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# Organic production of horticultural crops with green manure, composted farmyard manure and organic fertiliser

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**ABSTRACT**

A three-year organic crop rotation was set up in a field with sandy loam soil, with a cover crop of rye and vetch grown over the three autumn/winter seasons for green manure, followed by potato and lettuce (1st year), Swiss chard and turnip (2nd year), and Portuguese cabbage and carrot (3rd year). Nitrogen (N) mineralisation was determined by field incubation in response to green manure (GM), GM with 20 and 40 t ha$^{-1}$ farmyard manure (FYM) compost (C20 and C40) and GM with 1 and 2 t ha$^{-1}$ of commercial organic fertiliser (CF1 and CF2). The second season crops (lettuce, turnip and carrot) yields were higher for the treatment C40 compared to all other treatments because most of the commercial fertiliser was mineralised during the previous crop. Swiss chard, grown in a short season (54 days), produced higher yield for CF2 compared with C40. However, this was not true for potato (1st year), probably because of increased compost mineralised N recovery during the longer growing season for the potatoes (124 days), nor for the cabbage (3rd year), which had a short growing season (56 days), because of increased N availability with continuous compost and green manure application. This study highlighted that field incubation can be used to assess mineralisation rates and that the fast N release of commercial fertilisers increased the yield of the first crop of the year, whereas the slowly released N of FYM compost increased yield of both crops of the year, with lower risk of N loss.

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## Introduction

Management of soil organic matter and crop nutrition in organic agriculture relies on several organic farming practices such as crop rotation, the use of green manures and soil fertilisation with composts and organic fertilisers. Cover crops are grown for green manure as well as for other purposes including control of soil-borne diseases, pests and weeds, enhancement of soil structure and microbiological activity and to diminish soil erosion (Dabney et al. 2001; Tejada et al. 2008). However, most of the interest in cover crops concerns the N availability for crop growth once the crop has been incorporated into the soil as green manure (Thorup-Kristensen et al. 2003). Cereal rye (*Secale cereale*) is a commonly used cover crop that can produce large amounts of biomass and reduce the biomass of

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several weed species (Mohler and Teasdale 1993). Vetch (*Vicia sativa*) can accumulate substantial amounts of biologically fixed N, which may become available for the following crop when the vetch is incorporated as green manure. The rapid release of mineral N increases the risk of leaching, but given rye's biomass efficiency to immobilise mineral N from soil, a combination of rye and vetch is advantageous to minimise N loss (Rosecrance et al. 2000). Although crop yields may be reduced in the first year after incorporation of non-leguminous cover crops with high C/N ratio because of soil N immobilisation (Salmeron et al. 2011), the incorporation of leguminous cover crops may also not increase crop yields in the first year, due to the reduced amount of cover crop biomass (Tonitto et al. 2006). These authors found that a leguminous cover crop which provided less than 110 kg N $ha^{-1}$ was not sufficient to increase yields. However, several studies indicated that the repeated use of leguminous and non-leguminous green manures increased crop yields in later years (Kuo and Jellum 2000; Kumar and Goh 2002).

Compost have been shown to have positive effects on agricultural soils and crop production, providing large quantities of nutrients to the soil, improving soil physical and biological properties and therefore increasing yields (Bonanomi et al. 2014). Still, the main purpose in using manures and manure composts in organic horticulture is to increase N availability (Amlinger et al. 2003). Fresh composts released inorganic N at a faster rate compared to mature composts (Antil et al. 2011). However, the application of fresh compost may cause serious agronomic and environmental problems due to high electrical conductivity and $NH_4^+$ concentration of the compost, soil N immobilisation and increased nutrient loss through leaching as a result of inopportune timing of application (Wong et al. 1999; Brito 2001). Composting may reduce environmental problems by transforming the organic waste into a safer and more stable material, eliminating the risk of disseminating pathogenic organisms, and reducing the viability of weed seeds (Gomez-Brandón et al. 2008). The influence of compost on crop growth during the first year of application is quite controversial, but generally crop growth is enhanced after successive compost application because compost acts as a slow-release source of N (Erhart et al. 2005).

