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USING FROST SENSITIVE COVER CROPS FOR TIMELY NITROGEN MINERALISATION AND SOIL MOISTURE MANAGEMENT

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Running Title: Cover crops manipulate nitrogen mineralisation

Abstract

Cover crops can be utilised to lower soil nitrate leaching. However, depending on the species grown and cover crop termination management this may lead to nitrogen (N) immobilisation and/or depletion of soil moisture available to the following cash crop, potentially impacting on crop yields. Cover crop management is also dependent on using herbicides to terminate growth prior to planting the next crop. We used an alternative method for cover crop termination by capitalising on plant senescence by frost in a multi-species cover crop established over-winter between wheat and maize. The cover crops accumulated greater quantities of N than the control. However, upon cover crop senescence due to cold temperatures, the partially terminated cover crop significantly increased topsoil available N from December to late February. This available N in the topsoil could be susceptible to leaching although this was not observed in our study. Cover crops did not have a significant prolonged effect on soil moisture over winter and late spring. The following maize yields were not significantly different between the control and cover crop treatment. Frost sensitive cover crop species could not be reliably terminated under a temperate climate, but provided a continuous supply of soil available N as the plants senesced. Depending on the soil moisture and weather conditions in the spring there could be a N leaching risk although this could be mitigated by establishing early spring crops.

Key Words: cover crops; soil health; regenerative agriculture; green manures

1 Introduction

Cover crops are established between periods of cash crop growth when the ground is bare and can alleviate the effects of soil compaction (Chen and Weil, 2010), prevent soil erosion (Posthumus et al., 2015), suppress weeds (Brust et al., 2014) and sequester carbon (Poeplau and Don, 2015). It is well documented that cover crops improve water quality by decreasing nitrate leaching (Cicek et al., 2015; Cooper et al., 2017; Justes et al., 2012;), surface run-off and sediment loss (Korucu et al., 2018). Despite these benefits several barriers to cover crop adoption exist: time and cost associated with cover crop establishment, nitrogen (N) immobilisation and potentially unfavourable soil moisture conditions (CTIC, 2017; Storr et al., 2019; White and Weil, 2010). Furthermore, in 2022 the use of glyphosate, widely used to terminate cover crops, may be withdrawn from use (European Commission, 2018) potentially limiting the opportunity for cover crop adoption.

The possible regulatory withdrawal of glyphosate will require farmers to consider using alternative herbicide options that are possibly more expensive or explore other options for cover crop termination e.g. cultivation, roller crimping, mowing. or utilise a species sensitive to frost. Exploiting the senescence of plants in cold conditions and frosts as a natural termination method could decrease the reliance on chemicals or machinery for cover crop termination. However, this termination method has been little explored in cover crop studies to date.

Cover crop termination management, both timing and method, can greatly affect the availability of water and available soil N to the following crop (Alonso-Ayuso et al., 2014). Improved soil water storage and water content was observed after a cereal rye cover crop that had provided surface residue (Basche et al., 2016; Daigh et al., 2014). However, cultivations (plough) used as a method of cover crop termination showed decreased soil moisture at the time of maize establishment (Krstić et al., 2018) or had no effect on soil moisture (Snapp and Surapur, 2018). These studies indicated varied effects of cover crops on soil moisture available to the following crop. An important consideration for farmers to adopt cover cropping is to reduce any detrimental effects on the establishment of the following crop. Therefore understanding soil moisture dynamics at this time is required for effective crop management.

The role of cover crops in nutrient acquisition and recycling is well established (Baggs et al., 2000; Justes et al., 2012;). However, estimating when these nutrients, particularly N, are mineralized following the use of cover crops is difficult (Snapp et al., 2005). N that is immobilised within the cover crop biomass and not released upon cover crop decomposition to match crop demand can be detrimental to the following cash crop yield (Cicek et al., 2015). The timing and method of cover crop termination affects mineralisation as delayed cover crop incorporation decreases N mineralisation (Alonso-Ayuso et al., 2014; Thorup-Kristensen and Dresbøll, 2010). Cover crops terminated 2-3 weeks prior to cash crop planting may ensure a better synchrony between N mineralisation and the following cash crop's N requirement (Crandall et al., 2005; Ketterings et al., 2015). However, early cover crop termination due to frost, which usually first occurs between October and December in the UK, may release N back into the soil at a time when it is susceptible to leaching (Hu et al., 2018; Thomsen et al., 2016).

The aim of this study was to evaluate the effect of using frost sensitive species as an alternative termination method for cover crops. The focus was to track the dynamics of topsoil N availability during the cover crop growth period and senescence after frost. It also investigated the effects of cover crops on moisture availability for following spring crops. Consideration was also given to the practical application of a using a frost sensitive species in a temperate climate and the effect on the yield of the following crop.

