Affinity Water and Portsmouth Water

NiCCs – Nitrogen release from Cover Crops, 2021- 2023 FINAL

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Rachel Thorman, Anne Bhogal, Sam Kendle and Geoff Bailey

Portsmouth Water

Affinity Water

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Author	Dr Rachel Thorman	**Technical reviewer**	Dr Anne Bhogal
Signature		Signature	
Date:	30/01/2024	Date:	30/01/2024

Project manager	Dr Anne Bhogal	**Quality reviewer**	Dr Anne Bhogal
Signature		Signature	
Date:	30/01/2024	Date:	30/01/2024

EXECUTIVE SUMMARY

The aim of this study was to quantify the effect of two cover crop species mixes on over winter nitrate leaching, and the impact of contrasting cover crop destruction techniques (chemical vs mechanical destruction) on soil nitrogen supply (quantity and timing of nitrogen returned to the soil) and the performance of the following spring cereal cash crop. The timing of nitrogen release from cover crops and potential legacy (year 2) effects on nitrate leaching and crop performance were also assessed. In addition, the study evaluated the effect of cover cropping on yields and gross margins to demonstrate the benefits and trade-offs of cover crops for the farm business. The work was undertaken over two cropping seasons (2021-2023), on two commercial farms: one in Hertfordshire and one in West Sussex. The 3 covers tested were:

- No cover: weedy stubble
- Mix 1: Phacelia (20%) & Oil Radish (80%) @ 15 kg/ha
- Mix 2: Japanese oats (45%), Buckwheat (45%) & Phacelia (10%) @ 10 kg/ha

Covers were destroyed by two methods: mechanically by either rolling on a frost (Hertfordshire: no tillage) or chopping and incorporating (West Sussex: reduced tillage) and chemically (glyphosate at both sites).

Key findings:

- There was clear evidence that cover crops can reduce nitrate leaching losses by up to 90% compared to weedy stubble.
- Cover crops increased spring soil nitrogen (N) supply by up to *c*.35 kg N/ha compared to the weedy stubble, but this depended on how well the covers had established (size of the above ground cover crop biomass) and the species mix (ability to scavenge N).
- Cover crops released more N following destruction and decomposition in the soil (mineralisation) than from the weedy stubble control.
- Cover destruction using glyphosate increased topsoil mineral N compared to mechanical destruction, regardless of the method used i.e. rolling on a frost or chopping. The greater and earlier mineral N availability following cover destruction using glyphosate is likely to have benefited spring cereal establishment and subsequent crop performance.
- Chopping as a destruction technique did not destroy oil radish (& its below ground tap root) where it was used in a cover crop mix. Oil radish re-growth required a robust post emergence herbicide for control in the subsequent spring cash crop.
- There was a reduction in the specific weight of spring oats grain to below that typically accepted by millers (50 kg/hl) where winter cover had been destroyed by rolling on a frost. The spring oat specific weight exceeded milling requirements when glyphosate was used. This may reflect the earlier mineralisation of N in the covers and subsequent N availability to the following spring oat crop where glyphosate had been used to destroy winter cover.
- Spring cereal yield, grain N offtake and total crop N uptake were consistently reduced where the covers had been destroyed mechanically (rolling on a frost or chopping) than by using glyphosate. Cover crops increased the spring cereal yield by 0.2-1.0 t/ha compared with the weedy stubble control.
- There was a mean 0.7 t/ha spring oat yield reduction from rolling on a frost, and up to a 1.0 t/ha spring barley yield penalty following chopping.
- Autumn soil mineral N content measured after harvest of the spring cash crops was 20-30 kg N/ha higher on the weedy stubble control, reflecting the poorer performance (and N utilisation) of the spring cereals where no cover crops were grown.

- There was no legacy effect of cover type or destruction technique on either the nitrate leaching losses measured over winter following spring cereal harvest or on the subsequent spring soil N supply. The crops grown in the legacy year (i.e. a cover crop and oilseed rape) had an autumn N requirement. If an autumn sown crop which did not have an autumn N requirement (e.g. winter cereal) had been used, there would have been an increased risk of losing autumn soil mineral N via over winter nitrate leaching.
- This study showed that it was more cost-effective to not grow a cover crop and destroy any weeds chemically, although the margins over and above growing a cover crop (with chemical destruction) were small and didn't take account of any environmental incentive a farmer might receive for growing a cover crop (e.g. SFI). There is also the potential to reduce fertiliser N inputs following cover crops, although further work is required to understand the level of reduction possible more fully.

Overall, this study has clearly shown the benefit of growing a cover crop to reduce nitrate leaching losses over winter and increase soil nitrogen supply to the following spring cash crop. Chemical destruction, using glyphosate, was far more effective than mechanical destruction (rolling on a frost or chopping and incorporating) at reducing the weed-burden and also resulted in a more rapid release of nitrogen which can be important for early development of the cash crop and subsequent yield and quality. The study has also shown the importance of incentive schemes to support cover crop use so 'harder to monetise' benefits such as improved water quality, soil health and biodiversity can be realised.

CONTENTS

1 BACKGROUND

The informed management of cover crops is key to the delivery of important UK Government policies including the 25-year Environment Plan and improvements in ground and surface waters. Cover crops have been included in the 'Sustainable Farming Incentive' 2023 actions for soils ('SAM 2: Multi-species winter cover') which is one of the environmental schemes being introduced under the Agricultural Transition Plan post-Brexit. Whilst the benefits of cover crops for erosion control and reduced overwinter nitrate leaching losses are well established, the legacy effect for subsequent crops in the rotation is unclear. Of particular relevance is the timing of nitrogen release from cover crop residues and how this influences the nitrogen fertiliser requirement of the following cash crop and subsequent nitrate leaching losses.

The use of cover crops in conventional farming systems has rapidly increased (Storr et al., 2019), but guidance for farmers is often very general or inconsistent and not necessarily based on UK experiences (White et al., 2016). A recent survey of UK farmers on their use highlighted the uncertainty of the effects of cover crops on crop available nutrient supply (Storr et al., 2019). Furthermore over 80% of the farmers were destroying cover crops with herbicide. Given the uncertainty over the future of glyphosate use in the UK post 2025, and the movement to 'regenerative' farming and the associated increase in minimum/zero tillage, more information is required to help farmers develop alternative destruction methods that are economically viable and do not compromise the establishment and management of the following cash crops. Further information is also required to understand the impact of cover crop species and destruction method on nitrogen cycling to more accurately quantify the timing and amount of nitrogen released.

This work builds on the research undertaken as part of the AHDB funded Maxi-Cover crop project (Bhogal et al., 2020) by focussing on the effect that cover crop species and destruction method have on nitrogen release i.e., how much and when. The information will help underpin advice on the appropriate management of cover crops in terms of the crop available nitrogen supply and long-term impact on nitrate leaching and crop performance. Measurements were carried out on two replicated field plot experiments comparing two cover crop species mixes, with a no-cover control treatment, destroyed by two different methods (glyphosate vs. mechanical).

2 OBJECTIVES

- To quantify the impact of contrasting cover crop destruction techniques on over winter nitrate leaching, soil nitrogen supply (and hence crop nitrogen fertiliser requirements) and performance of the following cash crop. In particular to determine the:
    - effect of cover crop species on the quantity and timing of nitrogen returned to the soil
    - effect of cover crop destruction method e.g., glyphosate vs mechanical destruction
- To determine the timing of nitrogen release from cover crops and potential legacy (year 2) effects on nitrate leaching and crop performance

3 SITE DETAILS

The work was undertaken on two farms: one within Affinity Water's catchment area in Hertfordshire, and one within Portsmouth Water's catchment area in West Sussex (Table 1). A fully randomised replicated plot trial was established at each site with 6 treatments replicated in 3 blocks of plots to give a total of 18 plots, using a randomised blocks design. Plot sizes were 12 m x 6 m (Hertfordshire) and 36 m x 6 m (West Sussex).

Table 1: Site details

Site	Soil texture (% clay)	Depth to chalk (cm)	Previous crop	Cover crop drilled	Cover crop destroyed	Spring crop & drilling date	Spring crop harvested
Hertfordshire	Clay (39%)	60-90 cm	Winter wheat	13/08/21	21/01/22	Spring oats 11/02/22	25/07/22
West Sussex	Silty clay loam (22%)	90 cm	Winter cereal	06/09/21	17/02/22	Spring barley 19/03/22	11/08/22

4 COVER CROP & CASH CROP TREATMENTS AND ASSESSMENTS (2021-2022)

4.1 Cover crops 2021-2022

Two cover crop treatments (Table 2) were drilled in mid-August 2021 (Hertfordshire) and early-September 2021 (West Sussex) and compared with a treatment without cover crop (weedy stubble). The cover crops were established by no till and immediately rolled at the Hertfordshire site. At the West Sussex site, cultivation was carried out on 2nd September with a Köckerling PC cultivator working at 5 cm deep. A Horsch Sprinter Drill was used to drill the cover crops on 6th September at a depth of *c*.1 cm. The cover crop species were selected and donated by RAGT seeds to give contrasting nitrogen scavenging mixes, with mix 1 containing a brassica, oil seed radish (variety: Terranova which is club root resistance) and mix 2 with no brassica (Table 2).

Table 2: Cover crop treatments

Treatment	Cover crop	Destruction method	
		Hertfordshire	West Sussex
1	No cover: weedy stubble	Mechanical = roll on a frost Vs Glyphosate	Mechanical = chop & incorporate Vs Glyphosate
2	Mix 1: Phacelia (20%) & Oil Radish (80%) @ 15 kg/ha		
3	Mix 2: Japanese oats (45%), Buckwheat (45%) & Phacelia (10%) @ 10 kg/ha		

The cover crops (& control treatment) were destroyed in late-January 2022 (Hertfordshire) and mid-February 2022 (West Sussex) (Table 1). At the Hertfordshire site, the farmer mechanically destroyed the cover crop and control treatments by rolling on a frost using a Cousins Sidewinder 10 m roller. The glyphosate treatments were sprayed off by ADAS staff using a 3 m handheld boom. At the West Sussex site, the farmer carried out both the mechanical and glyphosate destruction methods. The cover crops and control treatment were destroyed mechanically by chopping using a flail topper mounted to the front of the tractor. On the same day the chemical destruction treatment plots were sprayed with glyphosate.

At the Hertfordshire site, the whole trial was sprayed with glyphosate prior to drilling and in mid-February 2022 (Table 1) was direct drilled to spring oats using a 6 m Kuhn Megant tine drill. About a month after cover crop destruction (Table 1) at the West Sussex site, all plots were cultivated using a Köckerling precision cultivator working to 10 cm deep, spring barley was then drilled using a Horsch Sprinter drill working to *c*.4 cm deep. Post drilling all plots were sprayed with a pre-emergence spray – liberator & stomp aqua (grass-weed & broad-leaved weed herbicides).

At the West Sussex site, after the spring barley was drilled each plot was divided in half, with one half of the plot receiving the recommended rate of nitrogen fertiliser (hand applied by ADAS) and the other half receiving no nitrogen fertiliser. Other fertilisers were applied as necessary. At the Hertfordshire site it was not possible to split the plots due to a seed bed application of nitrogen fertiliser across the field. Subsequent harvest measurements were taken where the recommended nitrogen had been applied.

4.2 Assessments 2021-2022

Soil samples were taken to depth in early October 2021 at the Hertfordshire site (60-90 cm deep) and late September 2021 at the West Sussex site (90 cm deep) to quantify soil mineral nitrogen (ammonium-N & nitrate-N: SMN). At the Hertfordshire site, cover crop biomass and nitrogen (N) uptake were also assessed at the same time. No assessment was made at the West Sussex site as the cover crop was not large enough. At the same time as leachate samples were taken, cover crop establishment was scored giving the percentage cover of individual species.

Porous ceramic water samplers were installed to just above the chalk bedrock (60-90 cm depending on the site, (Table 1), with 5 pots installed per plot to measure over-winter nitrate leaching losses (sampled every 2 weeks or after 25 mm drainage). Measurements continued until the end of drainage, although at the Hertfordshire site measurements ceased after the detection that seed bed fertiliser nitrogen had been applied across the field. Drainage volumes were calculated using the IRRIGUDE meteorological model and combined with nitrate-N concentrations to calculate nitrate-N leaching losses (kg/ha). Daily rainfall data was obtained from the farmers' own rain gauges on site. In order to measure over winter nitrate leaching in winter 2022/23, the porous pots were buried at the end of drainage (spring 2022) and then recovered (autumn 2022) following establishment of the winter crop and prior to the onset of drainage.

SMN was also measured in spring 2022 shortly before cover crop destruction, which together with an assessment of total cover crop biomass and nitrogen content, gave an estimate of soil nitrogen supply (SNS) to the following spring cereal crop. To track cover crop nitrogen release following cover crop destruction, fortnightly soil samples (Hertfordshire, 0-20 cm: West Sussex, 0-15 cm) were taken from each plot for the determination of SMN. The first sample was taken within the 1st week following destruction and continued for a period of 4-11 weeks. At the Hertfordshire site measurements terminated earlier than planned after seed bed fertiliser nitrogen had been applied across the field.

The spring cereals were harvested using a plot combine at the West Sussex site, and by hand at the Hertfordshire site due to a large black grass burden. Grain nitrogen content, grain specific weight, grain yields, and dry matter content of the spring cereal crops were measured from all plots using standard techniques. Prior to harvest grab samples were taken from each plot to determine the total crop nitrogen uptake.

