboratory incubation study to evaluate the effects of urine and dicyandiamide (DCD) on methanotrophs.

Biodiversity: There was no significant effect on the abundance of (non-target) methanotrophs.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts						No Effect	

Study Type: Randomised, replicated and controlled

3.4.2.14 Profitability of Nitrification Inhibitors for Abatement of Nitrate Leaching on a Representative Dairy Farm in the Waikato Region of New Zealand[52]

Citation: Doole & Paragahawewa 2011

Key message: Nitrification inhibitors are valuable mitigation practices to prevent further degradation to river water quality.

Location: Waikato, New Zealand

Description: A simulation primarily to test the cost effectiveness of applying dicyandiamide (DCD) to the soil.

Water*: Nitrate** leaching was reduced under DCD treatment. ***Caveats: Note that the assumed increases in dry matter yields causes greater stocking densities. If stocking densities were held constant, the reduction in nitrate leaching would likely be even greater.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Simulation

3.4.2.15 Effect of 7-year application of a nitrification inhibitor, dicyandiamide (DCD), on soil microbial biomass, protease and deaminase activities, and the abundance of bacteria and archaea in pasture soils[62]

Citation: Guo et al 2013

Key message: DCD is relatively benign, specifically targeting the ammonia oxidation process yet having little or no long-term effect on bacteria and archaea abundance or on key soil enzyme activities responsible for nitrogen cycling

Location: Southland/Waikato/Canterbury, New Zealand

Description: A trial to test the long-term effects (>7 years) on non-target soil microbial communities of dicyandiamide (DCD) application to grazed pasture.

Soil: There was no significant effect on soil ***pH***, ***soil microbial biomass carbon or nitrogen***, ***protease activity*** or ***deaminase activity*** indicating that soil ***quality*** was not affected by DCD application over a 7-year period. ***Biodiversity: Abundance*** of soil ***archaea*** and ***bacteria*** was not significantly affected by DCD treatment.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		No Effect				No Effect	

Study Type: Randomised, replicated and controlled

3.4.2.16 Field studies assessing the effect of dicyandiamide (DCD) on N transformations, pasture yields, N2O emissions and N-leaching in the Manawatu region[53]

Citation: Kim et al 2014

Key message: (1) Applications of DCD to urine patches and grazed pasture showed variable impacts on pasture accumulation. (2) Nitrate losses were reduced in one of the two study years.

Location: Manawatu, New Zealand

Description: Three experiments were conducted: (1) a mowing trial, in which the effect of DCD application on pasture yields, soil nitrogen and DCD dynamics was assessed; (2) a grazing trial to evaluate the effect of DCD on grazed pasture yields; (3) a flux chamber trial to investigate effects of DCD on nitrous oxide emissions; and (4) a drainage trial to evaluate the effect of DCD on nitrogen leaching losses and pasture productivity.

Soil: Soil ***pH*** was similar between plots treated with DCD and control plots. ***Water: Nitrate concentrations*** did not differ significantly between treated plots and controls. However, ***nitrate loads*** were significantly reduced in treated plots (compared to control) in one of two study years. This is attributed to drainage volume, given that ***nitrate concentrations*** are similar. ***Yield:*** Three separate experiments evaluated DCD effects on ***dry matter yield*** over 2 to 3 years. In all cases, annual ***dry matter yields*** were higher in the urine+DCD plots than in the urine only plots; however, this difference was only significant on two occasions: (i) in the mowing trial, ***dry matter yields*** were significantly higher for DCD-treated plots in one of the three study years, (ii) in the grazing trial, differences in ***dry matter yields*** were not significant in any of the three years, and (iii) in the drainage trial, one of the two years showed significantly greater ***dry matter yields*** in the DCD-treated plot. ***Caveats:*** In one of the two study years that showed no effect of DCD on nitrate losses, total losses in that year were low in the control, resulting in limited potential for further reduction through DCD treatment. In addition, the authors were unsure as to the cause of the lower drainage volume in treated plots, so they urge cautious interpretation of the nitrate results.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		No Effect	Positive				Mixed

Study Type: Randomised, replicated and controlled

3.4.2.17 Effects of the nitrification inhibitor dicyandiamide (DCD) on pasture production, nitrous oxide emissions and nitrate leaching in Waikato, New Zealand[37]

Citation: Ledgard et al 2014

Key message: Decreases in nitrate leaching of up to 74% were observed, but timing of applications is important and three applications may be necessary to achieve greatest benefits.

Location: Waikato, New Zealand

Description: A 3-year study to examine the effects of dicyandiamide (DCD) application (two to five applications per year) on pasture production, soil nitrogen transformations, nitrous oxide emissions and nitrate leaching (a lysimeter study) from dairy pastures.

Water: Decreases in nitrate leaching of up to 74% were observed under DCD treatment. DCD applications between April and June were most effective for reducing nitrate leaching. ***Yield:*** In one year of the mowing trial a 4% ($P<0.05$) increase in pasture growth was observed. However, there was no other significant effect of DCD applications on pasture production. ***Caveats:*** We were unable to access the full text, so the information presented is from the abstract.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				Positive/No Effect

Study Type: Unsure

3.4.2.18 Effect of timing and formulation of dicyandiamide (DCD) application on nitrate leaching and pasture production in a Bay of Plenty pastoral soil[41,42]

Citation: Menneer et al 2008a,b

Key message: (1) Granular or liquid DCD had similar effects on plant growth and nitrate leaching. (2) Application of DCD could increase overall grazed pasture productivity. (3) DCD may need to be applied more than once during autumn/winter to ensure sustained inhibition of nitrification.

Location: Rotorua, New Zealand

Description: A trial to investigate the timing (either May/autumn or July/winter) and formulation (granular or liquid) of dicyandiamide (DCD) application on pasture growth and nitrate leaching. Treatments were urine only (equivalent to 598kg N ha^{-1}) or urine plus DCD (at 18kg ha^{-1}).

Soil: DCD treatment reduced ***magnesium*** and ***calcium*** losses (which may help reduce the rate of soil acidification) compared to the control (urine only) and this was significant for autumn treatment. ***Water:*** In autumn, DCD treatment initially led to significant reductions in ***nitrate*** leaching but this was subsequently followed by increased losses, resulting in non-significant reductions in total losses of just 17 per cent. Winter application of DCD significantly reduced ***nitrate*** leaching losses by 62 per cent. ***Yield:*** Autumn application of DCD led to significantly increased ***dry matter yields*** by approximately 34 per cent (8 and 8.3T ha^{-1} for granular and liquid DCD application respectively, compared to 6.1T ha^{-1} in the control). Winter application of DCD had no effect on ***dry matter yields***.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Positive	Positive				Positive

Study Type: Randomised, replicated and controlled

3.4.2.19 Effects of the nitrification inhibitor dicyandiamide on soil mineral N, pasture yield, nutrient uptake and pasture quality in a grazed pasture system[32]

Citation: Moir et al 2007

Key message: Pasture yield was increased by treatment with dicyandiamide.

Location: Christchurch, New Zealand

Description: A study to quantify the effects of fine particle suspension (FPS) dicyandiamide (DCD) on soil mineral N components, pasture yield, nutrient uptake and pasture quality under grazed pasture conditions.

Soil: Calcium, ***magnesium*** and ***potassium*** cation concentrations in non-treated and DCD-treated pastures were not significantly different. ***Biodiversity: Botanical composition*** and ***clover content*** of sward was not affected by DCD treatment. ***Yield:*** DCD significantly increased ***pasture growth*** on both inter-urine and urine patch areas during all 4 years of the trial. DCD treatment increased mean annual ***pasture dry matter*** (DM) yields from 10.3t DM ha^{-1} to 12.4 t DM ha^{-1} in inter-urine areas and from 12.4 t DM ha^{-1} to 16t DM ha^{-1} for the urine patches. Pasture quality (pasture ***dry matter***, ***crude protein***, ***carbohydrate*** or ***metabolizable energy***) was unaffected by DCD treatment.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		No Effect			No Effect		Positive

Study Type: Randomised, replicated and controlled

3.4.2.20 The effect of dicyandiamide on pasture nitrate concentration, yield and N offtake under high N loading in winter and spring[30]

Citation: Moir et al 2012

Key message: DCD application can substantially reduce pasture nitrate concentrations to safe levels under high nitrogen loading conditions

Location: Christchurch, New Zealand

Description: A study to investigate the effects of applying the dicyandiamide (DCD) on soil extractable nitrogen and pasture nitrate concentrations (note that the study did not measure nitrate in leachate/runoff) in winter and spring.

Yield: Application of DCD significantly (P<0.001) increased ***total dry matter*** production: by 39-42 per cent, compared to urine-alone treatment and by 12 per cent on the urea-only treatment.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts							Positive

Study Type: High

3.4.2.21 The effectiveness of a granular formulation of dicyandiamide (DCD) in limiting nitrate leaching from a grazed dairy pasture[31]

Citation: Monaghan et al 2009

Key message: (1) Granular form of DCD was found to reduce nitrogen losses in drainage. (2) DCD applications should be scheduled for grazing events that precede or include the months of greatest drainage loss (May and June in this study)

Location: Invercargill, New Zealand

Description: A study into the effectiveness of applying dicyandiamide (DCD) to dairy pasture to reduce nitrate leaching (two or three applications of DCD per year compared to a control with no DCD). Effects on water quality, pasture productivity and sward botanical composition were assessed over a four-year period.

Water: DCD-treated plots had significantly lower ***nitrate concentrations*** in autumn and winter leachate than the control, resulting in mean annual losses of 6.8kg N ha^{-1} compared to 12.9kg N ha^{-1} in the control (P<0.05). There was no effect, however, on mean annual losses of ***ammonium nitrogen*** (which represented only 7 to 13 per cent of the ***nitrate/ammonium nitrogen load*** in drainage. Lastly, greater reductions of ***nitrogen drainage losses*** were observed in successive years. Small amounts of ***DCD*** (7 per cent of total applied) were detected in drainage. ***Biodiversity:*** There was no consistent effect of DCD treatment on ***sward botanical composition***. ***Yield:*** Application of DCD had no significant effect on ***pasture productivity*** in any of the measurement years (overall DCD-treated plots had less than 1 per cent increase over the four year period). ***Nitrate*** was found to be lower (indicating higher quality) in DCD-treated plots in approximately 70 per cent of measurements. ***Caveats:*** Soils are poorly drained, so leaching losses likely to be lower.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive		No Effect		Positive
*Although there was no effect on yield quantity, quality was higher due to lower nitrate concentration							

Study Type: Randomised, replicated, controlled and over a four-year period

3.4.2.22 *Effect of the nitrification inhibitor dicyandiamide (DCD) on microbial communities in a pasture soil amended with bovine urine*[54]

Citation: O'Callaghan et al 2010a

Key message: Application of dicyandiamide to pasture has a relatively benign effect on non-target soil microbes

Location: Hamilton, New Zealand

Description: An experiment to assess the short-term effects of dicyandiamide (DCD) on the activity and diversity of both target (ammonium-oxidising bacteria and archaea) and non-target soil microbial populations. Bovine urine was applied to pots of perennial ryegrass/white clover (i.e. pasture) at 600 kg urine-nitrogen ha^{-1} and then some also received the experimental treatment of DCD at 30kg ha^{-1}. This single high rate of application is used as to detect potential impacts of DCD application on soil microbial populations under worst-case scenario conditions.

Soil: Following application of urine, ***soil pH*** and ***soil ammonium*** were significantly increased and, when DCD was also applied, they stayed elevated (***pH*** above 7.5 and ***ammonium*** above 800mg NH_4-N g^{-1} soil) throughout the 56-day monitoring period (whereas in the absence of DCD they declined faster). There was no impact on ***soil pH*** or ***soil ammonium*** of DCD only (no urine), which remained similar to the control (no urine, no DCD). When DCD was applied with urine, ***hot water extractable carbon and nitrogen (HWC and HWN)*** were maintained at higher levels than when treated with urine alone. There was no effect of DCD treatment on ***microbial carbon*** or ***microbial nitrogen***. ***Water:*** Following treatment with urine, nitrate levels were significantly lower when DCD was also applied. ***Biodiversity:*** There was no effect of DCD application on the diversity of ***non-target soil bacterial community*** or on the population abundance of ***ammonium-oxidising archaea***. Populations of targeted ***ammonium-oxidising bacteria***, however, were significantly reduced.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Mixed	Positive		No Effect	No Effect	

Study Type: Replicated and controlled

3.4.2.23 *Non-target impacts of the nitrification inhibitor dicyandiamide on soil biota*[44]

Citation: O'Callaghan et al 2010b

Key message: Application of dicyandiamide (DCD) to pasture is a relatively benign intervention that has an important role to play in mitigating the environmental hazards imposed by ongoing land use intensification

Location: [Laboratory experiment] New Zealand

Description: A study to assess the how the use of inhibitors to reduce leaching and denitrification in intensively grazed dairy pastures might impact upon non-target soil biota. Laboratory experiments were conducted to investigate how dicyandiamide (DCD), a nitrification inhibitor, affects diversity of soil bacterial populations (relative proportions of the dominant bacterial phyla: Proteobacteria, Acidobacteria, Actinoacteria and Firmicutes), earthworms (*Aporrectodea caliginosa*) and Collembola (*Folsomia candida*). Measurements were taken at 2, 28 and 56 days after treatment.

