Early sowing dates and pre-plant nitrogen affect autumn weed control and nitrogen content of winter cover crops in rotation with spring crops

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Highlights

- Five cover crops in two years and two sites in Northern Italy were compared.
- Cover crop biomass was significantly lower with late than with early sowing date.
- Cover crop biomass was significantly higher in white mustard than in other species.
- Pre-plant N increased cover crop biomass, suggesting cover crops were N-limited.
- Weed growth was higher in legumes than in white mustard and black oat.

Abstract

Agroecological services of cover crops depend mostly on their biomass accumulation, which in turn depends on growing season weather and on nitrogen (N) availability. We hypothesised that cover crop growth and weed control can be increased with an early sowing date and under high residual soil inorganic N left after the previous cash crop harvest. This hypothesis was tested in Northern Italy, with a two-year field experiment in two locations with five cover crops, comparing two cover crop sowing dates (beginning of September, SD1, and mid September, SD2), and evaluating the effects of pre-plant soil mineral N addition (N0 and N1). The cover crops, grown between two maize crops, were terminated in March. Weather conditions in both years were drier than normal, reducing on average cover crop growth. In November, cover crop aboveground biomass and N content ranged between 0.5 and 3.3 t DM ha^{-1} and between 18 and 70 kg N ha^{-1}, respectively, with significantly lower values for SD2 compared to SD1 for most species. In most cases high pre-plant soil mineral N significantly increased cover crop biomass and N content, suggesting that cover crop growth was N-limited. Weed growth was higher in Egyptian clover and hairy vetch (0.7 t DM ha^{-1} on average) than in white mustard and black oat (0.2 t DM ha^{-1} on average), due to limited competitive ability of legumes. Cover crop biomass accumulation and weed control were enhanced by early sowing (in particular for legumes) and in conditions of high mineral N residue in the soil (in particular for non-legumes).

Keywords

Aboveground biomass; Agroecological services; Black oat; Hairy vetch; Rye; White mustard.

1. Introduction

In arable cropping systems, cover crops are cultivated between the harvest (or pre-harvest, in the case of interseeding) of a cash crop and the sowing of the subsequent cash crop, in a period during which the soil would otherwise remain bare (Justes, 2017). After its termination, cover crop biomass remains on the soil surface in no-tillage or strip-tillage systems, or it is incorporated in the soil as green manure in minimum or conventional tillage systems. Many agroecological services depend on cover crop above- and below-ground biomass growth, leaf area expansion, and nutrient content. Aboveground biomass and leaf area growth of cover crops can reduce weeds' biomass and density by competing for water, nutrients, and light (Osipitan et al., 2019). Moreover, higher cover crop biomass results in increased organic matter returned to the soil with positive advantages for soil life, carbon (C) sequestration and aggregate stability (Jian et al., 2020; McClelland et al., 2021; Wood and Bowman, 2021). Among nutrients, cover crops have relevant effects on nitrogen (N) because they reduce losses of nitrate via leaching (Thapa et al., 2018), and when the dead cover crop mulch decomposes after termination, part of the N can be mineralised and made available to the cash crop which follows (Poffenbarger et al., 2015).

Growth, development and nitrogen content of cover crops depend on plant genotype, and on the interacting effects of weather, soil chemical, physical and biological properties, and crop management (Connor et al., 2011). Solar radiation and thermal time during the cover crop growing season at a specific location depend on the chosen sowing date, influenced by the previous cash crop's harvest date and on adequate soil humidity, affected by precipitation (amount and frequency). Nitrogen availability in soil is also strongly influenced by N management during the previous cash crop season, which affects the residual inorganic N present in the soil after crop harvest. As for all arable crops, the rate of crop N demand strongly increases during the linear growth phase (Connor et al., 2011), a stage which can be reached before winter if sowing is carried out in early autumn. Legume cover crops cannot rely on N_2-fixation in cool conditions: below 15 °C symbiotic N_2-fixation is dramatically reduced (Alexandre et al., 2012) and below 7-9 °C it is almost inhibited (Robin et al., 2005). Therefore, in cool conditions legume species need to take up N from the soil to sustain their growth. The specific soil and atmospheric conditions of the location where the cover crop is cultivated are therefore very important to ensure its success.

The Northern Italian plain is characterised by a humid subtropical climate (Cfa; Köppen-Geiger classification); spring-summer crops are widely cultivated thanks to the availability of irrigation water (Bechini and Castoldi, 2009; Tadiello et al., 2022). In that region, winter cover crops are of interest when soil is left bare during autumn and spring (Tadiello et al., 2022). Maize (*Zea mays* L.), the main crop in the area, is frequently sown before the end of March and the first half of April; as a consequence, its harvest is carried out in August or at the beginning of September if cultivated for silage, or a few weeks later if cultivated for grain (Blandino et al., 2023). Other spring-summer crops like soybean (*Glycine max* (L.) Merr.), tomato (*Solanum lycopersicum* L.) and rice (*Oryza sativa* L.) are sown later (in April or May) and harvested in September or October. In this context, the application of the CAP Strategic Plan 2023-2027, which emphasises environmental protection, must be considered. It includes obligations such as implementing winter vegetative cover in specified Nitrate Vulnerable Zones to mitigate nitrate leaching. This program also mandates maintaining soil coverage for at least 60 consecutive days between 15 September and 15 May, ensuring that crop residues or natural cover will prevent bare soil. These measures aim to enhance environmental sustainability and soil health within Lombardy (Northern Italy), aligning with the broader directives of the CAP Strategic Plan.

In these conditions winter cover crops can be sown from the beginning of September and through the whole month of October. Sowing in September is likely to maximise biomass production, because it allows the crop to take advantage of the favourable temperature and solar radiation between September and mid November for cover crop growth (Severini et al., 2021; Tadiello et al., 2022) and to reduce nitrate leaching. Soil N available for cover crops is made up of unused residual soil mineral N from the previous cash crop, and of N mineralised during the autumn (Olfs et al., 2005). Nitrogen management in the previous spring-summer cash crop and historical manure applications (affecting soil N mineralisation potential) are highly variable among farms, and thus both inorganic soil N after harvest of summer crops and fall organic N mineralisation can vary a lot depending on the specific farm context. This is confirmed by periodic monitoring (August-November) of post-harvest soil nitrate concentration, with average values (in the 0-30 cm layer) that differ by about 60-120 kg $N\text{-}NO_3^-$ ha^{-1} among geographical areas in Lombardy (ERSAF – Regione Lombardia, 2022), probably arising from uncertainties in N budget components, due to factors affecting crop N uptake and N losses during the cash crop growing season. Weed management in rotations characterised by spring-summer annual crops can be improved by winter cover crops if they can avoid the dissemination of annual weeds that would reach maturity in spring before soil preparation for crops like soybean or tomato which are not planted as early as maize. This is the case for example for *Senecio* *vulgaris* L., *Stellaria media* (L.) Vill., *Tussilago farfara* L., *Cerastium glomeratum* Thill., *Poa annua* L., *Lamium purpureum* L., *Cardamine hirsuta* L. and *Capsella bursa-pastoris* (L.) Medik. Different species of cover crops have different weed control capacity, due to variable competing ability against weeds, and due also to the allelopathic properties of some cover crop species (Pérez and Ormeño-Núñez, 1993; Kruidhof et al., 2008; Bhadoria, 2010; Tabaglio et al., 2013; Gfeller et al., 2018).

Winter cover crops can be classified as winter-hardy (normally surviving winter frost) or winter-killed (being totally or partially damaged by sub-zero temperatures) (Thorup-Kristensen et al., 2003). Winter-killed cover crops are appreciated in conservation agriculture, because their termination is easy and occurs without the use of herbicides, if frost kills the crop stand (Labreuche and Bodilis, 2010; Gabbrielli et al., 2022). For some of the most interesting cover crop species, either winter-killed (white mustard, *Sinapis alba* L.; Egyptian clover, *Trifolium alexandrinum* L. and black oat, *Avena strigosa* Schreb.) or winter-hardy (rye, *Secale cereale* L. and hairy vetch, *Vicia villosa* Roth.), however, published information about their growth, N content and weed control in autumn in temperate climates is extremely limited. There are a few examples of work from Hashemi et al. (2013) and Murrell et al. (2017) for rye, Schappert et al. (2019) and Tadiello et al. (2022) for black oat, Kulig et al. (2010), Handlířová et al. (2016 and 2017), Tadiello et al. (2022) for white mustard and Egyptian clover. More specifically, the consequences of delaying cover crop sowing on the fall growth and N accumulation of these species were seldom quantified. The few available experiments indicate that postponing sowing by about two weeks reduced cover crop growth and N uptake for both rye (Hashemi et al., 2013) and white mustard (Stivers-Young, 1998). Moreover, it is also important to understand the effect of varying mineral N availability in soil at cover crop sowing on the cover crops' growth in autumn. Mikó et al. (2012) and Rühlemann and Schmidtke (2016) applied 50 kg N ha^{-1} before sowing white mustard in Hungary and Germany, respectively, and observed a positive effect of applied N on mustard growth and N uptake, indicating that autumn growth can be N-limited.

