MANAGEMENT OF WINTER COVER CROP RESIDUES UNDER DIFFERENT TILLAGE CONDITIONS AFFECTS NITROGEN UTILIZATION EFFICIENCY AND YIELD OF EGGPLANT (*Solanum melanogena* L.) IN MEDITERRANEAN ENVIRONMENT

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ABSTRACT

Efficient nitrogen (N) management is required for sustaining crop yield and minimizing environmental impacts. The aims of this study were to evaluate the effects of winter cover crops and their residue management on N-uptake, N use efficiency (NUE) and yield of the following eggplant (*Solanum melanogena* L.) crop. Two 2-year field experiments (2009/2010 and 2010/2011 growing seasons) were carried out in a Mediterranean environment of Central Italy in a *Typic Xerofluvent* soil. The treatments consisted in: (a) three winter cover crops [hairy vetch (*Vicia villosa* Roth.), oat (*Avena sativa* L.), and oilseed rape (*Brassica napus* L.)] and one bare soil; (b) three cover crop residue managements [residues left in strips on soil surface (RS); residues incorporated into the soil at a depth of 10 cm in minimum tillage (MT) and residues incorporated into the soil at a depth of 30 cm in conventional tillage (CT)]. The cover crop biomass characteristics, soil mineral N, SPAD readings, crop yield and N-uptake of eggplant were determined. At cover crop termination, hairy vetch showed the highest aboveground biomass and nitrogen content (6.18 Mg ha^{-1} of DM and 3.1 %, respectively) and the lowest value of C/N ratio (12.7). The mineralization rate of cover crop aboveground biomass was higher in hairy vetch (72%), intermediate in oilseed rape (63%) and lower in oat residues (49%), while it was slower in RS compared to MT and CT among the residue managements. Yield, fruit and straw N-uptake of eggplant were high following hairy vetch (35.2 Mg ha^{-1} of FM, 93.9 kg N ha^{-1} and 78.3 kg N ha^{-1}, respectively) and low following oat (13.2 Mg ha^{-1} of FM, 29.1 kg N ha^{-1} and 33.6 kg N ha^{-1}, respectively). Similarly NUE was high in hairy vetch, followed by oilseed rape and oat (48.6, 19.4, -30.8 %, respectively), even if RS residue management in hairy vetch and oat and MT residue management in oilseed rape proved to be more effective for improving the eggplant yield and nitrogen utilization efficiency. The amount of residual N left in the soil, following eggplant cultivation, was higher in the hairy vetch than in oat and oilseed rape treatments. Cover crop species and their residue management strongly influenced NUE and yield of eggplant. No-tillage strategy is preferable with legume cover crop residues in order to reduce the risks of N loss.

KEY WORDS: Cover crops; Green manuring; Mulching; Nitrogen release; Nitrogen uptake; Conservation agriculture.

HIGHLIGHTS

- Eggplant was grown after green manuring or mulching of winter cover crop residues
- Mineralization rate of cover crop biomass was slower in RS compared to MT and CT
- Eggplant yield and NUE were higher following hairy vetch and lower following oat
- Mulching is preferable with legume cover crop residues to reduce the risks of N loss

1. INTRODUCTION

Produce is grown in modern specialized agricultural systems by adding large auxiliary energy inputs such as synthetic fertilizers, without paying much attention to environmental degradation and human health risks (Poudel et al., 2001). In vegetable production, nitrogen is the most important plant nutrient (Gaskell and Smith, 2007), in fact plants lacking in nitrogen grow slowly, and produce a poor yield and quality, while excess nitrogen increases the risk of loss by leaching or gaseous emissions (Gentile et al., 2009; Nyiraneza and Snapp, 2007). Therefore, an efficient nitrogen management is required to increase crop yield and minimize the negative environmental impacts of cropping systems (Gaskell and Smith, 2007). One approach is to increase soil nitrogen use efficiency by strengthening internal nitrogen cycling (Drinkwater and Snapp, 2007).

Recent interest in cover crop use is due to the increase in cost of agrochemicals such as fertilizers and herbicides and the decline of soil fertility associated with many vegetable farming practices (Teasdale et al., 2008). Winter cover crops are often included in annual vegetable cropping systems in order to increase the organic matter and nitrogen content in the soil (Kuo and Sainju, 1998; Schomberg and Endale, 2004). In the Mediterranean environment, grasses (*Poaceae*), crucifers (*Brassicaceae*) and legumes (*Fabaceae*) are commonly used as winter cover crops (Radicetti et al., 2013a). Grasses and crucifers are generally more efficient in catching residual nitrogen from the soil (Kuo et al., 2001), while legume cover crops are becoming more and more popular because may provide additional nitrogen by symbiosis. After cover crop killing, the nitrogen accumulated in the cover crop biomass could be available through the mineralization process and thus contributing to the reduction of the nitrogen fertilizer requirement of subsequent cash crops (Baggs et al., 2000). The rate at which the decomposing cover crop residues release nitrogen depends on their chemical characteristics, the physical-chemical and biological activities of the soil and environmental factors such as temperature and moisture (Kuo and Jellum, 2002). Although it is widely recognized that winter cover crops can increase the crop yield of the subsequent summer crop, the soil management practices used for killing cover crops need to be evaluated in order to synchronize nitrogen release from cover crop residues and crop demand (Snapp and Borden, 2005). In the Mediterranean area, winter cover crops are generally mowed or chopped and incorporated into the soil as green manure in spring, to allow time for residue decomposition and bed preparation for the subsequent vegetable transplanting. Another approach is to kill the cover crops and leave the residues on the soil surface as organic dead mulches in no-tilled crop production systems (Teasdale et al., 2008). Leaving cover crop residues on the soil surface generally slows down the decomposition rate of the residues and nitrogen release better than incorporating the residue due to the reduced contact between cover biomass and soil microorganisms (Sainju et al., 2007). Leaving the aboveground biomass of various cover crops in organic dead mulch strips in no-tillage systems has been proposed as a way of improving the yield of the following summer vegetable crops due to better nitrogen supply and weed control (Campiglia et al., 2011; Radicetti et al., 2013a). Predicting the effect of cover crop residue management on nitrogen mineralization could enhance the synchronization between nitrogen release and crop demand thus improving nitrogen use efficiency and reducing nitrogen loss. We hypothesized that the combination of winter cover crop species and cover crop residue management can affect the N mineralization rate, and therefore affect yield of the subsequent vegetable crop. It is important to understand how cover crop species and their residue management affect soil nitrogen availability in order to develop appropriate nitrogen management strategies for sustainable vegetable production. The objectives of this study were to evaluate the effects of different cover crop species and residue management on: (1) nitrogen supply to subsequent eggplant crop; (2) soil mineral nitrogen availability; (3) nitrogen use efficiency of eggplant crop; (4); nitrogen remaining in the soil after eggplant harvest, and (5) eggplant yield.

2. MATERIALS AND METHODS

2.1. Study site description

The experiment was carried out at the experimental farm of the University of Tuscia in Viterbo, Italy (Latitude 42°24'53'' N, Longitude 12°03'55'', Altitude 310 m asl) for two growing seasons (2019/2010 and 2010/2011). The climate of the region is typically Mediterranean with long-term annual rainfall of 720 mm falling mainly between October and May. The mean annual air temperature of the area is 14°C, with minimum temperatures in February and maximum temperatures in July. The volcanic soil is a *Typic Xerofluvent* (Soil Survey Staff, 2009) with the following characteristics in the top layer (0 – 30 cm): 104 g kg^{-1} of dry soil clay, 133 g kg^{-1} of dry soil silt, 763 g kg^{-1} of dry soil sand; pH 6.9 (water, 1:2.5); organic matter 13.2 g kg^{-1} of dry soil (Lotti); and total nitrogen 0.94 g kg^{-1} of dry soil (Kjeldahl).