2 Materials and Methods

2.1 Experimental Design and Site Characteristics

A replicated field trial was established near Ely, Cambridgeshire on organo-mineral soils (Table 1). The field site was selected in collaboration with the host farm to investigate the impact of using cover crops on soil health in an arable and salad rotation. The trial took place between August 2017 - May 2018 on a large commercial farm (>5000 ha) with all field operations (Table 1) carried out by the host farm: the host farm was also responsible for all crop nutrition, fungicide and herbicide interventions. A frost sensitive cover crop was established between wheat and maize crops, and consisted of 60% black oats (*Avena stigosa* cv. Cadence), 35% oil radish (*Raphanus sativus* cv. Final) and 5% white mustard (*Sinapis alba* cv. Braco). This mixture was established at 25 kg ha^{-1} and cost £42 ha^{-1}. Plant establishment counts are outlined in Table 2. The control (zero intervention with wheat regrowth) and cover crop treatments consisted of 3 replicates on randomly allocated plots 24m x 80m in size to accommodate commercial farm operations. Data from electrical conductivity scans (electromagnetic induction - EMI) was used to select a homogenous part of the field for plot placement. Glyphosate was applied prior to maize establishment as the cover crop had not been completely terminated by frost.

Table 1 here

2.2 Soil Moisture, Nitrogen and Biomass Determination

Volumetric soil moisture was determined in field at 0.1, 0.2 and 0.3m depths using a PR2 profile probe (Delta T, Burwell, UK). Measurements were taken at 6-8 day intervals from January until May 2018. Soil moisture access tubes were installed 3 weeks prior to the collection of data to allow the soil to settle around the access tube. An access tube was installed in each plot of the control (n=3) and cover crop treatment (n=3).

Available-N ($N\text{-}NH_4$ and $N\text{-}NO_3$) and aboveground biomass measurements were sampled at 3 week intervals between 4th September 2017 and 10th May 2018. For the determination of available-N three sub-samples of soil (0- 0.15m depth) were taken and combined for each plot. Specific measurements for N leaching were not taken in this study and thus the leaching potential of treatments were inferred from the available N at 0-0.15m (i.e. higher concentrations in the topsoil would indicate greater inputs for leaching potential).The fresh soil samples were stored at <4°C before sieving to <5.6 mm and extraction with 2M KCl (1:5 soil to solution ratio) and analysis using the Burkard SFA-2000 segmented flow. Henceforth, available-N refers only to $N\text{-}NO_3$, as the level of $N\text{-}NH_4$ was 0 mg kg^{-1} soil.

Aboveground biomass was determined from a 0.25m^2 quadrat, with one sample taken per plot and mean averaged across the cover crop treatment and control. Plant material was dried at 65°C and weighed. Total C and N were determined using an Elementar Vario III. The data obtained was used to calculate the C:N ratio and N present in the aboveground biomass.

2.3 Determination of Maize Yield

Maize yield was determined by weighing 2 rows of 10 plants and extrapolated to fresh weight (t ha^{-1}) in each plot. Plants were cut at a height of 0.22m to replicate forage harvesting and weighed in the field to 0.1 kg. Three randomly selected maize plants from each treatment were dried at 65^{o}C for 48 hours to determine dry matter content. Maize yield was determined on 3rd October 2018.

2.4 Statistical Analysis

Soil moisture data was screened for erroneous results that were likely produced by air pockets surrounding the probe sensors. Mean and standard deviation were calculated for each date interval and depth, any data ± 2 standard deviations from the mean were excluded. Data was further sense-checked and compared to field notes to remove data points that were affected by soil cracks that appeared near to the soil moisture access tubes. The PR2 profile probe recorded a measurement at 120° about its vertical axis per depth interval: these measurements were mean averaged per depth for each installation point. Following laboratory analysis available N raw data was multiplied by 5 to account for the dilution factor and mean averaged (n=3). Data were analysed using a T-test to a 0.05 probability level in Excel.

2.5 Climatic Records

A weather station (Pessl Instruments) located on the farm collected data at hourly intervals and was operated by a third party (FieldClimate). Rainfall, mean and mean minimum temperatures were recorded hourly but for ease of interpretation are shown in Figure 1 as weekly totals (rainfall) or averages of the mean and minimum temperature.

Figure 1 here

3 Results

3.1 Effect of cover crops on volumetric soil moisture

Spring 2018 was particularly wet (180.8mm) compared to the 30yr average rainfall of 145.5mm in Eastern England between March and May (Met Office, 2018). There were no significant differences between the cover crop and control for soil moisture content during the period of measurement, January – May (Figure 2). For most of measurement period soil moisture in the control and cover crop treatment was maintained at approximately 42, 47 and 51 vol% for 0.1, 0.2 and 0.3m depth, respectively. Soil moisture content decreased at 0.1m depth towards the end of April and early May. Soil moisture in the control was a significantly greater than the cover crop treatment for only one data point at 0.2m depth on 24th January 2018.

The persistent rainfall during the winter and spring of 2018 and low temperatures limiting evapotranspiration (Figure 1) maintained the volumetric soil moisture at or near field capacity for all depths for both the control and cover crop treatments (Figure 2). However, rainfall recorded in the week commencing 15th January was particularly high (58.7mm) whilst the weeks commencing 19th March and 16th April were especially dry (1.8 and 1.6mm, respectively). These short-term extremes in rainfall were not reflected in the measured soil moisture.