We therefore hypothesised that increased cover crop growth and weed control can be obtained with an early sowing date and with high mineral N in the soil before cover crop sowing. To verify these hypotheses, the aim of this research was to determine the effects of sowing date and pre-plant nitrogen availability on the growth, nitrogen content and competition against weeds of three winter killed (white mustard, Egyptian clover and black oat) and two winter-hardy (rye and hairy vetch) cover crops. The measurements were carried out in November, at a time when the frost had not yet damaged the biomass, to ensure representativeness of the complete fall growth. Two residual mineral N levels after harvest of the spring-summer crop (maize) were simulated through cover crop pre-plant addition of mineral N (no fertilization vs. addition of 50 kg N ha^{-1}). The five cover crop species span a range of botanical families (*Poaceae*, *Fabaceae*, *Brassicaceae*) and of response to frost, and include two widely adopted species in the study area (black oat and white mustard). We expected that the five species would respond differently to the experimental factors involved (sowing date and pre-plant N availability). The first sowing date was determined as soon as soil water content was adequate for cover crop sowing after the harvest of the cash crop (i.e., between the end of August and the beginning of September), while the second one was about 300 °C d after, still subject to proper soil and weather conditions. This thermal time interval allowed both sowing dates to occur in

September, a month that is adequate for cover crop sowing after the harvest of maize, sorghum or tomatoes.

2. Materials and methods

2.1. Experimental site and design

The experiment was started in summer 2017 in two fields located in Lombardy, Northern Italy. The first field was at Cascina Santa Martina of Morando Bolognini Foundation in Sant'Angelo Lodigiano, Lodi (45°13'57.6"N 9°25'36.7"E, altitude 73 m asl). The soil was loam, according to USDA texture classification, (44.8% sand, 40.7% silt and 14.5% clay), without gravel, subacidic (pH_W 6.0), and with 1.5% organic matter content (C/N 8.8). The second field was located at Agricola Motti in Orzinuovi, Brescia (45°23'53.0"N 9°54'33.8"E) and had a sandy-loam soil (54.3% sand, 31.0% silt and 14.7% clay), with high presence of gravel (54% on a weight basis), neutral reaction (pH_W 6.8), and 3.9% organic matter content (C/N 9.1); the high organic matter content was due to historical application of cattle manure until three years before starting this experiment.

Methods adopted for determining soil properties were as follows, according to the Italian official methods (Italian Ministry for Agriculture and Forestry Policy, 2000): texture, pipette method; pH, electrochemical measurement by a Crison GLP 21 + pH-meter (Crison S.A., Spain); organic C, by dry combustion using a ThermoQuest NA1500 elemental analyser (Carlo Erba, Milano, Italy). The climate of Sant'Angelo Lodigiano and Orzinuovi (period 1988-2016) is characterised by average annual rainfall of 830 and 957 mm and average annual temperatures of 13.2 and 14.4 °C, respectively (Figure 1). Both fields were flat, did not receive organic fertilizers in the three years before the start of the experiment, and were cultivated with maize in the year before the start of the experiment. Previous maize crops at the two sites received an application of 250 kg N ha^{-1} as urea (46-0-0), 20% of which was applied just before sowing and the rest as sidedressing when plants were at the sixth-seventh leaf growth stage. Weed control was obtained by chemical pre-emergence weeding.

The experimental factors tested were cover crop sowing date, type of cover crop, and pre-plant mineral N availability; this latter factor was tested only at Sant'Angelo Lodigiano. The first factor (sowing date) had two levels: a first date (SD1) ranging from 30 August to 6 September, and a second one (SD2) set approximately two weeks later. All sowing dates are reported in Table 1. The second factor (type of cover crop) had seven levels corresponding to five cover crops, plus two control treatments without cover crops. The five cover crops were the following: two grasses, black oat (cv. Saia) and rye (cv. Stanko); two legumes, hairy vetch (cv. Villana) and Egyptian clover (cv. Mario); and a brassica, white mustard (cv. Architect). The selected species were representative of both winter-hardy cover crops (rye and hairy vetch) and winter-killed cover crops (black oat, Egyptian clover and white mustard) commonly cultivated in Northern Italy. The two control treatments included a chemically weeded bare soil (treated with glyphosate at 1.44 kg a.i. ha^{-1}), and a bare soil with naturally grown weeds (no cover crop treatment). The chemically weeded control was included to calculate the apparent N recovery of cover crop N in maize planted after cover crops, but was not used in the context of this study, which is focused on cover crops only. The third factor (pre-plant soil mineral N) had two levels, corresponding to two residual soil mineral N contents after maize harvest: the first level (N0) was obtained by not adding N, while the second level (N1) received 50 kg N ha^{-1} $year^{-1}$ as calcium nitrate (15.5% N) before cover crop sowing. Nitrogen fertilizer was homogenously applied on N1 plots using a M1000 pneumatic spreader (Elho, Bennas, Finland) the day before cover crop sowing, and incorporated in the soil during subsequent cultivation.

At Orzinuovi, the experimental factors were combined according to a split-plot design, with sowing date being the whole-plot factor, and type of cover crop the sub-plot factor. At Sant'Angelo Lodigiano, the experimental design was a split-split-plot with sowing date, type of cover crop and pre-plant soil mineral N being the whole-plot, sub-plot, and sub-sub-plot factor, respectively. At both sites there were four replicates (blocks) separated from each other by a strip of eight meters cultivated in both years with white mustard; cover crops were seeded on plots of 48 m^2 (6 × 8 m). Treatments were applied to the same plots in the two years of the experiment.

2.2. Cultivation

In both years, soil was harrowed at a depth of 15 cm one or two days before cover crop sowing using a KARAT 9/300 cultivator (Lemken, Alpen, Germany) at Sant'Angelo Lodigiano, and a CLC Evo 300 cultivator (Kverneland, Klepp, Norway) at Orzinuovi. Cover crops were sown in rows spaced 15 cm with a universal seeder Tramline CE 300 (Sulky, Huntingdon, UK) and 750 A (John Deere, Moline, IL, USA) at Sant'Angelo Lodigiano and at Orzinuovi, respectively. In both years and both locations seeding rates in kg seed ha^{-1} and plant population density (plants m^{-2}; in brackets) were the following: black oat 50 (260), rye 150 (430), Egyptian clover 25 (770), hairy vetch 40 (115), and white mustard 15 (210). At Sant'Angelo Lodigiano in 2018 rye was damaged by larvae of *Duponchelia fovealis* Zeller and an insecticide (Tau-Fluvalinate at 250 mL ha^{-1}) was applied. On 10 October 2017 at Sant'Angelo Lodigiano and on 25 September 2018 at Orzinuovi the field was irrigated to avoid the severe risk of a compromised establishment of cover crop stands due to low precipitation. We irrigated by sprinkler, providing 30 and 20 mm of water at Sant'Angelo Lodigiano and Orzinuovi, respectively. In March, cover crops and weeds were terminated with glyphosate (1.78 kg a.i. ha^{-1}). Two weeks after termination, the field was cultivated with the same minimum tillage equipment used before cover crop sowing, and fertilized with mineral N, P, and K (6-12-24 at a rate of 400 kg ha^{-1}) in pre-seeding, and maize was sown. At sidedressing, urea was applied at 115 and 150 kg N ha^{-1} at Sant'Angelo Lodigiano and Orzinuovi, respectively. In both years, maize was harvested for silage. Dates of field operations at Sant'Angelo Lodigiano and Orzinuovi in the two years of trials are reported in Table 1. Sowing of maize in 2018 at Sant'Angelo Lodigiano was delayed from 20 April to 14 May due to a prolonged period of frequent rain showers, although little rain actually fell.