2.2. Experimental design and treatments

The following experimental treatments were applied in a winter cover crop–eggplant sequence: (a) four cover crops including hairy vetch (*Vicia villosa* Roth., var. Capello), oat (*Avena sativa* L., var. Donata), and oilseed rape (*Brassica napus* L., var. Licapo)] and a control without cover crops (hereafter called no cover); (b) three cover crop residue managements [incorporating the residues at 30 cm of soil depth in order to simulate conventional tillage (hereafter called CT); incorporating the residues at 10 cm of soil depth in order to simulate minimum tillage (hereafter called MT); and residues left on the soil surface (hereafter called RS)]. The experimental design was a split-plot (4 cover crops x 3 cover crop residue managements), where the cover crop was the main factor and the cover crop residue management the split factor. The main plot size was 72 m^2 (6 m x 12 m) and the sub-plot size was 24 m^2 (6 m x 4 m). The treatments were replicated three times for a total of 36 plots.

2.3. Experimental field management

The soil was ploughed in at depth of 30 cm within the first week of September before beginning the experiment in both growing seasons. It was then fertilized with 100 kg of P_2O_5 ha^{-1} as triple super phosphate and harrowed for seedbed preparation. All cover crop species were broadcast sown and superficially buried by harrowing on 24 September 2009 and 13 September 2010. The seed rate was the same in both growing seasons and corresponded to 60, 100, and 15 kg ha^{-1} for hairy vetch, oat, and oilseed rape, respectively. The no cover was managed similarly to the cover crop plots and was kept weed-free throughout the cover crop growing season by hand weeding soon after weed emergence. All cover crops were mechanically suppressed at the same time on 21 May 2010 and 4 May 2011 and the cover crop aboveground biomass was treated as follows: (a) chopped with a straw chopper and immediately incorporated into the soil using a mold-board plough to a depth of 30 cm (CT); (b) chopped as CT and incorporated into the soil by means of rotary tiller to a depth of approximately 10 cm (MT); and (c) mowed approximately 5 cm above the soil surface and placed in strips as mulch layers with a hay-conditioner farm machine (Marangon s.r.l., MDN 210 model) (RS). In RS, each mulch strip was composed of a 50-cm wide uniform layer of cover crop residues which were arranged at a distance of 1.0 m centre strip from one another alternating a strip mulched with a 50-cm wide strip of un-mulched soil (Radicetti et al., 2013b). The mulch strips covered 50% of the total ground area and were used as transplanting beds for the eggplant seedlings (Fig. 1). At cover crop termination, in the no cover plots, the transplanting beds were prepared as follows: (a) the soil was ploughed and harrowed twice with a disc harrow in order to simulate CT system; (b) the soil was tilled with a rotary hoe in order to simulate MT system, and (c) the soil was left no-tilled in order to simulate RS system. Soon after cover crop termination on 27 May 2010 and 12 May 2011, the var. eggplant (*Solanum melanogena* L. var. Mirabella) seedlings were transplanted by hand at 33 cm one from another and in rows 1 meter apart with a density of 3 plants m^{-2}. The same arrangement was maintained in all treatments. In the RS plots, the eggplant seedlings were transplanted in the middle of the mulch strips with minimal disturbance of the mulch layer and with cover crop residues surrounding each eggplant seedling. Irrigation water was supplied by drip irrigation tape installed over the mulch layer (in RS treatments) and on soil surface (in MT and CT treatments) on eggplant rows at a distance of 5 cm from the plant rows. The drip tape had on-line emitters with a capacity of 3 l h^{-1}. The amount of water input (610 and 556 mm in 2010 and 2011 cropping season, respectively) was uniformly distributed across treatments and was determined by evapotranspiration estimated with a class A pan evaporimeter and converted by crop coefficients (Allen et al., 1998). All plots were maintained weed-free by hand-weeding as needed from eggplant transplanting until the final eggplant harvest in order to avoid weed interference in soil nitrogen uptake. Fertilizers were not used on the eggplant crop. In both years, repeated copper treatments were applied during eggplant cultivation in order to control foliar diseases. The eggplant fruits were harvested manually four times per year: on 4 August, 18 August, 10 September and 27 September in 2010 and on 27 July, 11 August, 29 August, and 12 September in 2011.

2.4. Sampling and measurements

The rainfall and air temperature data throughout the study period were collected from a weather station located at 200 m from the experimental site. Just before cover crop termination, the aboveground biomass of cover crops was hand-clipped at the soil surface and collected using a quadrat 50 cm x 50 cm (0.25 m^2) placed randomly four times over each plot. A sub-sample of each cover crop aboveground biomass was weighed wet and dried at 60 °C until constant weight in order to determine the dry matter and moisture concentration. Samples of dried cover crop aboveground biomass were homogenized using a mill for biomass and the nitrogen content was determined with an elementary analyzer (Thermo Fisher Scientific, model FlashEA 1112 NC Analyzer, Bath, UK) (Di Matteo et al., 2014). The remaining sub-samples were used to fill nylon bags (10 cm x 10 cm, 10 cm x 14 cm, and 10 cm x 32 cm to be used in RS, MT, and CT, respectively) in order to determine the cover crop biomass reduction and the amount of nitrogen left in the residues (Campiglia et al., 2014a). The nylon bags were filled with the biomass of fresh cover crop, placed in the centre of each plot in the eggplant row and marked with a nylon thread tied to a metal stick. The bags were randomly distributed across the soil surface in RS plots, while in the other treatments the nylon bags were buried up to 10 cm and 30 cm deep in order to simulate MT and CT treatments, respectively. The nylon bags were collected at eggplant harvest. The remaining cover crop biomass was carefully separated from soil and dried at 60 °C until constant weight, weighed, and then ground and analyzed for nitrogen concentration with an elementary analyzer (Thermo Soil – Flash EA1112 NC Analyzer, Bath, UK). The difference between initial and final cover crop aboveground biomass was assumed to be the mass of cover crop which decomposed during the eggplant period. In both years from all plots, 6 soil samples per plot were collected at eggplant transplanting and at final eggplant harvesting in the 0-30 cm layer and mixed together in order to obtain a uniform sample for determining soil NO_3-N (Cataldo et al., 1975) and NH_4-N (Anderson & Ingram, 1993) concentration by means of colorimetric methods. The SPAD-502 (Minolta, Osaka, Japan) was used to obtain readings estimating chlorophyll concentration of eggplant crop on the 4^{th} fully grown leaf from the top of the plant. The readings were performed every 10 days throughout the eggplant crop period. Ten measurements, one per plant, were taken in each replication and averaged (Minotti et al., 1994). At the first eggplant harvesting, the ripened fruit of 10 eggplant plants were harvested from the two middle eggplant rows (5 plant per row) of each sub-plot. The same plants were harvested each time. At final eggplant harvest, the eggplant plants were harvested and cut manually at the soil surface in order to determine the marketable eggplant yield and the oven dried weight (70 °C until constant weight) of the remainder of the plant (hereafter called straw). At each eggplant harvesting the fruit nitrogen content was measured with an elementary analyzer (Thermo Fisher Scientific, model FlashEA 1112 NC Analyzer, Bath, UK). The total N accumulation was calculated by multiplying the biomass (fruit and/or straw) dry weight by the corresponding nitrogen concentration value. At the final eggplant harvest, soil dry bulk density at 0 – 30 cm depth was measured by collecting 6 soil cores per plot using a soil corer with a 47 mm diameter and 50 mm high.

The following formulas were used for calculating eggplant N uptake and N use efficiency (hereafter called NUE) as reported by Gao et al. (2009):

$$Nup = (a \times b) + (c \times d)$$

Where Nup is N uptake (kg of N ha^{-1}), a is the marketable eggplant yield (kg ha^{-1} of DM), b is the N content of marketable eggplant fruits (g of N g^{-1} of dry eggplant fruit), c is the eggplant straw yield (kg ha^{-1} of DM), and d is the N content of eggplant straw (g of N g^{-1} of dry eggplant straw).

$$NUE = [(e - f) / g] \times 100$$

Where NUE is the nitrogen use efficiency (%), e is N uptake of eggplant in CT, MT, and RS plots with cover crops (kg of N ha^{-1}), f is N uptake of eggplant in CT, MT, and RS in plots without cover crops (no cover), and g is the N supplied to the eggplant crop (kg of N ha^{-1}), released from cover crops aboveground biomass from their termination to final eggplant harvesting.