Figure 2 here

3.2 Cover crop aboveground biomass

Steady rainfall and warm temperatures from cover crop establishment until mid-October (Figure 1) aided rapid cover crop growth with maximum biomass observed by mid-November: this was approximately 3 months after establishment and was significantly greater than the control (wheat regrowth only; Figure 3). The minimum weekly temperature fell below 0°C on several occasions between the beginning of December to the end of March (Figure 1), which facilitated frost kill and plant senescence resulting in a reduced cover crop biomass (Figure 3). The cover crop biomass reduced by 41% from the peak in November to the lowest point in January (Figure 3). A small recovery in the cover crop aboveground biomass was measured in January, however the general trend was a gradual decline until May. Apart from the initial measurement, the cover crop aboveground biomass was greater than the wheat regrowth in the control, and at several data points there was a significant difference between the biomass of the cover crop and control over the trial period (Figure 3).

Figure 3 here

3.3 Effect of cover crop on Nitrogen dynamics

Initially there was a rapid decrease in topsoil N in the control and cover crop treatments (Figure 4). Given the small biomass of the cover crop and wheat regrowth (Figure 3) at the beginning of the trial it is possible that some of the decrease in N was also attributable to N leaching below the measurement depth. Between the beginning of October and end of November topsoil N was low (< 5 kg N ha^{-1}) for both the control and cover crop treatments (Figure 4). This period corresponded with maximum cover crop growth and N in cover crop biomass (Figures 3 and 5). The control plots had minimum wheat regrowth and lower biomass N (Figure 3 and 5) indicating topsoil N loss could be attributed to leaching, rather than uptake in the wheat regrowth during this period. At peak aboveground biomass in November the difference between the control and cover crop biomass N was 110kg N ha^{-1}. For the remainder of the measurement period the topsoil N in the cover crop treatment was greater than that of the wheat regrowth in the control and corresponded to a decrease in N held in the aboveground biomass of the cover crops (Figure 5).

Topsoil available N gradually decreased over winter between December and mid-February in the cover crop treatment (Figure 4). This corresponded with decreased aboveground biomass of the cover crop as it senesced in colder temperatures (Figure 3). Topsoil available N decreased from mid-February to mid April. After glyphosate was applied (4l ha^{-1}) in April (to ensure the cover crop was terminated) a large increase in topsoil N was observed until the end of the trial in May.

Nitrogen in the aboveground biomass (Figure 5) showed increased N held within the cover crop biomass compared to the control treatment (N in the wheat regrowth), this was significant for the latter period of the trial (end of January 2018 to May 2018). Total N within the plant biomass and topsoil system fluctuated over the duration of the trial.

Figure 4 here

Figure 5 here

The C:N ratio of both the cover crop treatment and control increased steadily throughout the trial (Figure 6). The C:N ratio of the cover crop treatment remained lower than the wheat regrowth and was significantly lower from early March until mid-April. Following the glyphosate application there was a substantial increase in the C:N ratio of the cover treatment. This response was not observed in the control.

Figure 6 here

3.4 Maize yield

There was no statistical difference between the maize yield following the CC treatment and the control (t test $p > 0.05$) (Table 3). Corrected to 100% dry matter, the control and cover crop treatments yielded 12.1 and 14.3 t ha^{-1}, respectively.

4 Discussion

4.1 Influence of frost sensitive cover crops on soil moisture availability and topsoil N

Some farmers have concerns that cover crops may dry out soils in the spring and reduce the amount of water available to the following cash crop (CTIC, 2017; Storr et al., 2019). Alternatively, in high rainfall years, cover crop residue may retain soil moisture and leave soils too wet for effective drilling, negatively affecting the next crop (White and Weil, 2010). Cover crops have been reported to reduce soil moisture (Nielsen et al., 2015), have no effect (Daigh et al., 2014; Snapp and Surapur, 2018) or can improve soil moisture availability (Basche et al., 2016). This trial showed no significant difference in soil moisture between the control with wheat regrowth and the cover crop treatment. The consistent over-winter rainfall was able to replenish the soil moisture transpired by the large cover crop biomass in the autumn (Figure 3) and a wet spring maintained soil moisture until late April. Despite some regrowth of the cover crop in the spring the majority of the cover crop had senesced over winter, which would have reduced the potential for plant transpiration to dry the soil. In both the control and cover crop treatment, residues provided a mulch effect (residue from the preceding crop and the senesced cover crop) that prevented evaporation from the soil surface helping to preserve soil moisture. Finally, the soil had a high organic matter content (27%), enabling greater water retention in the topsoil than might be observed for other soil types (e.g. sandy soils).

Cover crops can be effective scavengers of soil N and thus decrease the possibility of N-leaching over winter (Cooper et al., 2017). This effect was observed in the large quantity of N in the biomass of the cover crop at peak biomass (155kg N ha^{-1}) compared to the wheat regrowth in the control (52kg N ha^{-1}) and a corresponding reduction in available topsoil N. However, during the autumn available topsoil N declined at a similar rate in the control and cover crop treatment, although there was a large difference in the biomass N. The difference is likely to be due to N leached below the rooting zone in the control plot, whilst this mobile N was captured more effectively by the cover crop.

Using frost sensitive cover crops meant the plants were partially terminated (senesced) earlier than winter-hardy cover crop varieties that would need to be terminated in the spring. This had implications on subsequent timing of N availability to following crops and increased vulnerability of the scavenged N to leaching over the winter and early spring period. The senesced cover crop residue increased topsoil N from December (5kg N ha^{-1}) to mid-February (17kg N ha^{-1}) indicating mineralisation was active although the air temperatures were low. This period contained two very significant rainfall events (in December and January) when soil moisture content was high, indicating significant N leaching risk. However, the observed upward trend in topsoil N indicated N was not leached significantly from the soil after these events.