2.3. Cover crop sampling and analysis

At both sites and in both years, aboveground biomass (AGB) was sampled in November (Table 1). At each sampling date, a surface of 1 m^2 per plot was harvested by hand (cut height 1 cm), weed plants were separated from cover crop plants and fresh weights of the biomass of cover crops and weeds were determined. A subsample of weeds and cover crops was dried at 105 °C to calculate their AGB on a dry weight basis. Dry samples were ground with a ZM 100 centrifugal mill equipped with a 0.2 mm mesh sieve (Retsch Gmbh & Co., Haan, Germany); thereafter total N concentration was determined by dry combustion using a ThermoQuest NA1500 elemental analyser (Carlo Erba, Italy).

2.4. Calculation and data analysis

Growing degree days (GDDs) were calculated by summing for each day the difference between the average air temperature and 0 °C, only for days when the temperature was positive (Tribouillois et al., 2015).

Nitrogen content in AGB (kg N ha^{-1}) of cover crops and weeds was calculated multiplying AGB dry matter (DM), expressed in t DM ha^{-1}, by total N concentration (% DM).

Data were analysed with R version 4.0.2. to study the effect of the experimental factors on the AGB and the N content of cover crops and weeds, and on the N concentration and C to N ratio of cover crops. The factor "type of cover crop" included the "no cover crop treatment" only for the variables AGB and N content of weeds. Data measured in the two fields were analysed with a linear mixed effects model in which the type of cover crop was the split-plot factor, as its levels were randomly assigned to split plots within each whole plot. The model included the random effect of both location and year. In detail, to account for the design scheme and the repeated measures over time, we added a random factor that resulted from nesting the "type of cover crop" within "sowing date" within "block" within "year" and within "location". When needed, the heterogeneity of variances due to the experimental factors was solved by weighing variances with the *varIdent* function, representing a constant variance function structure (Pinheiro and Bates, 2000). A separate analysis was carried out only on the data measured at Sant'Angelo Lodigiano, to study the effects of "sowing date", "type of cover crop", "pre-plant mineral N", "year" and their interaction on the measured variables. Also in these analyses, the factor "type of cover crop" included the "no cover crop treatment" only for the variables AGB and N content of weeds. In defining the random effect of the nested design, we have considered “pre-plant mineral N” as the sub-sub-plot factor, “type of cover crop” as the sub-plot factor, and “sowing date” the whole-plot factor. As previously explained, these spatial units were then nested within year and block. Means were separated by the Sidak post-hoc test using the R packages “emmeans” (version 1.8.0). When interactions between experimental factors were significant, means were calculated across the levels of other non-significant factors and then compared within each level of the factors involved in the interaction. Significant mean differences are reported at $P<0.05$.

3. Results

3.1. Weather and climatic conditions

Water availability was particularly low in the two cultivation seasons. Average accumulated precipitation in September and October in Sant'Angelo Lodigiano and Orzinuovi was 174 and 196 mm in the long-term, while in our seasons it was 147 and 100 mm in 2017, and 114 and 168 mm in 2018, respectively, for the two sites. October was particularly dry in 2017 (only 3 mm rain in Sant'Angelo Lodigiano, and 13 mm in Orzinuovi), while September was dry in 2018 (10 mm in Sant'Angelo Lodigiano, 40 mm in Orzinuovi). Therefore, to reduce crop water stress, irrigation was applied in both years (see Materials and Methods).

Accumulated GDDs with a minimum cardinal temperature of 0 °C from sowing to November sampling in Sant'Angelo Lodigiano (Table 2) was, on average for two years, 1238 °C d for SD1 and 887 °C d for SD2. In Orzinuovi the average was 1368 °C d and 1095 °C d for SD1 and SD2, respectively. Using an average sowing date on September 4th for SD1 and September 18th for SD2, and an average sampling date on November 19th, the accumulated GDDs between sowing and termination for the long-term climatic series were 1138 °C d in Sant'Angelo Lodigiano and 1237 °C d in Orzinuovi for SD1, and 854 and 936 °C d for SD2.

In Orzinuovi, there were 41 and 58 days with minimum temperatures below 0 °C in the two cultivation seasons, respectively. In 57% of these days the temperatures were in the range between -2 and 0 °C, in 41% of the days between -2 and -5 °C, and only in 2% of cases they were below -5 °C. In Sant'Angelo Lodigiano, there were 64 days with negative temperatures in both cover crop growing seasons. The percentage of days in the three ranges of minimum temperature was 59% between -2 and 0 °C, 35% between -5 and -2 °C, and 6% below -5 °C.

3.2. Cover crop aboveground biomass

The aboveground biomass of cover crops in late autumn ranged from 0.5 to 3.3 t DM ha^{-1} (Figure 2). The analysis of variance conducted with the data of the two locations and two years showed that the interaction "sowing date" × "type of cover crop" was significant (P<0.05; Table S1). Compared to SD1, SD2 resulted in a significant decrease in AGB for all cover crops except rye (Figure 2). The reduction in biomass was larger for Egyptian clover (-65%) and hairy vetch (-52%) compared to black oat (-37%) and white mustard (-39%). Differences among cover crop types occurred for both sowing dates (Figure 2). White mustard (2.0-3.3 t DM ha^{-1}) produced significantly more biomass than the other cover crops. In SD1 the AGB of black oat, and in SD2 the AGB of black oat and rye were higher than that produced by Egyptian clover.

At Sant'Angelo Lodigiano, AGB of cover crops was significantly affected by the interactions "type of cover crop" × "pre-plant soil mineral N", "sowing date" × "type of cover crop" × "year", and "sowing date" × "pre-plant soil mineral N" × "year" (P<0.05; Table S2). Compared to low pre-plant soil mineral N (N0), N1 resulted in a significant general increase of cover crop AGB, except in the second year for SD2 (Table 3). The only cover crop that did not increase AGB in N1 compared to N0 was Egyptian clover (Table S3). Differently, the increase of AGB in N1 compared to N0 was 20% for black oat, 28-29% for rye and hairy vetch, and 49% for white mustard (Table S3).

3.3. Cover crop nitrogen concentration and C to N ratio of aboveground biomass

Differences of N concentration in AGB and of C to N ratio of AGB among cover crop types were evident. Hairy vetch had the highest N concentration in AGB in both sowing dates (3.8-3.9%), while white mustard had the lowest (2.1-2.9%). The other species showed a different ranking depending on the sowing date (Table 4). The C to N ratio of AGB followed a trend opposite to the N concentration in AGB, with larger values in white mustard (19.8 and 13.9 in SD1 and SD2, respectively) and black oat (19.6 and 14.1 in SD1 and SD2, respectively) compared to Egyptian clover (13.2 and 11.4 in SD1 and SD2, respectively) and hairy vetch (10.1 and 9.9 in SD1 and SD2, respectively) (Table 4).

The N concentration in AGB and the C to N ratio of AGB were significantly affected by the interaction “sowing date” × “type of cover cop” when data of the two locations and years were considered ($P<0.05$; Table S1). The N concentration in AGB of the two legumes remained constant in the two sowing dates, while it significantly decreased in white mustard, black oat, and rye with SD1 compared to SD2 (Table 4). Therefore, AGB of rye, black oat, and white mustard in SD1 had significantly higher C to N ratio compared to AGB of the same species sown later; the same was observed for Egyptian clover (Table 4).

At Sant’Angelo Lodigiano, N concentration in AGB was significantly affected by the two-way interactions “sowing date” × “type of cover crop”, “type of cover crop” × “year”, and “pre-plant soil mineral N” × “year” ($P<0.05$; Table S2); the C to N ratio of AGB was significantly affected by the three-way interactions “sowing date” × “type of cover crop” × “year”, and “sowing date” × “pre-plant soil mineral N” × “year” ($P<0.05$; Table S2). The effect of pre-plant soil mineral N on the N concentration of AGB was significant only in 2017 (Table S4), with slightly higher values in N1 (3.2%) compared to N0 (3.0%). The average C to N ratio did not change in N1 compared to N0 in both years for SD2, while for SD1 it was significantly higher in N0 compared to N1 in 2017 (on average 16.7 vs. 15.2), and in N1 compared to N0 in 2018 (on average 12.7 vs. 11.9) (Table S5).

3.4. Cover crop nitrogen content in aboveground biomass

Nitrogen content in aboveground biomass of cover crops in the two locations and two years was significantly affected by the interaction “sowing date” × “type of cover crop” ($P<0.05$; Table S1). The two legumes accumulated significantly more N (+26 and +40 kg N ha^{-1} for Egyptian clover and hairy vetch, respectively) with SD1 compared to SD2, while N content of the other species did not change with sowing date (Figure 3). With SD1, N content of hairy vetch and white mustard (on average 70 kg N ha^{-1}) was significantly higher than that of Egyptian clover and rye (on average 36 kg N ha^{-1}). Differently, with SD2 white mustard and black oat were the cover crops with the highest N content (on average 52 kg N ha^{-1}), while for Egyptian clover the N content was the lowest (15 kg N ha^{-1}), with the exception of vetch that was not statistically different from it.