The agronomic efficiency of nitrogen (AE_N) was evaluated with the following formula (Kaupa and Rao, 2014):

$$AE_N = (h - i)/g$$

Where AE_N is the agronomic efficiency of nitrogen (kg of dry eggplant fruits per kg of nitrogen), h is the eggplant yield in CT, MT, and RS plots with cover crops (kg ha^{-1} of DM), i is the eggplant yield in CT, MT, and RS in plots without cover crops (no cover), and g is the N supplied to the eggplant crop (kg of N ha^{-1}) and released from cover crop aboveground biomass from their termination to final eggplant harvesting.

2.5. Statistical analyses

All data were subjected to analysis of variance (ANOVA) using JMP statistical software package version 4.0 (SAS Institute, 1996). The analysis of variance was carried out for the 2-year period, considering the year as repeated measure across time. In order to homogenize the variance, after the Bartlett test we transformed the percentage data into angular transformation before analysis (Gomez and Gomez, 1984). The data reported in the tables were back transformed. A split-plot experimental design was adopted for cover crop aboveground biomass, cover crop nitrogen content, and soil inorganic N concentration at cover crop termination, where the year was considered as the main factor and the cover crops as the split factor. A split-split-plot experimental design was used for eggplant characteristics, soil inorganic N concentration at final eggplant harvesting, cover crop residue characteristics at final eggplant harvesting, NUE and AE_N, where the year was treated as main factor, the cover crop species as the split factor, the cover crop residue management as the split-split factor. Treatment means were compared with Fisher's protected least significant difference (LSD) test at the 0.05 probability level.

3. RESULTS

3.1. Weather conditions

Marked variations in rainfall and air temperatures (minimum and maximum) were recorded over the 2 study periods (2009/2010 and 2010/2011) (Fig. 2). The total rainfall was always higher compared to the historical average and it was concentrated in the autumn-winter period in 2009/210, while in 2010/2011 there was also an abundant rainfall throughout the spring-summer period. The air temperatures were particularly low in December 2010 and February 2011 when they dropped several times below 0 °C with a peak of – 5 °C. Throughout the eggplant cultivation period the average air temperature was slightly higher in 2011 than 2010 (22.1 vs. 21.4 °C, respectively).

3.2. Cover crop and residue characteristics

At cover crop termination, the cover crop aboveground biomass was significantly affected by year x cover crop interaction ($P \leq 0.05$). It was higher in 2009/2010 than 2010/2011, except in hairy vetch that showed similar values both years (Table 1). However, cover crop aboveground biomass was generally higher in hairy vetch, intermediate in oat, and lower in oilseed rape, while its nitrogen content tended to be higher in hairy vetch, followed by oilseed rape, and oat. As expected the C:N showed a similar trend to that of the nitrogen content. At final eggplant harvesting, the cover crop aboveground residue biomass was notably reduced (Table 1), although there was a significant cover crops x cover crop residue management interaction (Fig. 3). The reduction of cover crop aboveground biomass ranged from 41.5% in oat RS to 76.1% in hairy vetch CT, and it was generally higher in CT, intermediate in MT, and lower in RS, except for hairy vetch that showed similar values in CT and MT soil tillage (Fig. 3). As expected the cover crop aboveground biomass released an abundant amount of N, especially in hairy vetch where the N released was more than twice compared to oat and oilseed rape (Fig. 4). Moreover in hairy vetch the N released was higher when the tillage was deeper (CT>MT>RS). At eggplant harvesting, the N remaining in the cover crop residues ranged from 51.8 kg of N ha^{-1} in hairy vetch RS to 8.0 kg of N ha^{-1} in oilseed rape CT. It was generally similar in oat regardless soil tillage management, while it was higher in RS than CT and MT in hairy vetch and in oilseed rape (Fig. 4).

3.3. Soil inorganic N and eggplant leaf SPAD values

The inorganic soil nitrogen (NO_3-N + NH_4-N) was always abundant following the legume cover crop (Table 2). At cover crop termination, it was about 60% higher in hairy vetch than the other treatments, and greater differences were observed after eggplant cultivation. In fact, at final eggplant harvest, the inorganic soil N ranged from 15.3 to 36.7 mg N kg^{-1} dry soil in no cover RS and in hairy vetch RS, respectively. The lowest soil inorganic N was generally observed in oat and no cover, while in oilseed rape the mineral nitrogen was a little higher. However only in hairy vetch the residue management had an effect on soil inorganic N at final eggplant harvesting, which was higher in RS, intermediate in MT, and lower in CT (Table 2).

The SPAD values generally tended to increase after eggplant transplanting reaching the highest values in the middle of the cropping period which then tended to decrease up to the final eggplant harvesting. However several differences were observed among cover crops and cover crop residue management. (Fig. 5). In hairy vetch, the SPAD values were high and similar in RS, MT, and CT throughout the cropping period, while in oat they were generally low especially in CT and MT at the beginning of the cropping period. In contrast the SPAD values observed in oilseed rape and no cover tended to be generally lower in RS compared to MT and CT.

3.4. Yield, nitrogen uptake and nitrogen in the residual biomass of the eggplant

There were significant year x cover crops ($P \leq 0.05$) and cover crops x cover crop residue management ($P \leq 0.01$) interactions on the marketable eggplant fruits, eggplant straw weight and their nitrogen content. Eggplant performed generally better in 2010 than 2011 except in oat which showed similar values between the years (Table 3). However, the amount of marketable eggplant fruits (on a fresh weight basis) varied considerably and ranged from 38.0 to 6.7 Mg ha^{-1} of fresh matter (hereafter called FM). It was high in hairy vetch, especially in RS and MT, intermediate in oilseed rape MT and CT, while it was low in oat MT and in no cover RS. A similar trend was observed in the straw weight of eggplant (Table 3). Nitrogen uptake of marketable eggplant fruits was similar in both years except for oilseed rape, which was higher in 2010 compared to 2011 (Table 4). It tended to be higher in hairy vetch, followed by oilseed rape, no cover and oat. High values of nitrogen uptake were observed in hairy vetch MT and RS, in oilseed rape MT, in oat RS and in no cover MT and CT (Table 4). A similar trend was noticed for nitrogen uptake of eggplant straw (Table 4). There were significant relationships between the total sum of the SPAD reading measured throughout the eggplant growing season and the nitrogen uptake of eggplant fruit (R^2=72) and the eggplant straw (R^2=0.76) (Fig. 6).

3.5. Nitrogen Use Efficiency (NUE) and Agronomic Efficiency (AE_N)

Nitrogen use efficiency (NUE) of eggplants varied greatly depending on cover crop species and residue management (Fig. 7). It tended to be higher when compared to no cover RS and lower when compared to no cover MT. However, the NUE was always positive in hairy vetch regardless the residue management ranging from 70.7% to 31.2%. It was negative in oat except in RS and CT when compared with no cover RS, while the NUE in oilseed rape was always positive in MT and when compared with RS no cover (Fig. 7).

There were significant year x cover crops ($P \leq 0.01$) and cover crops x cover crop residue management interactions ($P \leq 0.05$) on the nitrogen agronomic efficiency of nitrogen (AE_n) (Table 5). It showed a similar trend observed for NUE when compared to no cover. The AE_n was similar between the experimental years in hairy vetch and oat, while it was higher for oilseed rape regardless the no cover managements in 2010 compared to 2011 (Table 5). However, the AE_n varied considerable and ranged between 15.9 and – 27.3 kg of eggplant dry fruit per kg N mineralized from cover crop. It was generally high in hairy vetch especially in RS (> 11), while it was always negative in oat MT residue management (<-12). In oilseed rape the AE_N showed higher values in MT, than CT and RS residue management.