However, in early spring (from mid-February to mid-April) decreased topsoil N and the gradual reduction of N in the cover crop biomass (92 to 74kg N ha^{-1}) suggested that some N was leached below the measurement depth of 0.15m. Less N was held in the cover crop biomass during this period compared with N content at peak cover crop biomass (155kg N ha^{-1}) in late autumn. During this period, the mean temperature increased from 0 to 10°C and weekly rainfall increased, this resulted in increased mineralisation rates that liberated more N from the cover crop residues and leached through the soil profile. Thus, early termination of cover crops using natural frost sensitivity may increase N leaching risk in the spring if vigorous re-growth has not occurred and the spring is particularly wet. One way of mitigating this issue is to direct drill an early spring crop into the senesced cover crop to utilise the mineralised N before it is leached.

At the end of the trial in the spring the topsoil N rapidly increased following glyphosate application and this could be attributed to the decomposition of cover crop residues which have a low C:N ratio, but possibly from glyphosate itself. Glyphosate has a very low C:N ratio (3:1) and can be directly mineralised by the soil microorganisms which increased N (and C) mineralization (Haney et al., 2000).

Despite the increased topsoil N in the cover crop treatment, there was no significant difference in maize yield compared to the control. Yield similarity may be due to the standard agronomic inputs, especially mineral N application, masking the effect of the additional soil available N provided by the cover crop treatment.

4.2 Viability and Management Implications of Frost Sensitive Cover Crops

Frost sensitive cover crops were selected to assess the feasibility of eliminating or reducing the need for glyphosate, which is cheap and commonly used to terminate cover crops but it is only licensed for use until 2022 (European Commission, 2018). This research indicated that frost did not completely terminate the cover crop species used in the trial during winter under a temperate climate.

However, partial termination of cover crop may still be useful. Firstly, cover crops would be at varied stages of decomposition prior to herbicide application in the spring, which would benefit soil N supply. Gradual frost-induced termination provided small but continuous quantity of soil available N compared to a large flush of N after termination of the whole cover crop biomass at once. Secondly, the decreased aboveground biomass of the cover crop may ensure more effective herbicide application as the shading of weeds or small cover crop plants by larger leaves was minimised. Additionally, when drilling the following spring cash crop a reduced cover crop aboveground biomass is less likely to interfere with drilling machinery.

A cover crop rather than a fallow that is allowed to naturally regenerate (akin to the wheat regrowth in the control) is less likely to act as a green bridge that would host pests and disease capable of infecting adjacent cash crops or lead to increased weed prevalence (Baggs et al., 2000; Suffert et al., 2011). The cover crop biomass also had a lower C:N ratio (range 8-15) than the wheat regrowth (range 10-17), which would be expected to mineralise quicker and become available for the following crop to uptake. A frost sensitive cover crop may help mitigate the trade-off between biomass services (biomass production, N retention & weed suppression) and nutrient services (N supply, cash crop production and profitability) of using a cover crop (Finney et al., 2017). There is likely to always be a compromise between ensuring the following cash crop is not disadvantaged by N retention and mitigating the risk of N leaching. This will be mediated by cover crop termination management, but increasingly unpredictable weather patterns make it harder to minimise negative effects to either crop production or the environment.

Whilst leaching of N through the soil profile will be a concern following the senescence of the frost sensitive cover crop, particularly in wetter years, there could be benefits of frost termination with i) earlier N availability for the following cash crop aiding establishment and growth and ii) reduced reliance on herbicide or tillage as a means to terminate cover crop biomass, as some of the biomass is partially controlled by the cold temperatures.

5 Conclusion

Frost only partially terminated the cover crops in the temperate region of East Anglia, U.K. However, the gradual and partial termination of the cover crop had several benefits: i) progressive supply of N, ii) reduced aboveground biomass permitted a more effective use of herbicide and iii) partial decomposition of the cover crops eased residue flow through machinery. The study showed that prior to maize establishment cover crops and the wheat regrowth had a similar effect on soil moisture at 0.1, 0.2 and 0.3m depths. Topsoil available N increased in the cover crop treatment between December and March, which could be particularly beneficial to early spring sown crops. Though in wetter years nitrate leaching could be a risk in late winter and early spring if the following cash crops are planted later and the soil hydrological conditions permit leaching through the soil profile.

6 Acknowledgements

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Table 1: Trial timeline and site characteristics at Littleport.

Trial Overview	
Location	52.476010, 0.358024
Wheat harvest	12/08/2017
Cover crop establishment[1]	24/08/2017
Cover crop termination[2]	21/04/2018
Forage maize establishment [3]	20/05/2018
Site Characteristics	
Soil type[4]	Drainic sapric histosol[5]
pH	7.6
Bulk density (g cm^{-3})	0.87
Total N (%)	1.00
SOM[6] (%)	27

[1]Horsch Sprinter ST drill; [2]desiccated with glyphosate; [3]Horsch Maestro 8.75 CC drill; [4]WRB working group IUSS, 2015; [5]some small areas of the field are a Mollic Gleysol where surface peat depth is <0.5m, topsoil texture was peaty to humose silty clay; [6]determined by loss on ignition (BS EN 13039:2011)

Table 2: Mean plant count per m^2 on 17th October 2017. SEM is shown in parentheses.