At Sant’Angelo Lodigiano, N content was significantly affected by the two-way interactions “sowing date” × “type of cover crop”, “sowing date” × “pre-plant soil mineral N”, “type of cover crop × “pre-plant soil mineral N” and “type of cover crop × year” ($P<0.05$; Table S2). On average, N content significantly increased with N1 compared to N0 in both sowing dates (Table S6). The only cover crop type that did not respond to pre-plant soil mineral N was Egyptian clover (Table S7).

3.5. Biomass and N content of weeds

In the two locations and in the two years, the AGB and N content of weeds in the cover crop treatments were significantly different among cover crop species, while the effect of sowing date and "sowing date" × "type of cover crop" was not significant ($P<0.05$; Table S1). On average, the largest biomass and N content of weeds was found in the no cover crop treatment (1.3 t DM ha^{-1} and 21 kg N ha^{-1}) and in the two legumes (on average, 0.7 t DM ha^{-1} and 16 kg N ha^{-1}), while the lowest values were found in white mustard and black oat (on average, 0.2 t DM ha^{-1} and 6 kg N ha^{-1}) (Table 5). At Sant'Angelo Lodigiano, the factor "pre-plant soil mineral N" and its interactions with other factors did not significantly affect the AGB and N content of weeds (Table S2).

4. Discussion

4.1. Thermal time accumulation

The accumulated GDDs between SD1 (30 August-6 September) and sampling (14-22 November) averaged 1303 °C d for the two years and the two locations, and 991 °C d for SD2 (Table 2). Similar values were reported for one year by Tribouillois et al. (2015), who calculated 1160 and 1118 °C d with a base temperature of 0 °C between planting (on 16 and 3 August) and sampling (on 12 October and 28 September), respectively for a French and a Swiss location where cover crops were cultivated under non-limiting water and N conditions. The mean air temperature (18.4 °C and 16.7 °C in the French and the Swiss site, respectively) was higher in the study of Tribouillois et al. (2015) than in our sites (16.6 °C and 15.4 °C on average for the two growing seasons in Sant'Angelo Lodigiano and Orzinuovi, respectively). Therefore, the duration of the period between planting and sampling (on average 56.5 d for the Swiss and French experiment) was shorter than the average duration in our experiment for SD1 (76.5 d). Tadiello et al. (2022) measured on average 829 and 1125 °C d between planting in September and sampling in November in 2017 and 2018 in Northern Italy. Therefore, considering that temperature strongly affects growth, and based on our results in terms of accumulated GDDs and aboveground biomass (Table 2), a value of about 900-1300 °C d could be considered the thermal requirement to achieve a good stand (> 1 t DM ha^{-1}) of several cover crops (grasses and brassicas) before winter killing in climatic conditions similar to those of our study.

4.2. Cover crop productivity in autumn

The productivity of the different species tested in our experiment was in the range observed in the literature for similar conditions. Biomass of white mustard in the interval 0.9-4.4 t DM ha^{-1} (average 2.1 t DM ha^{-1}) was measured for growing conditions similar to ours (Stivers-Young, 1998) or for longer seasons at higher latitudes (Handlířová et al., 2016 and 2017). With a longer period and favourable weather conditions, biomass accumulation can be even higher, e.g., 4.6-7.8 t DM ha^{-1} as reported by Herrera and Liedgens (2009), and Herrera et al. (2010 and 2017) in the Swiss midlands near Zurich. In our experiment hairy vetch accumulated less AGB in autumn (on average 1.9 and 0.9 t DM ha^{-1} for SD1 and SD2, respectively) compared to what was achieved after winter, when - about two weeks before maize sowing - its biomass was 1.8 times compared to autumn (data not shown). Indeed, in the same cultivation region and years, Severini et al. (2021) measured 2.4-4.8 (average 3.7) t DM ha^{-1} for hairy vetch at the end of April-beginning of May from September sowing. A higher biomass accumulation (on average 5.7 t DM ha^{-1}) was obtained by Teasdale et al. (2012) by sowing hairy vetch after minimum tillage in a silty loam soil in Maryland (USA) at the beginning of September and sampling in June. Rye cover crop was extensively studied in temperate climates in a wide latitudinal range (from about 30 °N to 50 °N). At mid November Murrell et al. (2017) found an average rye AGB of 0.83 t DM ha^{-1}, with higher values (1.48 t DM ha^{-1}) for early sowing (August), and lower values for sowing between the second decade of September and the first decade of October (0.18 t DM ha^{-1}). As with hairy vetch, rye AGB in our experiment at cover crop termination at the end of winter increased compared to autumn (2.2 vs 1.2 t DM ha^{-1}, respectively; data not shown). For a later termination date, this species can reach 9-11 t DM ha^{-1}, as measured in May by Severini et al. (2021).

In our experiment, the second sowing date, due to lower radiation and temperature, resulted in significantly lower AGB compared to SD1 for all cover crops, except rye (Figure 2). Sowing from mid September onwards is not suggested for legume cover crops, which have shown less ability to compete with weeds. Winter-hardy species, like hairy vetch and rye, could still be planted in the second half of September if the following cash crop in spring is planted later; in this case the reduced growth in autumn is compensated by biomass produced in spring.

At Sant'Angelo Lodigiano, in three out of four year × sowing date combinations, cover crops responded to mineral N applied before planting (Table 3), which simulated residual soil inorganic N left after the summer crop, or mineralisation of soil organic N during the cover crop growing season. This indicates that under the no fertilization treatment, cover crop growth was N-limited, except for Egyptian clover and for hairy vetch, but only at the second sowing date (Table S3). Therefore, in conditions of high pre-plant soil mineral N, cover crops not only will remove excess nitrogen from the soil (thus reducing N leaching), but also accumulate more biomass thanks to increased N availability compared to low pre-plant N levels. Indeed, the positive response of cover crops to 50-80 kg N ha^{-1} application was reported in several experiments on white mustard and rye (Mikó et al., 2012; Komatsuzaki and Wagger, 2015; Rühlemann and Schmidtke, 2016; Mirsky et al., 2017).

4.3. Nitrogen concentration and C/N ratio in aboveground cover crop biomass

Measured N concentration in aboveground cover crop biomass reflected species differences, with grasses and brassicas showing in general significantly lower concentrations and higher C/N ratios compared to hairy vetch in both years (Table 4). Differences among species were likely due to differences in leaf/stem ratio (visually assessed during sampling), which was higher for rye compared to black oat, and higher for hairy vetch than for Egyptian clover (data not shown).

Significant differences of aboveground N concentration were also found between sowing dates, but only for rye, black oat and white mustard (Table 4). This was likely due to two causes. The first one is that cover crops sown at different dates had reached different development stages at the time of sampling. The second one is that cover crops had similar N content in the two sowing dates (Figure 3), (presumably due to similar N availability), not reduced for the late sowing date thanks to low leaching, and lower AGB in the late compared to the early sowing date (Figure 2). On the contrary, for hairy vetch and Egyptian clover, the leaf/stem ratio was probably constant throughout the autumn; this may explain the lack of significant effects of sowing date on their aboveground N concentration. Gselman and Kramberger (2008) in four field trials carried out at two locations in north-eastern Slovenia showed that the benefits of legume winter cover crops with regard to symbiotic N_2-fixation were achieved only by very early sowing (mid August); however, the amount of soil mineral N in late autumn and in early spring was decreased under the N-demanding *Lolium multiflorum* Lam. more than under the legumes.

For white mustard, the literature reporting measurements in conditions similar to ours demonstrates some variability of N concentration in above ground biomass (2.7-4.7%, with AGB ranging from 1.1 to 4.4 t DM ha^{-1}), probably depending on local N availability (Stivers-Young, 1998; Kulig et al., 2010; Mikó et al., 2012). These results indicate that in some of the cited experiments, N availability was higher compared to our conditions. The effect of sowing date on white mustard aboveground N concentration is not extensively documented and it has been reported to increase with sowing dates delayed by about two weeks (Stivers-Young, 1998). Substantial variability in the literature exists also for the C/N ratio of white mustard, which was found as low as 17.8 by Baggs et al. (2000), and as high as 35.2 by Rühlemann and Schmidtke (2016). The literature confirms that the aboveground N concentration of hairy vetch is high in autumn (4.3%; Büchi et al., 2015), and remains rather high also in the spring (2.8-4.4%; Tosti et al., 2014; Lawson et al., 2015), as long as the vetch is still in the vegetative stages. Accordingly, the C/N ratio in the three experiments mentioned usually comprised between 9.5 and 11.3 and never exceeded 15.2. For rye cover crops, measurements of N concentration at the end of the autumn are extremely rare, while they are much more common for the spring (0.9-1.5%; Staver and Brinsfield, 1998; Cline and Silvernail, 2001; Komatsuzaki and Wagger, 2015), when the values are in general lower compared to the average 2.9% that we measured in autumn.