4. DISCUSSION

Differences in the cover crop aboveground biomass and its nitrogen content observed between years can be attributed to the large variability of climatic conditions throughout the cover crop growing season (Gabriel and Quemada, 2011; Brennan and Boyd, 2012). In 2010/2011 the significant reduction of aboveground biomass production, observed in oat and above all in oilseed rape, was probably due to the severe frost damage that occurred in December in the early stages of the cover crops (Fig. 2). Hairy vetch was more cold tolerant and appears suitable to be used as winter cover crop in Mediterranean environment and is capable of accumulating a large amount of aboveground biomass and nitrogen (Campiglia et al., 2010a). In fact, at cover crop termination hairy vetch added a quantity of nitrogen accumulated in the aboveground biomass to the system that was approximately three times higher than that provided by oat and oilseed rape. This organic nitrogen was made available to the subsequent eggplant crop through the mineralization process. Several studies have shown that the residue decomposition and nitrogen mineralization are important microorganism-driven processes related to the chemical characteristics of the organic residues (Ruffo and Bollero, 2003; Nourbakhsh, 2006; Sainju and Whitehead, 2006). As a general rule, if the amount of nitrogen content in organic residues is larger than that required by the microbial biomass, there is a net mineralization with the release on inorganic nitrogen (Rosecrance et al., 2000). The low C/N ratio observed in the hairy vetch residues probably determined a higher mineralization rate compared to oat and oilseed rape residues, which were characterized by a higher C/N ratio. Consequently the residues of hairy vetch probably started to mineralize very quickly immediately after the cover crop termination (Kramberger et al., 2009) and supplied more mineral nitrogen to the soil than oat and oilseed rape (Kuo and Sainju, 1998). Moreover, based on the data on soil inorganic N concentration measured at cover crop termination, we assume that hairy vetch could have released fixed nitrogen into the soil even before its termination determining a high level of soil mineral nitrogen before eggplant transplanting (Campiglia et al., 2014b). Although this effect is favorable for the growth of the following eggplant crop, it may result in a high risk of nitrogen leaching in the wet spring seasons. As suggested by Brennan and Boyd (2012) a legume-cereal cover crop mixture, instead of a sole legume, could be considered in order to avoid nitrogen losses because it combines the N scavenging of the non-legume with the N fixing ability of the legume.

The management of the cover crop aboveground biomass strongly influenced residue decomposition. In this experiment the reduction of the cover crop aboveground biomass was generally faster in tilled (CT and MT) than in no-tilled soil (RS). When fresh plant material is incorporated into the soil, mineralization occurs faster than when the materials are left on the soil surface (Mulvaney et al., 2011). In fact, in oilseed rape and oat the reduction of the cover crop residues was higher in CT than in MT. A deeper soil tillage, as occurred in CT, probably caused a greater dilution of the cover crop residues in the soil compared to MT, therefore the contact between the organic materials and soil microorganisms increased and accelerated the mineralization process (Mulvaney et al., 2011). The higher soil inorganic nitrogen content in hairy vetch at eggplant harvesting compared to oilseed rape, oat, and no cover treatments was probably due to the greater amount of nitrogen supplied by the legume. Hairy vetch as a winter cover crop, generally increases soil mineral nitrogen in both no-tilled and tilled soils in summer vegetable cropping systems (Ruffo and Bollero, 2003; Sainju and Whitehead, 2006; Campiglia et al., 2010a). However, when incorporated into the soil hairy vetch residues can release a large amount of mineral nitrogen in a short period of time (Kuo and Sainju, 1998) which makes it difficult to synchronize the nitrogen uptake of the crop especially in summer vegetables such as eggplant which showed a slow growth in the first period after transplanting. Therefore, the high amount of nitrogen released from the hairy vetch cover crop, especially when soil-incorporated in conventional tillage (CT), may be lost if it is not caught by the subsequent crop, while leaving the residues on the soil surface as organic dead mulch can be a viable management practice to delay the mineralization process (Campiglia et al., 2010b). Moreover mulch can increase soil moisture content and stabilize temperature fluctuations that improve nitrogen utilization by the eggplant crop (Sainju et al., 2003). This hypothesis is supported by the eggplant yield and nitrogen uptake of eggplant marketable fruits which had higher values in RS than CT residue management. On the contrary, the oat residues mineralized slowly and the nitrogen uptake by the eggplant grown in CT and MT was lower than that in no cover without cover crop residues. This effect could be due to the high C/N value of the residues which may have promoted the immobilization of the available soil mineral nitrogen (Rosecrance et al., 2000). When the oat residues were left on the soil surface and arranged in strips, the mineralization process was delayed further due the reduced contact between the residues and the soil. Consequently in oat treatments, the eggplant yield and the nitrogen uptake by eggplant fruit significantly increased in RS compared to MT and CT. Therefore, even if the use of cover crops with a high C/N (i.e. oat) decreases the yield of the following vegetable crop, this negative effect can be mitigated with an adequate residue management such as using mulch instead of green manuring strategies or applying high rates of nitrogen fertilizer to eggplant, although this practice is not advisable from an ecological point of view (Kramberger et al., 2014). The oilseed rape residues showed intermediate C/N and nitrogen content values between oat and hairy vetch. They had a similar effect on eggplant yield to that observed in oat when they were left on soil surface, while the eggplant yield increased compared to oat especially in MT when they were green manured. The small quantity of mineral nitrogen deriving from the mineralization process of oilseed rape was probably more easily caught by the shallow eggplant root system (Aujla et al., 2007) when the residues were concentrated in the upper soil layer (10 cm) than when diluted in 30 cm of soil layer. This hypothesis is supported by the nitrogen uptake by marketable eggplant fruits which was much higher in MT than in CT even if the reduction of the aboveground biomass was more consistent in CT than MT. Therefore, the ability of the eggplant to uptake the nitrogen coming from the mineralization of cover crop aboveground biomass varied greatly not only in relation to the different cover crop species but also according to the cover crop residue management. Therefore, the nitrogen use efficiency (NUE) and the agronomic efficiency (AEn) of eggplant grown on cover crop residues were variable. Both indices were very high in hairy vetch residues, while they were low, even negative, in oat residue although significant differences were observed in relation to cover crop residue management. According to this study it seems that when the nitrogen supply by cover crop residues is high and the C/N ratio of the material is low, such as in hairy vetch (C/N=13), it is preferable to use a RS strategy to delay the mineralization rate of nitrogen and avoid the risk of losing nitrogen into the environment. When the nitrogen supply by cover crop residues is small and the C/N ratio is intermediate, such as oilseed rape (C/N=29), it is advisable to use MT considering that the mineralized nitrogen is easily caught by a shallow root system. When the nitrogen supply by cover crop residues is small and the C/N ratio of the material is high, such as in oat (C/N=47), it is preferable to adopt a RS strategy in order to avoid the immobilization of the available soil mineral nitrogen. However, considering that the NUE of eggplant was generally negative following oat cover crop, a large amount of mineral fertilizers may be required to reduce the yield gap compared to the eggplant grown following hairy vetch and oilseed rape cover crops. In this study the SPAD readings of eggplant leaves detected the eggplant nitrogen deficiencies and there was a strong relationship between the nitrogen uptake by eggplant and the total sum of the SPAD reading throughout the growing season. Therefore, SPAD readings could be useful tools for adjusting nitrogen fertilizer rates in summer vegetable crops after cover crop cultivation due to the uncertainty of nitrogen availability throughout the mineralization processes of cover crops residues (Miguez and Bollero, 2006). However, the nitrogen supplied by the cover crop could be even higher than the requirements of the subsequent main crop. In this study, after eggplant harvesting, a considerable quantity of nitrogen was left in the system as both soil mineral nitrogen and organic nitrogen still present in the residual cover crop biomass of the hairy vetch especially in RS conditions. Therefore, the nitrogen accumulated by cover crops is only partially recovered by the succeeding crop, a part of cover crop nitrogen enriches the soil organic nitrogen pool and it can be mineralized later (Tonitto et al., 2006). This outcome suggests that when legume cover crops are used in intensive vegetable cropping systems, it may be necessary to enhance nitrogen recovery and reduce the potential of nitrogen loss by capturing the excess of nitrogen before it is lost. As suggested by Campiglia et al (2014a), the residual nitrogen could be used alternatively and profitably by cultivating an autumn-winter vegetable such as endive or savoy cabbage in close rotation with the summer vegetable.