Species	Black oats	Radish	Mustard	Wheat regrowth
Control				270 (42)
Cover crop	42 (6)	52 (4)	9 (2)	31 (9)

Figure 1: Weekly rainfall (mm), mean and minimum temperature (°C) recorded over the duration of the trial. Weekly rainfall coloured in black signified when a topsoil N and aboveground biomass sample was taken.

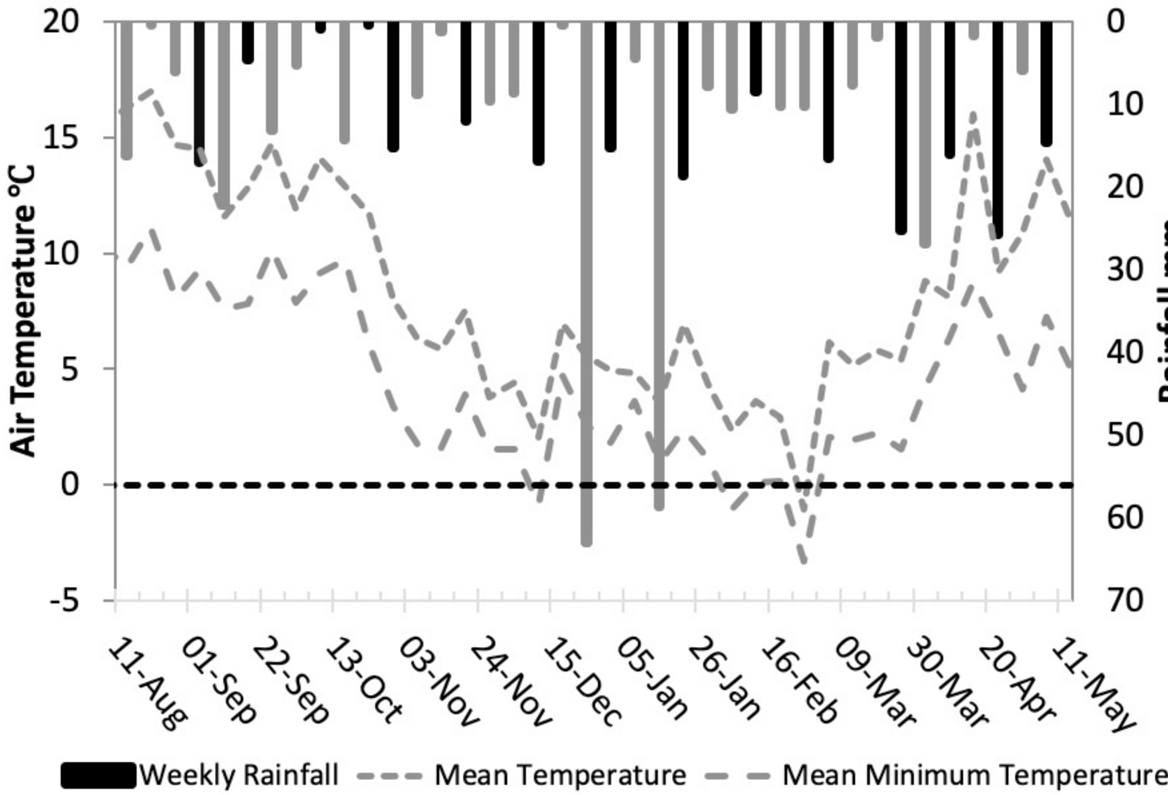
Figure 2: Mean soil moisture (Vol %) at 0.1, 0.2 and 0.3m depths (A, B and C, respectively). Statistical significance is denoted by **,T-Test; $p<0.05$). n = 3, unless data points were removed by the data screening process.

Figure 3: Dried above ground biomass measured between September 2017 and May 2018. Statistical significance is denoted by **, T-test ($p <0.05$). n = 3, error bars = standard error of the mean (SEM).

Figure 4: Topsoil NO_3-N (kg N ha^{-1}) measured between September 2017 and May 2018. Statistical significance is denoted by **, T-test ($p <0.05$). n = 3, error bars = SEM.

Figure 5: Above ground Biomass N (kg ha^{-1}) measured between September 2017 and May 2018. Statistical significance is denoted by **, T-test ($p <0.05$). n = 3, error bars = SEM.

Figure 6: Above ground biomass C:N ratio. Statistical significance is denoted by **, T-test ($P<0.05$). n = 3, error bars = SEM.