5 LEGACY TREATMENTS AND ASSESSMENTS (2022-2023)

5.1 Crops 2022-2023

At the Hertfordshire site in mid-August 2022 (after harvest of the spring oat crop), the entire field the trial was located in was sown to a cover crop mix (80% radish & 20% phacelia). The cover crop was destroyed by rolling on a frost in early-February 2023, and the site drilled with spring oats in late-February. Given the problems the site had with blackgrass, it was decided in discussion with Affinity Water not to take spring oat harvest measurements. Alternatively, assessments of spring cover crop biomass and nitrogen uptake were taken.

At the West Sussex site after harvest of the spring barley, winter oilseed rape was drilled by mid-September 2022.

5.2 Assessments 2022-2023

In early October 2022, soil samples were taken to depth at the Hertfordshire site (60-90 cm deep) and at the West Sussex site (90 cm deep) to quantify SMN. All assessments at the West Sussex site during the legacy year were taken from the half of the plot which had received nitrogen fertiliser the previous season.

At the Hertfordshire site in early-November 2022, the porous ceramic water samplers were re-installed in the half of each plot that had not been affected by the extra seedbed nitrogen application in spring 2022. The water samplers at the West Sussex site remained in the same positions as in winter 2021/2022. As in autumn 2021, the water samplers were installed just above the chalk bedrock (60-90cm depending on the site with 5 pots installed per plot to measure over-winter nitrate leaching losses (sampled every 2 weeks or after 25 mm drainage). Measurements continued until the end of drainage. Drainage volumes were calculated using the IRRIGUDE meteorological model and combined with nitrate-N concentrations to calculate nitrate-N leaching losses (kg/ha). Daily rainfall data was obtained from the farmers' own rain gauges on site.

SMN to depth and nitrogen uptake were also measured in spring 2023 to give an estimate of spring soil nitrogen supply. At the Hertfordshire site, the measurements were taken in mid-January prior to cover crop destruction. At the West Sussex site, they were taken in early February.

At the West Sussex site, the winter oil seed rape was harvested on the 10th of August 2023 using a plot combine. Measurements were made of seed nitrogen content and seed yield.

6 RESULTS AND DISCUSSION 2021-22

6.1 Soil mineral nitrogen and above ground biomass autumn 2021-22

6.1.1 Hertfordshire

By early October 2021, when the soil was sampled to depth, there was *c*.10 kg N/ha less soil mineral N (SMN) measured from the mix 1 treatment and *c*.5 kg N/ha less measured from the mix 2 treatment compared to the stubble control which contained *c*.53 kg N/ha, although the differences were not statistically significant (P>0.05). Conversely, above ground biomass measurements taken at the same time as the soil measurements showed that mix 1 had taken up *c*.12 kg N/ha more nitrogen than from the stubble control (P<0.01) and mix 2 had taken up *c*.4.5 kg N/ha (P>0.05). These differences in SMN and nitrogen uptake reflected plant growth with about twice as much (P>0.05) above ground dry biomass measured in early October from mix 2 (0.36 t/ha) and more than three times as much (P<0.01) above ground dry biomass from mix 1 (0.61 t/ha) compared to the stubble control (0.19 t/ha).

Both mix 1 and mix 2 established well and produced 80% and *c*.65% cover, respectively, by mid-October and the start of nitrate leaching measurements. There was also considerable growth of winter wheat volunteers (as well as weeds) on the stubble control treatment resulting in *c*.50% cover (Plate 1).

Plate 1. Crop growth at the Hertfordshire site (20th October 2021): a) Stubble control; b) Mix 1; c) Mix 2

6.1.2 West Sussex

The soil was sampled to depth in late September 2021, but due to insufficient vegetation no biomass sampling was undertaken. The SMN ranged from *c*.72 kg N/ha (mix 1) to 76 kg N/ha (stubble control) to 91 kg N/ha (mix 2) (P<0.1). About 10 days later when nitrate leaching measurements started, mix 1 and mix 2 had produced *c*.30% and *c*.20% cover, respectively, whereas the stubble control treatment had minimal biomass with only 3% cover (Plate 2).

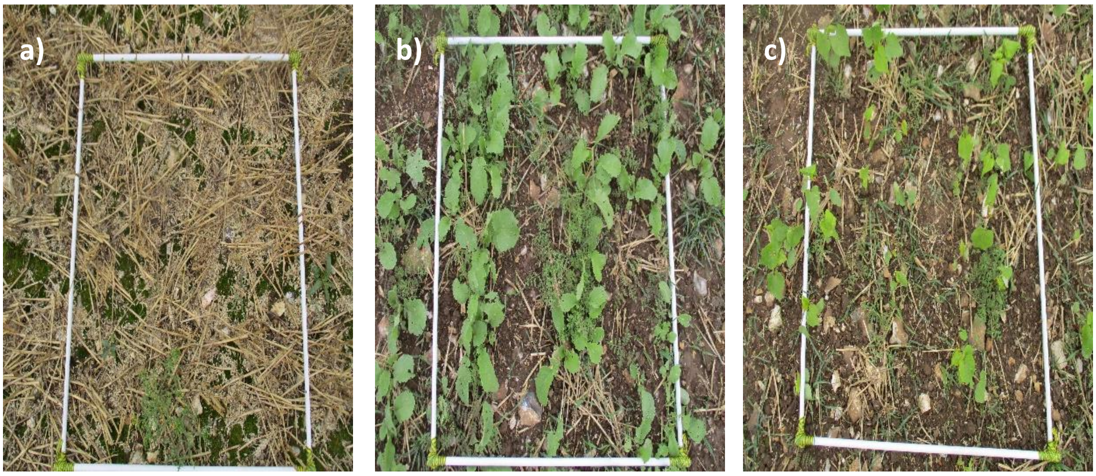

Plate 2. Crop growth at the West Sussex site (30th September 2021): a) Stubble control; b) Mix 1; c) Mix 2

6.1.3 Cross site comparison

Not surprisingly given the difference in soil type and soil depth, there was a significant effect of site ($P<0.05$) on the SMN measured to depth in autumn 2021. There was *c*.30 kg N/ha extra SMN in the deeper soils at the West Sussex site (*c*.80 kg N/ha) than at the Hertfordshire site (*c*.50 kg N/ha). Despite this difference, mix 1 consistently had the lowest ($P<0.1$) measured SMN across both sites, likely reflecting the quick growing and nitrogen scavenging properties of oil radish – the main species in the mix. Cover crop above ground biomass and nitrogen uptake was greater at the Hertfordshire site at this time due to an earlier (*c*.1 month) sowing date, with insufficient above ground biomass at the West Sussex site to enable a sample to be taken. This highlights the importance of early sowing of cover crops to ensure good crop cover at the onset of drainage and over winter.

6.2 Nitrate leaching losses winter 2021-22

6.2.1 Hertfordshire

Rainfall over the sampling period in winter 2021-22 (October to late-January) was relatively low at 177 mm, which led to only *c*.90 mm of drainage and consequently low nitrate leaching losses. Despite this, both of the drilled cover crops were more effective at reducing nitrate leaching losses compared to the un-drilled weedy stubble control treatment (Figure 1). Reflecting differences in above ground biomass growth and nitrogen uptake, mix 1 and mix 2 reduced over winter nitrate leaching losses by 95% and 70% respectively compared to the stubble control which lost *c*.8.5 kg N/ha by leaching, although the difference between the control and mix 2 was not statistically significant ($P>0.05$) (Figure 1).

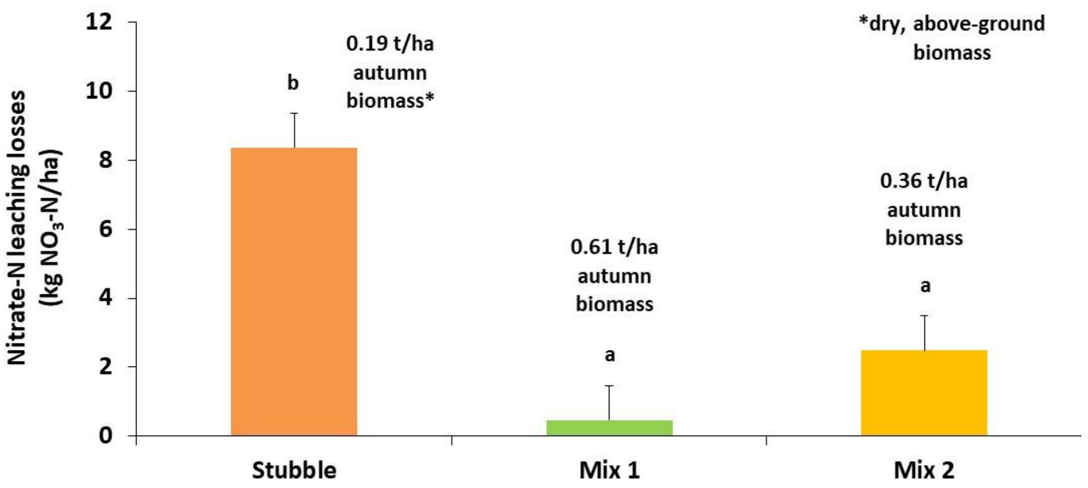

Figure 1. Nitrate leaching losses at the Hertfordshire site October 2021-late-January 2022 (177 mm rainfall; 90 mm drainage). Average values, + one standard error, N=3. Letters indicate values that are significantly different (P<0.01). Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia.

Over the whole measurement period, the average, flow-weighted nitrate-N concentrations from the two cover crop treatments (*c*.0.5-3 mg NO_3-N/l) were well below the EU limit of 11.3 mg NO_3-N/l. The average, flow-weighted nitrate-N concentration from the stubble control at *c*.9 mg NO_3-N/l was closer to the EU limit, with concentrations exceeding it on one measurement occasion (Figure 2).

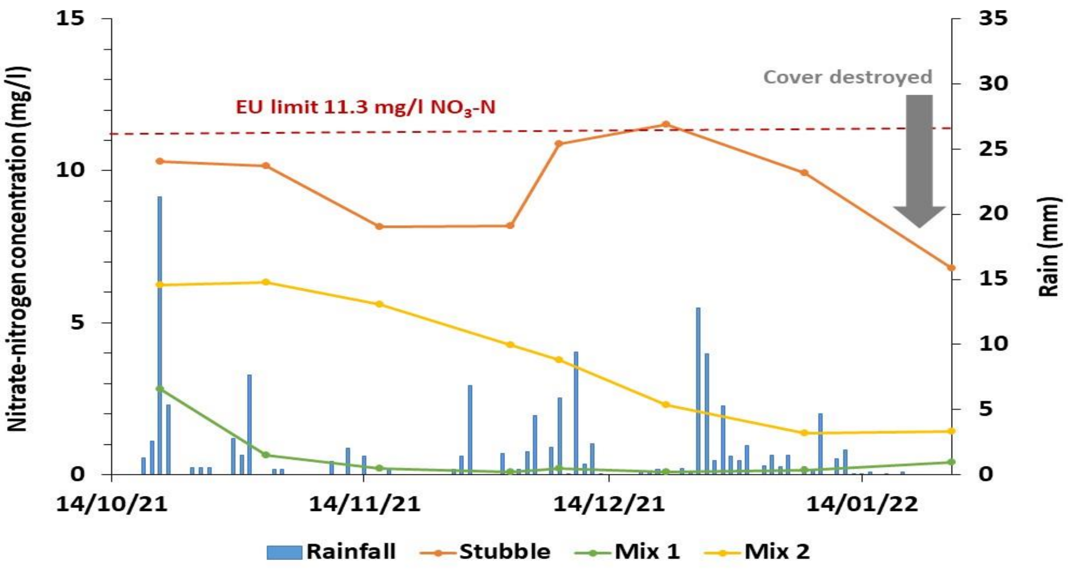

Figure 2. Nitrate concentration of the drainage waters and rainfall at the Hertfordshire site, October 2021-January 2022 (Covers destroyed in late January 2022, 4 days before the last nitrate measurement). Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia.

When the site was drilled with spring oats on the 11th February 2022, mistakenly seed bed nitrogen fertiliser was applied at a rate of 55 kg N/ha. The effect this had on nitrate leaching losses was clear (Figure 3). During the fortnight after drilling there was 42 mm of rain, which resulted in nitrate-N concentrations rapidly increasing from <7 mg NO_3-N/l to *c*.30 mg NO_3-N/l; over 2.5 times greater than the EU limit of 11.3 mg NO_3-N/l (Figure 3). Over this 2-week period the mean nitrate leaching loss was *c*.5 kg N/ha. After sampling had ceased *c*.40 mm of rain fell until the end of drainage in late March, which is likely to have further increased leaching losses of the fertiliser nitrogen leading to low nitrogen use efficiency and consequently a financial loss to the farmer.