Regarding the response to N of the five cover crops, the very small significant effect of N fertilization on aboveground N concentration only in the first year (2017) (Table S4) and the lack of effect in the second year might be justified by a difficulty in absorbing high N quantities in conditions of dry soil and low N mobility.

4.4. Nitrogen content in aboveground cover crop biomass

The trend of nitrogen content in aboveground cover crop biomass followed that of AGB. Indeed, treatments characterised by high N content had a high AGB (e.g., white mustard) and/or a high N concentration (e.g., hairy vetch). Therefore, the highest N content (Figure 3) was recorded for hairy vetch, white mustard and black oat, with higher values for SD1 compared to SD2, while legumes had low N content in SD2 due to low AGB. Nitrogen content measured for white mustard in this experiment is in line with the range 59-104 kg N ha^{-1} reported for similar planting and sampling dates in temperate climates (Stivers-Young, 1998; Mikó et al., 2012; Mikó, 2016). For black oat, Schomberg et al. (2006) have measured, averaged over three years, an N content of 74 kg N ha^{-1} in the spring (after fall planting). Most published N content values for hairy vetch were measured in spring, with much higher values (147-175 kg N ha^{-1}; Teasdale et al., 2012; Büchi et al., 2015) compared to those measured by us in autumn. Hashemi et al. (2013) reported variable maximum N content in autumn for rye planted at the beginning of September, ranging from 23 to 131 kg N ha^{-1} depending on the year.

4.5. Weed control in cover crop stands

Weed control by white mustard and black oat in our experiment showed a reduction of 83% of weed biomass compared to the no cover crop treatment (Table 5). This is in agreement with other studies where the ratio between weed biomass in the cover crop treatment and weed biomass in the control treatment was 12% in October and November for white mustard (Brust et al., 2014, at three sites and two years in Germany, with planting in July or August), 28% for white mustard two months after planting (Dorn et al., 2013), 10% for black oat 12 weeks after planting during two years in Germany

(Schappert et al., 2019). However, the ability of white mustard to control weed growth in spring could be limited due to frost damage (Campiglia et al., 2015). The incomplete average weed control by rye in our experiment (Table 5), due to a huge weed infestation in Orzinuovi in 2018, was in contrast with its documented success in controlling weeds in autumn (Kruidhof et al., 2008; Hayden et al., 2012; Werle and Blanco-Canqui, 2018). Due to poor cover crop growth, weed control by legumes at the end of autumn was modest in our experiment, with a reduction of about 50% of weed biomass compared to the no cover crop treatment (Table 5). With hairy vetch biomass growth during the subsequent spring, weed control normally improves, as documented by Hodgdon et al. (2016).

A better weed control in autumn by black oat and white mustard compared to other cover crops could be partly attributed to their plant height. Indeed, at Sant'Angelo Lodigiano (Corti et al., 2023), both species had higher canopies (on average 429 and 721 mm for black oat and white mustard, respectively) compared to legumes (on average 214 and 208 for Egyptian clover and hairy vetch, respectively) and rye (on average 222 mm). Other relevant cover crop traits allowing competition against weeds are early seedling growth rate, leaf insertion angle, degree of tillering/branching, and release of allelochemicals. White mustard is very competitive for light thanks to a high early growth rate (Bodner et al., 2010) and an open angle of leaf insertion that favours light interception. Differently, hairy vetch and Egyptian clover are less competitive because of low growth rates both after sowing and later in the fall, because their optimal temperature for growth is around 25-27 °C (Bodner et al., 2010; Pessotto et al., 2023). Black oat exhibits high tillering performance and provides excellent soil coverage in relation to total biomass produced (Komatsuzaki and Wagger, 2015). Furthermore, black oat suppresses broadleaf weeds by releasing allelochemicals, even if its suppressive ability is less than that of rye (Pérez and Ormeño-Núñez, 1993; Gfeller et al., 2018).

5. Conclusions

In a two-year experiment in two locations in Northern Italy we compared the growth, N content and weed control of five pure cover crop species, to verify the hypothesis that early planting and high residual mineral N in soil before sowing increases biomass production and weed control. Cover crop growth was limited by water availability, due to drier than normal meteorological conditions in September and October. In November, about 2.5 months after sowing, the above ground biomass ranged between 0.5 and 3.3 t DM ha^{-1}, with significantly higher values for the first compared to the second sowing date for most species, and significantly higher values for white mustard compared to other cover crops. Hairy vetch had the highest N concentration at both sowing dates (3.8-3.9%), while white mustard had the lowest (2.1-2.9%). In most cases pre-plant soil mineral N significantly increased cover crop biomass, suggesting that in current conditions cover crop growth might be N-limited, while the effect of pre-plant soil mineral N on N concentration was significant only in the first year. Nitrogen content ranged between 15 kg N ha^{-1} (Egyptian clover at the second sowing date) and 65-74 kg N ha^{-1} (hairy vetch and white mustard at the first sowing date). Weed growth was higher in legumes (0.7 t DM ha^{-1}) than in white mustard and black oat (0.2 t DM ha^{-1}), due to the limited competitive ability of Egyptian clover and hairy vetch.

This type of result can be expected in similar pedoclimatic and cropping system conditions. Therefore, farmers operating on loamy soils in temperate climates should sow cover crops (white mustard, black oat, hairy vetch and Egyptian clover) as soon as possible after the harvest of the summer cash crop (subject to adequate soil water content), to obtain good dry matter production, nitrogen content and weed control. We have shown that decreasing the thermal time available for cover crop growth by about 300 °C d (corresponding on average to the shift between the first and the second sowing date) resulted in a mean biomass reduction of 0.8 t DM ha^{-1}. Our experimental setup did not allow us to verify cover crop productivity when thermal time accumulation was lower than 900 °C d; under this threshold it is likely that biomass accumulated before the end of the autumn will be lower than 1 t DM ha^{-1}. We also found that cover crops are likely to produce more if planted on soils that either have a high residual nitrate content or a high soil nitrogen mineralisation potential, like those that are routinely amended with animal manure.

Future work will evaluate, both with field experiments and with simulation modelling, the effect of nitrogen availability and sowing date under diverse weather conditions, exploring not only relatively dry years like those of this experiment, but also under optimal (e.g., irrigated) soil humidity, a condition that may also affect soil nutrient availability. For legume cover crops, different thermal ranges and different levels of soil mineral N concentrations could also be explored to assess the effects on N_2-fixation and growth rate in fall-winter seasons. The effects of the cover crops grown under different conditions on the subsequent cash crop should also be considered.

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Table captions

Table 1. Dates of sowing (SD1 and SD2), sampling and termination of cover crops and of sowing and harvesting of the subsequent cash crop (maize) relative to both the experimental sites and the two years of trial.

Table 2. Duration (d) and thermal time accumulated (growing degree days GDDs, °C d) between cover crop sowing and biomass sampling in November, in the two cultivation seasons in the two locations. GDDs are calculated with minimum cardinal temperatures of 0 °C. Days of sowing in the two dates (SD1, SD2) are detailed in Table 1.

Table 3. Aboveground biomass measured in five cover crops cultivated for two years at Sant'Angelo Lodigiano adopting two sowing dates (SD1 and SD2; Table 1), and low (N0) and high (N1) pre-plant soil mineral N. Means are averaged across cover crops. Within each sowing date and cultivation year, different letters indicate significant differences (P<0.05) between pre-plant soil mineral N, according to Sidak test. Standard errors of the means are reported in parenthesis.

Table 4. Nitrogen concentration in aboveground biomass and C to N ratio of aboveground biomass measured in five cover crops for two years in two locations in Northern Italy, adopting two sowing dates (SD1 and SD2; Table 1). Means are averaged across the two locations and years. Within each sowing date, different letters indicate significant differences (P<0.05) among cover crops according to Sidak test; within each cover crop treatment, the symbol "*" indicates significant differences (P<0.05) between sowing dates according to Sidak test. NS, not significant. Standard errors of the means are reported in parenthesis.