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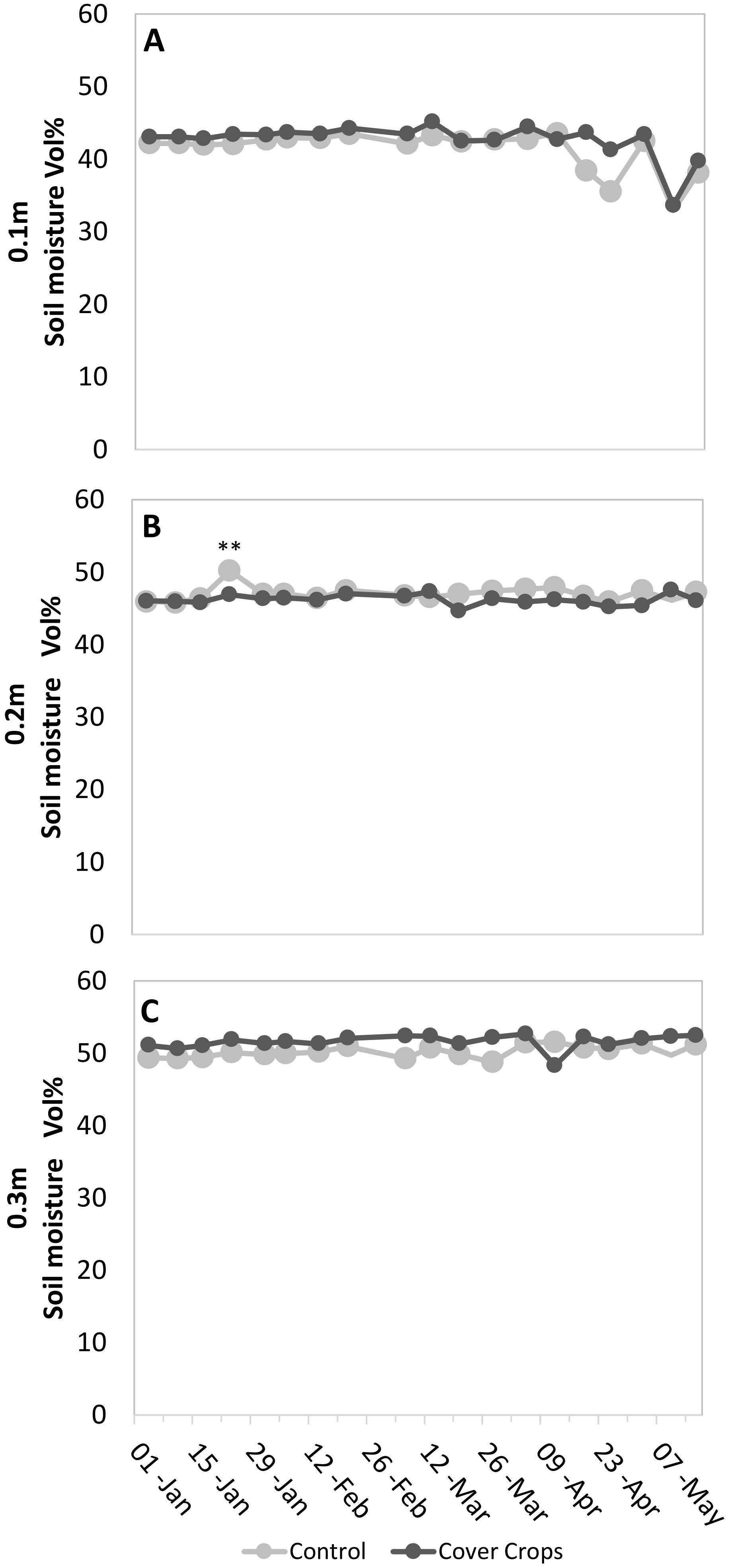
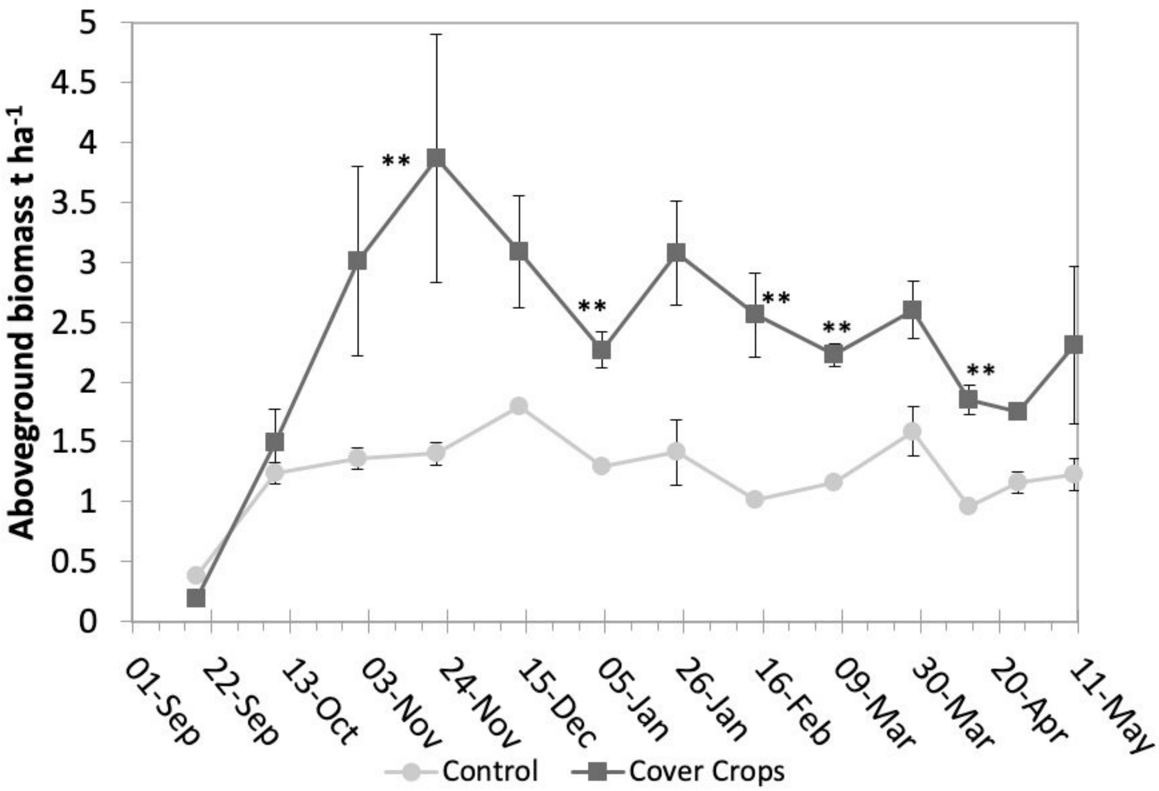