5. CONCLUSIONS

The combination of winter cover crop species and cover crop residue management affected the speed of the residue decomposition, the release of nitrogen and the performances of the subsequent vegetable crop. The results of this study showed that the mineralization of the cover crop aboveground biomass was always faster when the residues were incorporated into the soil [conventional tillage (CT) and minimum tillage (MT)], than when they were left on the soil surface and arranged in mulch strips (RS). In particular the reduction of oilseed rape and oat residues was also accelerated by a deeper soil tillage such as that carried out in CT. However, the reduction of the cover crop aboveground biomass throughout the following eggplant cropping seasons, was mainly due to the chemical characteristics of the cover crop species such as nitrogen content and C/N ratio. Hairy vetch showed a residue reduction approximately 2-fold higher than oat residues and an approximately 3-fold higher amount of nitrogen was released compared to oilseed rape and oat. As a consequence in hairy vetch treatments, the eggplant yield and the nitrogen uptake by eggplant crop were much higher than those observed in the other treatments. An interactive effect of the winter cover crop species and cover crop residue management was observed on nitrogen use efficiency (NUE) and the agronomic efficiency (AEn) of eggplant. Both indices were high and always positive in hairy vetch, while they were low and even negative in the oat and oilseed rape residues. However, the NUE and the AEn of eggplant grown in presence of hairy vetch and oat residues were generally higher in RS compared to MT and CT, while in presence of oilseed rape residues the NUE and the AEn was higher in MT. We conclude that when legume cover crop residues are incorporated into the soil the release of nitrogen could be in excess in respect to the nitrogen demand of the following vegetable summer crop, therefore leaving the cover crop residues on the soil surface as dead mulches may be a feasible strategy for slowing down the mineralization process and enhancing the synchronization between nitrogen release and crop requirements throughout the cropping season. This could increase the nitrogen use efficiency of the following summer vegetable crop and leave a consistent quantity of residual nitrogen in the system which could be profitably used when cultivating an autumn-winter crop in close rotation.

ACKNOWLEDGEMENT

This research was funded by the University of Tuscia. The authors wish to thank Claudio Stefanoni and Fulvia Gatti for their technical assistance and for participating in data collection. The authors would also like to thank Dr. Eric Brennan, from USDA ARS Crop Improvement and Protection Research, who provided valuable comments and suggestions while this manuscript was being written.

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Table 1. The effect of year x cover crops interaction on the cover crop aboveground biomass, its nitrogen content and C/N ratio at cover crop termination and on cover crop aboveground biomass decomposed at eggplant harvesting. Values belonging to the same variable followed by the same letter are not significantly different according to LSD (0.05), in rows for year (upper case letter) and columns for cover crop (lower case letter).

	Cover crop aboveground biomass (Mg m^{-2} of DM)				C/N ratio		Nitrogen content (%)				Decomposed cover crop biomass at eggplant harvesting (%)			
	2009/2010		2010/2011				2009/2010		2010/2011		2009/2010		2010/2011	
Hairy vetch	6.09	aA	6.27	aA	12.7	c	3.1	aA	3.0	aA	72.4	aA	71.6	aA
Oat	6.07	aA	5.29	bB	46.5	a	1.1	cA	1.2	cA	44.3	cA	53.8	bA
Oilseed rape	4.78	bA	2.79	cB	29.4	b	1.7	bB	2.0	bA	68.3	bA	57.6	bB

Table 2. Mean effect of cover crop at cover crop termination and interaction effect of cover crops x cover crop residue management at eggplant harvesting on soil inorganic nitrogen (NH_4 + NO_3) concentration at 0 – 30 cm depth. Values belonging to the same characteristic and treatment without common letters are statistically different according to LSD (0.05), in rows per nitrogen fertilization level (upper case letter) and columns per cover crop (lower case letter). RS = Residues left on the soil surface in no-tilled soil, MT = Minimum tillage, and CT = Conventional tillage.

	Soil inorganic N concentration at cover crop termination (mg inorganic N kg^{-1} dry soil)	Soil inorganic N concentration at eggplant final harvest (mg inorganic N kg^{-1} dry soil)		
		RS	MT	CT
Hairy vetch	33.8 a	36.7 aA	30.0 aB	23.6 aC
Oat	19.7 b	16.9 cA	17.3 cA	15.7 cA
Oilseed rape	20.3 b	19.4 bA	22.2 bA	19.6 bA
No cover	22.9 b	15.3 cA	19.1 cA	16.1 cA

Table 3. The effect of year x cover crops interaction and cover crops x cover crop residue management interaction on the marketable fruit yield and the straw weight of eggplant crop. Values belonging to the same characteristic with different letters in rows for years or residue management (upper case letter), and in columns for cover crops (lower case letter) are statistically different according to LSD (0.05). RS = Residues left on the soil surface in no-tilled soil, MT = Minimum tillage, and CT = Conventional tillage. FM = Fresh Matter.

Treatments	Marketable eggplant fruit yield (Mg ha^{-1} of FM)				
	Year		Cover crop residue management		
	2010	2011	RS	MT	CT
Hairy vetch	36.5 aA	33.9 aB	38.0 aA	36.1 aA	31.6 aB
Oat	13.4 dA	12.9 cA	18.4 bA	6.7 dC	14.3 cB
Oilseed rape	25.9 bA	15.4 bB	17.6 bB	24.7 bA	19.7 bB
No cover	20.2 cA	13.4 bcB	11.3 cC	21.4 cA	17.7 bB
	Straw weight (Mg ha^{-1} of DM)				
	Year		Cover crop residue management		
	2010	2011	RS	MT	CT
Hairy vetch	3.4 aA	3.5 aA	3.2 aB	3.5 aA	3.3 aB
Oat	1.8 cA	1.6 cA	2.1 bA	1.4 cB	1.7 cB
Oilseed rape	2.6 bA	2.2 bB	2.1 bB	2.7 bA	2.5 bA
No cover	2.5 bA	2.0 bB	1.6 cB	2.7 bA	2.5 bA

Table 4. The effect of year x cover crops interaction and cover crops x cover crop residue management interaction on the nitrogen uptake of fruits and straw of eggplant crop. Values belonging to the same characteristic with different letters in rows for years or residue management (upper case letter), and in columns for cover crops (lower case letter) are statistically different according to LSD (0.05). RS = Residues left on the soil surface in no-tilled soil, MT = Minimum tillage, and CT = Conventional tillage.

Treatments	Nitrogen uptake of marketable eggplant fruit (kg N ha^{-1})				
	Year		Cover crop residue management		
	2010	2011	RS	MT	CT
Hairy vetch	93.8 aA	93.98 aA	99.7 aA	100.1 aA	82.0 aB
Oat	29.3 dA	28.92 cA	40.5 bA	15.5 dC	31.4 cB
Oilseed rape	58.7 bA	37.20 bB	42.5 bB	55.8 bA	45.5 bB
No cover	38.5 cA	33.65 bA	27.2 cB	41.0 cA	40.0 bA
	Nitrogen uptake of eggplant straw (kg N ha^{-1})				
	Year		Cover crop residue management		
	2010	2011	RS	MT	CT
Hairy vetch	82.9 aA	73.7 aB	70.7 aB	88.4 aA	75.8 aB
Oat	34.6 cA	32.5 cA	42.5 bA	25.2 cC	33.0 cB
Oilseed rape	58.0 bA	45.8 bB	41.4 bB	59.8 bA	54.5 bA
No cover	53.9 bA	40.7 bB	32.4 cC	58.0 bA	51.5 bB

Table 5. The effect of year x cover crops interaction and cover crops x cover crop residue management interaction on agronomic efficiency (AEn) of nitrogen compared to no cover managed in no-tilled soil (RS), minimum tillage (MT), and conventional tillage (CT), respectively. Values belonging to the same characteristic with different letters in rows for years or residue management (upper case letter), and in columns for cover crops (lower case letter) are statistically different according to LSD (0.05).