Table 5. Weed aboveground biomass and N content harvested in the six cover crop treatments for two years in two locations in Northern Italy adopting two sowing dates (SD1 and SD2; Table 1). Means are averaged across the two locations, the two years, and the two sowing dates. Different letters indicate significant differences (P<0.05) among cover crops according to Sidak test. Standard errors of the means are reported in parenthesis.

Tables

Table 1.

Crop type	Operation	Sant'Angelo Lodigiano		Orzinuovi	
		Season 2017-2018	Season 2018-2019	Season 2017-2018	Season 2018-2019
Cover crop	First sowing date (SD1)	6 September 2017	6 September 2018	30 August 2017	5 September 2018
	Second sowing date (SD2)	22 September 2017	22 September 2018	14 September 2017	14 September 2018
	Sampling	22 November 2017	14 November 2018	22 November 2017	22 November 2018
	Termination	28 March 2018	29 March 2019	16 March 2018	16 March 2019
Maize	Sowing	14 May 2018	20 April 2019	1 April 2018	29 March 2019
	Harvest	28 August 2018	28 August 2019	7 August 2018	5 August 2019

Table 2.

Sowing date	Sant’Angelo Lodigiano		Orzinuovi	
	Season 2017-2018	Season 2018-2019	Season 2017-2018	Season 2018-2019
Duration (d)				
SD1	75	69	84	78
SD2	59	53	69	69
Growing degree days (°C d)				
SD1	1154	1321	1331	1405
SD2	851	923	1005	1184

Table 3.

Sowing date	Year	Pre-plant soil mineral N	Aboveground biomass (t DM ha^{-1})
SD1	2017	N0	2.3 (0.1) b
		N1	2.8 (0.1) a
	2018	N0	1.3 (0.1) b
		N1	2.1 (0.1) a
SD2	2017	N0	1.6 (0.1) b
		N1	1.8 (0.1) a
	2018	N0	0.9 (0.1) a
		N1	1.1 (0.1) a

Table 4.

Sowing date	Cover crop	Cover crop N concentration (% DM)			C/N ratio		
		Mean (SE)	Difference between cover crops	Difference between sowing dates	Mean (SE)	Difference between cover crops	Difference between sowing dates
SD1	Black oat	2.2 (0.2)	d	*	19.6 (1.0)	a	*
	Rye	2.7 (0.2)	c	*	15.2 (1.0)	b	*
	White mustard	2.1 (0.2)	d	*	19.8 (1.1)	a	*
	Egyptian clover	3.2 (0.2)	b	NS	13.2 (0.9)	c	*
	Hairy vetch	3.9 (0.2)	a	NS	10.1 (0.9)	d	NS
SD2	Black oat	3.0 (0.2)	b	–	14.1 (1.0)	a	–
	Rye	3.0 (0.2)	b	–	13.0 (1.0)	ab	–
	White mustard	2.9 (0.2)	b	–	13.9 (1.1)	a	–
	Egyptian clover	3.3 (0.2)	b	–	11.4 (0.9)	b	–
	Hairy vetch	3.8 (0.2)	a	–	9.9 (0.9)	c	–

Table 5.

Cover crop	Weed AGB ($t\ DM\ ha^{-1}$)	Weed AGB reduction compared to the no cover crop treatment (%)	Weed N content ($kg\ N\ ha^{-1}$)
No cover crop	1.3 (0.3) a	–	21 (7) a
Black oat	0.3 (0.3) cd	80	6 (7) c
Rye	0.4 (0.3) bcd	71	11 (7) bc
White mustard	0.2 (0.3) d	87	6 (7) c
Egyptian clover	0.7 (0.3) b	43	17 (7) ab
Hairy vetch	0.6 (0.3) bc	55	15 (7) ab

Figure captions

Figure 1. Daily mean air temperature and accumulated monthly precipitation in Orzinuovi and Sant'Angelo Lodigiano (Italy) for the period 1988-2016 and the years 2017 and 2018.

Figure 2. Aboveground biomass (dry matter, DM) measured in five cover crops cultivated for two years in two locations in Northern Italy adopting two sowing dates (SD1 and SD2; Table 1). Means are average across the two locations and the two years. Within each sowing date, different letters indicate significant differences ($P<0.05$) among cover crops according to Sidak test; within each cover crop, the symbol "*" indicates significant differences ($P<0.05$) between sowing dates according to Sidak test. Error bars represent one standard error of the mean.

Figure 3. Nitrogen content in aboveground biomass measured in five cover crops for two years in two locations in Northern Italy adopting two sowing dates (SD1 and SD2; Table 1). Means are average across the two locations and the two years. Within each sowing date, different letters indicate significant differences ($P<0.05$) among cover crops according to Sidak test; within each cover crop, the symbol "*" indicates significant differences ($P<0.05$) between sowing dates according to Sidak test. Error bars represent one standard error of the mean.

Figure 1

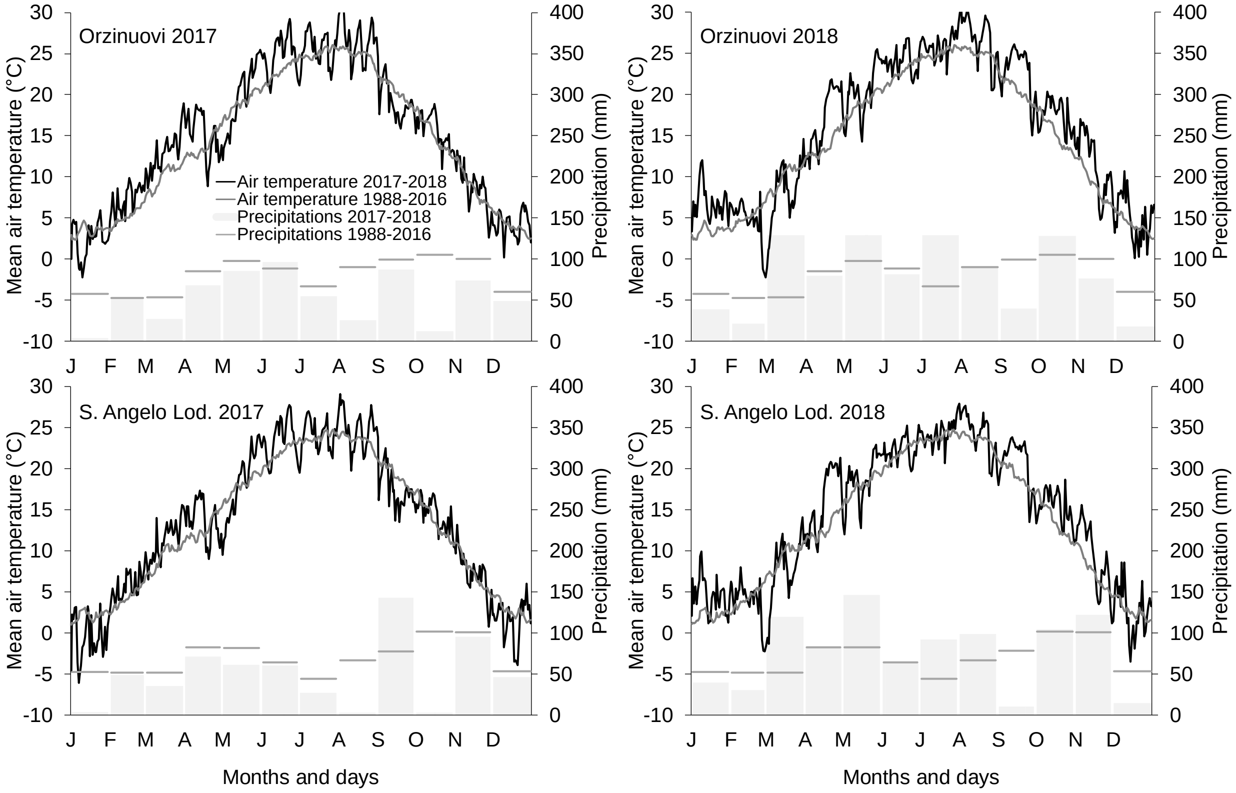
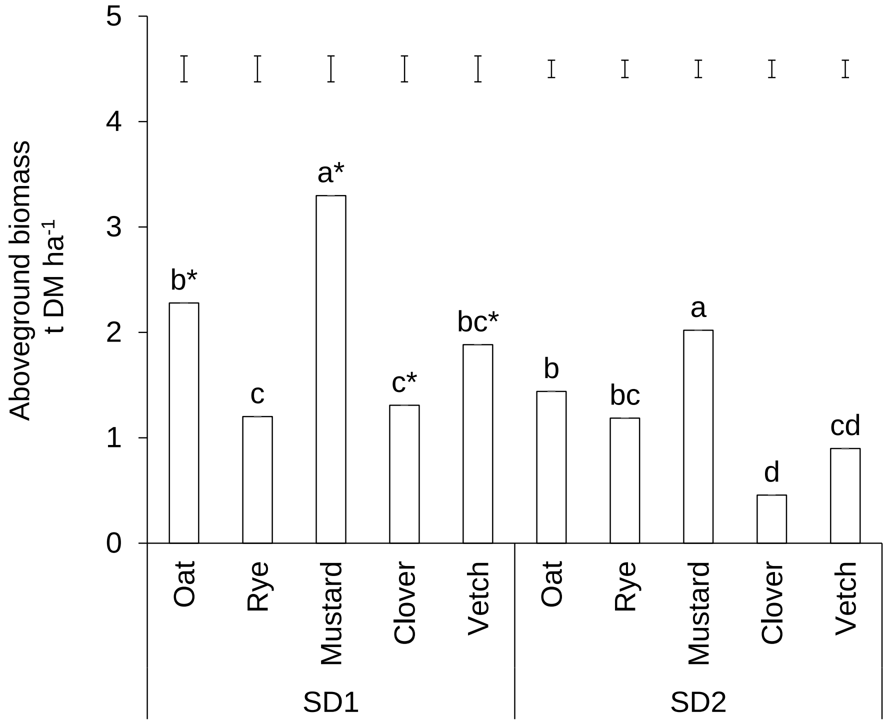
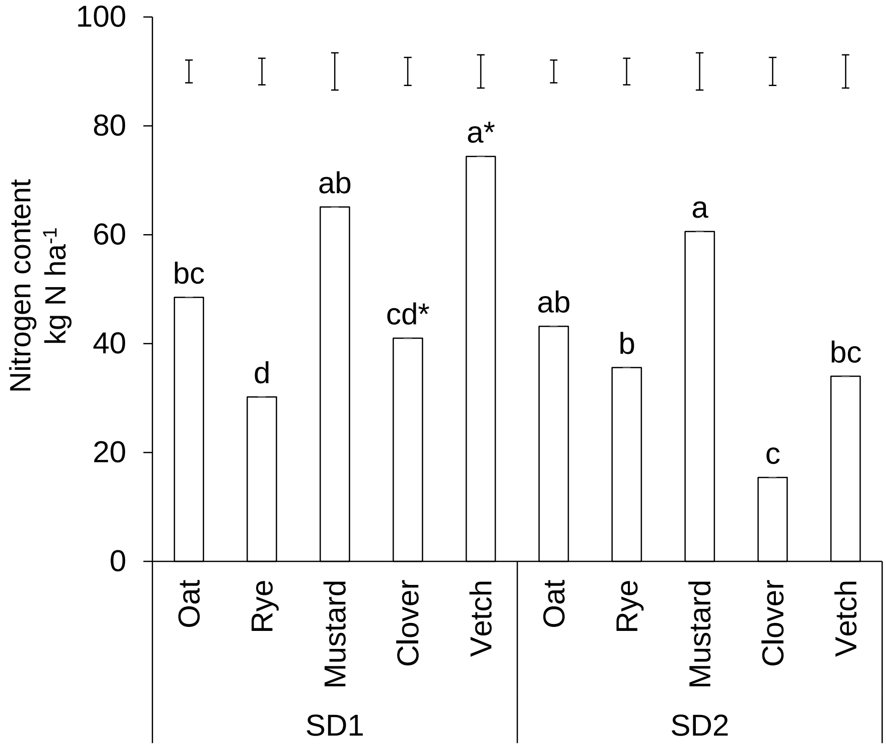