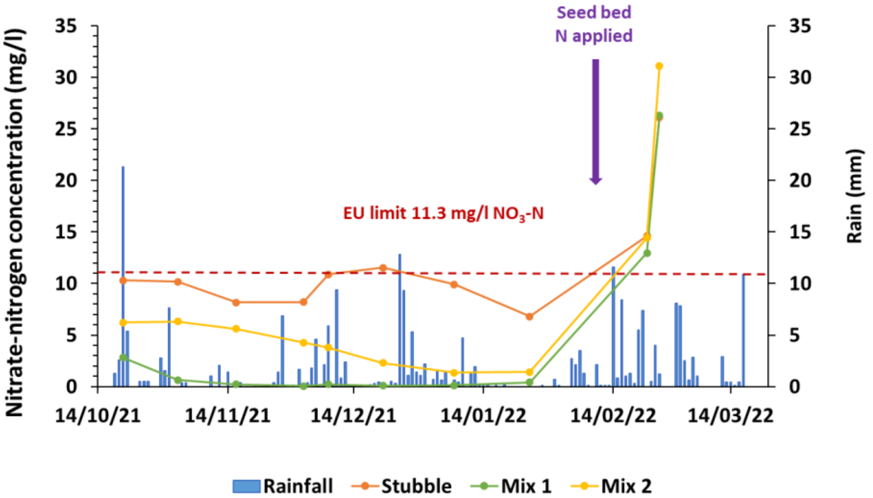

Figure 3. Nitrate concentration of the drainage waters and rainfall at the Hertfordshire site, October 2021-March 2022 (Covers destroyed in late January 2022). Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia.

6.2.2 West Sussex

Rainfall over winter 2021-22 (October to mid-February) was higher than at the Hertfordshire site at 464 mm and led to *c*.170-190 mm of drainage (depending on cover type) and nitrate leaching losses of up to *c*.25 kg N/ha. Similar to the Hertfordshire site, the cover crops were highly effective at reducing nitrate leaching losses compared with the stubble control treatment (Figure 4). Cover crop mix 1 and mix 2 reduced over winter nitrate leaching losses by 90% and 70% respectively compared to the stubble control which lost 23 kg N/ha by leaching (P<0.001) (Figure 4).

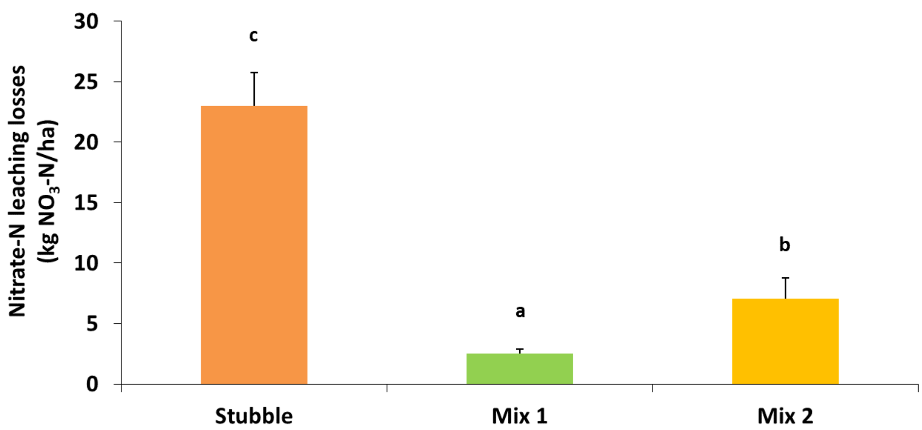

Figure 4. Nitrate leaching losses at the West Sussex site October 2021-mid-February 2022 (464 mm rainfall; 170-190 mm drainage). Average values, + one standard error, N=3. Letters indicate values that are significantly different (P<0.001). Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia.

Over the whole measurement period, the average, flow-weighted nitrate-N concentrations from the two cover crop treatments (*c*.1.5-4 mg NO_3-N/l) were well below the EU limit of 11.3 mg NO_3-N/l, even though the nitrate-N concentration from mix 2 exceeded it on two measurement occasions. The average, flow-weighted nitrate-N concentration from the stubble control at *c*.12 mg NO_3-N/l exceeded the EU limit with measured nitrate-N concentrations greater than it from mid-November to early-February (Figure 5).

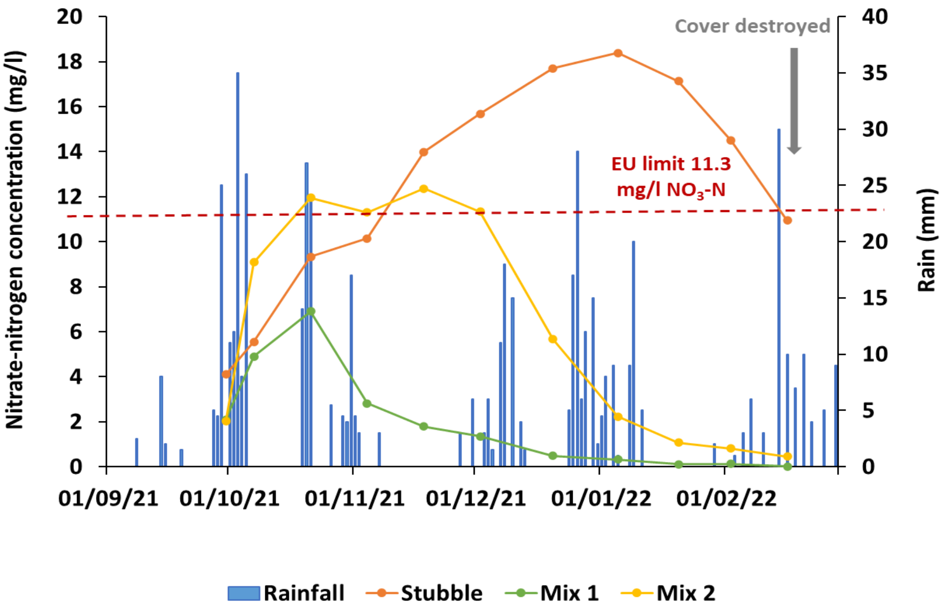

Figure 5. Nitrate concentration of the drainage waters and rainfall at the West Sussex site, September 2021-February 2022 (Covers destroyed in mid-February 2022, 1 day after the last nitrate measurement). Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia.

6.2.3 Cross site comparison

There was a difference between sites in the amount of nitrate-N leached over winter 2021-22 with a mean loss of *c*.4 kg N/ha from the Hertfordshire site and *c*.11 kg N/ha from the West Sussex site ($P<0.05$), most likely reflecting the differences in soil type/depth and autumn SMN. Overall, the cover type affected ($P<0.001$) nitrate leaching with the mix containing the brassica, oil radish (i.e. mix 1), associated with the lowest losses and increasing in the order; mix 1 (*c*.1.5 kg N/ha) < mix 2 (*c*.5 kg N/ha) < stubble control (*c*.16 kg N/ha). The difference between mix 1 and the stubble control was greater at the Hertfordshire site than at the West Sussex site ($P<.0001$).

6.3 Soil nitrogen supply spring 2022

6.3.1 Hertfordshire

There were small differences ($P<0.05$) in soil nitrogen supply (SNS = above ground cover N + soil mineral N) ahead of cover destruction in spring 2022, ranging from 58 kg N/ha on the stubble control treatment to 61 kg N/ha on the mix 1 treatment and 74 kg N/ha on the mix 2 cover crop (Figure 6). These differences were largely due to nitrogen in the above ground cover crop, rather than SMN and would not be considered sufficient to warrant a change in nitrogen fertiliser policy for the following spring oat crop. Given the effectiveness of mix 1 in reducing nitrate leaching losses, however, it may have been expected that the SNS would be greater on this treatment than both the control stubble and mix 2, however it is probable that we have not fully accounted for all of the oil radish nitrogen. Some of the nitrogen taken up by the oil radish would be partitioned below ground in the tap root, which was not included in the biomass measurements used to determine cover crop nitrogen.

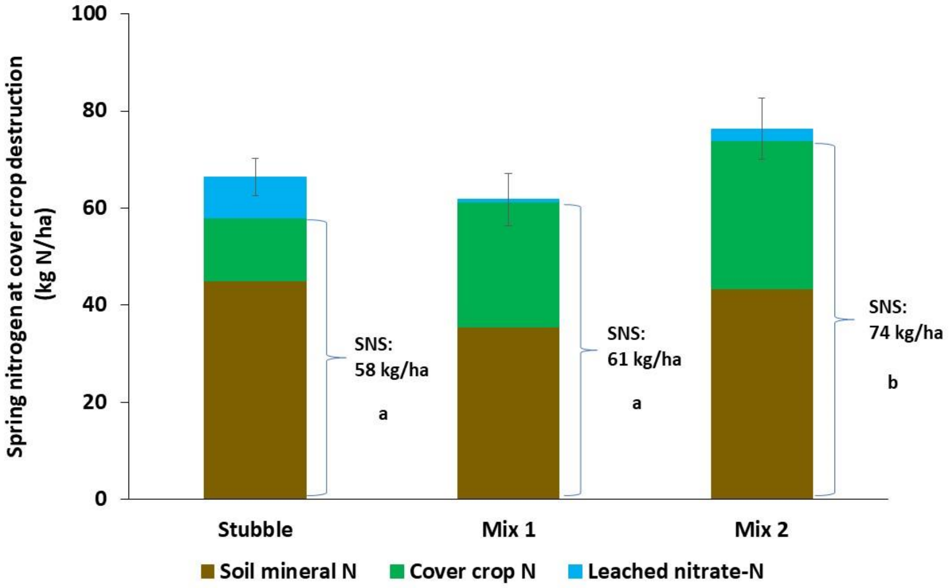

Figure 6. Nitrogen in the soil, crop and lost by spring 2022 at the Hertfordshire site (c.45-55 kg N/ha was in the soil in autumn 2021); SNS = soil nitrogen supply (potentially available for use by the following spring oat crop). Average values, + one standard error, N=3. Letters indicate SNS values that are significantly different (P<0.05). Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia.

6.3.2 West Sussex

There was a significant effect (P<0.01) of cover type on soil nitrogen supply (SNS = above ground cover N + soil mineral N) ahead of cover destruction in spring 2022. The SNS was *c*.25-35 kg N/ha greater from the cover crop mixes than from the stubble control, due to a higher amount of nitrogen in the above ground crop biomass (Figure 7). These differences suggest that a reduction in manufactured nitrogen fertiliser would be justified on the cover crop treatments (assuming all the nitrogen in the above ground biomass became available for use by the following cash crop), however there was high rainfall in late February (*c*.35 mm), so some of this nitrogen could have been lost via leaching. Similar to the Hertfordshire site, it is probable that not all the nitrogen taken up by mix 1 has been accounted for as below ground biomass and nitrogen uptake wasn't measured.

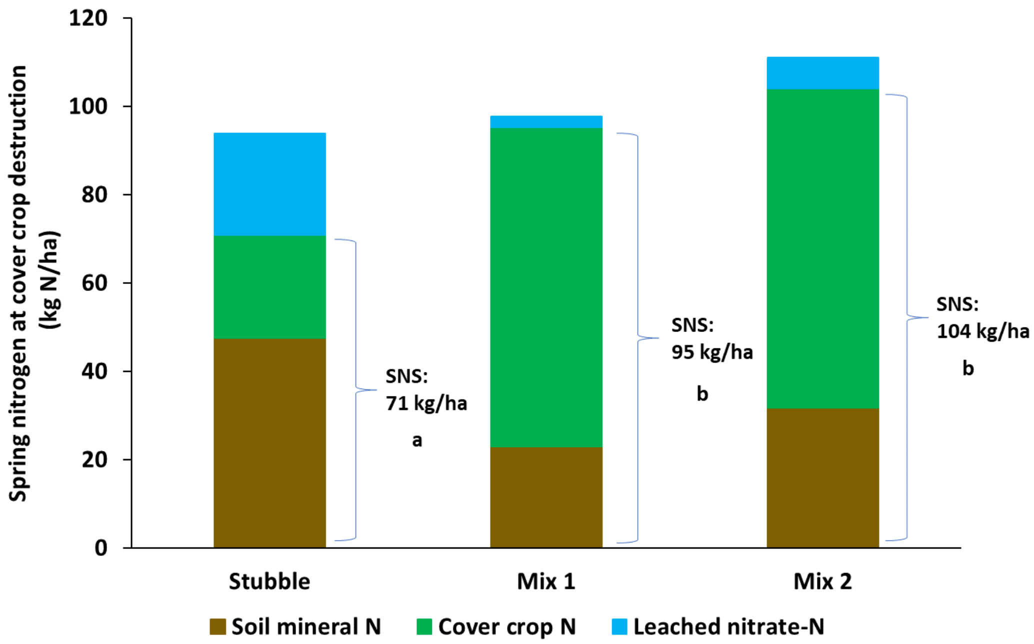

Figure 7. Nitrogen in the soil, crop and lost by spring 2022 at the West Sussex site (c.70-90 kg N/ha was present in the soil in autumn 2021); SNS = soil nitrogen supply (potentially available for use by the following spring oat crop). Average values, + one standard error, N=3. Letters indicate SNS values that are significantly different (P<0.01). Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia.