Treatments	Year		Cover crop residue management		
	2010	2011	RS	MT	CT
AE_N compared to RS no cover (Kg of eggplant dry fruit per kg N mineralized from cover crop)					
Hairy vetch	13.6 aA	13.0 aA	15.9 aA	14.3 aA	10.7 aB
Oat	-1.6 bA	0.2 cA	8.3 bA	-12.5 bC	2.1 cB
Oilseed rape	11.7 aA	6.1 bB	5.3 bB	13.9 aA	7.2 bB
AE_N compared to MT no cover (Kg of eggplant dry fruit per kg N mineralized from cover crop)					
Hairy vetch	11.9 aA	12.3 aA	14.5 aA	12.7 aAB	9.8 aB
Oat	-5.0 bA	-5.3 cA	3.6 bA	-16.9 bC	-2.2 cB
Oilseed rape	8.1 aA	3.4 bB	1.8 bB	11.2 aA	4.2 bB
AE_N compared to CT no cover (Kg of eggplant dry fruit per kg N mineralized from cover crop)					
Hairy vetch	8.9 aA	9.1 aA	11.2 aA	9.7 aAB	6.1 aB
Oat	-14.1 cA	-16.8 cA	-6.5 bA	-27.3 cC	-12.5 cB
Oilseed rape	4.1 bA	-10.9 bB	-8.5 bB	2.5 bA	-4.2 bB

Figure 1. Plan of the eggplant seedling geometry in: residues left on the soil surface in no-tilled soil (RS), minimum tillage (MT), and conventional tillage (CT).

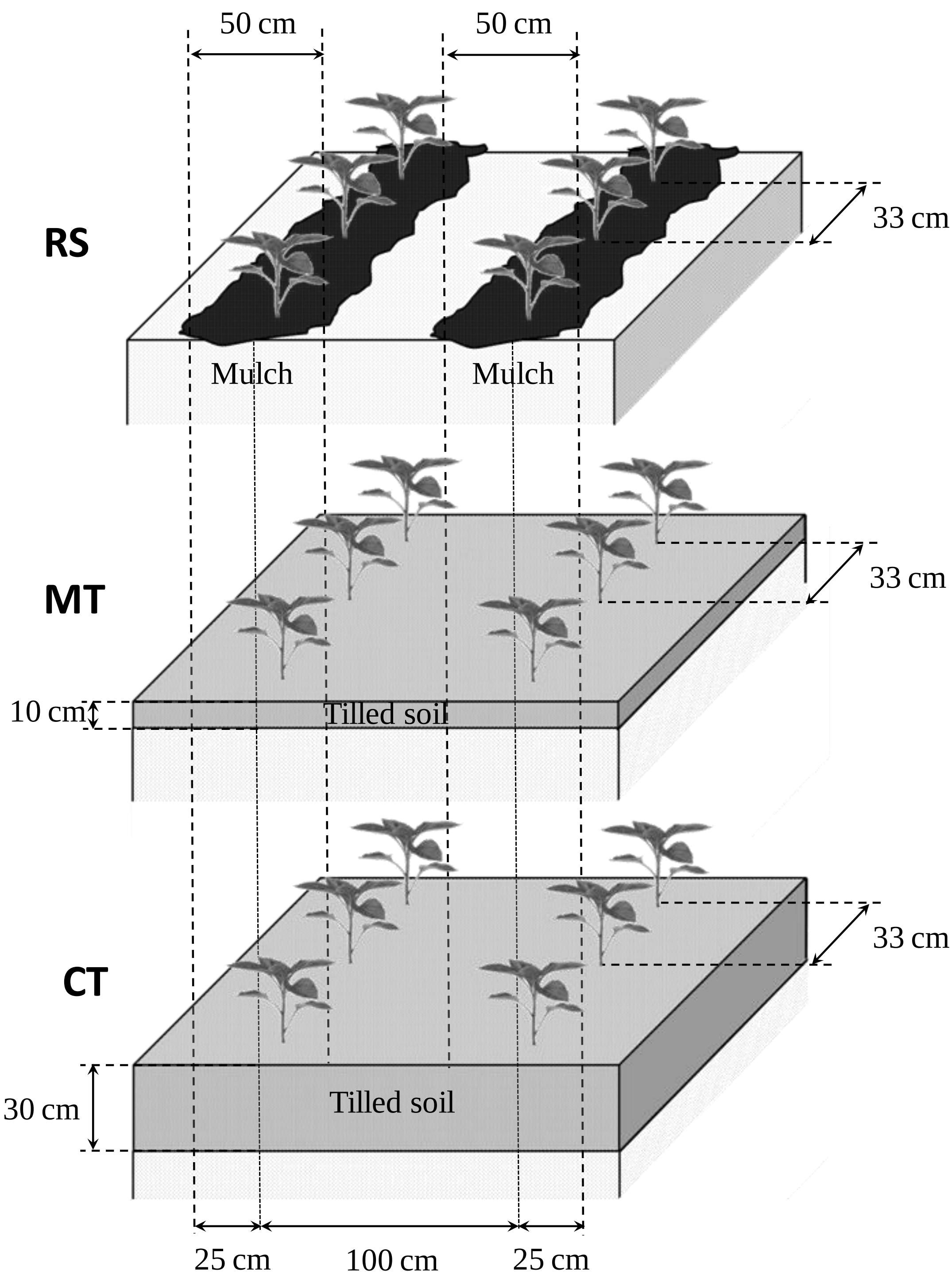

Figure 2. Rainfall, minimum and maximum average air temperatures at the experimental site at 10-day intervals from September 2009 to September 2011.