Orzinuovi 2017
Orzinuovi 2018
S. Angelo Lod. 2017
S. Angelo Lod. 2018
Air temperature 2017-2018
Air temperature 1988-2016
Precipitations 2017-2018
Precipitations 1988-2016
Mean air temperature (°C)
Precipitation (mm)
J F M A M J J A S O N D
Months and days

Figure 2



5
4
3
2
1
0
Aboveground biomass
t DM ha-1
b*
c
a*
c*
bc*
b
bc
a
d
cd
Oat
Rye
Mustard
Clover
Vetch
Oat
Rye
Mustard
Clover
Vetch
SD1
SD2

Figure 3


100
80
60
40
20
0
Nitrogen content
kg N ha-1
bc
d
ab
cd*
a*
ab
b
a
c
bc
Oat
Rye
Mustard
Clover
Vetch
Oat
Rye
Mustard
Clover
Vetch
SD1
SD2

Supplementary material

Table S1. Summary of the analysis of variance for the experiment conducted for two years in two locations in Northern Italy adopting two sowing dates. The degrees of freedom of the numerator (DF), the results of the F tests (*F*) and associated p-values (P) are reported.

Variable	Source[a]	DF	*F*	P
AGB (t DM ha^{-1})	Sowing date	1	52.965	<0.0001
	Cover crop type	4	38.599	<0.0001
	Sowing date × cover crop type	4	3.725	0.0068
N concentration (% DM)	Sowing date	1	54.631	<0.0001
	Cover crop type	4	68.534	<0.0001
	Sowing date × cover crop type	4	10.326	<0.0001
C/N	Sowing date	1	89.910	<0.0001
	Cover crop type	4	125.515	<0.0001
	Sowing date × cover crop type	4	17.507	<0.0001
N content (kg N ha^{-1})	Sowing date	1	17.186	0.0009
	Cover crop type	4	17.094	<0.0001
	Sowing date × cover crop type	4	8.033	<0.0001
Weeds AGB (t DM ha^{-1})	Sowing date	1	1.207	0.2892
	Cover crop type	5	20.653	<0.0001
	Sowing date × cover crop type	5	1.933	0.0920
Weeds N content (kg N ha^{-1})	Sowing date	1	1.336	0.2658
	Cover crop type	5	9.932	<0.0001
	Sowing date × cover crop type	5	1.066	0.3817

[a]The factor “Cover crop type” includes the “No cover crop” treatment for the variables “Weeds AGB” and “Weed N content”.

Table S2. Summary of the analysis of variance for the experiment conducted for two years at Sant'Angelo Lodigiano adopting two sowing dates, and two levels of pre-plant soil mineral N. The degrees of freedom of the numerator (DF), the results of the F tests (*F*) and associated p-values (P) are reported.

Variable	Source[a]	DF	*F*	P
AGB (t DM ha^{-1})	Sowing date	1	77.222	0.0001
	Cover crop type	4	47.377	<0.0001
	Pre-plant soil mineral N	1	55.281	<0.0001
	Year	1	119.005	<0.0001
	Sowing date × Cover crop type	4	8.085	<0.0001
	Sowing date × Pre-plant soil mineral N	1	6.237	0.0153
	Cover crop type × Pre-plant soil mineral N	4	4.521	0.0029
	Sowing date × Year	1	1.388	0.2834
	Cover crop type × Year	4	13.232	<0.0001
	Pre-plant soil mineral N × Year	1	1.992	0.1633
	Sowing date × Cover crop type × Pre-plant soil mineral N	4	2.257	0.0735
	Sowing date × Cover crop type × Year	4	3.929	0.0077
	Sowing date × Pre-plant soil mineral N × Year	1	6.513	0.0133
	Cover crop type × Pre-plant soil mineral N × Year	4	0.421	0.7926
	Sowing date × Cover crop type × Pre-plant soil mineral N × Year	4	1.271	0.2914
N concentration (% DM)	Sowing date	1	12.236	0.0129
	Cover crop type	4	71.746	<0.0001
	Pre-plant soil mineral N	1	4.675	0.0346
	Year	1	7.825	0.0313
	Sowing date × Cover crop type	4	30.368	<0.0001
	Sowing date × Pre-plant soil mineral N	1	0.090	0.7657