Soil: The effects on soil are presumed by the authors to be positive, given the importance of ***soil biota*** as ecosystem engineers, maintaining soil health, and also as indicators of soil fertility.
Biodiversity: Soil ***bacterial diversity*** in DCD-treated soil was unchanged compared to controls (no treatment). Trials treated with urine+DCD were also similar to those treated with urine only (although in these urine-treated soils, Firmicutes comprise 50% of soil ***bacterial community*** compared to just 10% in the control and DCD-only treatments). There was no effect of any of the treatments on ***survival or maturation rate of earthworms*** (*Aporrectodea caliginosa*). There was generally very little effect of DCD in soil on ***Collembola*** (*Folsomia candida*) ***population size*** under DCD-only treatment, which were similar to those in control soil at 28 and 56 days after application. Treatment with urine increased the ***population size*** of Collembola, though only significantly so for DCD+urine (urine alone did not significantly affect Collembola ***population size***).

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive*	Positive*			Positive	Positive	
*These are inferred from positive changes to soil biota							

Study Type: Replicated controlled

3.4.2.24 The effect of soil pH and dicyandiamide (DCD) on N2O emissions and ammonia oxidiser abundance in a stimulated grazed pasture soil[60]

Citation: Robinson et al 2014

Key message: DCD application did not significantly affect soil pH

Location: Christchurch, New Zealand

Description: The effect of three pH treatments (alkaline, acid and native) and four urine and DCD treatments (control: no urine or DCD, urine-only, DCD-only and urine + DCD) were assessed in terms of their effect on N_2O emissions and ammonia oxidiser community growth.

Soil: DCD application did not significantly affect ***soil pH***.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts		No Effect					

Study Type: Replicated and controlled

3.4.2.25 Influence of dicyandiamide on nitrogen transformation and losses in cow-urine-amended soil cores from grazed pasture[36]

Citation: Singh et al 2009

Key message: Addition of DCD to urine reduced potential nitrate nitrogen leaching.

Location: New Zealand

Description: A study to determine the effect of dicyandiamide (DCD) on gaseous emissions and potential leaching of nitrate. Treatments included four levels of urine applied at 0 (control), 14.4, 29.0 and 57.0 g N/m² with and without DCD at 2.5 g/m².

Water: Addition of DCD to urine reduced ***potential nitrate*** nitrogen leaching by 60-65 per cent. ***Yield:*** There was no significant effect of DCD treatment on ***pasture dry matter*** production. ***Caveats:*** We were unable to access the full text, so the information presented is from the abstract.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts			Positive				No Effect

Study Type: Unsure

3.4.2.26 Effect of rate and form of dicyandiamide application on nitrate leaching and pasture production from a volcanic ash soil in the Waikato, New Zealand[55]

Citation: Sprosen et al 2009

Key message: DCD in both liquid and granular forms proved effective in reducing nitrate leaching from urine in grazed pastures

Location: Waikato, New Zealand

Description: A mowing trial to examine the effect of liquid and granular dicyandiamide (DCD), applied in at 0, 7, 14 and 28 kg ha^{-1}, on the fate of urea applied at 600 kg N ha^{-1} in artificial urine. Leaching of nitrate was measured using ceramic cup samplers at 600 mm depth in the 14kg DCD ha^{-1} treatments.

Water: DCD reduced ***nitrate*** leaching by 24 per cent, but there was no significant effect of DCD form. ***Yield:*** DCD treatment increased ***pasture production*** by an average of 15 per cent ($P<0.001$), but reduced ***white clover content***. There was no significant effect of rate or form of DCD. However, there was a trend ($P<0.1$) of increased rates of granular DCD giving increased ***pasture production***. Increased rates of liquid DCD had no effect on ***productivity***.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts			Positive				Mixed

Study Type: Randomised, replicated and controlled

3.4.2.27 *Administration of dicyandiamide to dairy cows via drinking water reduces nitrogen losses from grazed pastures*[56]

Citation: Welten et al 2014

Key message: Orally administered dicyandiamide (DCD) is effective at reducing nitrate leaching losses to drainage.

Location: Waikato, New Zealand

Description: A study to examine the environmental effects of administering dicyandiamice (DCD) in troughwater to dairy cows that grazed 12 replicated plots (grazing intensity of up to 319 cows/ ha/ day). Nitrate leaching losses were measured using ceramic cup samplers (600mm soil depth) and gaseous emissions of nitrous oxide (N2O) were quantified using a static chamber technique.

Water: DCD treatment was effective (*P*<0·05) in restricting ***nitrate-N concentrations*** in leachate to <11·0 mg/l over the entire drainage period (compared to the control, which peaked at 17·9 mg/l and then declined to 13·0 mg/l). This resulted in a 40 per cent reduction (*P*<0·05) in ***total nitrate-N*** leaching losses, from 32 kg N/ha in the control to 19 kg N/ha in the DCD treatment.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Randomised, replicated and controlled

3.4.2.28 *Impact of dicyandiamide on the internal nitrogen cycle of a volcanic, silt loam soil receiving effluent*[43]

Citation: Williamson et al 1996

Key message: (1) Use of dicyandiamide (DCD) led to reduced nitrate leaching despite high temperatures and simulated rainfall. (2) Higher soil temperatures (particularly soil temperatures above a threshold of 13-16°C) resulted in faster degradation of DCD and consequently higher nitrate concentrations in soil.

Location: Waikato basin, New Zealand

Description: An experiment to test the effectiveness and persistence of dicyandiamide (DCD) on the retaining effluent nitrogen in a free-draining silt loam soil. Dairy shed effluent was applied (soil received 10mm every twice monthly). DCD was also applied to some of plots with the first application of dairy effluent. The effect of DCD on nitrate in leachate was monitored over a 99-day period and compared to control plots that received effluent at the same rate, but no DCD.

Soil: Microbial biomass carbon was increased in DCD soil from days 8 to 22, but had reverted to levels similar to controls after 99 days. ***Microbial biomass nitrogen*** was significantly higher in DCD soil than in controls throughout the trial period. ***Water: Nitrate*** concentration in soil was significantly negatively correlated to DCD concentration. Moreover, ***nitrate*** concentration was higher when soil temperatures were higher reflecting the inverse for DCD concentrations (lower at higher temperatures due to a higher rate of degradation). Inhibition of nitrification was not apparent for 40 days after application. Over a 99-day period, the mean ***total nitrogen*** leached from soils treated with DCD-amended effluent was significantly lower than that from un-amended effluent (from 20kg of soil: 1457mg N and 1934mg N, respectively). Overall, 22kg ***nitrogen*** ha^{-1} was conserved as a result of using DCD.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts		Positive	Positive				

Study Type: Replicated, controlled

3.4.2.29 Reducing nitrogen leaching from dairy farm effluent-irrigated pasture using dicyandiamide: a lysimeter study[57]

Citation: Williamson et al 1998

Key message: (1) Use of dicyandiamide can reduce nitrate leaching when high nitrogen loading dairy effluent is applied repeatedly. (2) Although dicyandiamide reduced nitrate leaching in winter, it was not enough to protect groundwater and repeated high effluent-nitrogen loadings must be avoided during winter.

Location: Waikato basin, New Zealand

Description: Trial to test the efficacy of dicyandiamide (DCD) at reducing nitrate leaching and groundwater contamination under high nitrogen loading conditions. Pasture was perennial ryegrass that was cut for silage and received repeated high-nitrogen loading using dairy effluent (total of 1100kg N ha^{-1}, applied fortnightly). The effect on water quality (leachate) of one application of DCD was tested.

Soil:* *Microbial carbon and ***nitrogen*** were not significantly affected by DCD treatment. ***Water:*** The use of DCD led to an 18 per cent reduction in the amount of ***nitrate leached*** compared to controls receiving the same level of effluent but no nitrification inhibitor. The inhibitory effect of DCD was seen approximately 30 days after application. DCD was most effective during the time of greatest ***nitrate leaching***. When pasture is receiving repeated high nitrogen loading from dairy effluent treatments during the winter, DCD will reduce the ***nitrate leached*** but, used alone, it cannot be relied upon to protect groundwater. Total ***DCD leached*** was less than 0.5 per cent of that which was applied. ***Yield:*** Plots receiving effluent plus DCD **yielded** significantly greater ***ryegrass dry matter yields***. DCD did not affect ***nutrient percentage composition*** of the ryegrass but total nitrogen, potassium and phosphate uptake was significantly greater for plots applied with DCD, which accounted for the lower amount of nitrogen leached.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts		No Effect*	Positive				Positive
*This was not a focus of the study, so only microbial carbon/nitrogen are assessed							

Study Type: Replicated, controlled

3.4.2.30 *Effects of the different rates of urease and nitrification inhibitors on gaseous emissions of ammonia and nitrous oxide, nitrate leaching and pasture production from urine patches in an intensive grazed pasture system*[58]

Citation: Zaman & Blennerhassett 2010

Key message: (1) Treatment with a combined does of DCD and nBPT was most effective in reducing nitrate leaching and increasing pasture production after application of cow urine to pastures. (2) Treatment with DCD was also effective at reducing nitrate leaching, but increased ammonia losses.

Location: Canterbury, New Zealand

Description: An experiment to examine the effects of applying a nitrification inhibitor, dicyandiamide (DCD), a urease inhibitor, N-(n-butyl) thiophosphoric triamide (nBPT), and to a perennial ryegrass/white clover pasture. There were 4 major leaching events in the 3 months following application of cow urine. The leachate was assessed for ammonium and nitrate content and the effects of 7 different urease/nitrification inhibitor treatments (urine +DCD [at 3 different rates of application: 5kg ha^{-1}, 7kg ha^{-1}, 10kg ha^{-1}], and urine plus a 'double inhibitor' mix of nBPT and DCD [at 4 different rates: 1:7, 1:10, 2:7 and 2:10, where the ratio denotes volume nBPT ha^{-1}: weight DCD ha^{-1}]) were monitored and compared to two controls: one in which no inhibitor was applied (i.e. urine only) and one in which no urine and no inhibitor was applied.

Water: Losses of ***ammonium*** to leachate were similar for all treatments and control. Nitrification inhibitor significantly reduced the amount of ***nitrate*** leached during leaching events and all treatments except DCD at 5 kg ha^{-1} were found to be equally effective in this regard. For DCD application, ***nitrate*** losses were lowest at 7kg ha^{-1} (i.e. the middle rate of application) and reduced ***nitrate*** losses by 57 and 26 per cent for autumn and spring applications, respectively. For double inhibitor application, ***nitrate*** losses were lowest at the 1:7 rate (i.e. the lowest combined rate of application), ***nitrate*** losses by 56 and 42 per cent for autumn and spring applications, respectively. Nitrification inhibitors did not reduce ***nitrate*** leaching from fields that have not had urine applied.
Yield: Application of DCD or double inhibitor increased ***pasture dry matter*** production for all treatment doses, compared to both controls (urine only and no urine/no inhibitor). These increases were significant, however, only for double inhibitor doses and only for the 1:7 and 1:10 ratios, which increased ***yields*** 13 to 18 per cent. Higher rates of application also increased ***pasture dry matter yields*** compared to the control (urine only), but not as much as the lower 1:7 and 1:10 dose.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				Positive

Study Type: Randomised, replicated, controlled

4 Fencing waterways

Fencing waterways offers multiple benefits to soil, water and biodiversity for relatively low cost

4.1 Description

The grazing of dairy cows on pasture can contribute to high levels of degradation in waterways through increased nutrient and microbial pollutants (from faeces and urine) and though erosion of banks, which leads to increased sediment loads[17,67]. Farmers are encouraged to fence waterways in order to reduce the concentration and amount of nutrients, pathogens and sediment from entering streams and rivers and protect downstream water supplies. The fencing of riparian zones can also result in increased vegetative cover and diversity, which can also increase filtration capacity for surface runoff water entering the watercourse.

4.2 Summary

The systematic search revealed 111 studies, of which 12 were determined to be relevant (they assessed effects of streambank fencing on soil, water or biodiversity). One of these could not be accessed at all[68] and only the abstract was available for another[69]. One further study was identified in a secondary search[70]. This gave 12 studies that were reviewed (11 in detail). Of these 10 were conducted in North America and one in Australia. Only one was from the UK.