A
B
C
**
0.1m
Soil moisture Vol%
0.2m
Soil moisture Vol%
0.3m
Soil moisture Vol%
60
50
40
30
20
10
0
01-Jan
15-Jan
29-Jan
12-Feb
26-Feb
12-Mar
26-Mar
09-Apr
23-Apr
07-May
Control
Cover Crops



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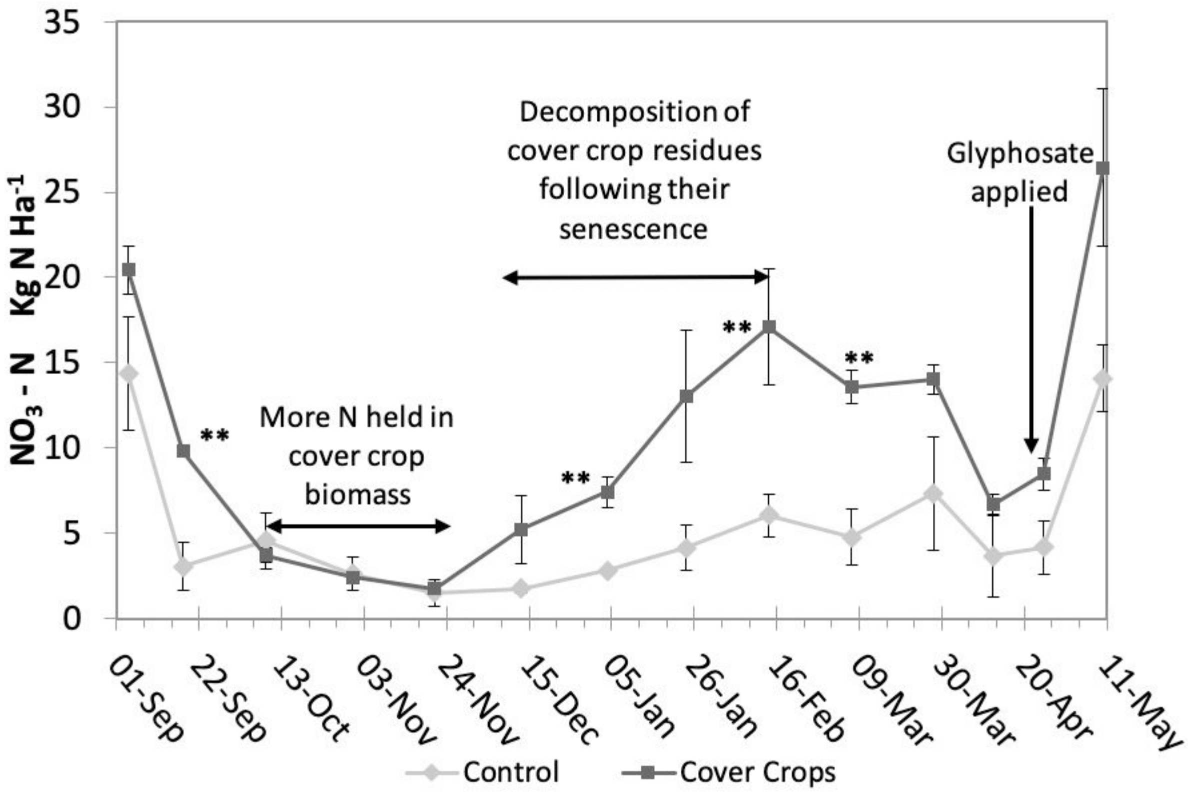