Variable	Source[a]	DF	F	P
	Cover crop type × Pre-plant soil mineral N	4	1.746	0.1517
	Sowing date × Year	1	1.187	0.3178
	Cover crop type × Year	4	5.076	0.0017
	Pre-plant soil mineral N × Year	1	7.367	0.0087
	Sowing date × Cover crop type × Pre-plant soil mineral N	4	1.994	0.1069
	Sowing date × Cover crop type × Year	4	1.397	0.2491
	Sowing date × Pre-plant soil mineral N × Year	1	0.970	0.3287
	Cover crop type × Pre-plant soil mineral N × Year	4	1.278	0.2888
	Sowing date × Cover crop type × Pre-plant soil mineral N × Year	4	1.168	0.3339
C/N	Sowing date	1	89.813	0.0001
	Cover crop type	4	123.724	<0.0001
	Pre-plant soil mineral N	1	0.012	0.9148
	Year	1	88.927	0.0001
	Sowing date × Cover crop type	4	32.142	<0.0001
	Sowing date × Pre-plant soil mineral N	1	4.266	0.0432
	Cover crop type × Pre-plant soil mineral N	4	1.723	0.1566
	Sowing date × Year	1	2.103	0.1972
	Cover crop type × Year	4	8.604	<0.0001
	Pre-plant soil mineral N × Year	1	3.692	0.0594
	Sowing date × Cover crop type × Pre-plant soil mineral N	4	1.465	0.2241
	Sowing date × Cover crop type × Year	4	4.895	0.0022
	Sowing date × Pre-plant soil mineral N × Year	1	5.427	0.0232
	Cover crop type × Pre-plant soil mineral N × Year	4	1.939	0.1156
	Sowing date × Cover crop type × Pre-plant soil mineral N × Year	4	1.948	0.1142
N content (kg N ha^{-1})	Sowing date	1	22.219	0.0033
	Cover crop type	4	23.670	<0.0001
	Pre-plant soil mineral N	1	55.790	<0.0001
	Year	1	23.337	0.0029

Variable	Source[a]	DF	*F*	P
	Sowing date × Cover crop type	4	15.323	<0.0001
	Sowing date × Pre-plant soil mineral N	1	5.586	0.0214
	Cover crop type × Pre-plant soil mineral N	4	4.044	0.0057
	Sowing date × Year	1	2.793	0.1457
	Cover crop type × Year	4	5.870	0.0006
	Pre-plant soil mineral N × Year	1	0.468	0.4966
	Sowing date × Cover crop type × Pre-plant soil mineral N	4	1.640	0.1759
	Sowing date × Cover crop type × Year	4	0.786	0.5400
	Sowing date × Pre-plant soil mineral N × Year	1	3.237	0.0770
	Cover crop type × Pre-plant soil mineral N × Year	4	0.624	0.6470
	Sowing date × Cover crop type × Pre-plant soil mineral N × Year	4	1.339	0.2658
Weeds AGB (t DM ha^{-1})	Sowing date	1	19.986	0.0042
	Cover crop type	5	3.497	0.0077
	Pre-plant soil mineral N	1	0.018	0.8925
	Year	1	81.614	0.0001
	Sowing date × Cover crop type	5	3.508	0.0076
	Sowing date × Pre-plant soil mineral N	1	0.002	0.9653
	Cover crop type × Pre-plant soil mineral N	5	0.962	0.4467
	Sowing date × Year	1	49.261	0.0004
	Cover crop type × Year	5	16.747	<0.0001
	Pre-plant soil mineral N × Year	1	0.054	0.8177
	Sowing date × Cover crop type × Pre-plant soil mineral N	5	0.957	0.4500
	Sowing date × Cover crop type × Year	5	9.375	<0.0001
	Sowing date × Pre-plant soil mineral N × Year	1	0.148	0.7012
	Cover crop type × Pre-plant soil mineral N × Year	5	0.795	0.5570
	Sowing date × Cover crop type × Pre-plant soil mineral N × Year	5	1.429	0.2242
Weeds N content (kg N ha^{-1})	Sowing date	1	16.327	0.0068
	Cover crop type	5	3.890	0.0040

Variable	Source[a]	DF	*F*	P
	Pre-plant soil mineral N	1	0.177	0.6750
	Year	1	67.580	0.0002
	Sowing date × Cover crop type	5	3.903	0.0040
	Sowing date × Pre-plant soil mineral N	1	0.130	0.7197
	Cover crop type × Pre-plant soil mineral N	5	1.057	0.3912
	Sowing date × Year	1	45.736	0.0005
	Cover crop type × Year	5	11.737	<0.0001
	Pre-plant soil mineral N × Year	1	1.247	0.2679
	Sowing date × Cover crop type × Pre-plant soil mineral N	5	1.059	0.3905
	Sowing date × Cover crop type × Year	5	8.028	<0.0001
	Sowing date × Pre-plant soil mineral N × Year	1	0.347	0.5578
	Cover crop type × Pre-plant soil mineral N × Year	5	0.488	0.7843
	Sowing date × Cover crop type × Pre-plant soil mineral N × Year	5	0.297	0.9132

[a]The factor "Cover crop type" includes the "No cover crop" treatment for the variables "Weeds AGB" and "Weed N content".

Table S3. Aboveground biomass measured in five cover crops cultivated for two years at Sant'Angelo Lodigiano adopting two sowing dates (SD1 and SD2; Table 1), and low (N0) and high (N1) pre-plant soil mineral N. Means are averaged across sowing dates and cultivation years. Within each cover crop, different letters indicate significant differences ($P<0.05$) between pre-plant soil mineral N, according to Sidak test. SE, standard errors of the means.

Cover crop	Pre-plant soil mineral N	Aboveground biomass (t DM ha^{-1})	SE	Differences between pre-plant soil mineral N
Black oat	N0	1.7	0.1	b
	N1	2.1	0.1	a
Rye	N0	1.6	0.1	b
	N1	2.0	0.1	a
White mustard	N0	2.1	0.1	b
	N1	3.2	0.1	a
Egyptian clover	N0	0.8	0.1	a
	N1	0.9	0.1	a
Hairy vetch	N0	1.3	0.1	b
	N1	1.6	0.1	a

Table S4. Nitrogen concentration in aboveground biomass measured in five cover crops cultivated for two years at Sant'Angelo Lodigiano adopting two sowing dates (SD1 and SD2; Table 1), and low (N0) and high (N1) pre-plant soil mineral N. Means are averaged across sowing dates and cover crops. Within each cultivation year, different letters indicate significant differences ($P<0.05$) between pre-plant soil mineral N, according to Sidak test. SE, standard errors of the means.

Year	Pre-plant soil mineral N	Cover crop N concentration (% DM)	SE	Differences between pre-plant soil mineral N
2017	N0	3.0	0.1	b
	N1	3.2	0.1	a
2018	N0	3.4	0.1	a
	N1	3.3	0.1	a

Table S5. Carbon to nitrogen ratio of aboveground biomass measured in five cover crops cultivated for two years at Sant'Angelo Lodigiano adopting two sowing dates (SD1 and SD2; Table 1), and low (N0) and high (N1) pre-plant soil mineral N. Means are averaged across cover crops. Within each sowing date and cultivation year, different letters indicate significant differences ($P<0.05$) between pre-plant soil mineral N, according to Sidak test. SE, standard errors of the means.

Sowing date	Year	Pre-plant soil mineral N	C/N ratio	SE	Differences between pre-plant soil mineral N
SD1	2017	N0	16.7	0.3	a
		N1	15.2	0.3	b
	2018	N0	11.9	0.3	b
		N1	12.7	0.3	a
SD2	2017	N0	12.1	0.3	a
		N1	12.0	0.3	a
	2018	N0	10.5	0.3	a
		N1	10.2	0.3	a

Table S6. Nitrogen content in aboveground biomass measured in five cover crops cultivated for two years at Sant'Angelo Lodigiano adopting two sowing dates (SD1 and SD2; Table 1), and low (N0) and high (N1) pre-plant soil mineral N. Means are averaged across cultivation years and cover crops. Within each sowing date, different letters indicate significant differences ($P<0.05$) between pre-plant soil mineral N, according to Sidak test. SE, standard errors of the means.

Sowing date	Pre-plant soil mineral N	Cover crop N content (kg N ha^{-1})	SE	Differences between pre-plant soil mineral N
SD1	N0	50	3	b
	N1	74	3	a
SD2	N0	41	3	b
	N1	50	3	a

Table S7. Nitrogen content in aboveground biomass measured in five cover crops cultivated two years at Sant'Angelo Lodigiano adopting two sowing dates (SD1 and SD2; Table 1), and low (N0) and high (N1) pre-plant soil mineral N. Means are averaged across the cultivation years and sowing dates. Within each cover crop, different letters indicate significant differences ($P<0.05$) between pre-plant soil mineral N, according to Sidak test. SE, standard errors of the means.

Cover crop	Pre-plant soil mineral N	Cover crop N content (kg N ha^{-1})	SE	Differences between pre-plant soil mineral N
Black oat	N0	48	3	b
	N1	61	3	a
Rye	N0	44	3	b
	N1	61	3	a
White mustard	N0	60	5	b
	N1	92	5	a
Egyptian clover	N0	27	4	a
	N1	30	4	a
Hairy vetch	N0	48	5	b
	N1	66	5	a