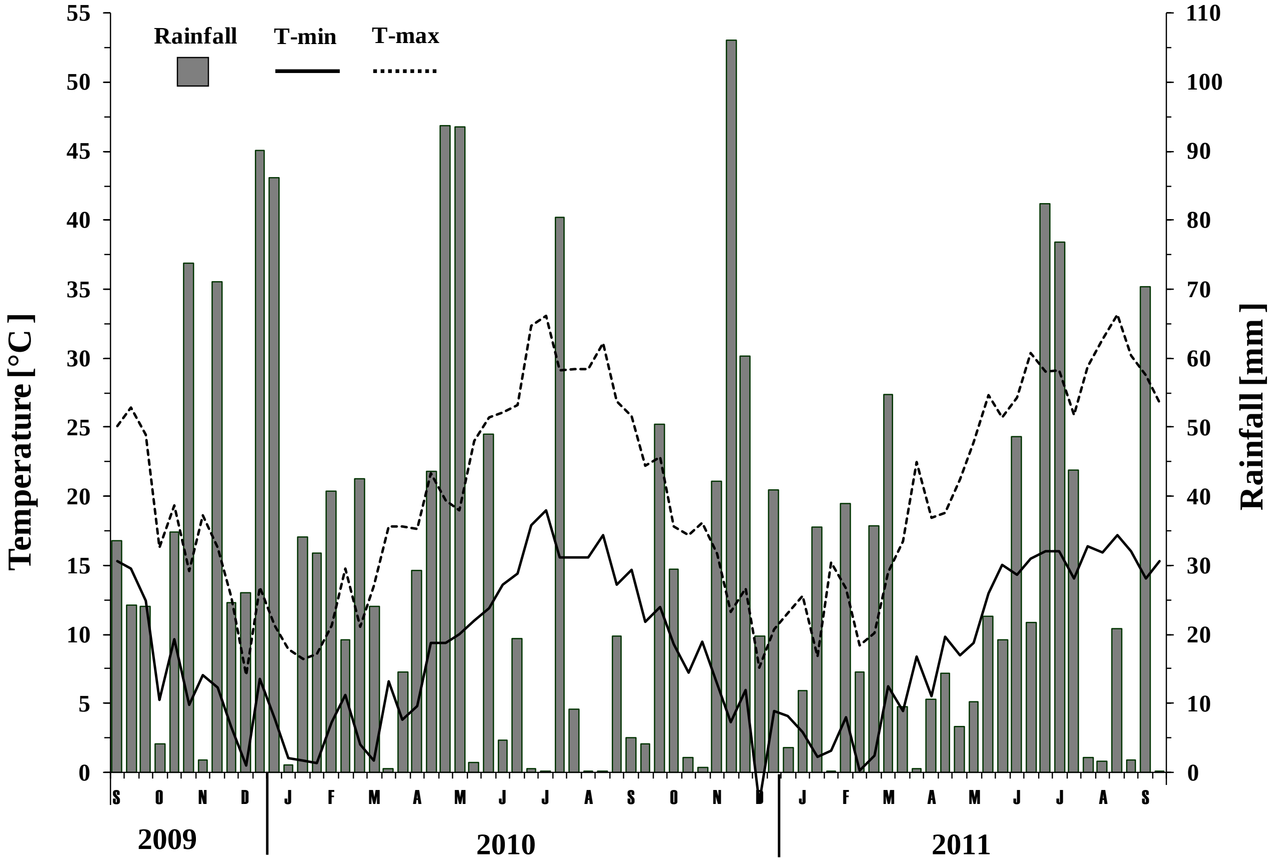

Figure 3. The effect of cover crop x cover crop residue management interaction on cover crop aboveground biomass reduction at eggplant harvesting. Values belonging to the same characteristic followed by the same letter are not significantly different according to LSD (0.05). RS = Residues left on the soil surface in no-tilled soil, MT = Minimum tillage, and CT = Conventional tillage.

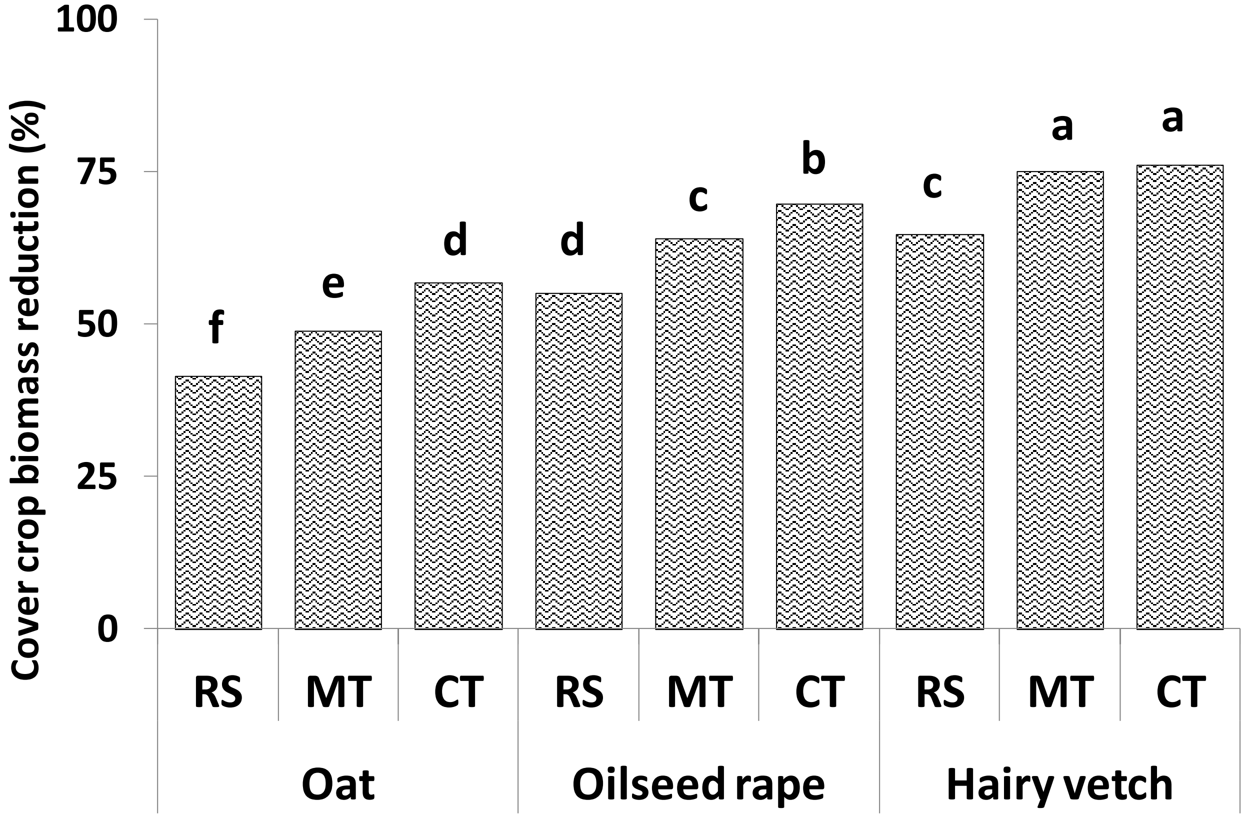

Figure 4. The effect of cover crop x cover crop residue management interaction on the N released throughout eggplant growing season and the remaining N in the cover crop aboveground biomass at eggplant harvest. Values belonging to the same characteristic followed by the same letter are not significantly different according to LSD (0.05). RS = Residues left on the soil surface in no-tilled soil, MT = Minimum tillage, and CT = Conventional tillage.

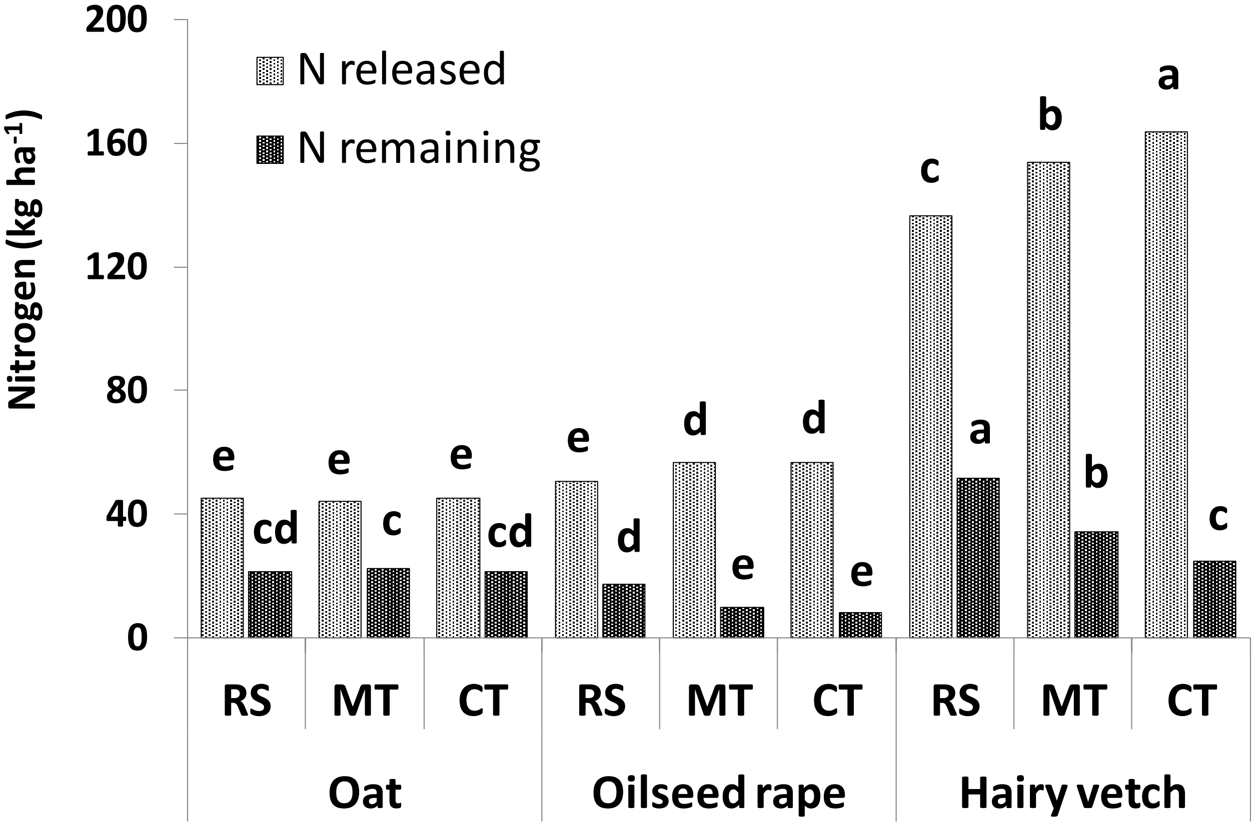

Figure 5. The effects of cover crop and cover crop residue management on chlorophyll content (SPAD readings) of eggplant leaves during the growing cycle of the crop. Data correspond to the 2011 and 2012 growing seasons. Error bars represent ± standard error from mean (n = 60). RS = Residues left on the soil surface in no-tilled soil, MT = Minimum tillage, and CT = Conventional tillage.