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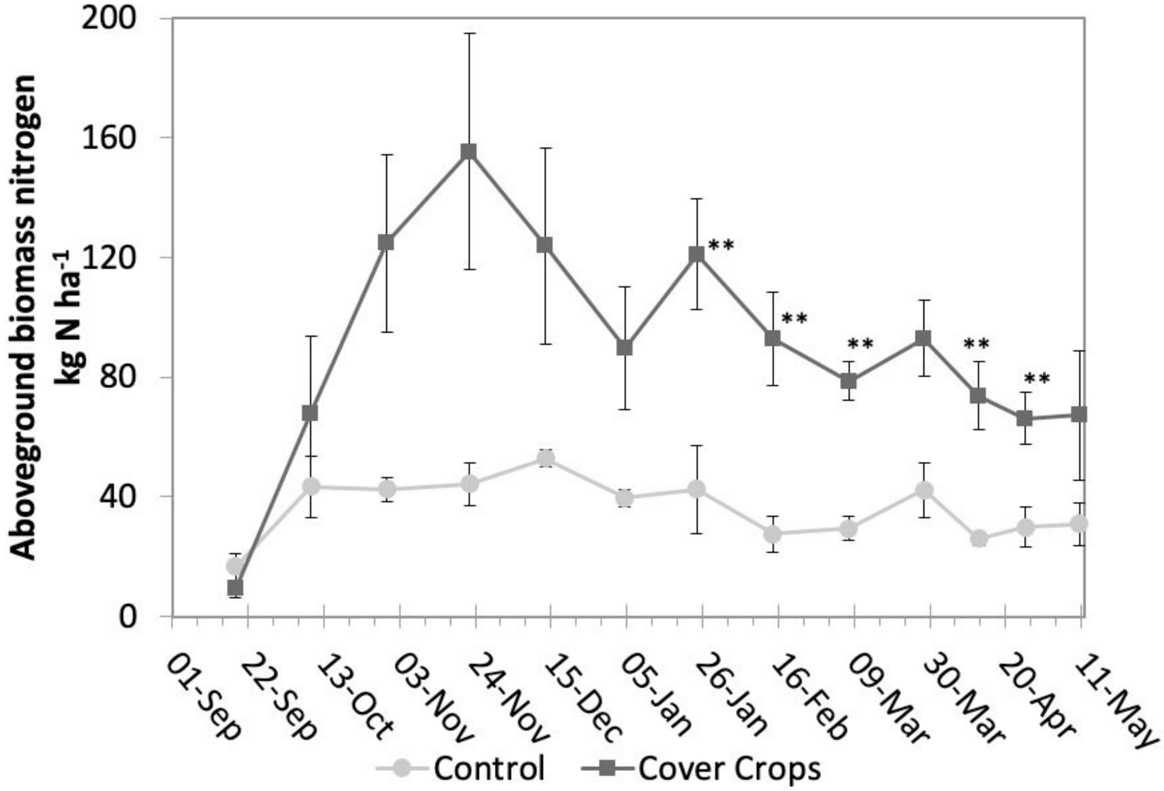

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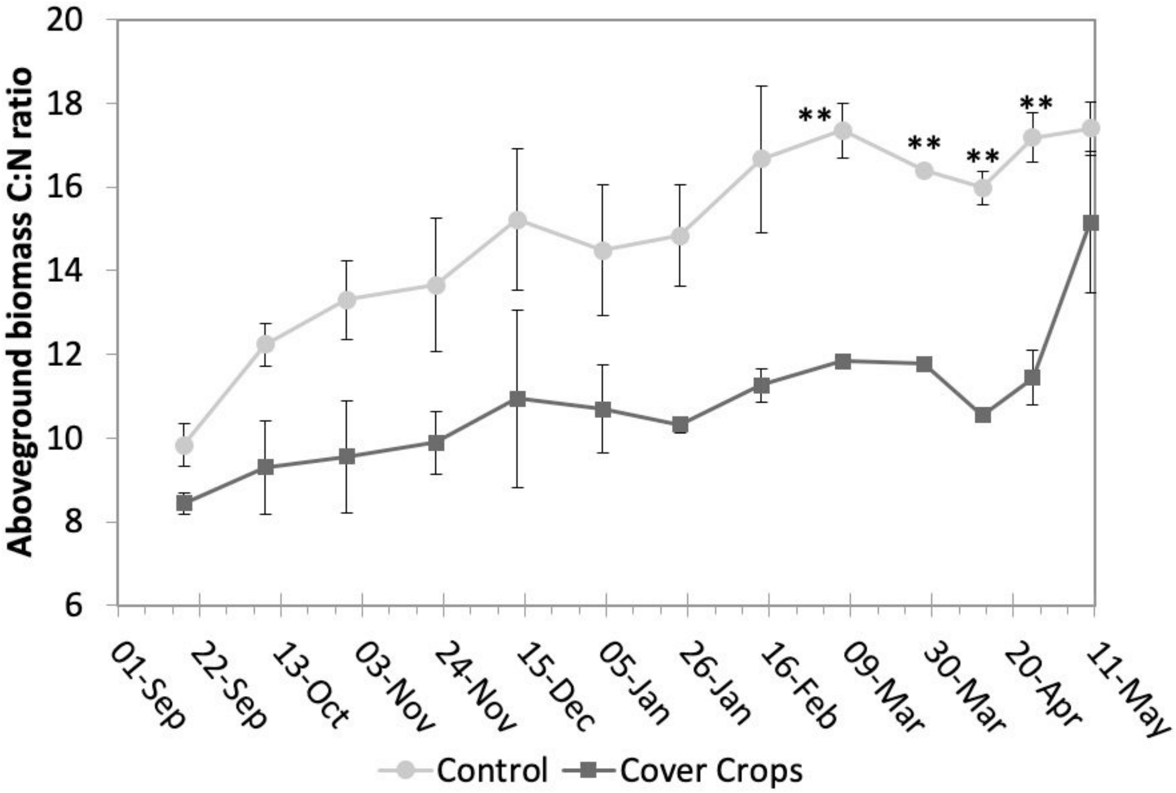

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