6.3.3 Cross site comparison

Overall and in line with the nitrate leaching results, the cover type significantly (P<0.001) affected spring SMN content increasing in the order; mix 1 (*c*.29 kg N/ha) < mix 2 (*c*.38 kg N ha) < stubble control (*c*.46 kg N ha) with the difference in SMN between the cover crops and stubble greater at the West Sussex site than at the Hertfordshire site (P<0.001). This likely reflects the differences measured in spring above ground biomass yield and above ground nitrogen uptake, both of which were greater (P<0.001) from the cover crops than from the weedy stubble control, with the difference larger at the West Sussex site than at the Hertfordshire site (P<0.01). Overall, the mean spring biomass yield and above ground nitrogen uptake at the West Sussex site were about twice (P< 0.001) that at the Hertfordshire site, most likely a consequence of the deeper, more retentive soil at the West Sussex site. Across both sites, these differences in soil and crop nitrogen resulted in a significant effect (P<0.001) of cover type on soil nitrogen supply (SNS = above ground cover N + soil mineral N) ahead of cover destruction in spring 2022. The SNS was *c*.25 kg N/ha greater from mix 2 than from the stubble control and *c*.15 kg N/ha greater from mix 1 than from the stubble control. Notably, below ground nitrogen uptake was not measured, so that actual amount of crop nitrogen uptake is likely to have been higher, particularly from mix 1 with its high proportion of oil radish and large tap root.

6.4 Cover crop N release spring 2022

6.4.1 Hertfordshire

The cover crops and weedy cover on the stubble control were destroyed on the 21st January 2022, either mechanically by rolling on a frost (Plate 3) or chemically by spraying glyphosate.

Plate 3. Cover crops destroyed mechanically at the Hertfordshire site – rolling on a frost.

Following destruction only 3 topsoil (0-20 cm) mineral nitrogen measurements were able to be taken before drilling and the application of seedbed nitrogen (Figure 8). Ten days after cover destruction (late-January), the SMN was greater ($P<0.05$) from the cover crop treatments (*c*.18 kg N/ha) than from the stubble control (*c*.14 kg N/ha), and also greater ($P<0.1$) following chemical destruction (*c*.18 kg N/ha) than from following mechanical destruction (*c*.16 kg N/ha). The same trends were also observed from the measurements taken 17 days after destruction (early-February) but were not statistically significant ($P>0.05$).

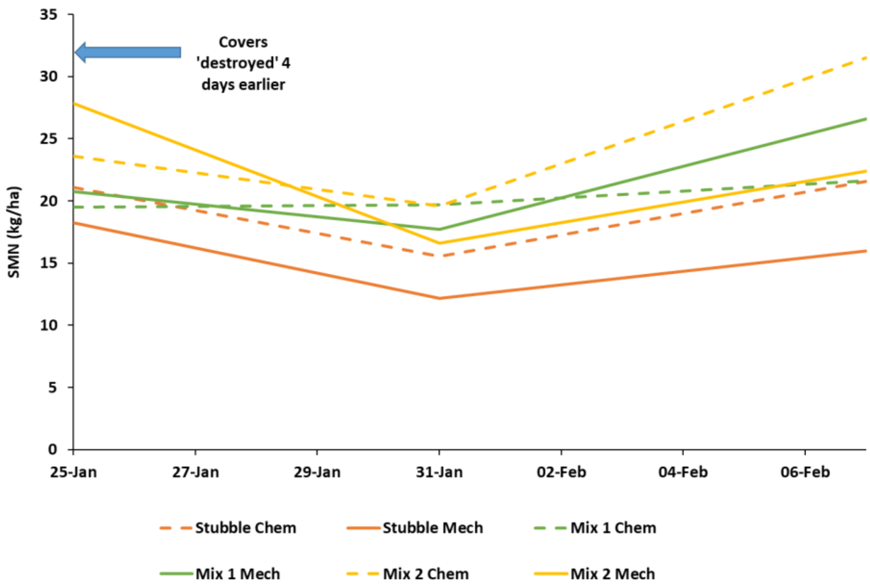

Figure 8. Topsoil mineral nitrogen (SMN) (0-20 cm) post cover destruction in late January 2022 at the Hertfordshire site. Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia. Mech = mechanical destruction (chop & incorporate); Chem = chemical (glyphosate) destruction.

6.4.2 West Sussex

The cover crops and biomass on the stubble control were destroyed on the 17th February 2022, either chemically by spraying glyphosate (Plate 4) or mechanically by chopping and later shallow incorporation (0-15 cm) (Plate 5).

Plate 4. Covers destroyed on 17th February 2022 chemically using glyphosate at the West Sussex site. Right hand side photo shows mix 1 immediately after this operation.

Plate 5. Covers destroyed on 17th February 2022 mechanically by chopping and later shallow incorporation at the West Sussex site. Right hand side photo shows mix 1 immediately after this operation.

Following destruction, 5 topsoil (0-15 cm) mineral nitrogen measurements were taken from cover destruction in mid-February to end of April 2022 (Figure 9). Over this period the mean SMN increased from *c*.11 kg N/ha to *c*.40 kg N/ha, with a noticeable increase following cultivation and drilling of the following spring barley crop (Figure 9). Mineralisation of the organic nitrogen within the cover crop and weedy stubble was presumably stimulated by the cultivation, alongside an increase in soil temperature.

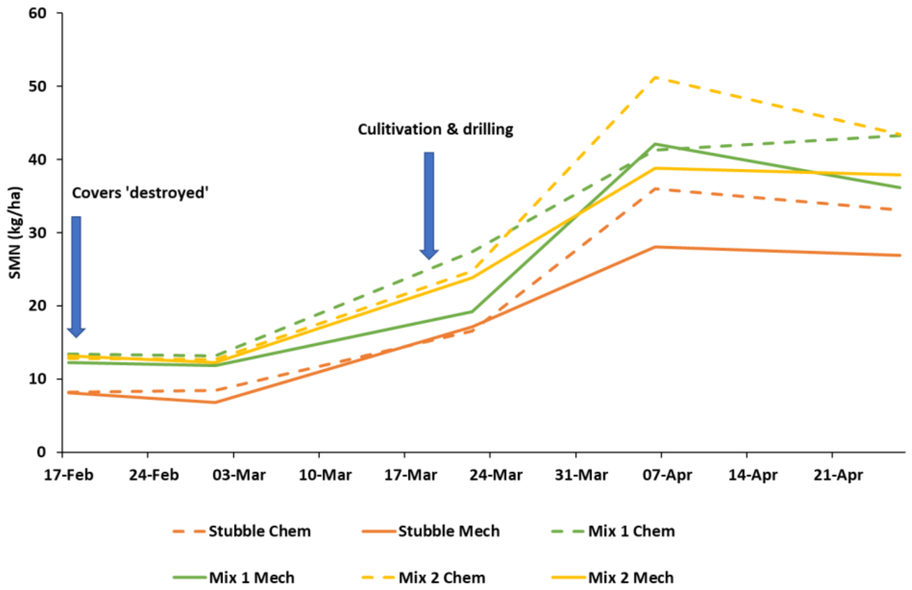

Figure 9. Topsoil mineral nitrogen (SMN) (0-15 cm) post cover destruction in mid-February 2022 at the West Sussex site. Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia. Mech = mechanical destruction (chop & incorporate); Chem = chemical (glyphosate) destruction.

On 3 of the measurement occasions, there was a significant effect ($P<0.01$) of cover type with greater topsoil mineral nitrogen from the cover crops than from the stubble control. On the remaining 2 measurement occasions the trend was the same. Interestingly, the cover crop effect was apparent on cover destruction day, which suggests that mineralisation of cover crop material had already started prior to destruction, most likely associated with some die-back during frosty conditions in late January/early February.

By early-April (*c*.7 weeks post cover destruction), the topsoil mineral nitrogen was significantly greater ($P<0.05$) where the covers had been destroyed chemically (*c*.43 kg N/ha) than where they had been mechanically destroyed (*c*.36 kg N/ha), suggesting that nitrogen release from the covers was lower on the mechanically destroyed covers. The same trend was seen at the late-April measurement timing, although this was not statistically significant ($P>0.05$).

6.4.3 Cross site comparison

A cross site statistical analysis of the topsoil mineral nitrogen data could not be conducted due to differences in sampling depth and sample timing, but it was clear that at both sites there was an effect of both cover type and destruction technique. Following cover destruction, more nitrogen was measured in the topsoil from where the cover crops had been grown compared with the weedy stubble control. This difference in SMN likely reflects the larger quantity of nitrogen taken up and subsequently released as a result of decomposition (or mineralisation) by the cover crops than by the weedy stubble. The method used to destroy the covers also affected nitrogen release (mineralisation) from the cover residues. There was an increased quantity of nitrogen measured following chemical destruction using glyphosate than from mechanical destruction, regardless of the method used i.e. cutting or rolling on a frost. It seems likely that the glyphosate breaks down the above ground biomass more rapidly allowing mineral nitrogen to become available for use by the following spring cash crop earlier than with mechanical destruction. It should be noted that following mechanical destruction, mineralisation of biomass nitrogen may result in a similar quality of nitrogen release over time as chemical destruction, but with a different release pattern (timing).

6.5 Performance of spring cash crop summer 2022

6.5.1 Hertfordshire

The spring oats were harvested in late July (25/07/22). In 2022, black-grass was a big weed problem in the field where the experiment took place in, which led to patchy oat establishment especially in block 1 (Plate 6). Consequently, to avoid transferring black-grass seed to other farms via harvest machinery, the harvest was carried out by hand with assessments based on quadrats.

Plate 6. Black-grass at the Hertfordshire site: a) during crop growth, 17th May 2022; b) at harvest, 25th July 2022

The mean spring oat yield was 3.4 t/ha, but there was a significant (P<0.001) effect of experiment block linked to the level of black-grass, with yields ranging from just 2.2 t/ha (block 1) to 5.2 t/ha (block 3), compared to the 2022 GB average oat crop yield of 5.4-5.7 t/ha (AHDB, 2022). Despite the black-grass problem, there was a 0.7 t/ha yield reduction (P<0.1) where the covers were mechanically destroyed (rolled on a frost) compared to where they were destroyed chemically using glyphosate (Figure 10).

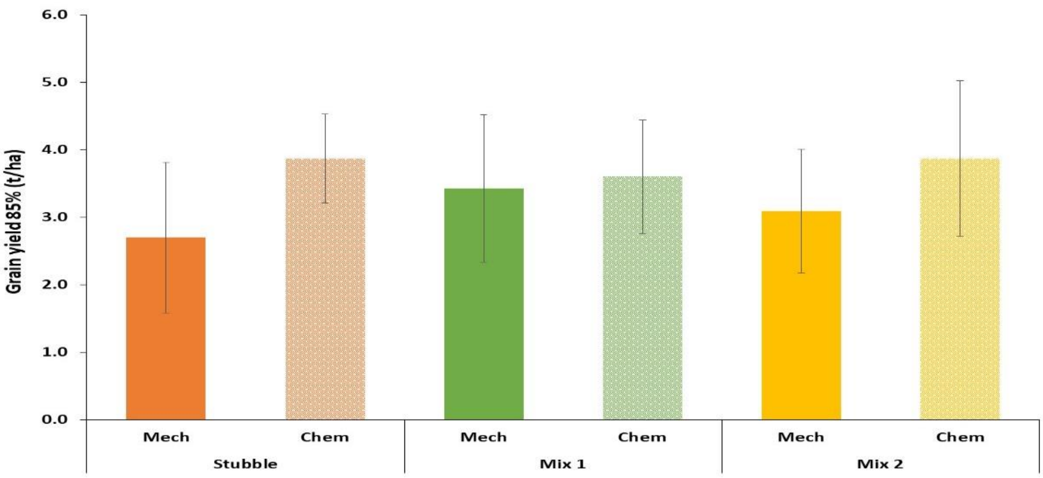

Figure 10. Spring oat yield at the Hertfordshire site, harvest late July 2022. Average values, ± one standard error, N=3. Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia. Mech = mechanical destruction (rolling on a frost); Chem = chemical (glyphosate) destruction.

Grain yields following the cover crops were 0.2 t/ha greater than the stubble control i.e., where no cover crop was grown (Figure 10), although the difference was not statistically significant (P>0.05).

Straw yield also reflected the detrimental effect of black grass with a significant effect (P<0.001) of experimental block. Straw yields ranged from 1.6 t/ha (block 1) to 3.3 t/ha (block 3). As with grain yield, straw yields were lower (P<0.05) where covers were mechanically destroyed (2 t/ha) compared to where they were destroyed chemically (2.5 t/ha), but there was no effect of cover type (P>0.05).

Overall *c*.70 kg N/ha was recovered in the oats, with *c*.10 kg/ha of additional crop nitrogen uptake where the covers had been destroyed with glyphosate (P>0.05), and <5 kg N/ha extra recovered from the cover crops compared to the stubble control (P>0.05). Similar trends were also seen with grain nitrogen offtake, but the effects were not statistically significant (P>0.05). There was, however, a significant effect of experimental block (P<0.01) with both grain nitrogen offtake and total nitrogen uptake increasing in the order block 1 < block 2 < block 3, reflecting the adverse effect of black grass.

There was a significant effect (P<0.05) of destruction method on the specific weight of grain with a greater mean specific weight from chemical destruction (55.4 kg/hl) than from rolling on a frost (48.6 kg/hl) (Figure 11).