		Soil		Water		Biodiversity		
Reference	**Country**	**Structure**	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	**Yield**
Hampson et al 2010	UK			Positive				
March & Robson 2006	Australia	No Effect		Mixed			No Effect	
Flores-López et al 2010	USA			Positive				
Galeone et al 2006	USA			Mixed	Positive	Positive	Positive	
Giulliano & Homyack 2004	USA					Positive	Positive	
Hagedorn et al 1999	USA			Positive				
Homyack & Giulliano 2002	USA			No Effect		No Effect	No Effect	
Line 2002	USA			Positive/No Effect				
Line 2003	USA			Positive/No Effect				
Line et al 2000	USA			Positive/No Effect	Positive			
Miller et al 2010	Canada	Positive	No Effect	Positive	Positive		Positive	
Owens et al 1996	USA	Positive		Positive				

4.2.1 Soil

There were no studies reporting negative effects on soil. Fencing decreased the amount of bare soil[71] and overall soil losses[69]. In addition, soil bulk density was decreased and water content increased in the fenced areas[71].

4.2.2 Water

Where an effect on water quality was observed, it was generally positive, including reductions in bacteria[70,72-75], phosphorous[70,76-78] (although dissolved phosphorous showed an increase[70]), nitrogen species[70,71,77], and sediment/suspended solids[69,70,75,77]. Effects on dissolved oxygen, temperature, conductivity and pH were less conclusive with only two studies, each showing different effects, examining these factors[75,78]. One study found that despite reduced nutrient concentrations, the overall nutrient load was higher in fenced sites[70]. Three studies showed an decrease in runoff volume or stream discharge[70,71,77]].

4.2.3 Biodiversity

Where an effect on abundance or diversity of wildlife was observed, this was positive due to naturally re-establishing plant cover[70,71], increased richness and evenness of macroinvertebrates[70] and small mammals[79], and increased abundance of pollution sensitive invertebrates[70].

4.2.4 Yield

None of the studies assessed the impact on yields. However, the main impact is likely to be on reduced land area available for cows to forage. The impact will therefore depend upon the proportion of the land that borders waterways and the distance between river and fence.

4.2.5 Other considerations and notes on best practice

This option generally represents a medium-level cost for farmers but would be less cost effective in farms with low livestock densities and long stretches of unfenced waterways[17]. If livestock are drinking from the river, then alternative drinking stations will need to be provided. This intervention is often combined with the construction of culverts or bridges to reduce pollutants from cattle crossing rivers and streams to access different pastures or different farm areas. To maximise effectiveness this intervention should also be combined with nutrient management to control nutrient loading[70].

Best practice guidelines indicate that a minimum buffer of 1.5 metres should be allowed between the river edge and fencing[80]. This riparian buffer zone should be allowed to re-establish with natural vegetation (invasive species should be tightly controlled) until such time as coppicing is required (usually on a 5-9 year cycle) to allow light to reach the river and banks, particularly in fast-flowing areas[80]. Non-native species should be removed first and any chemical treatment used around waterways should be checked with the relevant authorities. Coppiced timber and vegetation can be securely stacked to provide habitat. For more information two other reviews may provide further insight into the relative effectiveness and cost of streambank fencing to reduce environmental impacts of dairy systems[67,81].

4.3 Literature review

4.3.1 Primary search

Source	Search terms (title/author/abstract)	Studies	*Relevant* studies	Search date
Web of Science	(fenc*) AND (dairy OR milk OR cow OR pasture) AND (water* OR river* OR stream*)	111	12	27 Aug 2015

4.3.2 Secondary search

Source	Search terms	Relevant studies	Search date
Reference lists		1	24-28 Aug 2015
Total		**13**	

4.4 Literature

4.4.1 Europe

4.4.1.1 Predicting microbial pollution concentrations in UK rivers in response to land use change[73]

Citation: Hampson et al 2010

Key message: Fencing of watercourses was found to be the most effective method for reducing microbial pollution in rivers

Location: Humber catchment, UK

Description: Faecal indicator organism models to examine the effectiveness of different types of intervention including the taxing of fertilisers, designation of environmentally sensitive areas, raising the price of the (now phased out) EU milk lease quota, reducing stocking rates, reducing fertiliser application rates, reducing milk consumption, and stream bank fencing.

Water: Models of stream bank fencing predict reductions in *Escherichia coli* concentrations of 59 per cent immediately below the improved area and 35 per cent at the subcatchment outflow. ***Caveats:*** This was not an experimental study, so conclusions rely upon model assumptions.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Simulated results

4.4.2 Australasia

4.4.2.1 Association between burrow densities of two Australian freshwater crayfish (Engaeus sericatus and Geocharax gracilis: Parastacidae) and four riparian land uses[78]

Citation: March & Robson 2006

Key message: Fencing of riparian zones is insufficient to ameliorating the effects of converting from natural forest to pasture.

Location: Corangamite Shire, Victoria, Australia

Description: A study to investigate the effect of riparian land-use (four categories: native forest; fenced mature native vegetation with pasture adjacent; fenced pasture; and pasture with cattle access to the stream) on two crayfish species (*Engaeus sericatus* and *Geocharax gracilis*) in three streams. Crayfish burrows densities were recorded along with a range of water quality and riparian condition variables.

Soil: Soil compaction was not significantly different between fenced and unfenced streambank pasture and erosion levels were qualitatively similar. ***Water:*** Phosphate levels and temperature were lower in fenced pasture and dissolved oxygen was higher. However, conductivity and salinity was higher in fenced pasture. ***Biodiversity:*** Exclusion of cattle did not lead to a significantly greater number of crayfish burrows. ***Caveats:*** The authors note that this was a relatively short-term study and it may not, therefore, have been powerful enough to detect all significant effects of land use or management.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	No Effect		Mixed			No Effect	

Study Type: Randomly selected and replicated site comparison

4.4.3 North America

4.4.3.1 A multivariate analysis of covariance to determine the effects of near-stream best management practices on nitrogen and phosphorus concentrations on a dairy farm in the New York Conservation Effects Assessment Project watershed[76]

Citation: Flores-López et al 2010

Key message: Protecting near-stream areas with fences can help reduce phosphorus levels in water bodies.

Location: New York, USA

Description: A study in which nitrate and soluble reactive phosphorous levels in streamwater and groundwater were monitored before and after establishment of a culvert crossing and fencing (i.e. 'treatment') to exclude livestock from a stream. This was compared to measurements from a stream that did not have fences or culvert to exclude livestock (i.e. the control). Replicate samples were taken from each stream, but only one treatment stream and one control stream were used.

Water: Treatment led to a 27 per cent decrease in ***soluble reactive phosphorous*** concentrations in streamwater. There was no significant effect on ***nitrate*** concentrations in streamwater.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Controlled, before/after site comparison

4.4.3.2 *Effects of Streambank Fencing of Pasture Land on Benthic Macroinvertebrates and the Quality of Surface Water and Shallow Ground Water in the Big Spring Run Basin of Mill Creek Watershed, Lancaster County, Pennsylvania, 1993-2001*[70]

Citation: Galeone et al 2006

Key message: (1) Fencing results in decreased nitrogen species, suspended sediment and total phosphorous. (2) However, dissolved phosphorous concentration and yield increased, highlighting importance of combining fencing with nutrient management to control nutrient loading.

Location: Pennsylvania, USA

Description: A study in which two adjacent basins were paired according to similar environmental conditions. Fencing of the entire 2 mile length of streams (either side of stream 5 to 12 feet from the stream edge) was then applied in the treatment basin. Assessment was by (1) comparison of the outlet of the treated versus the control basins, (2) comparison of sites upstream and downstream of the fenced pasture, and (3) comparison of data from both pre- and post-treatment monitoring. Monitoring was done during 'low-flow' conditions as well as during storm events.

<u>Water</u>: Stream discharge volume was greater in the control site than in the fenced site (1.62ft^3/s and 1.19ft^3/s per mile squared of drainage, respectively), but this was not necessarily entirely attributed to the experimental treatment. An analysis of covariance indicated that overall water-quality changes for the treated sites showed a 14 to 37 per cent decrease in ***total nitrogen***, ***dissolved nitrate***, ***dissolved ammonia***, ***total phosphorous*** and ***suspended sediment*** at the basin outflow, relative to control/upstream sites. Faecal-streptococcus data also showed significant reductions relative to control sites during the post-treatment period at the basin outflow. ***Dissolved phosphorous***, however, showed an increase of 19 per cent. Effects at an upstream monitoring point found generally higher ***nutrient loads***, but ***suspended sediment*** was lower. ***<u>Biodiversity</u>:*** Post-treatment changes in benthic macroinvertebrate indices indicated that fencing led to ***increased richness***, increased **abundance of pollution sensitive species** relative to hardy species (*EPT index*), lower percentage of oligochaetes (associated with improved water quality), and, at the basin outlet, a greater ***evenness*** in the macroinvertebrate community with a greater number of ***pollution sensitive taxa***. The improved benthic macroinvertebrate status was attributed to improved ***habitat quality*** (see paper for details). In addition, riparian herbaceous cover was noted to naturally re-establish at fenced sites. ***<u>Caveats</u>:*** Cattle crossings were installed to allow the livestock opportunities to cross the river and to access drinking water. These allowed direct faecal contamination, so the effect of fencing treatment is likely to be less than if alternative water sources were supplied and culverts or bridges constructed for cattle to cross waterways.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive/Mixed	Positive	Positive	Positive	

Study Type: Controlled, paired site, before/after study

4.4.3.3 *Short-Term Grazing Exclusion Effects on Riparian Small Mammal Communities*[79]

Citation: Giulliano & Homyack 2004

Key message: Ungrazed riparian zones, arising from exclusion of cattle from streamside areas, supported greater abundance and diversity of small mammals.

Location: Pennsylvania, USA

Description: A study to evaluate the effects on small mammals of fencing off of riparian areas from grazing. Vegetation structure and abundance and richness of small mammals were compared at sites that had recently (1-2 years) had livestock excluded with control (grazed) sites. Fences were constructed 10 to 15 metres from the stream bank. Note that this study reports a different set of data, but is based on the same study as Homyack & Giulliano (2002)[82].

Biodiversity: Small mammal ***species richness*** was 1.7 times higher in fenced sites than in grazed, while small mammal ***abundance*** was 2.2 times higher. Meadow voles and meadow jumping mice showed significantly higher ***abundance*** in fenced sites but short-tailed shrews showed no significant difference.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts					Positive	Positive	

Study Type: Paired site comparison of control versus treated sites. Nine replicates and randomly selected sample locations

4.4.3.4 Determining sources of fecal pollution in a rural Virginia watershed with antibiotic resistance patterns in fecal streptococci[72]

Citation: Hagedorn et al 1999

Key message: Fencing waterways to restrict cattle access significantly reduced faecal coliforms in stream samples.

Location: Virginia, USA

Description: A study to investigate the levels of faecal pollution in an area where grazing pastures generally have allowed cattle unfettered access to streams. Following identification of high faecal pollution from cattle, alternative water sources were provided and streams fenced off.

Water: Fencing lowered ***faecal coliform counts*** during August to October: mean counts were significantly reduced 60 to 96 per cent at the three sampling sites, two of the sampling sites' levels were reduced to below recreational-water standards for Virginia.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Unclear as to how the study was designed

4.4.3.5 Effect of Streambank Fencing on Herpetofauna in Pasture Stream Zones[82]

Citation: Homyack & Giulliano 2002

Key message: No significant difference was found between fenced and unfenced sites for species richness, abundance or biomass for reptiles or amphibians

Location: Pennsylvania, USA

Description: Note that this study reports a different set of data, but is based on the same study as Giulliano & Homyack (2004)[79].

Water: No effect of fencing was observed on ***pH***, ***dissolved oxygen***, ***salinity***, ***conductivity***, ***water temperature***, or colonies of ***faecal coliforms*** (p= 0.4 to 0.9). ***Biodiversity:*** Reptile and amphibian ***species richness*** did not differ significantly between site types or between years. ***Morisita's index*** indicated a high degree of similarity between reptile and amphibian communities on fenced and unfenced streams. Reptile and amphibian ***abundance*** did not differ between treated sites and controls. For individual taxa ***abundances***, green frogs and American toads were found more frequently in unfenced sites. Northern queen snakes, eastern garter snakes and tadpoles were more common in fenced sites. The remaining five most frequently captured species did not have significantly different ***abundances*** between fenced and unfenced sites. ***Caveats:*** Recovery of riparian areas may need longer to establish the water quality, food source or vegetation type/cover to support reptile and amphibian populations or simply that more time may be needed before population numbers will be observed to increase in response to improved environmental conditions.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect		No Effect	No Effect	

Study Type: Ten randomly selected replicates of unfenced (control) streams were paired for site comparison with fenced sites.

4.4.3.6 Changes in land use/management and water quality in the long creek watershed[74]

Citation: Line 2002

Key message: Implementation of beneficial management practices (including exclusion fencing) in the watershed have significantly reduced phosphorus and bacteria levels.

Location: North Carolina, USA

Description: A study to investigate water quality changes in an area that has had a 60 per cent decrease in cropland area, a >200 per cent increase in residential areas and in which more than 200 conservation practices have been applied to the remaining agricultural land.