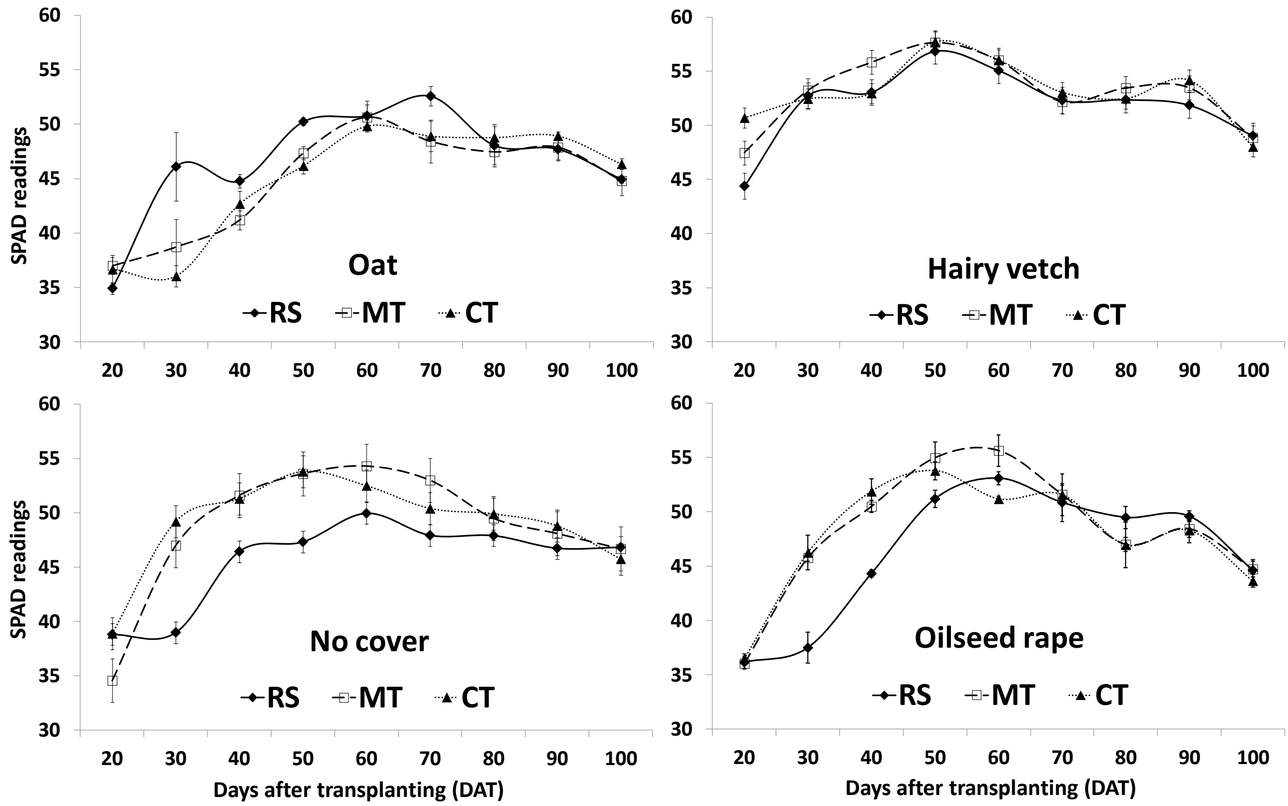

Figure 6. Relationship between the Nitrogen uptake of eggplant fruit or straw and the total sum of the SPAD reading measured throughout the eggplant growing season. Data correspond to the 2009/2010 and 2010/2011 growing seasons and the significance level is *** significant at P < 0.001 level.

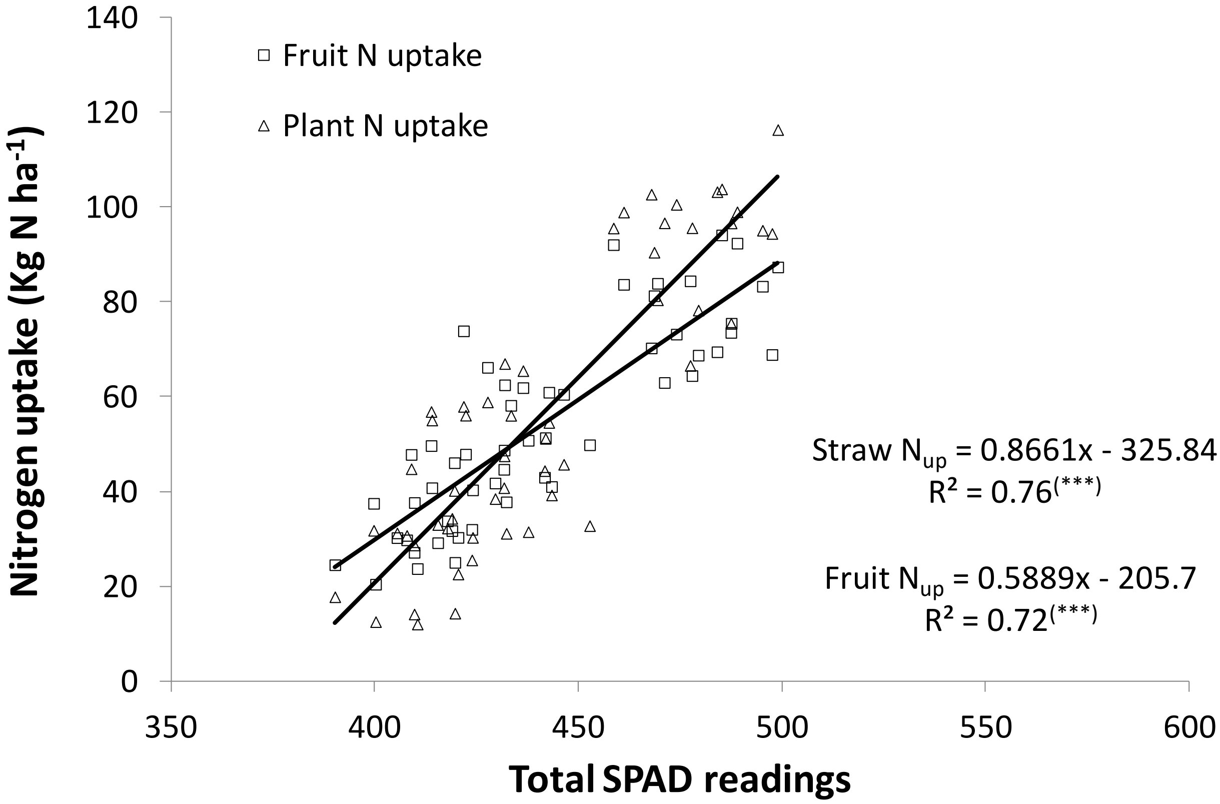

Figure 7. Effect of cover crop x cover crop residue management interaction on the N use efficiency (NUE) of eggplant compared no cover managed in no-tilled soil (RS), minimum tillage (MT) no cover, and conventional tillage (CT) no cover. Values belonging to the same variable and treatment followed by the same letter are not significantly different according to LSD (0.05).