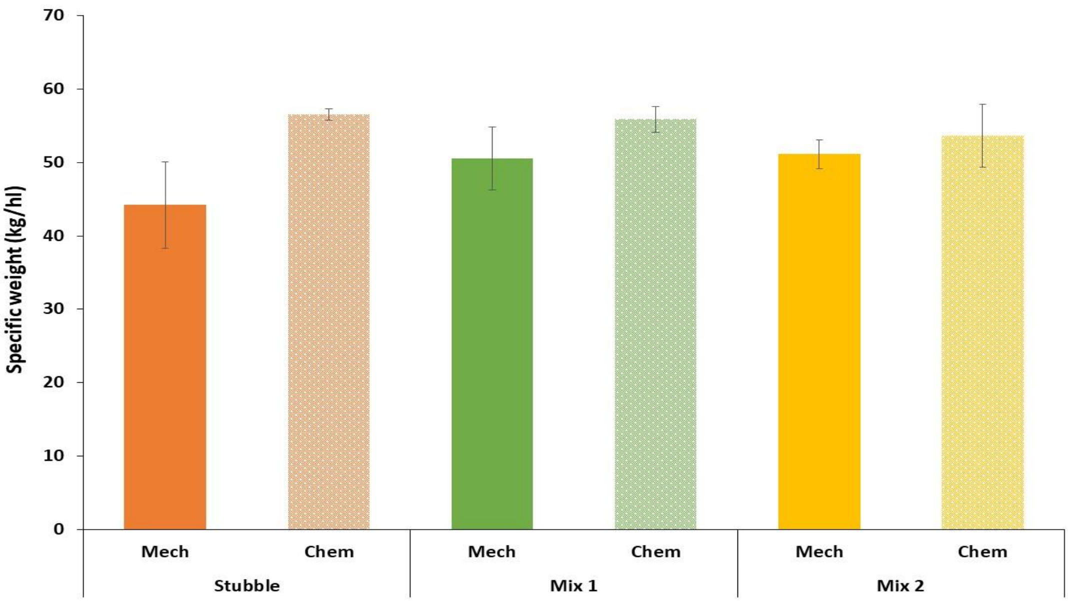

Figure 11. Spring oat specific weight at the Hertfordshire site, harvest late July 2022. Average values, ± one standard error, N=3. Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia. Mech = mechanical destruction (rolling on a frost); Chem = chemical (glyphosate) destruction.

Grain specific weight is a measure of the density of the grain, with a specific weight of 50 kg/hl typically accepted by millers, although 52 kg/hl is preferred (Pers. Comm., Dr Sarah Clarke, ADAS). The mean specific weight from chemical destruction was consistent with the average GB value for oats from harvest 2022 of 55 kg/hl (AHDB, 2022). The mean specific weight from mechanical destruction, however, is likely to lead to quality issues and financial implications for the farmer, since oats which meet milling quality requirements command a higher price (Pers. Comm., Dr Sarah Clarke, ADAS). Specific weight is predominantly determined by plant variety genetics, and factors affecting the length of the grain filling period, but poorly managed crop nutrition and lodging can also reduce specific weight (PepsiCo, 2019). Nitrogen management affects both spring oat yield and quality with seedbed nitrogen proving to be beneficial (Clarke et al., 2022). Early nitrogen was shown to produce a better crop canopy (and subsequent grain filling), as a result of improved crop establishment and rooting

(Clarke et al., 2022). The higher specific weight measured following glyphosate destruction possibly reflects the earlier mineralisation of nitrogen in the covers and nitrogen availability to the following spring oat crop than from rolling on a frost. This early nitrogen may have been of particular importance given the hot, dry summer and general poor grain filling period in 2022. The effect of the black grass problem was also evident with specific weight from block 1 not meeting milling requirement and increasing in the order block 1 (47.7 kg/hl) < block 2 (52.2 kg/hl) < block 3 (56.1 kg/hl) (P=0.054).

Furthermore, there was a significant effect (P<0.05) of destruction method on thousand grain weight, with a greater mean thousand grain weight from chemical destruction (37.7 g) than from rolling on a frost (35.9 g). Thousand grain weight is a harvest assessment to determine whether treatments have affected grain size and fill. Cover type also affected (P = 0.051) thousand grain weight with the stubble control showing the lowest weight at 35.4 g compared with mix 1 and mix 2 at 37.9 g and 37.2 g, respectively. Black grass again was shown to affect grain quality, with thousand grain weight significantly (P<0.001) increasing in the order block 1 (34.0 g) < block 2 (36.9 g) < block 3 (39.5 kg/hl) (P=0.054).

6.5.2 West Sussex

Clear differences in the appearance of the spring barley crop early in the growing season could be seen between treatments, with more growth and a thicker crop where cover crops had previously been present than where the stubble control had been (Plate 7).

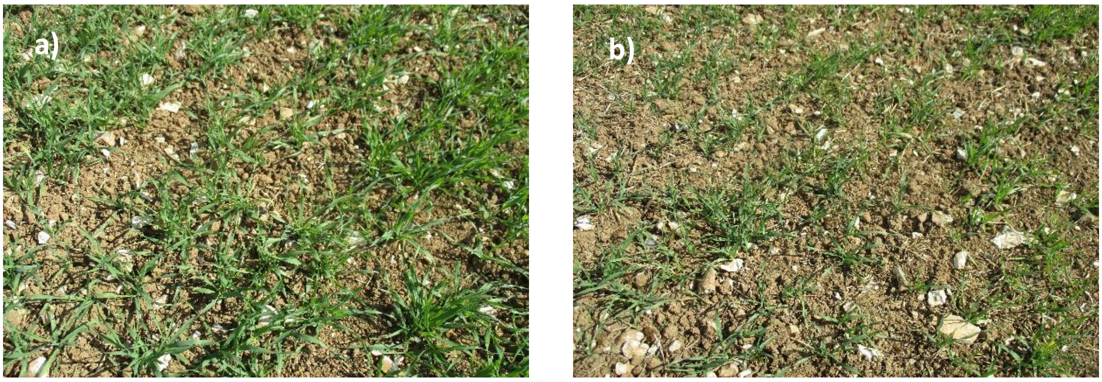

Plate 7. Spring barley 26th April 2022 at the West Sussex site: a) Mix 1, chemically destroyed; b) Stubble control, chemically destroyed.

There were also noticeable differences depending on the destruction technique e.g., where mix 1 had been present, re-growth of the oil radish could easily be seen where mechanical destruction had taken place (Plates 8 & 9). Presumably, the chopping of the covers had only limited effectiveness in destroying the oil radish with its below ground tap root.

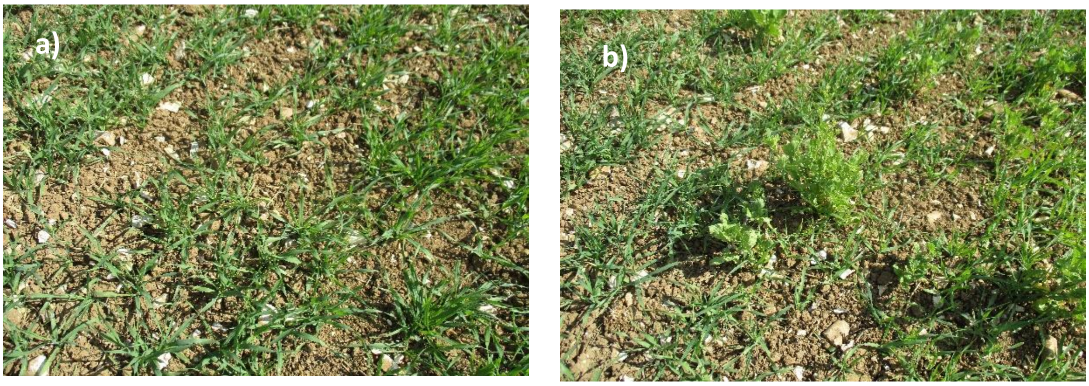

Plate 8. Spring barley 26th April 2022 at the West Sussex site: a) Mix 1, chemically destroyed; b) Mix 1, mechanically destroyed.

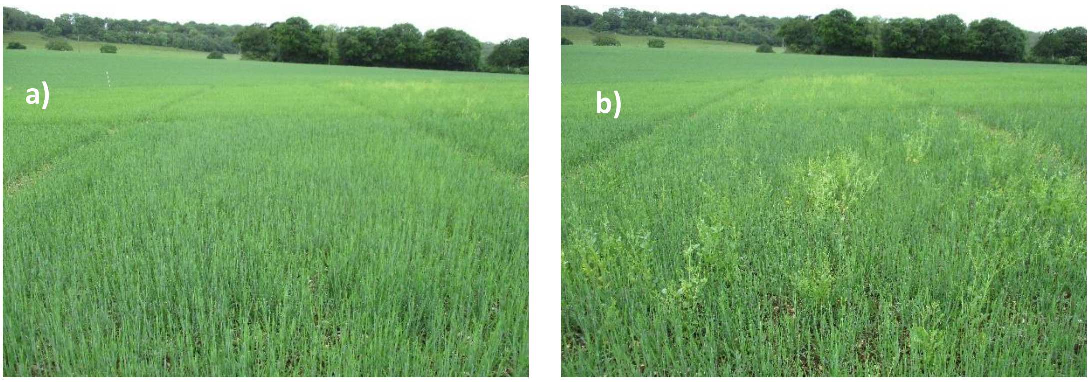

Plate 9. Spring barley 20th May 2022 at the West Sussex site: a) Mix 1, chemically destroyed; b) Mix 1, mechanically destroyed.

This effect of the oil radish re-growth was highlighted in the measurement of botanical composition which was undertaken in early May 2022 (Figure 12). There were more weeds (P<0.001) where mix 1 had grown (*c*.8%) than where mix 2 or stubble had been (*c*.2%), primarily due to the oil radish regrowth (Plates 8 & 9). There was, however, an interaction (P<0.001) between cover type and destruction technique with a much greater difference in % cover between the destruction techniques with mix 1, than mix 2 or the stubble control, presumably due to the oil radish being more difficult to destroy than other weed and cover crop species. The percentage cover of spring barley was also significantly (P<0.05) lower where mechanical destruction had taken place (*c*.32%) than where the destruction was chemical (*c*.40%). This may have been a consequence of the greater (P<0.001) weed burden (*c*.8%) with the mechanical destruction than with chemical destruction (*c*.0.5%) and/or greater early nitrogen release by the chemical destruction giving the spring barley a 'better' start.

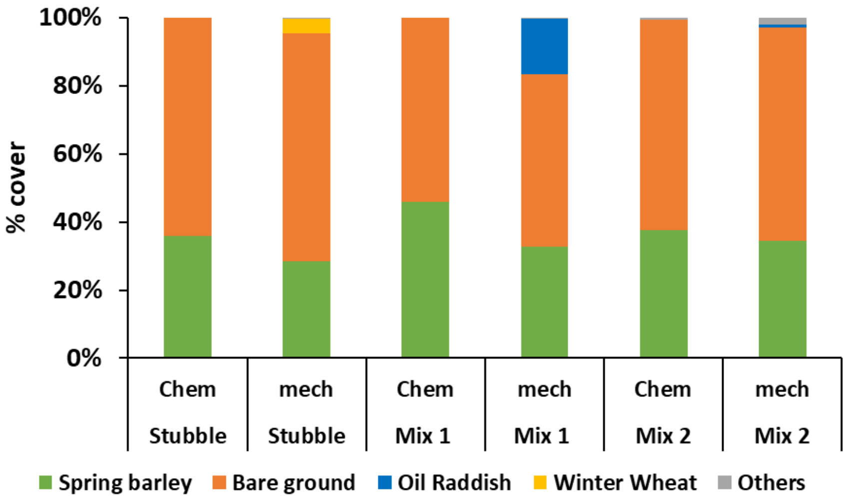

Figure 12. Botanical composition in the spring barley crop - early May 2022 at the West Sussex site. Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia. Mech = mechanical destruction (chop & incorporate); Chem = chemical (glyphosate) destruction.

The spring barley was harvested in mid-August (11/08/22) from both sides of the plot i.e. the plus nitrogen half which received manufactured nitrogen fertiliser, and from the zero nitrogen half which did not receive any manufactured nitrogen fertiliser.

Yield and nitrogen uptake - with manufactured nitrogen fertiliser

The mean spring barley yield was 7.4 t/ha, which was about 1.5 t/ha greater than the 2022 GB average spring barley crop yield of 5.7-6.1 t/ha (AHDB, 2022).

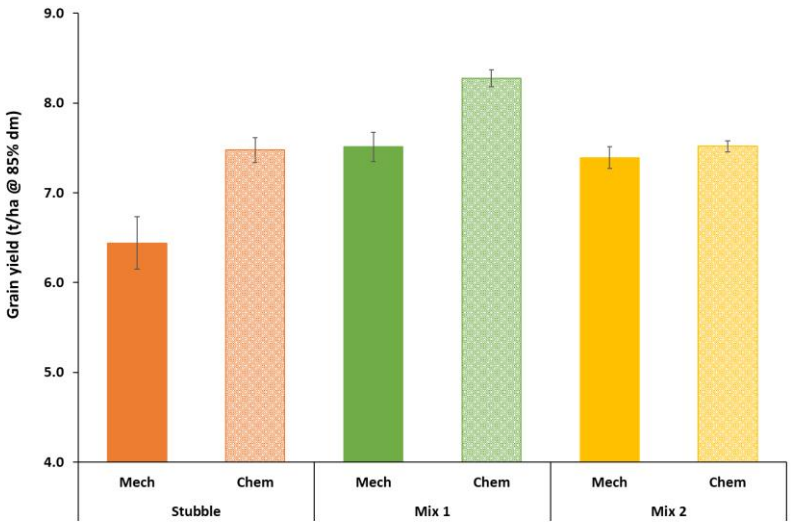

Figure 13. Spring barley yield (plus N fertiliser) at the West Sussex site, harvest mid-August 2022. Average values, ± one standard error, N=3. Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia. Mech = mechanical destruction (rolling on a frost); Chem = chemical (glyphosate) destruction.