Water: Following exclusion fencing, ***faecal coliform*** and ***faecal streptococci*** levels decreased by 90 per cent.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect/ Positive				

Study Type: Before and after monitoring. Not possible to separate effects of fencing from other potential influencing variables.

4.4.3.7 Changes in a stream's physical and biological conditions following livestock exclusion[75]

Citation: Line 2003

Key message: Livestock exclusion fencing significantly reduced bacteria levels in a monitored stream.

Location: North Carolina, USA

Description: A study to investigate water quality changes before and after erecting livestock exclusion fencing on a dairy farm. Monitoring was conducted for a total of 7.5 years, including 2.25 years prior to treatment (fencing). Fencing was 10 to 16 metres from the bank and the ungrazed area was planted with trees and in some severely eroded areas was reshaped and reseeded.

Water: Fencing led to significant reductions in ***faecal coliforms*** and ***enterococci***, which was attributed both to the reduction of direct faecal deposition in streams as well as enhanced filtration in riparian vegetation zones. In addition, reduced ***turbidity*** (49 per cent lower) and reduced ***total suspended sediment*** (60 per cent lower) was observed as a result of fencing. No significant effects were observed for ***dissolved oxygen***, ***pH***, ***conductivity***, or ***temperature***.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect/ Positive				

Study Type: Before and after monitoring of sites above and below fenced areas.

4.4.3.8 Nonpoint-Source Pollutant Load Reductions Associated with Livestock Exclusion[77]

Citation: Line et al 2000

Key message: Livestock exclusion fencing significantly reduced stream pollutants

Location: North Carolina, USA

Description: A study to investigate water quality changes before and after erecting livestock exclusion fencing on a dairy farm. Monitoring was conducted for a total of 7.5 years, including 2.25 years prior to treatment (fencing). Fencing was 10 to 16 metres from the bank and the ungrazed area was planted with trees and in some severely eroded areas was reshaped and reseeded.

Water: Fencing led to significant reductions in total Kjeldahl nitrogen (78.5 per cent), total phosphorous (75.6 per cent), total suspended solids (82.3 per cent), total solids (81.7 per cent). It also led to reductions in discharge (55.2 per cent). The 32.6 per cent reduction in nitrate and nitrite was not significant, but the authors expect this to decrease further as vegetation (and denitrification) in the riparian strip increase.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect/Positive	Positive			

Study Type: Before and after monitoring of sites above and below fenced areas.

4.4.3.9 Influence of Streambank Fencing on the Environmental Quality of Cattle-Excluded Pastures[71]

Citation: Miller et al 2010

Key message: Fencing may improve environmental quality by acting as a buffer or filter for runoff quantity and quality.

Location: Alberta, Canada

Description: Cattle were excluded from a 40-80 metre riparian zone and the effects on rangeland health, environmental quality and water quality were assessed over a three year period.

Soil: Fencing significantly ($P \leq 0.10$) decreased the amount of ***bare soil*** by 72 to 93 per cent. ***Soil bulk density*** was significantly reduced (by 6 to 8 per cent) by cattle exclusion in two of the three years, and ***soil water content*** was increased in one of the three years by 15 per cent. Soil surface chemical properties (***total carbon***, ***total nitrogen***, ***ammonium-N***, ***nitrate-N***, ***available P***) were generally unaffected by fencing although for one of the three years (a drier year) ***total C*** was significantly higher (11 per cent) and ***ammonium-N*** was significantly lower (41 per cent). ***Water:*** Lower runoff volume was recorded for fenced compared to control (grazed) pasture in two of three years. Fenced pasture had significantly lower mass loads for ***total nitrogen***, ***total dissolved nitrogen***, and ***total particulate nitrogen*** for two of the study's three years. Other water quality variables showed either no significant effect of fencing in any year (electrical conductivity, nitrate-N, ammonium-N) or an effect in only one of the three years (total suspended solids, total phosphorous, total dissolved phosphorous, total particulate phosphorous and dissolved reactive phosphorous). ***Biodiversity:*** In all three years, cattle exclusion significantly ($P \leq 0.10$) increased ***vegetation cover*** by 13-21 per cent and ***standing litter*** by 38-742 per cent. ***Caveats:*** Bigger effects may have been observed if the sites were monitored for longer and/or if higher stocking densities were used.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive	No Effect	Positive	Positive		Positive	

Study Type: Controlled

4.4.3.10 Sediment losses from a pastured watershed before and after stream fencing[69]

Citation: Owens et al 1996

Key message: Fencing of streams can decrease soil losses and sediment loads

Location: Ohio, USA

Description: An experiment to assess the effect of fencing streams to exclude cattle on pasture grazed year-around (no fertilizer, no rotational grazing). Sediment loss via the stream was measured at the base of the watershed. After 7 years the stream was fenced so that the cattle no longer had access to it and the effects on sediment and soil losses was monitored.

Soil: Soil losses decreased by 40 per cent, from 2.5 to 1.4 Mg/ha. ***Water:*** Sediment concentration decreased by more than 50 per cent. ***Caveats:*** We were unable to access the full text, so the information presented is from the abstract.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive		Positive				

Study Type: Before (7 years) and after (5 years) study

5 Year-round housed dairy system

Potential benefits to natural capital are not well evidenced and full life-cycle analyses are needed

5.1 Description

The decline in dairy farm numbers in Europe has been offset by increasing herd numbers and there is increasing interest in the large-scale systems seen elsewhere in the world, such as the USA and China, where one dairy operation may consist of thousands of cows. Recently, the UK has had several planning applications for large-scale dairies[83]. Although there is no definitive description of such a system, they tend to be housed year-round, do not graze outside (although cows may spend a 3-month dry period of the lactation cycle outdoors), produce high milk yields, and require high nutrient and energy inputs[83,84]. Grazing land can be turned over to growing forage (to either be fed fresh to cows or conserved). Various terms may be used to describe this type of farm, including megadairies, superdairies, intensive dairies, zero-grazed dairies and housed dairies. They are advocated by some who expect increased efficiency of resource use and land area in milk production. However, there are frequently concerns from local stakeholders, particularly over water quality and availability[85].

5.2 Summary

Very few studies were found that compare the natural capital impacts of year-round housed dairy system with grazed alternatives and none that experimentally tested effects on water, soil or biodiversity. Clearly more research is needed on the impacts before any conclusions can be reached on its negative or positive effect on natural capital overall. Better researched but not assessed here are the effects on animal welfare and milk quality.

		Soil		Water		Biodiversity		
Reference	Country	Structure	Fertility	Quality	Quantity	Diversity	Abundance	Yield
Meul et al 2012	Belgium							Decrease
Van den Pol-van Dasselaar et al 2008*	Northwest Europe	Positive		Positive		Negative		Increase

*This was a review of relevant literature rather than a controlled or replicated comparison of systems

5.2.1 Soil

There is limited evidence for the effect of this management system on soil. However, soil compaction due to trampling of pasture during grazing is can be less tightly controlled than compaction due to farm machinery on arable cropland where forage is grown.

5.2.2 Water

There is limited evidence for the effect of this management system on water, but nutrient losses into waterways are expected to be lower under zero-grazed systems.

5.2.3 Biodiversity

There is limited evidence for the effect of this management system on biodiversity. One review points to the positive effects on biodiversity of some grazed systems.

5.2.4 Yield

Milk yields per cow are widely reported to be higher than conventional farms. However, one study showed similar per cow milk yields between intensive grazed dairies and intensive housed dairies[84].

5.2.5 Other considerations

Full evaluation of the effects of a shift towards large, year-round housed dairy herds requires a life cycle analysis that considers all inputs and outputs from each dairy system including for example, the off-farm impacts that are attributed to production of concentrated feeds. Moreover, a landscape approach should be taken that considers the counterfactual scenario – if the UK and ROI entire dairy herd is moved to a zero grazing system, then that will have repercussions for current pasture – for example, much of the biodiversity in upland pastures relies upon grazing[86]. Furthermore, grassland pasture cannot necessarily be converted to arable farming, so grazing may remain a better use of marginal land[87]. There are also important considerations around milk quality, such as fatty acid composition, but these are not presented or evaluated here[e.g.88-90].

5.3 Literature review

5.3.1 Primary search

Source	**Search terms (title)**	**Studies**	***Relevant* studies**	**Search date**
Web of Science	(megadair* OR mega-dair*) OR (superfarm* OR super-farm*) OR (zerograz* OR zero-graz*) OR (hous* AND year-round) AND (water OR soil OR biodiversity OR species)	46	1	3 Sept 2015

5.3.2 Secondary search

Source	**Search terms**	**Relevant studies**	**Search date**
Google Scholar	off farm impacts concentrated feed dairy	1	3 Sept 2015
Google Scholar	intensive dairy impact soil water biodiversity	0	3 Sept 2015
Total		**2**	

5.4 Literature

5.4.1 Europe

5.4.1.1 Higher sustainability performance of intensive grazing versus zero-grazing dairy systems[84]

Citation: Meul et al 2012

Key message: Dairy farms with zero-grazed cows are less environmentally or economically sustainable than those with intensively grazed cows

Location: Flanders, Belgium

Description: A comparison of two types of intensive dairy farming system: ten intensively grazed dairy farms and ten zero-grazed dairy farms. Performance was assessed using environmental, economic and animal welfare indicators. Environmental sustainability and resource efficiency were found to be higher in intensively grazed systems than in zero-grazed systems, but no measurement of soil or water health was taken on the farm and biodiversity effects were not included in the study.

[Effects on water, soil or biodiversity were not tested]. ***Yield:*** Land productivity and overall farm profitability were significantly higher in intensively grazed farms than in zero-grazed farms.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts							Negative

Study Type: Replicated and controlled site comparison

5.4.2 Review

5.4.2.1 To graze or not to graze, that's the question[88]

Citation: Van den Pol-van Dasselaar et al 2008

Key message: Grazing for a limited part of the day is generally good. However, farmers' personal motives will affect the decision as to what extent to graze dairy cows.

Location: Northwest Europe

Description: Notes that grazing is decreasing in importance in northern Europe and that zero-grazed dairy herds make up less than 5 per cent of the UK's herd (in 2005) but are becoming more common. In Ireland, grass-based systems are most important, but elsewhere in Europe the proportion zero-grazed is over 30 per cent (Denmark).

Soil: Trampling of grassland occurs for grazed pasture, whereas compaction due to farm machinery can be more tightly controlled on arable cropland where forage is grown and taken to cows. ***Water:*** Nitrate leaching is lower in zero-grazed systems. Phosphate losses are lower in zero-grazed systems. ***Biodiversity:*** Grazing can increase biodiversity. ***Yield:*** Grass yields are higher in zero-grazed than in unrestricted grazing systems. ***Caveat:*** A decision to change farming system from a conventionally grazed system to one that keep cows housed year-round will have wider ramifications than simply on-farm or neighbourhood effects. A full life cycle analysis and landscape approach will be needed to assess this.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive		Positive		Negative		Positive

Study Type: A review of different systems without any experimental comparison

6 Use of anaerobic digester for dairy slurry

Anaerobic digestion can benefit local water quality whilst increasing pasture yields

6.1 Description

There are two principle opportunities for the use of anaerobic digestion (AD): (1) on-farm AD to process dairy livestock manures, which we focus on here, and (2) AD facilities sited at dairy processing facilities to treat industrial effluents (see this review[91] on dairy industry opportunities for AD). During AD the organic matter in farm slurries and dairy effluents is broken down by bacteria to generate simple organic acids, which are then converted to methane by further bacteria[92]. One of the better-reported benefits is the biogas (methane, carbon dioxide, water vapour, ammonia and hydrogen sulphide) that is produced, which can be used to produce electricity or heat, replacing fossil fuel use[92]. Further benefits include production of digestate for use as a fertiliser (to be sold or used on-farm), odour reduction (particularly for livestock manures), reduction in wastewater treatment costs, and reduced greenhouse gas emissions (methane is converted to carbon dioxide, which has a lower warming potential)[92].

6.2 Summary

Just 3 studies were identified in a systematic literature search, of which 2[93,94] were relevant. Searches on google scholar identified a further 2[95,96]. The remainder were identified from reference lists of other articles[97-104]. In total, 41 academic and grey literature articles were consulted. Much of focus has been on technological improvements to digesters and on reductions in greenhouse gas emissions[105]. Of the studies that investigated soil, water or biodiversity effects, almost half (6 of 13) also investigated yield effects. There were 6 and 7 studies that examined the effects of AD on soil and water, respectively. Europe had the most studies (8), followed by North America (4) and Asia (1). No studies were identified that examined biodiversity effects.

		Soil		Water		Biodiversity		
Reference	**Country**	**Structure**	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	**Yield**
Abubaker et al 2012	Sweden		Positive					Increase
Bachmann et al 2011	Germany							No Change
Ernst et al 2008	Germany		Negative	Positive				
Kocar 2008	Turkey	Positive						Increase
Möller et al 2008	Germany		Positive					Increase/No Change
Svoboda et al 2013	Germany			Positive				
Thomsen et al 2013	Denmark		No Effect					
Walsh et al 2012	UK			Positive				Increase
Garg et al 2005	India	Positive			Positive			Increase
Güngör & Karthikeyan 2008	USA			Positive				
Morris & Lathwell 2004	USA							
Martin 2003	USA			Positive				
Saunders et al 2012	USA			Positive				

6.2.1 Soil

One study found that effects on carbon cycling were similar between AD and non-AD treatments[93], while another found that carbon and nitrogen from microbial biomass was significantly higher in conventional slurry than in AD slurry[102], indicating inhibitory effects on microbial activity. Two studies found increased nitrogen in soils treated with AD slurry[98,102]. Soil structure and texture, including bulk density and hydraulic conductivity, were improved through addition of digestate[101,106]. However, certain earthworm species (*Aporrectodea caliginosa*) showed decreased biomass under biogas residue treatment, potential leading to further negative effects upon soil fertility and structure[102].

6.2.2 Water

Anaerobic digestion was found to decrease pathogens and bacteria in slurry[94,99]. One study also showed that AD helped reduce the potential for phosphorous leaching in fields[100], although another found that there was no reduction in potential impact when using AD[99]. The effect on nitrate concentrations and nitrate load were also varied with one study showing lower nitrate concentrations in AD slurry under particular earthworm conditions[102], while other studies found similar effects between the two[95,96,99]. Anaerobic digestion reduced the chemical oxygen demand in dairy cattle manure with resultant lower potential nonpoint source pollution of water supplies following spreading on land[99]. In addition, biogas residue also increased soil water retention, particularly when applied at higher rates, which was attributed to increased organic carbon content and increased aggregation[101].

6.2.3 Biodiversity

There were no studies on the effect of AD on biodiversity.

6.2.4 Yield

One study found that there was generally no significant difference between treatments for legume crop yields or for grassland[98]. However, although digested and undigested slurry resulted in similar non-leguminous crop aboveground biomass yields overall, spring wheat yields were significantly higher with digested slurry treatment (c.f. non-digested slurry), which the authors attribute to the incorporation of the slurry into the soil shortly after spreading[98]. Similarly, another study found dry matter yields of two non-leguminous crops under digested slurry treatment were higher than from non-digested slurry and similar to NPK fertiliser treatment[103]. Two studies found that under conventional farming practices, liquid digestate and undigested slurry gave greater crop yields than inorganic fertilisers[95,97]. However, under organic farming practices, liquid digestate and NPK compound fertiliser gave highest yields[95], highlighting the importance of understanding the starting point and baseline conditions of the soils.

Co-digested slurry was slightly more effective in supplying the crops with nitrogen, but this effect was generally not significant[98,103]. Digested slurries that had field residues and nitrogen incorporated into the influent gave increased dry matter yields and nitrogen uptake compared to digested dairy slurry alone[98].

6.2.5 Other considerations and notes on best practice

The costs of anaerobic are high and may not be feasible for all farmers. Key considerations include the size of the farm and whether cattle are generally housed (larger herds that are housed for longer will generate more usable slurry and therefore more useful biogas and digestate)[99,107], the infrastructure and prices available for selling biogas or utilising it on-farm; and the benefits from selling digestate or utilising it on crops to reduce commercial fertiliser costs[92]. Moreover, profitability may be tightly linked to biogas prices[92].

A useful summary is given by the WRAP project[108], which suggests that the delivery of nitrogen to crops from digestate is maximised through a series of best practices:

1. Digestate should be analysed to measure the amount of ammonium nitrogen it contains, which will form a part of careful nutrient planning.
2. Digestate should only be applied during the active growing , when the nitrogen will be used efficiently.
3. Digestate should be delivered to the crop using precision spreading techniques such as a bandspreader or shallow injector to maximise crop uptake and reduce ammonia losses.
4. Digestate must be applied in accordance with Nitrate Vulnerable Zones regulations.
5. Farmers should cooperate with anaerobic digestion facility operators to time spreading with crop need (rather than, for example, just aiming to avoid Nitrate Vulnerable Zone closed spreading periods).

6.4 Literature review

6.4.1 Primary search

Source	Search terms (title)	Studies	*Relevant* studies	Search date
Web of Science	((anaerobic AND digest*) OR biogas OR digestate) AND (dairy OR dairies) AND (soil OR water OR biodiversity)	3	2	12 Oct 2015

6.4.2 Secondary search

Source	Search terms	Relevant studies	Search date
	anaerobic digestate dairy soil quality	1	12 Oct 2015
	anaerobic digestate dairy leaching	1	3 Sept 2015
Reference lists		8	3-15 Oct 2015
Total			

6.5 Literature

6.5.1 Europe

6.5.1.1 Biogas residues as fertilisers – Effects on wheat growth and soil microbial activities[104]

Citation: Abubaker et al 2012

Key message: Treatment with biogas residues gave greater yields than treatment with inorganic fertiliser and increased soil microbial activity. Residue quality varies and should be an important consideration for AD operators.

Location: Uppsala, Sweden

Description: [Note: this experiment did not assess AD of dairy waste]. A study to assess the fertilising performance of four biogas residues (from different municipal waste sources) against that of pig slurry and mineral fertiliser (NPK). Spring wheat yield and soil microbial activity were monitored using a pot experiment over a 3 month period.

Soil: Treatment with pig slurry gave similar ***nitrogen mineralisation capacity*** to that of one of the biogas residue treatments, which were both higher than all other treatments. Lowest ***nitrogen mineralisation capacity*** was for the controls (no fertiliser). ***Potential ammonia oxidation*** rate was generally higher in pig slurry and biogas residue treatments than in NPK or controls. ***Yield:*** Two of the four biogas residues gave greater biomass yields than NPK fertilisation and all gave greater biomass yields than controls. Pig slurry gave highest biomass yields.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Positive					Increase

Study Type: Randomised, replicated and controlled

6.5.1.2 *Codigested dairy slurry as a phosphorus and nitrogen source for Zea mays L. and Amaranthus cruentus L.*[103]

Citation: Bachmann et al 2011

Key message: Using co-digested slurries has similar effects on phosphorous and nitrogen plant nutrition to treatment with undigested dairy slurries. Co-digested slurry is valuable as a phosphorous fertiliser, providing similar levels of plant phosphorous uptake as highly soluble mineral fertiliser.

Location: Trenthorst, Germany

Description: A pot experiment to assess the effects of co-digested slurry (dairy, maize silage and wheat grain), dairy slurry, highly soluble mineral NPK fertilizer, and a control NK fertiliser (i.e. without any P) on phosphorous and nitrogen uptake in maize and amaranth crops.

Yield*: *Dry matter yields for amaranth under co-digested slurry treatment were not significantly different from NPK fertiliser treatment and higher than those from undigested slurry. Dairy slurry and co-digested dairy slurry did not differ in terms of their effectiveness at providing highly soluble mineral ***phosphorous***. For maize, co-digested slurry gave higher ***dry matter yields*** than undigested slurry, but not significantly so. Co-digested slurry was slightly more effective in supplying the crops with nitrogen, but this effect was generally not significant.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts							No Change

Study Type: Replicated and controlled

6.5.1.3 *C and N turnover of fermented residues from biogas plants in soil in the presence of three different earthworm species (Lumbricus terrestris, Aporrectodea longa, Aporrectodea caliginosa)*[102]

Citation: Ernst et al 2008

Key message: Nitrification, microbial biomass and basal respiration were negatively influenced (mediated by the effect on earthworm activity) by presence of biogas residue in soil, compared to conventional slurry.

Location: Trier, Germany

Description: An experiment to investigate the effects of biogas residue (from cattle slurry, grass silage and maize) on carbon and nitrogen turnover in the presence of three earthworm species (*Lumbricus terrestris*, *Aporrectodea longa* and *Aporrectodea caliginosa*) and compare the resulting changes in soil chemical and microbiological properties with those of a conventional slurry treatment.

Soil*: *Biomass of *L. terrestris* and *A. longa* was greater after treatment with conventional slurry or biogas residue. ***Biomass*** of *A. caliginosa* decreased in both treatments, but particularly under treatment with biogas residue. ***Microbial biomass carbon*** and ***nitrogen*** was significantly higher in conventional slurry than in fermented slurry treatments. Effects on ***microbial biomass*** are possibly due to lower total organic carbon or lower decomposability by earthworms of fermented slurry.

Total nitrogen concentrations were significantly larger in treatments with fermented slurry (compared to conventional slurry), in the presence of *A. longa* and *A. caliginosa*. ***Water: Nitrate concentrations*** were higher in conventional slurry treatments than in fermented slurry treatments for *A. longa* and *A. caliginosa*.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Negative	Positive				

Study Type: Controlled

6.5.1.4 Anaerobic Digesters: From Waste to Energy Crops as an Alternative Energy Source[106]

Citation: Kocar 2008

Key message: Treatment with anaerobically digested cattle slurry gave higher yields than treatment with commercial organic or chemical fertilizers (aerobically digested cattle fertilizer, composted poultry fertilizer and compost fertilizer). Soil texture was also improved.

Location: Assumed Izmir, Turkey (Author University)

Description: An experiment into the effect of anaerobically digested cattle slurry on safflower yields, compared to other organic and inorganic fertilisers.

Soil: Anaerobic digestion improved soil texture. ***Yield:*** Anaerobically digested cattle slurry gave higher yields than treatment with commercial organic or chemical fertilizers (aerobically digested cattle fertilizer, composted poultry fertilizer and compost fertilizer). ***Caveats:*** We were unable to access the full text, so the information presented is from the abstract.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive						Increase

Study Type: Unsure

6.5.1.5 Effects of different manuring systems with and without biogas digestion on nitrogen cycle and crop yield in mixed organic dairy farming systems[98]

Citation: Möller et al 2008

Key message: Anaerobic digestion (AD) allows better synchronisation of crop nitrogen demand and supply only if it is incorporated into the soil following spreading. AD also allows other biomass (e.g. crop residues and cover crops) to be incorporated, which increases the amount of mobile manures and gives greater scope for nitrogen application.

Location: Limburg, Germany

Description: Three-year field trials to assess nutrient cycling, nitrogen uptake and crop yield for grassland and arable land under five different treatments: (1) solid farmyard manure; (2) undigested liquid slurry; (3) digested liquid slurry; (4) digested liquid slurry and field residues (e.g. crop residues and cover crops); and (5) digested liquid slurry and field residues with additional nitrogen inputs (through digestion of purchased substrates).

Soil*: *Mineral nitrogen soil content was higher in digested treatments (3-5) than undigested (1-2) and the highest levels were observed in digested slurry (treatment 3), although this was not significantly greater than the other digested treatments (4-5). ***Yield*:** No significant difference was found between treatments for ***legume crop*** aboveground biomass yields. For non-legumes, treatment 5 gave greatest yields, followed by 4, 3, 2 and 1 (in that order). Digested and undigested slurry resulted in similar ***non-leguminous crop*** aboveground biomass yields overall, but for ***spring wheat*** aboveground biomass yields were significantly higher with digested slurry treatment probably due to the fact that slurry was incorporated into the soil shortly after spreading. ***Nitrogen uptake*** in harvested products did not differ between undigested and digested slurry treatments (2 & 3),but was generally higher for digested dairy slurry that had been supplemented with field residue or field residue plus nitrogen (4 & 5). ***Dry matter yield*** in grassland was higher for digested slurry than for undigested, but only significantly so for 1 of 3 years. ***Nitrogen uptake*** was similarly higher for digested slurry, but the effect was not significant. Digested slurries with field residues and nitrogen gave increased ***dry matter yields*** and ***nitrogen uptake***.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Positive					No Effect / positive

Study Type: Randomised, replicated and controlled

6.5.1.6 Crop production for biogas and water protection—A trade-off?[96]

Citation: Svoboda et al 2013

Key message: Biogas residues had similar nitrate leaching potential to animal manures but were significantly lower for grassland than for maize.

Location: Kiel, Germany

Description: An experiment to evaluate nitrogen leaching potential of biogas residues and animal slurry when applied to forage production systems of grass and maize on sandy soil (i.e. relatively high leaching potential).

Water*:** When applied to maize, leachate ***nitrate concentrations and ***nitrate load*** generally increased as nitrogen applied as fertiliser increased. Mineral nitrogen fertilizer resulted in higher average ***nitrate concentrations*** and ***nitrate loads*** than organic fertilizer. Biogas residues resulted in similar ***nitrate concentration*** to untreated cattle slurry and lower concentrations than pig slurry, but ***nitrate load***, although slightly lower for biogas residues, were not significantly different from raw animal slurries. Application to grass resulted in low ***nitrate concentrations*** and low ***nitrate loads*** in leachate for all treatments (peak concentration of 17mg l^{-1} compared to 271mg l^{-1} for maize) with no significant difference between treatments. ***Caveats*:** However, soils that already have high nutrient surpluses may find that this is exacerbated by application of biogas residues (or any other fertiliser), highlighting the need for careful nutrient management and planning.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Randomised, replicated and controlled

6.5.1.7 Carbon dynamics and retention in soil after anaerobic digestion of dairy cattle feed and faeces[93]

Citation: Thomsen et al 2013

Key message: Long-term carbon retention in soil is broadly similar between raw cattle slurry and anaerobically digested slurry.