On average across both destruction methods, grain yields following the cover crops were *c*.0.5 t/ha (mix 2) and *c*.1.0 t/ha (mix 1) greater than (P<0.001) the stubble control i.e., where no cover crop was grown (Figure 13). However, there was a 0.8-1.0 t/ha yield reduction (P<0.05) where the covers (mix 1 and stubble control) were mechanically destroyed compared with where they were destroyed chemically using glyphosate (Figure 13). The yield reduction with mix 2, however, was much smaller at only *c*.0.15 t/ha.

Straw yields were also lower (P<0.1) where the biomass was mechanically destroyed (*c*.4.6 t/ha) compared with where it was destroyed chemically (4.9 t/ha), although this wasn't consistent across all cover types (P<0.01). Straw yields increased in the order; stubble (4.5 t/ha) < mix 1 (4.8 t/ha) < mix 2 (4.9 t/ha), but this depended on destruction technique (P<0.01).

There was a *c*.11 kg N/ha reduction (P<0.01) in grain nitrogen offtake where the covers were mechanically destroyed compared with where they were destroyed chemically. An extra 5-12 kg N/ha was in the grain following the cover crops compared with the stubble control (P<0.05). Similar patterns were also seen with total crop nitrogen uptake (above-ground). Overall *c*.150 kg N/ha was in the above-ground spring barley biomass at harvest, with *c*.15 kg/ha of additional crop nitrogen uptake where the covers had been destroyed with glyphosate (P<0.001) compared with mechanical destruction, and an additional *c*.10-15 kg N/ha in the crop following the cover crop mixes compared with the stubble control (P<0.01). The effect of destruction technique did, however, differ between cover types (P<0.01), with a difference of *c*.20-25 kg N/ha on mix 1 and the stubble control, and no effect of destruction technique on mix 2 (Figure 14).

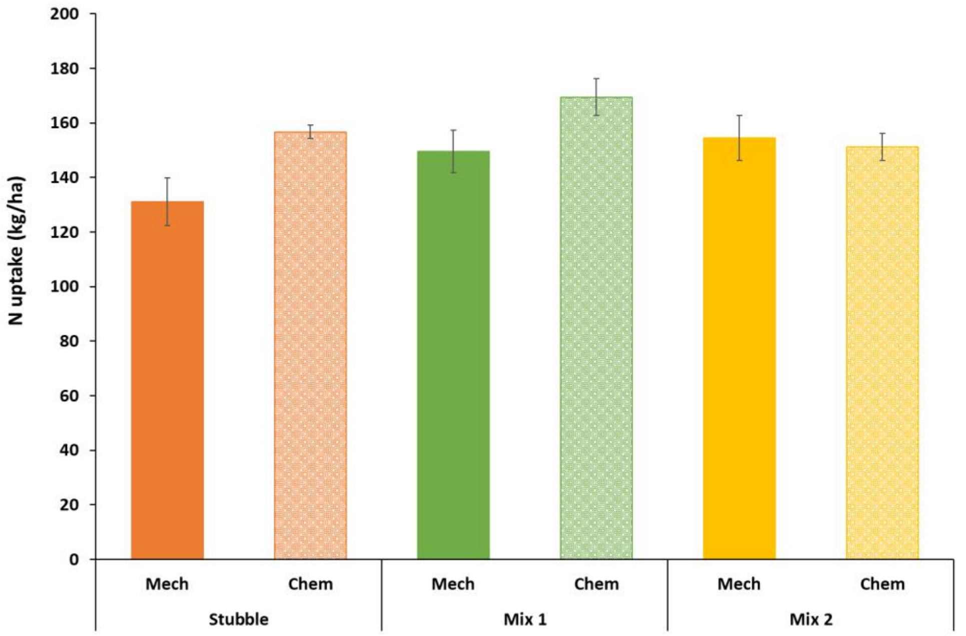

Figure 14. Spring barley total crop N uptake (plus N fertiliser) at the West Sussex site, harvest mid-August 2022. Average values, ± one standard error, N=3. Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia. Mech = mechanical destruction (rolling on a frost); Chem = chemical (glyphosate) destruction.

The mean spring barley grain nitrogen content was 1.8%, compared to the 2022 GB average spring barley value of 1.4-1.7% (AHDB, 2022). There was no effect of destruction technique or cover type (P>0.05), with the differences in grain nitrogen offtake due to differences in yield rather than nitrogen content.

Yield and nitrogen uptake - without manufactured nitrogen fertiliser

There was an average spring barley yield reduction (P<0.001) of *c*.3 t/ha in the absence of nitrogen fertiliser with a mean yield from the zero nitrogen treatments of 4.4 t/ha. Grain yields following the cover crops were *c*.0.7 t/ha (mix 2) and *c*.1.2 t/ha (mix 1) greater than (P<0.001) the stubble control (Figure 15). Similar to the plus nitrogen treatments, where no nitrogen fertiliser had been applied, there was a significant (P<0.001) yield reduction (*c*.0.7 t/ha) where the covers were mechanically destroyed compared with where they were destroyed chemically (Figure 15).

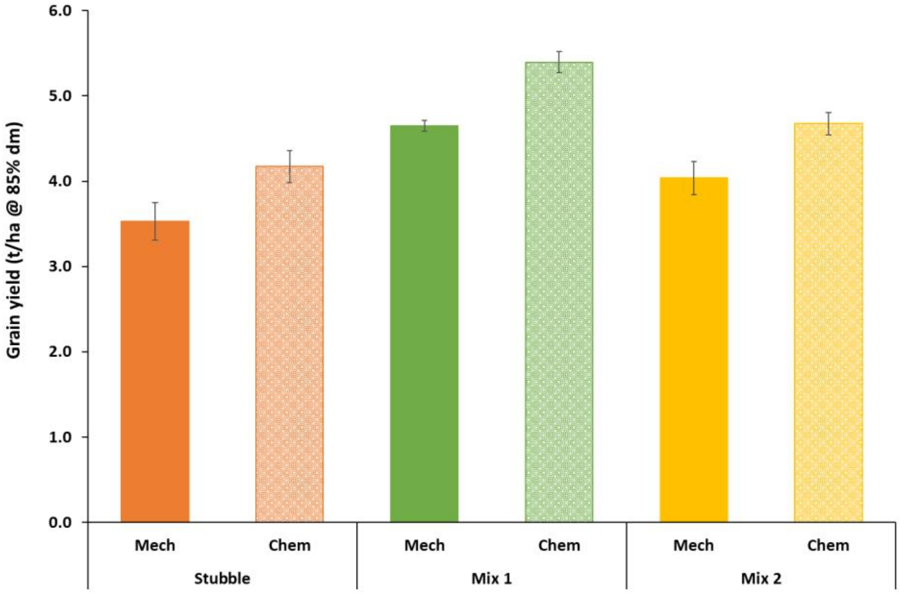

Figure 15. Spring barley yield (zero N fertiliser) at the West Sussex site, harvest mid-August 2022. Average values, ± one standard error, N=3. Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia. Mech = mechanical destruction (rolling on a frost); Chem = chemical (glyphosate) destruction.

Straw yields were *c*.1 t/ha greater (P<0.05) where cover crops had been grown compared with the stubble control, but there was no effect (P>0.05) of destruction technique.

Grain nitrogen offtake was *c*.70 kg/ha lower in the absence of nitrogen fertiliser (P<0.001). As with the plus nitrogen treatments, there was a reduction (*c*.6 kg N/ha in grain nitrogen offtake) where the covers were mechanically destroyed compared with where they were destroyed chemically (P<0.001). Similarly, an extra 5-10 kg N/ha was in the grain following the cover crops compared with the stubble control (P<0.001). Similar patterns were also seen with total crop nitrogen uptake. There was *c*.2.5 times more nitrogen in the crop because of fertiliser nitrogen application with total crop nitrogen uptake on the fertilised plots of *c*.150 kg N/ha. Crop nitrogen uptake was *c*.90 kg N/ha lower where no fertiliser nitrogen had been applied. In the absence of nitrogen fertiliser, there was *c*.10 kg/ha of additional crop nitrogen uptake where the covers had been destroyed with glyphosate (P<0.01) compared with mechanical destruction, and an additional *c*.5-15 kg N/ha from the cover crops compared with the stubble control (P<0.001) (Figure 16).

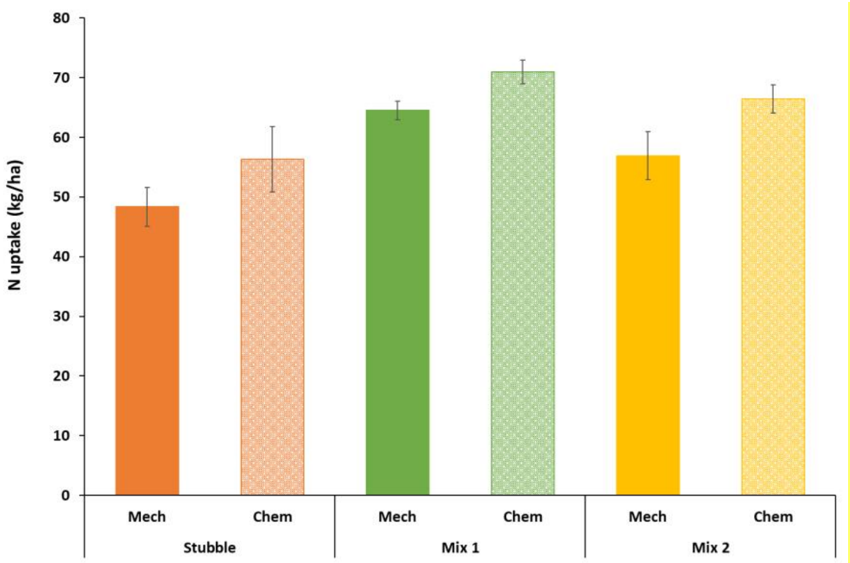

Figure 16. Spring barley total crop N uptake (zero N fertiliser) at the West Sussex site, harvest mid-August 2022. Average values, ± one standard error, N=3. Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia. Mech = mechanical destruction (rolling on a frost); Chem = chemical (glyphosate) destruction.

Where no fertiliser nitrogen had been applied, the mean spring barley grain nitrogen content was 1.2%, which was *c*.0.6% lower than with fertiliser nitrogen (P<0001) and highlights the importance of fertiliser nitrogen management in achieving the correct grain N% for the target market. As with the plus nitrogen fertiliser treatments, there was no effect of destruction technique or cover type on grain nitrogen (P>0.05).

6.5.3 Cross site comparison

Since different spring cash crops were grown at the 2 sites, it is difficult to compare the harvest results directly. Nevertheless, the results showed that over both sites, crop yield, grain nitrogen offtake and total crop nitrogen uptake were all significantly lower (P<0.01) where the covers had been destroyed mechanically (rolling on a frost or chopping & incorporating) than chemically using glyphosate. The difference in total crop nitrogen uptake between destruction techniques was, though, a larger effect for the stubble treatment (P<0.05) than for the cover crops. There was also an effect of cover type on crop yield with a significantly greater (P<0.1) yield from mix 1 compared with the stubble control. As discussed in the sections above, differences in grain yield and quality as a result of the different treatments (and replicate blocks at the Hertfordshire site) are most likely due to the impact of weeds and nitrogen availability early in the growing season. Black grass was a problem at Hertfordshire and incomplete destruction of weeds/covers on the mechanical treatment at West Sussex. Moreover, results from the SMN sampling post cover destruction in spring (Section 6.4) suggest that nitrogen availability was higher following the cover crop treatments which had been destroyed chemically at both sites, which is likely to have benefited crop establishment and subsequent performance.

6.6 Cost/Benefit analysis

A simple cost-benefit assessment was produced for each of the treatments at the two sites in the 2021-22 cropping season, based on the various operations and inputs performed by the host farmers and using costs/prices that the farmer actually incurred. Cover crop seeds were provided free of charge by RAGT, therefore the cost of the different mixes used was estimated from an online search of seven UK seed merchants, taking the individual price (£/kg) for oil radish, phacelia, Japanese (black) oats and buckwheat and calculating an average price for each mix based on the proportion of each species used to create the mix (see Table 2). Phacelia at *c.*£8/kg and oil radish at *c.*£4.50/kg were the most expensive cover crop seeds used in the mixes, with Japanese (black) oats and buckwheat much cheaper at *c.*£2/kg and £/3 kg respectively.

6.6.1 Hertfordshire

Table 3 shows the cost benefit for the 2021-22 cropping season at the Hertfordshire site.

Table 3. Cost/benefit of the different cover crop treatments at the Hertfordshire site at harvest 2022

Cover crop:	Stubble		Mix 1		Mix 2	
Destruction method:	**Chemical**	**Mechanical**	**Chemical**	**Mechanical**	**Chemical**	**Mechanical**
Spring oat yield (t/ha)	3.9	2.7	3.6	3.4	3.9	3.1
Price (£/t)	180	180	180	180	180	180
OUTPUT (£/ha)	**702**	**486**	**648**	**612**	**702**	**558**
VARIABLE COSTS (£/ha)						
Cover crop seed*	0	0	78	78	32	32
Spring oat seed	82	82	82	82	82	82
Fertiliser (N, S, Mg & Mn)	159	159	159	159	159	159
Slug pellets	44	44	44	44	44	44
Sprays**	80	66	80	66	80	66
Total cost	**365**	**351**	**443**	**429**	**397**	**383**
GROSS MARGIN (£/ha)	**337**	**135**	**205**	**183**	**305**	**175**
FIELD OPERATIONAL COSTS (£/ha)						
Cover crop drilled	0	0	72	72	72	72
Cover crop spray	16	0	16	0	16	0
Cover crop roll ***	0	26	0	26	0	26
Slug pellets	24	24	24	24	24	24
Spring oats drilled	72	72	72	72	72	72
Fertiliser x 2	33	33	33	33	33	33
Sprays x 3	49	49	49	49	49	49
Combine	86	86	86	86	86	86
Total costs	**280**	**290**	**352**	**362**	**352**	**362**
NET MARGIN (£/Ha)	**56**	**-155**	**-147**	**-179**	**-47**	**-187**

*Cover crop seeds complimentary supplied by RAGT; estimated cost of each mix based on March 2023 prices from a survey of 7 seed companies individual component prices.
Sprays: 20/1/22 herbicide (chemical treatment only); 3/3/22 pre-drilling herbicide; 6/5/22 herbicide & nutrient (Mn & Mg); 31/5/22 fungicide; 31/5/22 fungicide & nutrient (Mn & Mg). * National Association of Agricultural Contractors (NAAC) price for rolling in 2022

As discussed in Section 6.5.1 oat yields were low due to a widespread blackgrass problem across the field. There was no yield benefit from growing cover crops if chemically destroyed, but where mechanical destruction was used growing a cover crop was beneficial compared to a weedy stubble destroyed mechanically. This meant that the no cover crop treatment had both the highest (chemical destruction) and lowest (mechanical destruction) gross margins.

The cover crops cost between £130/ha and £180/ha to grow, with seed costs highest for Mix 1 and chemical destruction (£30/ha) marginally higher than rolling on a frost mechanically (£26/ha). Total input costs (variable and fixed) were higher than outputs, resulting in a net loss where cover crops had been grown. Net margins were also negative for the stubble treatment mechanically destroyed due to low yields. As discussed in section 6.5.1, blackgrass affected replicate blocks 1 and 2, with the grain yield recorded on block 3 (lower blackgrass density) significantly higher. Repeating the cost benefit using just the yields from block 3 improved margins, so that there was no net loss on any of the treatments (Table 4). The highest margins were still achieved where no cover crop had been grown and chemical destruction of weedy cover had been used, but differences between treatments were considerably smaller.

Table 4. Cost/benefit of the different cover crop treatments at the Hertfordshire site at harvest 2022 – utilising block 3 (low black grass density) yields only.

Cover crop:	Stubble		Mix 1		Mix 2	
Destruction method:	**Chemical**	**Mechanical**	**Chemical**	**Mechanical**	**Chemical**	**Mechanical**
Spring oat yield (t/ha)	5.0	4.9	5.3	5.6	5.3	4.8
Price (£/t)	180	180	180	180	180	180
OUTPUT (£/ha)	**900**	**882**	**954**	**1008**	**954**	**864**
VARIABLE COSTS (£/ha)*						
Total cost	365	351	443	429	397	383
GROSS MARGIN (£/ha)	**535**	**531**	**511**	**579**	**557**	**481**
FIELD OPERATIONAL COSTS (£/ha)*						
Total costs	280	290	352	362	352	362
NET MARGIN (£/Ha)	**255**	**241**	**159**	**217**	**205**	**119**

*See Table 3 for full breakdown of variable and field operational costs

6.6.2 West Sussex

Table 5 shows the cost benefit for the 2021-22 cropping season at West Sussex. Although Mix 1 was the most expensive cover crop mix, gross margins were greatest following chemical destruction of this treatment due to a high spring barley grain yield. However, although Mix 2 was cheaper, there was insufficient yield benefit compared to the no cover crop (stubble) treatment to re-coup the cost of this mix. Gross margins were lowest on all the mechanical destruction treatments, although growing a cover crop (particularly the cheaper Mix 2) off-set this loss to some extent, with the lowest yields and gross margins where no cover crop had been grown and the over-winter weed growth was destroyed mechanically.

Once the field operation costs (i.e. cost of establishing and destroying the cover crop) had been taken into account it was most cost effective to not grow a cover crop and destroy any weeds in the spring chemically, with net margins greatest on the stubble + chemical destruction treatment, albeit only £21/ha greater than on the mix 1 + chemical treatment (Table 5). It is important to note that no changes to the nitrogen fertiliser programme were made as a result of growing the cover crop, with

SNS measurements in the spring (Section 6.3.2) suggesting that a reduction in nitrogen use may have been appropriate, particularly where mix 1 had been grown, which would have reduced the cost of fertiliser inputs on this treatment. Note this was not the case at the Hertfordshire site.

Table 5. Cost/benefit of the different cover crop treatments at the West Sussex site at harvest 2022

Cover crop:	Stubble		Mix 1		Mix 2	
Destruction method:	Chemical	Mechanical	Chemical	Mechanical	Chemical	Mechanical
Spring barley yield (t/ha)	7.48	6.44	8.28	7.51	7.52	7.39
Price (£/t)	264	264	264	264	264	264
OUTPUT (£/ha)	**1975**	**1700**	**2186**	**1983**	**1985**	**1951**
VARIABLE COSTS (£/ha)						
Cover crop seed*	0	0	78	78	32	32
Spring barley seed	105	105	105	105	105	105
Fertiliser (N & S)	128	128	128	128	128	128
Sprays**	198	184	198	184	198	184
Total cost	**431**	**417**	**509**	**495**	**463**	**449**
GROSS MARGIN (£/ha)	**1544**	**1283**	**1677**	**1488**	**1522**	**1502**
FIELD OPERATIONAL COSTS (£/ha)						
Cultivation	0	0	74	74	74	74
Cover crop drill & roll	0	0	80	80	80	80
Cover crop spray	16	0	16	0	16	0
Cover crop flail	0	37	0	37	0	37
Cultivation	74	74	74	74	74	74
spring barley drilled	60	60	60	60	60	60
Fertiliser x 2	30	30	30	30	30	30
Sprays x 4	64	64	64	64	64	64
Combine	123	123	123	123	123	123
Total costs	**367**	**388**	**521**	**542**	**521**	**542**
NET MARGIN (£/Ha)	**1177**	**895**	**1156**	**946**	**1001**	**960**

*Cover crop seeds complimentary supplied by RAGT; estimated cost of each mix based on March 2023 prices from a survey of 7 seed companies individual component prices.
**Sprays: 17/2/22 herbicide (chemical treatment only); 23/3/22 pre-emergence herbicide; 21/5/22 herbicide, micronutrient (Cu & Mn) & fungicide; 28/5/22 growth regulator & fungicide; 9/6/22 fungicide.

It was more expensive to destroy the cover crop and weeds on the stubble treatment mechanically (£37/ha) compared to chemical destruction (*c*.£30/ha - cost of glyphosate & spray operation). Mechanical destruction by mowing did not adequately destroy all the weeds, with significant regrowth observed both on the stubble treatment (wheat volunteers) and mix 1 (radish re-growth). Although, pre- and post- emergence herbicides are commonly required in most seasons, the host farmer had to use a 'more robust' herbicide where the cover crop & weedy stubble were flailed. 'Normally' a relatively cheap 'light weight' herbicide spray costing *c*.£15/ha would be used at this time, whereas the heavier weed burden across the trial required the use of a more 'robust' product costing £28.50/ha (host farmer: pers. comm). This is not reflected in the cost-benefit analysis, as for ease of operation, the same spray programme was used on all plots post drilling the spring barley crop. The overall comment from the host farmer regarding weeds following mechanical destruction was *'I would be very uneasy using this technique on a field scale, especially if grass weeds are even a slight issue'*.

6.6.3 Cross site comparison

At both experimental sites, the most cost-effective treatment was to grow no cover crop and destroy any weeds chemically, although at the West Sussex site the difference in margin to growing a cover crop and destroying it chemically was small. Mechanical destruction of weeds and cover crops consistently led to the lowest margins, although growing a cover crop (particularly the cheaper Mix 2) off-set this loss to some extent. Mowing a cover crop was the most expensive way of destroying it, followed by chemical destruction, with the cheapest method, rolling on a frost, although this latter option is dependent on there being a frost. On all treatments and at both sites, additional weed control was required later in the season, which although typical for most crops and seasons, required a more costly product at the West Sussex site due to the high weed burden on the mechanical destruction treatments. Interestingly, Hertfordshire was a no till site, so cover crop establishment costs were lower than at West Sussex (minimum tillage), but several applications of slug pellets were used at the no till site which were not required at the reduced tilled site. Black grass was also a problem. No adjustments to nitrogen fertiliser were made at either site, although a slight reduction in nitrogen could have been justified at the West Sussex site based on spring SNS measurements, particularly following mix 1. This would have provided additional cost savings, which may, in this case have made the mix 1 chemical destruction treatment the most cost effective.

Whilst the use of cover crops is likely to increase farm costs it is important to consider the wider benefits they can provide, such as the improved water quality this study has demonstrated, as well erosion control, improved soil health and enhanced biodiversity. These benefits are an important consideration for mitigating against environmental pollution and providing ecosystem services to the wider public. The new Sustainable Farm Incentive has measures to increase green cover over winter as part of a series of actions for soils. Specifically SFI 2023 will pay a farmer £129/ha for establishing a multi-species winter cover crop comprising of at least two species (SFI23 handbook). The level of this payment would not have fully covered the cost of establishing and destroying the cover crops used in this study, which ranged from £130-£270/ha. However, when combined with the yield benefit, particularly following mix 1 (oil radish and phacelia), growing a cover crop becomes more cost-effective (Table 6).

Table 6. Net Margin including SFI 2023 multi-species winter cover crop payment (£129/ha). Note the net margins used in this table for the Hertfordshire site are those based on block 3 oat yields only (i.e. a single value for each treatment), due to the impact of blackgrass on the yield of the other replicate blocks.

Cover crop:	Stubble		Mix 1		Mix 2	
Destruction method:	Chemical	Mechanical	Chemical	Mechanical	Chemical	Mechanical
Net Margin + SFI payment (Hertfordshire)	255	241	288	346	334	248
Net Margin + SFI payment (West Sussex)	1177	895	1285	1075	1130	1089

7 RESULTS AND DISCUSSION – LEGACY 2022-23

7.1 Soil nitrogen autumn 2022

7.1.1 Hertfordshire

Soil mineral nitrogen (SMN) to depth measured in early October 2022 was, on average 110 kg N/ha, and differed (P<0.1) between blocks. About 130 kg N/ha was measured from block 1, *c*.115 kg N/ha from block 2 and *c*.85 kg N/ha from block 3. These differences in SMN reflect the effect the black grass had on the spring oat crop harvested in summer 2022. A poorer yield and lower recovery of fertiliser nitrogen by the crop, particularly in block 1 where the black grass was worst, would have resulted in more nitrogen remaining in the soil post-harvest, than where there was less black grass i.e., in blocks 2 & particularly 3.

Similarly, and most likely reflecting the yield and total nitrogen recovery differences measured in the spring oat crop at harvest, there was *c*.20 kg N/ha more SMN measured where the biomass had been destroyed mechanically in spring 2022 compared with chemical destruction using glyphosate, however the difference was not statistically significant (P>0.05). There was also no effect (P>0.05) of legacy cover type on autumn SMN, although the stubble control had *c*.11.5 kg N/ha more SMN than mix 2 and *c*.3.5 kg N/ha more soil nitrogen than mix 1, again reflecting the treatment differences measured at harvest.

7.1.2 West Sussex

SMN to depth measured in early October 2022 was *c*.95 kg N/ha at the West Sussex site. There was *c*.30-45 kg N/ha less SMN (P<0.01) where the cover crops had been grown over winter in 2021-22 than where there was the stubble control. This again probably reflects the reduced yield and crop nitrogen uptake on the stubble control treatment. Despite an extra *c*.20 kg N/ha of SMN in the legacy mechanically destroyed stubble treatment compared with the legacy chemically destroyed stubble treatment, overall there was no statistically significant effect (P>0.05) of destruction method on autumn SMN in 2022.

7.1.3 Cross site comparison

There was no effect of site on SMN to depth in autumn 2022 (P>0.05). Overall, though, there was an effect of legacy cover type with *c*.30 kg N/ha less SMN in the legacy mix 2 treatment than in the legacy stubble control (P<0.05), and *c*.20 kg N/ha less SMN in the legacy mix 1 treatment than in the legacy stubble control, although this wasn't statistically significant (P>0.05). These differences are likely a consequence of the poorer performance (lower yields and crop nitrogen uptake) of the spring cereals where no cover crops were grown and demonstrate how poor nitrogen use efficiency can lead to high residual nitrogen in the soil post-harvest.

7.2 Nitrate leaching losses winter 2022-23

7.2.1 Hertfordshire

Rainfall over winter 2022-23 (October to end-March) was 466 mm, which led to *c*.155 mm of drainage. There was no significant effect of experimental block, legacy cover type or legacy destruction technique (P>0.05) on total over winter nitrate leaching losses, despite differences in autumn SMN, with a mean loss of *c*.9 kg N/ha (Figure 17).