Location: Askov & Jyndevad, Denmark

Description: An experiment to assess carbon fate in cow feed applied to soil under four treatments: (1) feed (60% maize silage, 21% alfalfa, 18% rapeseed cake) applied directly to soil, (2) anaerobically digested feed, (3) cow faeces (cows were fed the same feed described above), and (4) anaerobically digested faeces.

Soil: Over the long-term (1-2 years) the fate of plant-derived carbon in soil is similar between raw treatments and anaerobically digested treatments. However, the authors note that anaerobic digestion results in higher proportions of less decomposable organic matter (e.g. lignin) in digested residue in the short-term, which is likely to affect soil microbial activity, with subsequent effects on the nitrogen cycle.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		No Effect					

Study Type: Replicated and controlled

6.5.1.8 Replacing inorganic fertilizer with anaerobic digestate may maintain agricultural productivity at less environmental cost[95]

Citation: Walsh et al 2012

Key message: Crop yields were generally higher when treated with anaerobically digested slurry and nitrate leaching potential was lower than inorganic fertilisers.

Location: Wales, UK

Description: A pot experiment to compare the effects of four different treatments (undigested cow slurry, liquid digestate (i.e. liquid fraction of biogas residue), ammonium nitrate and NPK compound fertiliser) on crop yields (half of pots seeded with perennial ryegrass and the other half with a perennial ryegrass/white clover mix) and nitrate leaching. Experiments were conducted on organic soils and conventionally farmed soils. Both undigested slurry and liquid digestate were sourced from the same organic dairy farm.

Water:* *Nitrate concentrations were lower in control (unamended soil), undigested slurry and liquid digestate treatments than in treatments with inorganic fertilisers. Undigested slurry had slightly lower ***nitrate concentrations***, but the difference was not significant. ***Yield:*** In conventional soils, liquid digestate and undigested slurry gave greater ***crop yields*** than inorganic fertilisers or controls.

In organic soils liquid digestate and NPK compound fertiliser gave highest yields. Across all treatment combinations liquid digestate gave the greatest (or equal greatest) ***crop yields***.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				Positive

Study Type: Randomised, replicated and controlled

6.5.2 Asia

6.5.2.1 *Use of flyash and biogas slurry for improving wheat yield and physical properties of soil*[101]

Citation: Garg et al 2005

Key message: Soil structure was improved by treatment with biogas residue giving short and long-term benefits to crop production and soil amelioration.

Location: New Delhi, India

Description: A study to assess the use of biogas residue (cattle dung) and flyash (from coal-fired power stations) on soil physical properties and wheat yields. Six treatments were used: control (no fertiliser), biogas residue at 4Mg ha^{-1} (low) and at 15Mg ha^{-1} (high), and flyash application at 4Mg ha^{-1} (low), 8Mg ha^{-1} (medium) and 12Mg ha^{-1} (high).

Soil: At tillering stage, soil treated with biogas residue at the high rate had lower bulk density of surface soil (0-15cm depth) over the unamended control, whereas all flyash treatments and application of slurry at the low rate had no significant effect. At harvest stage, both biogas treatments and treatment with the high rate of flyash reduced surface soil bulk densities compared to controls. Hydraulic conductivity in surface soil was increased by application of biogas residue at both rates of application. ***Water:*** Biogas residue also increased the volumetric moisture content of surface soil at saturation, particularly at the higher rate of application, which is attributed to increased organic carbon content and increased aggregation. ***Yield: Root growth density*** was highest under the high rate of biogas residue, lower in flyash and lowest in the control. This is attributed to improved soil physical condition. Increased nutrient availability and improved soil condition caused the ***leaf area index*** to be higher under biogas residue than flyash or control and higher with increased rate of application. Highest ***grain yields*** were from treatment with the high rate of biogas residue.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive			Positive			Positive

Study Type: Randomised, replicated and controlled

6.5.3 North America

6.5.3.1 *Phosphorus forms and extractability in dairy manure: A case study for Wisconsin on-farm anaerobic digesters*[100]

Citation: Güngör & Karthikeyan 2008

Key message: Anaerobic digestion decreased the water extractability of manure phosphorous, helping reduce eutrophication potential.

Location: Wisconsin, USA

Description: A study to investigate the effect of anaerobic digestion on water-extractable phosphorous. Six on-farm dairy manure digesters were included in the study.

Water: Anaerobic digestion decreased the water extractability of manure phosphorous by 22–47%.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Replicated and controlled

6.5.3.2 Anaerobically Digested Dairy Manure as Fertilizer for Maize in Acid and Alkaline Soils[97]

Citation: Morris & Lathwell 2004

Key message: Digested slurry is as good as, or better, than inorganic fertiliser.

Location: [assumed] USA

Description: [Note: could not access full text] Greenhouse experiments to assess the relative effectiveness of undigested and digested dairy slurry (and inorganic N fertiliser) on maize yields on acid and alkaline soils.

Yield: Undigested or digested slurries gave equal or greater yields than inorganic nitrogen fertiliser. Anaerobically digested dairy manure increased maize growth in early stages of development compared to inorganic fertiliser nitrogen sources for acid soils.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts							Positive

Study Type: Unsure (at least controlled)

6.5.3.3 A Comparison of Dairy Cattle Manure Management with and without Anaerobic Digestion and Biogas Utilization[99]

Citation: Martin 2003

Key message: Anaerobic digestion reduced total volatile solids and chemical oxygen demand in dairy cattle manure with resultant lower potential nonpoint source pollution of water supplies following spreading on land. Anaerobic digestion also reduced the potential for contamination of water by non-pathogenic and pathogenic microorganisms.

Location: New York, USA

Description: An investigation into air and water quality benefits and costs of anaerobic digestion (AD). The study uses a comparison between two dairy farms in New York State that use similar manure management processes except that one uses anaerobic digestion and the other does not.

Water: AD reduced the density of ***fecal coliforms*** by 99.9% and ***Mycobacterium avium paratuberculosis*** (responsible for Johne's in cattle and linked to Crohn's disease in humans), whereas no reductions were observed on the farm without AD. Anaerobic digestion reduced ***total volatile solids*** and ***chemical oxygen demand*** in dairy cattle manure with resultant lower potential nonpoint source pollution of water supplies following spreading on land. AD did not provide a reduction in the potential impact of ***nitrogen or phosphorous*** on water quality through nutrient enrichment.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Comparison of two matched sites

6.5.3.4 Effect of Anaerobic Digestion and Application Method on the Presence and Survivability of E. coli and Fecal Coliforms in Dairy Waste Applied to Soil[94]

Citation: Saunders et al 2012

Key message: Anaerobic digestion can reduce pathogenic bacteria in raw dairy slurry.

Location: Washington, USA

Description: A study to investigate the fate of indicator bacteria, *Escherichia coli* and fecal coliform in anaerobically digested dairy slurry compared to raw slurry.

Water: Raw dairy slurry had increased indicator bacteria, *E. coli,* and fecal coliform relative to anaerobically digested slurry. In addition, soils with digested slurry had fewer *E. coli* and fecal coliform at the end of each trial than soils that received digested slurry. There is thus reduced potential for contamination of runoff water.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			Positive				

Study Type: Randomised, replicated and controlled

7 Precision agriculture for pasture nutrient management

Precision agriculture in pastures may offer significant benefits but requires extensive testing

7.1 Description

Precision agriculture refers to the adoption of practices that try to increase the scale of resolution at which the needs of crop units (e.g. fields or zones within fields) or livestock units (e.g. groups of similar aged animals or even individual animals) are measured and managed[109]. Precision nutrient management requires farmers to (1) carefully plan the crops that they will grow and the necessary soil physical and chemical conditions for optimal growth, (2) measure the existing soil parameters, (3) respond to these through precise management of fertilisers and (4) regularly review progress and repeat this process[110]. Most dairy farms are managed in a uniform way, yet pastures can exhibit enormous variability in their yield, even within a single farm[111]. Accordingly, much of the fertiliser that is used on the farm is wasted, despite the fact that fertilisers comprise a large proportion of the variable costs in modern farming[111]. New technologies allow precise measurement of within pasture variation in nutrient needs and also provide the means to respond with tailored amounts and types of fertiliser.

7.2 Summary

A systematic review and further searches of the literature found no studies that investigated the impact of precision agriculture methods in managing nutrients on pastures. In practice, the environmental benefits of increased nutrient use efficiency are usually taken as given and the focus of research is instead on the advancement of technologies to support measuring and managing within-field variation in nutrient supply and crop response. There is a huge variety of precision agriculture technologies available (see review[109]] yet, despite the importance of pastures and livestock globally, much of the advancement has come from arable farming[112].

The main barrier to widespread adoption is the upfront costs of the technology, the technical expertise needed[113], and the lower profit margins (generally) for pastoral products compared to arable crops[111]. However, recent reviews have argued for the adoption of precision management of fertiliser application on pastures highlighting the potential benefits in terms of economic savings on annual farm costs, increased yields and better environmental performance[110-112], particularly in view of the tight profit margins found in dairy farming, which mean that efficiency savings are vital[111].

7.2.1 Soil

Although no studies were available for precision agriculture on dairy pastures specifically, soils under a precision agriculture system will be managed for optimum fertility and structure to maximise crop quality and yield.

7.2.2 Water

Precision nutrient management will be expected to reduce the amount of nutrients applied in excess of pasture requirements, thereby reducing nutrient losses through leaching and runoff and subsequent decreases in water quality.

7.2.3 Biodiversity

Aquatic biodiversity in particular will be expected to benefit from reduced fertiliser runoff into water supplies, which can lead to eutrophication in local streams and lakes.

7.2.4 Yield

Precise nutrient management is expected to maintain or increase yields whilst decreasing variable costs of fertiliser use.

7.2.5 Other considerations and notes on best practice

The more variability there is in environmental conditions (particularly soil), the greater the potential rewards for a more precise fertiliser regime[112]. Maximum improvements will be made when different precision agriculture tools are used in conjunction with one another[109]. It is less about the specific technologies adopted and more about the careful gathering and interpretation of pasture data[112].

7.4 Literature review

7.4.1 Primary search

Source	**Search terms (title)**	**Studies**	***Relevant* studies**	**Search date**
Web of Science	((precision AND agriculture) AND (dair* OR pasture OR grassland))	9	0	29 Oct 2015

7.4.2 Secondary search

Source	**Search terms**	**Relevant studies**	**Search date**
Google scholar	Dairy precision agriculture	0	29 Oct 2015
Review articles	Reference lists	0	29 Oct 2015
Total		**0**	

8 Controlled traffic farming

Controlled Traffic Farming is likely to be beneficial to soil structure, soil fauna and crop yields

8.1 Description

Farm traffic management techniques are designed to prevent overcompaction of soils and reduce direct damage to plants, which can depress grass yields[114]. In controlled traffic farming (CTF), farm traffic is concentrated onto permanent wheel lanes, which are separated from crop zones. Compaction of soil by farm machinery is thereby halted in the crop zone, whilst increased compaction of soil in the traffic lanes increases their load-bearing capacity and improves their driveability, particularly in less favourable weather conditions[115,116]. The technique is often aided by the use of precise navigation aids and auto steering technology.

8.2 Summary

There were very few studies that investigated the effect on soil, water or biodiversity of implementing CTF for production of dairy silage. However, this has been identified as an important research area by the Agricultural and Horticultural Development Board, after recent research found that around 65% of a field is passed over during a single silage harvesting event with more than 50% of the field passed over at least four times[117,118]. In arable farming, tillage is used to alleviate the impacts of soil compaction. However, annual tilling is not suited to perennial grass swards, so it is even more important to prevent compaction in the first place[114,119].

		Soil		Water		Biodiversity		
Reference	**Country**	**Structure**	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	**Yield**
Douglas & Crawford 1991	Scotland	Positive						Increase
Douglas et al 1992	Scotland	Positive			Positive			Increase
Douglas et al 1998	Scotland	Positive			No Effect		Positive	
Głąb 2008	Poland	Positive			Negative			Increase
Hansen 1996	Norway	Positive					Positive	Increase

*This is a comparison of trafficked versus non-trafficked

8.2.1 Soil

CTF systems are generally implemented in order to maintain and improve soil structure. CTF was found to reduce compaction, particularly in the upper soil layers, resulting in lower bulk density in perennial grass leys and alfalfa grown for silage[119-122]. Effects on bulk density were more pronounced for heavier machinery and when conditions are wet[121]. Measurements in CTF systems demonstrating reduced shear strength[120,123], reduced penetration resistance[122], and increased volume and number of pores[119,120,122,123] further demonstrated improvements in soil structure compared to conventional traffic systems.

8.2.2 Water

Infiltration rate was greater in CTF than conventional systems[123]. There was limited evidence for the effect on soil water content and availability for crop growth. CTF led to decreased soil water content under an alfalfa crop[122], whilst the opposite was true for a perennial ryegrass[120]. Further studies are needed to assess crop and soil-specific effects on water content, availability and retention. A recent review of all farm types (i.e. not specific to grasslands for dairy silage) found that CTF reduced runoff volume by 28-42% with reductions likely to be greater under higher rainfall conditions[116]. There are very few data on the effects of CTF on nutrient and agrochemical leaching even for arable crops but effects are expected, on balance, to be similar between treatments[116].

8.2.3 Biodiversity

Just two studies identified the effects of CTF on biodiversity and these reported an increase in earthworm number and weight[119] or activity[123].

8.2.4 Yield

A recent review of 10 studies that investigated yield effects of compaction and damage to soil by farm traffic found that yields in trafficked areas were 9-74% lower than un-trafficked areas[114]. The studies review here suggest that soils compacted by farm traffic showed yield reductions, particularly at the first cut, for grass ley[119-121] and alfalfa[122] and the effects were more pronounced for heavier or more frequent traffic[121]. Dry matter yields were also less variable in CTF than conventional systems[120].

8.2.5 Other considerations

The major costs associated with this intervention are the costs of replacing machinery, where necessary, to ensure that wheel spacing is compatible between operations. For grass silage production, 12 metre machinery width is common[114]. In addition, the cost of GPS and auto steer technology should be factored in to budgets. See Kroulik et al 2011[124] for detailed review of guidance technologies.

If the cost of implementing a CTF system is too prohibitive, then a reduced ground pressure traffic system might be considered, in which farm machinery is fitted with larger, lower pressure tyres to reduced damage to swards and reduce soil compaction[120].

8.3 Literature review

8.3.1 Primary search

Source	**Search terms (title)**	**Studies**	***Relevant* studies**	**Search date**
Web of Science	(controlled OR reduc* OR zero) AND (traffic OR pressure) AND (dairy OR dairies OR silage OR grass) AND (soil OR water OR species OR biodiversity)	0	0	20 Oct 2015

8.3.2 Secondary search

Source	**Search terms**	**Relevant studies**	**Search date**
Google	Controlled traffic dairy silage	0	20 Oct 2015
Reference lists		5	20-21 Oct 2015
Total		**5**	

8.5 Literature

8.5.1 Europe

8.5.1.1 Wheel-induced soil compaction effects on ryegrass production and nitrogen uptake[121]

Citation: Douglas & Crawford 1991

Key message: Minimising compaction gave significantly greater yields in wet conditions, but effects were smaller and did not last as long in dry conditions. Impaired uptake of nitrogen was related closely to increased traffic and soil density.

Location: Edinburgh, Scotland

Description: A study to compare soil compaction and grass yield under high traffic, low traffic and zero traffic farming systems. Further, the timing of traffic on soil and crop response was assessed.

Soil: Increased bulk density was detected up to 20cm depth in soils that had been passed over with farm traffic. Effects were more pronounced for heavier machinery and for traffic during spring (April), compared to summer (June). ***Yield:*** Growth and yield decreased by management systems that had heavier or more frequent traffic.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive						Increase

Study Type: Replicated and controlled

8.5.1.2 Soil and crop responses to conventional, reduced ground pressure and zero traffic systems for grass silage production[120]

Citation: Douglas et al 1992

Key message: A controlled traffic farming system improved soil structure, leading to increased grass yields.

Location: Edinburgh, Scotland

Description: A four-year comparison of CTF with conventional and reduced pressure (larger, lower pressure tyres fitted to machinery) traffic systems for a perennial ryegrass sward managed for silage production. Bulk density, shear strength, water content and dry matter yields were monitored.

Soil: Throughout the top 250mm of soil, but particularly in the top 150mm, ***bulk density*** in the CTF system was significantly lower than in the reduced pressure or conventional treatments. At the end of four years of treatment, ***Shear strength*** was lower in the CTF than the reduced pressure system, which had lower shear strength than the conventional traffic system. CTF had a larger proportion of readily drained ***pores***. ***Water:*** Soil ***water content*** equalling or exceeding field capacity was most common in the conventional system. ***Yield:*** Dry matter yields and root length were greater and less variable in the CTF than the conventional treatments, particularly at the first cut.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive			Positive			Increased

Study Type: Replicated and controlled

8.5.1.3 Structural improvement in a grassland soil after changes to wheel-traffic systems to avoid soil compaction[123]

Citation: Douglas et al 1998

Key message: Implementing CTF can lead to improved soil structure, which is attributed to natural processes including increased earthworm activity.

Location: Edinburgh, Scotland

Description: A study to investigate whether soils can be improved through substituting conventional systems with reduced pressure farming (standard tyres on farm machinery replaced with larger, lower pressure alternatives) and substituting reduced pressure systems with CTF. The effect of such substitutions on soil was measured over two years on a perennial ryegrass sward.

Soil: The CTF system showed lower vane ***shear strength*** than controls. The ***volume of macropores*** was increased following introduction of CTF, compared to controls and this difference was significant throughout much of the top 10 to 100mm of topsoil. ***Pore size*** and ***surface area value*** were larger in the substituted CTF system than in controls. Infiltration rate was greater in CTF than reduced pressure or conventional systems. ***Soil organic matter*** was lower in CTF than in controls, which was attributed to enhanced organic matter turnover as a result of increased air-filled porosity and increased earthworm activity. ***Water:*** There was no significant difference in soil ***water content*** between treatments. ***Biodiversity:*** There were increased numbers of large pores in CTF soils compared to controls and their size and shape suggested that they were a result of increased earthworm activity.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts	Positive			No Effect		Positive	

Study Type: Replicated and controlled.

8.5.1.4 Effects of tractor wheeling on root morphology and yield of lucerne (Medicago sativa L.)[122]

Citation: Głąb 2008

Key message: Traffic had a negative effect on soil structure. However, the response by the crop lucerne, of increasing root dry matter, resulted in increased soil water retention.

Location: Krakow, Poland

Description: A 4-year study to assess the effect of soil compaction by farm traffic on yields of lucerne (alfalfa). Four treatments were applied: no traffic; low traffic (2 tractor passes), medium traffic (4 passes) and high traffic (6 passes).

<u>Soil</u>*: *Penetration resistance and ***bulk density*** of control (CTF) soils were significantly lower than trafficked soils. ***Porosity*** was significantly higher in CTF soils than in other soils. ***<u>Water</u>*:** CTF led to decreased ***soil water content*** (probably due to increased root DM of lucerne under compaction treatments), although the effect was only significant when CTF was compared to the heaviest traffic treatment. ***<u>Yield</u>*:** Dry matter yields of lucerne were generally higher in the no traffic system and this difference was always significant with respect to the comparison between no traffic and heavy traffic.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive			Negative			Increase

Study Type: Randomised, replicated and controlled

8.5.1.5 Effects of manure treatment and soil compaction on plant production of a dairy farm system converting to organic farming practice[119]

Citation: Hansen 1996

Key message: Using a CTF system led to a reduction in soil compaction, which increased crop yields.

Location: Surnadal, Norway

Description: A study to assess the effects of farm traffic on soil structure, earthworm density and grass yields in a crop rotation. A sandy loam, which is expected to be particularly vulnerable to compaction, was studied for 5 years of treatment (including 3 years of ley), plus one year to monitor residual effects.

<u>Soil</u>*:** Soil compaction in trafficked farms reduced pore space from 53% to 48% and reduced air-filled pore space from 12% to 7%. ***Bulk density was also greater under trafficked systems. ***<u>Biodiversity</u>*: Earthworm** number and weight were decreased by 74% and 62%, respectively. ***<u>Yield</u>*:** Soils compacted by farm traffic showed ley yield reductions of up to 34% (mean 27%) over a three-year period (from 7.4 to 5.5 t DM/yr ha^{-1}). Residual effects on yields were not significant in the year following treatment.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts	Positive					Positive	Increase

Study Type: Replicated and controlled

9 Establish tree shelterbelts

There is limited, but positive, evidence for effects on soil fertility, biodiversity and pasture yields

9.1 Description

Shelterbelts (aka timberbelts) have been suggested as a method to reduce ammonia emissions when used around livestock housing or slurry pits (both by disrupting air flows and directly recapturing ammonia gas) or to provide leeward shelter to livestock when used around pastures[125,126]. Shelterbelts are a narrow strip of trees that provide a sheltered area in the lee of the wind that is approximately 12 times the height of the trees[127]. They are similar to, but distinct from, other forms of agroforestry, such as shadebelts, woodlot blocks, tree-on-pasture or forest grazing[127].

9.2 Summary

Just three studies experimentally tested the effects of shelterbelts on soil, water or biodiversity in a dairy farming context and all were based on studies into provision of shelter for pasture in New Zealand. In addition, there was a useful review on the benefits of shelterbelts to livestock[127].

		Soil		Water		Biodiversity		
Reference	Country	Structure	Fertility	Quality	Quantity	Diversity	Abundance	Yield
Hawke & Tombleson 1993	New Zealand		Positive					Increase
Fukuda et al 2011	New Zealand					Positive	Positive	
Radcliffe 1985	New Zealand		Positive		Mixed			Increase

*This is a study of ways to improve shelterbelt management for enhanced biodiversity conservation.

9.2.1 Soil

In the immediate lee of the shelterbelt, soil pH, potassium, phosphate and magnesium levels were higher than in the rest of the pasture[126,128]. In addition, soils were found to be generally warmer in the sheltered zone[128], though further studies are needed to confirm this finding.

9.2.2 Water

Rainfall in the immediate lee of the shelterbelt (25m) was reduced due to a rainshadow effect[128], and increased growth in sheltered pasture was attributed to (unmeasured) increased soil moisture content[128].

9.2.3 Biodiversity

Generally, establishing a tree shelterbelt will enhance the biodiversity of a farm, particularly when it replaces low biodiversity areas such as monoculture crops or hard-paved farm infrastructure. There were no studies that made a comparison of biodiversity in the pasture itself under shelterbelt/no shelterbelt treatments. However, one study investigated management practices to maximise biodiversity benefits and found that fencing to exclude grazing livestock, using native tree species and switching to organic farming all improved the biodiversity value of the shelterbelt[129].

9.2.4 Yield

Yields were generally higher in the sheltered zone, with one study reporting 15% yield increases in the 10m zone either side of the shelterbelt[126], and another reporting 60% increases in the sheltered zone excluding the 25m zone immediately in the lee of the trees[128].

9.2.5 Other considerations and notes on best practice

The primary reason for establishing shelterbelts on dairy farms in the UK are likely to be for reasons of reducing ammonia emissions around slurry lagoons and cattle housing or to provide shelter for cows on pasture[17,125,127].

To maximise shelter from a shelterbelt, trees should be spaced and managed such that approximately half of the wind goes through the trees and the rest is deflected over the top[127]. Further, the porosity of the belt should be maintained throughout the height of the shelterbelt through careful management of pruning, underplanting or thinning[127]. Careful consideration should be given to the choice of tree species both for optimum wind protection and for maximising biodiversity conservation value[127,129].

9.3 Literature review

9.3.1 Primary search

Source	Search terms (title)	Studies	*Relevant* studies	Search date
Web of Science	(shelterbelt OR tree OR forest) AND (dairy OR dairies OR silage)	71	1	20 Oct 2015

9.3.2 Secondary search

Source	Search terms	Relevant studies	Search date
Google	Shelterbelt dairy	1	20 Oct 2015
Reference lists		1	20 Oct 2015
Total			

9.5 Literature

9.5.1 Australasia

9.5.1.1 Production and interaction of pastures and shelterbelts in the central North Island[126]

Citation: Hawke & Tombleson 1993

Key message: Nutrient redistribution likely caused the observed changes in soil properties and yields. Timber production was significant and its value should compensate for the loss of grass production area.

Location: Matea, New Zealand

Description: A study into the effect of *Pinus radiata* shelterbelts on a pasture of ryegrass, white clover, pea species, browntop, Yorkshire fog, cocksfoot and sweet vernal that had experienced rotational grazing by sheep and cattle. The two shelterbelts (6 row and 7 row) were over 600m long, 21m wide, 15m high and stocked at 3500 stems/km.

Soil: Soil ***pH*** and ***potassium*** and ***magnesium*** levels were higher close to the tree shelterbelt. ***Yield:*** Total ***dry matter production*** was 15% higher in the 10m zone either side of the shelterbelt than in open pasture. ***Caveats:*** No control was used, so it is unclear whether effects are due to within field redistribution of nutrients (e.g. by increased faecal deposition in shelterbelts), sheltering effects of the trees, root competition or some other factor.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts		Positive					Increase

Study Type: Study

9.5.1.2 Effects of organic farming, fencing and vegetation origin on spiders and beetles within shelterbelts on dairy farms[129]

Citation: Fukuda et al 2011

Key message: Using native trees, fencing shelterbelts to exclude livestock and switching from conventional to organic farming can increase the biodiversity value of shelterbelts.