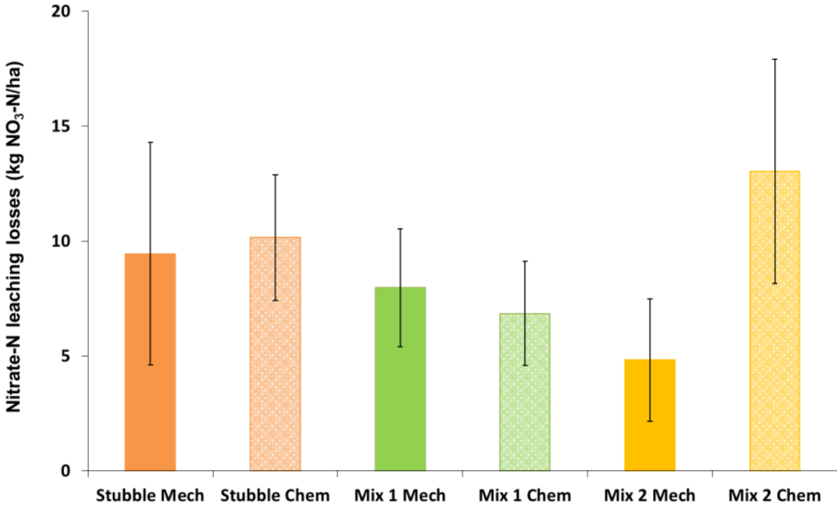

Figure 17. Nitrate leaching losses October 2022-March 2023 at the Hertfordshire site (466 mm rainfall; *c*.155 mm drainage). Average values, + one standard error, N=3. Legacy 2021-22 treatments: Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia

Over the whole measurement period, the average, flow-weighted nitrate-N concentrations from the six treatments ranged from *c*.3-8 mg NO_3-N/l with an overall mean concentration of *c*.5.5 mg NO_3-N/l, and below the EU limit of 11.3 mg NO_3-N/l.

7.2.2 West Sussex

Rainfall over winter 2022-23 (October to end-January) was 696 mm, which led to *c*.330 mm of drainage. As at the Hertfordshire site, there was no significant effect of legacy cover type or legacy destruction technique (P>0.05) on total over winter nitrate leaching losses, despite differences in autumn SMN with a mean loss of *c*.18 kg N/ha (Figure 18).

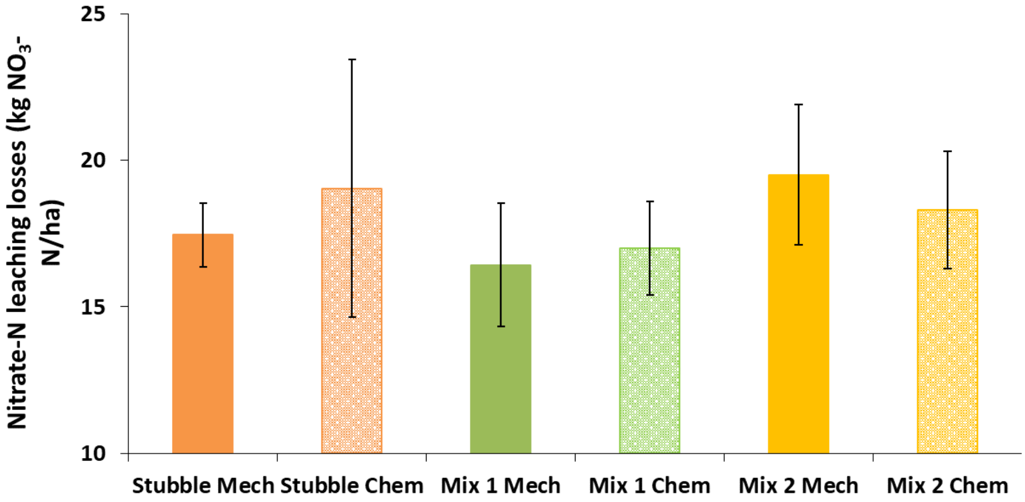

Figure 18. Nitrate leaching losses October 2022-end-January 2023 at the West Sussex site (696 mm rainfall; *c*.330 mm drainage). Average values, + one standard error, N=3. Legacy 2021-22 treatments: Stubble = control; Mix 1 = phacelia & oil radish; Mix 2 = Japanese oats, buckwheat & phacelia

Over the whole measurement period, the average, flow-weighted nitrate-N concentrations from the six treatments ranged from just *c*.5-6 mg NO_3-N/l with an overall mean concentration of *c*.5.5 mg NO_3-N/l, and below the EU limit of 11.3 mg NO_3-N/l.

7.2.3 Cross site comparison

The total over winter nitrate leaching loss from the West Sussex site (*c*.18 kg N/ha) was double (P<0.01) that from the Hertfordshire site (*c*.9 kg N/ha), most likely due to the differences in soil type and the greater rainfall at West Sussex. Across both sites, there was no significant effect of legacy cover type or legacy destruction technique (P>0.05) on total over winter nitrate leaching losses. It is important to note that both legacy crops (winter oilseed rape and cover crop – oil radish/phacelia mix) grown after the spring cash crops have an autumn nitrogen requirement and were able to take up available soil mineral nitrogen. If the legacy crops had not had an autumn nitrogen requirement (e.g. winter cereal), it is possible that the soil mineral nitrogen present in the autumn would have been at greater risk of loss via nitrate leaching.

7.3 Soil nitrogen supply spring 2023

7.3.1 Hertfordshire

In mid-January 2023 (*c*.2 weeks prior to cover crop destruction), SMN to depth averaged *c*.35 kg N/ha. There was no effect (P>0.05) of legacy cover type or legacy destruction technique on spring SMN, although there was a similar trend (P<0.1) to that in Autumn 2022 with SMN increasing in the order block 3 (*c*.25 kg N/ha) < block 2 (*c*.30 kg N/ha) < block 1 (*c*.45 kg N/ha). Above ground cover crop nitrogen uptake was also measured in mid-January 2023, with a mean nitrogen uptake of about *c*.20 kg N/ha, but no significant effect (P>0.05) of experimental block, legacy cover type or legacy destruction technique. The spring soil nitrogen supply (SNS = above ground cover crop N + soil mineral

N) was *c*.55 kg N/ha. The SNS was also not significantly (P>0.05) affected by legacy cover type or legacy destruction technique, although probably driven by the spring SMN there was an effect of experimental block (P<0.1) that followed the same trend. It's likely that the effect of experimental block was discernible since the spring oat yield and crop nitrogen uptake differences between blocks were much larger than the effects of cover type or destruction technique.

7.3.2 West Sussex

In early-February 2023 SMN to depth averaged *c*.15 kg N/ha, with no effect (P>0.05) of legacy cover type or legacy destruction technique. Above ground nitrogen uptake from the winter oilseed rape crop was also measured in early-February 2023, with a mean nitrogen uptake of about *c*.35 kg N/ha. There was no significant effect (P>0.05) of legacy cover type or legacy destruction technique on above ground spring crop nitrogen uptake. The spring soil nitrogen supply (SNS = above ground oilseed rape crop N + soil mineral N) was *c*.50 kg N/ha and was also not significantly (P>0.05) affected by legacy cover type or legacy destruction technique.

7.3.3 Cross site comparison

Spring SMN to depth at the Hertfordshire site was about double (P<0.05) that of the West Sussex site (section 7.3), reflecting not only the greater (P<0.01) nitrate leaching losses at the West Sussex site section 7.2), but also the larger above ground crop nitrogen uptake by the oilseed rape at this site (section 7.3). However, overall, there was no statistical difference (P>0.05) in the spring soil nitrogen supply (SNS = above ground crop N + soil mineral N) between the two sites, nor any effect of legacy cover type or legacy destruction technique (P>0.05).

A comparison of the nitrogen recovered in the soil and crop in spring 2023 with that in the soil in autumn 2022 indicated that there was about 40 kg N/ha that was not accounted for by over winter nitrate leaching losses across both sites (with no statistically significant difference between sites). The amount of this 'unaccounted' for nitrogen was however affected by legacy cover crop type (P>0.05), increasing in the order; mix 2 (*c*.25 kg N/ha) < mix 1 (*c*.35 kg N/ha) < weedy stubble control (*c*.50 kg N/ha). This effect of legacy cover type was, however, different (P<0.05) depending on the legacy destruction technique, being most notable where mechanical had been used in 2022 and particularly on the weedy stubble treatment.

There are several 'loss' mechanisms which could explain the 'unaccounted' for nitrogen, such as denitrification with nitrogen loss via nitrous oxide & di-nitrogen, however, immobilisation into soil organic nitrogen is the most plausible explanation. The largest amounts of 'unaccounted' for nitrogen were associated with the legacy weedy stubble control treatment destroyed mechanically, presumably related to more 'resistant' carbon in the 'weedy' vegetation than in the cover crops, and the mechanical destruction not being as effective at breaking biomass down as glyphosate.

7.4 Crop performance summer 2023

7.4.1 West Sussex

The winter oilseed rape (Plate 10) was harvested in mid-August (11/08/23) to give a mean yield of 4.1 t/ha, which was about 1 t/ha greater than the 2023 GB average winter oilseed rape yield of 2.8-3.0 t/ha (AHDB, 2023).

Plate 10. Winter oilseed rape crop at the West Sussex site, 4th April 2023

There was no effect (P >0.05) of legacy cover type or legacy destruction technique on either the oilseed rape yield or on the oilseed nitrogen offtake, where the mean offtake was *c*.105 kg N/ha.

8 CONCLUSIONS

This study has clearly demonstrated that drilling a cover crop can reduce nitrate leaching losses by up to 90% compared to a weedy stubble control. Leaching losses were dependant on over winter rainfall, the amount of cover achieved and cover crop type with the cover crop mix containing the fast growing, nitrogen scavenging oil radish giving the greatest benefit in reducing leaching losses.

The reduction in nitrate leaching losses by the cover crops increased soil nitrogen supply in the spring by up to *c*.35 kg N/ha. If all the nitrogen in the above ground cover crop would become available to the following cash crop, a decrease in the nitrogen fertiliser requirement of the cash crop would potentially be justified. This justification was dependant on the amount of cover crop biomass and nitrogen uptake, so cannot be guaranteed in all situations.

It was evident from topsoil mineral nitrogen measurements taken following spring cover destruction, that cover crops released more nitrogen during decomposition (mineralisation) than from the weedy stubble control, reflecting the greater nitrogen uptake over winter by the cover crops.

Chemical destruction of over winter cover using glyphosate increased the amount of topsoil mineral nitrogen compared to mechanical destruction, regardless of the method used i.e. rolling on a frost or chopping. It is probable that glyphosate breaks down vegetation more rapidly allowing mineral nitrogen to become available for use by the following spring cash crop earlier than with mechanical destruction.

Mechanical destruction of over winter cover by chopping had limited effectiveness in destroying oil radish (& its below ground tap root) where it was used in a cover crop mix. The resultant oil radish re-growth required a more robust post emergence herbicide for control in the subsequent spring cash crop.

Rolling on a frost to destroy over winter cover had implications on the quality of the following spring oat crop. The grain specific weight was reduced to below that typically accepted by millers (50 kg/hl). Where glyphosate had been used to destroy over winter cover, the spring oat specific weight exceeded milling requirements. The higher specific weight measured following glyphosate destruction possibly reflects the earlier mineralisation of nitrogen in the covers and nitrogen availability to the following spring oat crop than from rolling on a frost.

Although there were different spring cash crops grown at the 2 sites, crop yield, grain nitrogen offtake and total crop nitrogen uptake were consistently reduced where the covers had been destroyed mechanically (rolling on a frost or chopping) than by using glyphosate. There was a mean 0.7 t/ha spring oat yield reduction from rolling on a frost, and up to a 1.0 t/ha spring barley yield penalty following chopping of over winter cover.

Across both sites, cover crops had a positive effect on the yield of the following spring cereal. The mean spring oat yield was 0.2 t/ha greater where cover crops had been used compared with a weedy stubble control, and cover crops resulted in an increase in the spring barley yield of 0.5-1.0 t/ha.

The differences in grain yield and quality are most likely due to the impact of incomplete destruction of weeds/covers on the mechanical treatment at West Sussex and nitrogen availability early in the growing season. The greater nitrogen availability following cover destruction using glyphosate is likely to have benefited spring cereal establishment and subsequent crop performance.

There was a legacy effect of cover type on the autumn soil mineral nitrogen content measured after harvest of the spring cash crops. Across both sites, autumn soil mineral N content was 20-30 kg N/ha higher on the weedy stubble control, reflecting the poorer performance (and N utilisation) of the spring cereals where no cover crops were grown.

There was no legacy effect of cover type or destruction technique on either the nitrate leaching losses measured over winter following spring cereal harvest or on the subsequent spring soil nitrogen supply.

The crops grown in the legacy year (i.e. cover crop and oilseed rape) had an autumn nitrogen requirement. If an autumn sown crop which did not have an autumn nitrogen requirement (e.g. winter cereal) had been used, there would have been an increased risk of losing autumn soil mineral nitrogen via over winter nitrate leaching.

This study showed that it was more cost-effective to not grow a cover crop and destroy any weeds chemically, although the margins over and above growing a cover crop (with chemical destruction) were small and didn't take account of any environmental incentive a farmer might receive for growing a cover crop (e.g. SFI). The study has clearly shown the importance of such incentive schemes to support cover crop use so these 'harder to monetise' benefits such as improved water quality, soil health and biodiversity can be realised. There is also the potential to reduce fertiliser nitrogen inputs following cover crops, although further work is required to more fully understand the level of reduction possible.

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