Location: North Island, New Zealand

Description: Six pairs of farms (one conventional, one organic) from different locations on North Island, New Zealand were visited to assess effects of management (fencing to exclude livestock; type of plant species in shelterbelt; and whether the farm is organic or conventional) on weed biomass and spider and beetle density and richness.

Biodiversity: ***Spider density*** was 40% higher on organic farms than conventional ones. ***Beetle communities*** and ***weed biomass*** did not differ significantly between organic and conventional farms. Native ***spider density*** and ***richness*** was higher in fenced than in unfenced shelterbelts. Native ***beetle richness***, but not ***density***, was increased by fencing. ***Pasture pest beetles*** were not significantly affected by fencing. The effect on ***weed biomass*** was variable. Native shelterbelt plant species resulted in significantly greater native ***spider*** and ***beetle richness***. ***<u>Caveats</u>:*** This does not compare pastures with shelterbelts to those without shelterbelts, but rather evaluates how to manage a shelterbelt to maximise biodiversity value.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts					Positive	Positive	

Study Type: Matched site comparison

9.5.1.3 Shelterbelt increases dryland pasture growth in Canterbury[128]

Citation: Radcliffe 1985

Key message: Providing a shelterbelt led to 60% increases in pasture production over a three-year period.

Location: Canterbury, New Zealand

Description: A three-year study of a mature shelterbelt (550m long X 8m wide X 17m high) and its effects on pasture growth and soils on the leeward side. Pasture was perennial ryegrass, cocksfoot, red and white clovers, rape and subterranean clover. Cages were set up at varying distances to the trees to assess the effects on pasture growth.

<u>Soil</u>: Higher levels of potassium and phosphate were found adjacent to the shelterbelt (25m from trees). Soils tended to be warmer in the sheltered zone (although results are inconclusive), which would allow an extended growing season. ***<u>Water</u>:*** Rainfall in the immediate lee of the shelterbelt (25m) was reduced due to a rainshadow effect. ***<u>Yield</u>:*** Approximately 60% more ***pasture dry matter*** was cut in the 25-130m zone in the lee of the shelterbelt compared to the 200m zone, for which the trees have no sheltering effect and the 0-25m zone, which may compete with the trees for nutrients, water and light. ***<u>Caveats</u>:*** Although this study assessed effects over three years, only a single site was used (with replicate measures from multiple locations) and there was no control. The authors acknowledge that their testing was probably insufficient to pick up the variation in soil moisture that they think is responsible for yield differences.

	Soil		Water		Biodiversity		Yield
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts		Positive		Mixed			Increase

Study Type: Single site study, no control

10 Fertilising pasture with selenium

No negative effects on natural capital were reported due to the addition of selenium to fertiliser

10.1 Description

Selenium is widely recognised as an essential nutrient that provides multiple benefits to animal and human health, including protection from some forms of cancer, improved immune system response to infections, inhibition of prostaglandins, which cause inflammation, reduced tumour growth rates, and increased male fertility[130,131]. Selenium in European human diets has declined as the proportion of selenium-rich wheat from North America has been replaced with wheat sourced from the UK, which has generally low levels of selenium in soils[130]. However, the chief reason for the addition of selenium to pastures is for livestock health, rather than subsequent benefits to human[130]. Selenium can be administered to cattle via a bolus, injection, drench or mineral rations, or it can be provided through fertilisation of forage with selenium[132], which is reviewed here.

10.2 Summary

There are very few studies that examine the effects of pasture-applied selenium on soil, water or biodiversity. The majority of studies came from Finland, where all fertiliser has been supplemented with selenium since 1985, resulting in a useful case study for the wider environmental effects of such a policy. However, the results of these studies are not limited to describing the effects of adding selenium to dairy pasture, as the effects are amalgamated with the addition of selenium to all forms of crop fertilisation. Moreover, other minerals found in fertilisers may affect selenium concentrations in water, further compounding the difficulty of determining whether the addition of selenium-amended fertiliser *per se* is causing an effect, or whether it is simply the addition of fertiliser. All the studies reviewed assessed impacts on water, which is the primary natural capital concern due to potential leaching from agricultural applications.

		Soil		Water		Biodiversity		
Reference	Country	Structure	Fertility	Quality	Quantity	Diversity	Abundance	Yield
Alfthan et al 1995	Finland			No Effect				
Mäkelä et al 1995	Finland			No Effect*				
Wang et al 1994	Finland			No Effect*			No Effect	
Wang et al 1995	Finland			No Effect*			No Effect	
MacLeod et al 1998	Canada			No Effect[$]				
Walburger et al 2008	USA			No Effect*[$]				

*These studies did find some evidence for agricultural activities causing increased selenium concentrations in water, but not at levels that cause concern
[$]These studies included a control (i.e. same treatment, but without selenium fertiliser supplement).

10.2.1 Soil

No studies reviewed the effects of selenium applications on soil. The range within which soil selenium concentrations should be kept is quite tight: too low and livestock (and ultimately humans) will experience selenium deficiencies but too high and the nutrient can be toxic[133]. Selenium is a naturally occurring mineral, however, and so long as it is applied within the recommended range, negative impacts on soil structure or fertility associated specifically with the selenium supplement are not expected.

10.2.2 Water

All six studies found that there was either no measurable effect of selenium fertilisation[134,135] or the effect is not expected to cause problems regarding water quality[132,133,136,137].

10.2.3 Biodiversity

High selenium levels found in parts of the USA with naturally high levels were concentrated in agricultural drainwater causing adverse effects to fish and aquatic bird communities[138,139]. However, just two studies into pasture- or forage-applied selenium assessed effects on biodiversity. One found no relationship between selenium levels in lake water and selenium in fish muscle[137] while the other simply stated that the observed levels of selenium were not expected to pose a threat to wildlife communities[133].

10.2.4 Yield

The studies did not estimate yield effects and no effects on yield are expected.

10.2.5 Other considerations

The primary reason for applying selenium is for animal health and welfare. Increasing selenium in forage when soil levels are deficient will improve the immune response of livestock and, through biofortification of milk, improve dietary intake rates in humans[130].

10.3 Literature review

10.3.1 Primary search

Source	**Search terms (title)**	**Studies**	***Relevant* studies**	**Search date**
Web of Science	(selenium AND (pasture OR forage OR silage OR grass*) AND soil OR water OR biodiversity)	90	1[132]	27/10/15

10.3.2 Secondary search

Source	**Search terms**	**Relevant studies**	**Search date**
Reference lists		5[133-137]	
Total		**6**	

10.4 Literature

10.4.1 Europe

10.4.1.1 The geochemistry of selenium in groundwaters in Finland[134]

Citation: Alfthan et al 1995

Key message: There was no effect of agricultural activities (including use of fertilisers supplemented with selenium) on selenium concentrations in ground water and safe drinking water thresholds were not exceeded.

Location: Finland

Description: A study into the concentration of selenium in ground water and wells in Finland to measure the background level of selenium in water supplies and to assess the effects of season, other chemicals, precipitation and agricultural activities on selenium levels.

Water: None of the samples exceeded the threshold of 10 pg/l set for drinking water in Finland. There was no effect of agricultural activities (including use of fertilisers supplemented with selenium) on selenium concentrations in ground water. ***Caveats:*** It is not possible to distinguish the effect of selenium-supplemented fertilisers with standard fertilisers, as phosphate, nitrogen and sulphur alter the solubility of selenium in the soil, potentially increasing leaching into groundwater.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect				

Study Type: Site comparison

10.4.1.2 Environmental effects of nationwide selenium fertilization in Finland[136]

Citation: Mäkelä et al 1995

Key message: There is some leaching of selenium into ground water from fertilisation.

Location: Southwestern Finland

Description: A study of thirteen lakes and eight groundwater pools on the effect that agriculture and selenium fertilization may have on selenium concentrations in water.

Water: In agricultural areas, selenium levels in lakes increase slightly in autumn alongside nitrogen and phosphorous levels indicating that there may be some leaching effect. However, overall differences between agriculturally affected areas and non-affected areas were not significant. Correlations between increasing nitrogen and phosphorus and increasing selenium suggest that there is some leaching of selenium into ground water from fertilisation. ***Caveats:*** It is not possible to distinguish the effect of selenium-supplemented fertilisers with standard fertilisers, as phosphate, nitrogen and sulphur alter the solubility of selenium in the soil, potentially increasing leaching into groundwater[134].

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect*				

* Agriculture did have an effect on selenium levels in water, but at levels that were not considered to be a concern

Study Type: Site comparison

10.4.1.3 The impact of selenium fertilisation on the distribution of selenium in rivers in Finland[133]

Citation: Wang et al 1994

Key message: There is some evidence of selenium fertilisation leading to increased levels in water, but not to levels that are considered a concern for water quality or wildlife safety.

Location: Finland

Description: A study to investigate the potential negative environmental effects of selenium-supplemented fertilisation on rivers in Finland.

Water: A decrease in river water selenium occurred following a decrease in the rate of selenium application between 1991 and 1992. Selenium in stream water was associated with the area of cultivated fields (r=0.153, P<0.05, n=203). However, none of the waters were considered to be polluted due to selenium levels. ***Biodiversity:*** Threshold estimates of selenium concentrations for animals with habits likely to lead to high exposure of bioaccumulative contaminants in aquatic ecosystems were not found in Finnish rivers or streams. ***Caveats:*** It is not possible to distinguish the effect of selenium-supplemented fertilisers from standard fertilisers as phosphate, nitrogen and sulphur alter the solubility of selenium in the soil, potentially increasing leaching to groundwater[134].

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect*			No Effect**	

*Agriculture did have an effect on selenium levels in water, but at levels that were not considered to be a concern.
**The levels reported in Finnish waters were below thresholds that are expected to cause damage to wildlife populations. Effects were not measured directly.

Study Type: Before and after study, site comparison

10.4.1.4 The impact of selenium supplemented fertilization on selenium in lake ecosystems in Finland[137]

Citation: Wang et al 1995

Key message: There is evidence for agricultural activities leading to increased selenium concentrations in lakes. However, there are no further negative impacts reported by the authors.

Location: Finland

Description: A study to investigate the potential negative environmental effects of selenium-supplemented fertilisation on levels of selenium in Finnish lakes.

Water: The concentration of selenium in lakes surround by cultivated fields was significantly higher than in lakes surrounded by forest in the later summer (Aug), but not spring (Mar-Apr), likely due to leaching of recently-applied fertilisers. There is no clear effect of selenium fertilisation on the level of selenium in lake sediments. ***Biodiversity:*** There was no evidence for selenium fertilisation leading to bioaccumulation of selenium in fish (perch) muscle. ***Caveats:*** It is not possible to distinguish the effect of selenium-supplemented fertilisers from standard fertilisers as phosphate, nitrogen and sulphur alter the solubility of selenium in the soil, potentially increasing leaching to groundwater[134].

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect*			No Effect	

*Agriculture did have an effect on selenium levels in water, but at levels that were not considered to be a concern.

Study Type: Site comparison

10.4.2 North America

10.4.2.1 Selenium concentration in plant material, drainage and surface water as influenced by Se applied to barley foliage in a barley – red clover – potato rotation[135]

Citation: MacLeod et al 1998

Key message: Surface water had selenium concentrations below the safe drinking water threshold.

Location: Prince Edward Island, Canada

Description: Selenium was applied to pasture and the effects on adjacent downslope surface waters was monitored and compared to other surface waters that were not likely to be affected by the pasture selenium application.

Water: Selenium concentration in surface water bodies near to pasture fields that had been fertilised with selenium were not significantly different to surface water bodies 3–8 km from the treated fields (controls). All surface water bodies had selenium concentrations well below the threshold for safe for drinking water.

	Soil		Water		Biodiversity		Yield
	Structure	Fertility	Quality	Quantity	Diversity	Abundance	
Impacts			No Effect				

Study Type: Replicated and controlled

10.4.2.2 The effect of fertilizing forage with sodium selenate on selenium concentration of hay, drain water and serum selenium concentrations in beef heifers and calves[132]

Citation: Walburger et al 2008.

Key message: Fertilisation of pasture with selenium is an effective strategy to overcome selenium deficiency in cattle; however selenium was detected in drain water one month after fertilisation.

Location: Oregon, USA

Description: An experimental study to assess the impact of selenium fertilisation on drain water from an alfalfa/orchardgrass hay field.

Water: Selenium was detected in drain water one month after fertilisation with selenium, but this dropped to below detectable levels in subsequent months.

	Soil		**Water**		**Biodiversity**		**Yield**
	Structure	**Fertility**	**Quality**	**Quantity**	**Diversity**	**Abundance**	
Impacts			No Effect*				

*Agriculture did have an effect on selenium levels in water, but the authors did not consider this as a pollution concern.

Study Type: Controlled

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