In organic agriculture, N is usually the limiting nutrient because its availability in the soil depends on organic matter mineralisation and it is required by crops in large amounts. N mineralisation depends on climatic conditions, crop and soil characteristics, and cultural practices (Amlinger et al. 2003). It also depends on the balance between N mineralisation and immobilisation (Reddy et al. 2008). If not properly managed, N supply may not match N crop demand, leading to a reduced N recovery by the crops, whereas N losses may increase (Thorup-Kristensen and Dresbøll 2010). Therefore, it is crucial to determine the N mineralisation rates of the organic materials incorporated into the soil during the crop rotation, in order to synchronise the release of N with crop demand.

Incubating amended soils under controlled laboratory conditions provides an indication of the soil's potential to mineralise N. Nevertheless, due to soil perturbations (storing, mixing and sieving) and the lack of temperature and soil moisture fluctuations, it is unlikely that this approach will accurately reflect the effective rates of mineralisation which occur in the field (Lomander et al. 1998). In contrast, soil incubation in buried soil cores (Hatch et al. 1990) resembles more closely the fluctuating environmental conditions in the field.

The objectives of this study were: (i) to improve fertiliser recommendations based on experimental data to facilitate increases in organic horticultural crop yields; (ii) to improve the synchronisation between N mineralisation and crop N demand, because N is usually the limiting nutrient; and (iii) to evaluate the correlation between soil N availability determined by field incubation and crop yields.

## Materials and methods

### *Experimental treatments*

A field experiment was set up on a horticulture farm that had been organically managed for two years and where the soil was a sandy loam dystric Cambi soil derived from granite in the NW of Portugal (41° 12′ N, 8° 7′ W, altitude 466 m and average rainfall of 1500 mm). A three-year organic

**Table 1.** Dry matter content (DM) and chemical characteristics of farmyard manure compost applied before potato (1st year), chard (2nd year) and cabbage (3rd year) (mean ± standard deviation).

| Nutrients | | 1st year | 2nd year | 3rd year |
|---|---|---|---|---|
| DM | (%) | 25.9 | 23.2 | 24.7 |
| pH ($H_2O$) | | 8.0 ± 0.05 | 9.1 ± 0.1 | 7.9 ± 0.02 |
| EC | (ds $m^{-1}$) | 4.3 ± 0.3 | 3.6 ± 0.1 | 5.2 ± 0.8 |
| C | (g $kg^{-1}$) | 328 ± 35 | 326 ± 49 | 313 ± 37 |
| N | (g $kg^{-1}$) | 19.7 ± 0.7 | 23.1 ± 2.4 | 25.4 ± 1.5 |
| C/N | | 17 | 14 | 12 |
| $NH_4^+$-N | (mg $kg^{-1}$) | 69 ± 16 | 338 ± 7 | 81 ± 3 |
| $NO_3^-$-N | (mg $kg^{-1}$) | 134 ± 38 | 23 ± 10 | 1334 ± 43 |
| Soluble C | (g $kg^{-1}$) | 7.4 ± 0.5 | 9.2 ± 0.6 | 7.8 ± 0.5 |
| Soluble N | (g $kg^{-1}$) | 1.4 ± 0.003 | 0.8 ± 0.03 | 1.2 ± 0.2 |
| P | (g $kg^{-1}$) | 6.7 ± 0.2 | 5.5 ± 0.4 | 5.8 ± 0.3 |
| K | (g $kg^{-1}$) | 44 ± 8.5 | 24 ± 3.8 | 29 ± 2.2 |
| Ca | (g $kg^{-1}$) | 11 ± 1.2 | 21 ± 3.8 | 20 ± 4.1 |
| Mg | (g $kg^{-1}$) | 8.0 ± 1.2 | 7.6 ± 0.9 | 5.0 ± 0.9 |

Note: Nutrient concentrations are expressed on a dry matter basis.

crop rotation was established with a cover crop of a rye (*Secale cereale* L.)/vetch (*Vicia sativa* L. cv. Barril) mixture grown over the three autumn/winter seasons for green manure followed by: (i) in the 1st year (2012), potato (*Solanum tuberosum* L. cv. Desirée) from April to August and lettuce (*Lactuca sativa* L. cv. Maravilla de verano) from August to October; (ii) in the 2nd year, Swiss chard (*Beta vulgaris* L. cv. Blonde a card) (chard) from May to July and turnip (*Brassica rapa* cv. Nabo) from July to August; and (iii) in the 3rd year, Portuguese cabbage (*Brassica oleracea* var. tronchuda cv. Penca da Póvoa) (cabbage) from April to June and carrot (*Dacus carota* L. cv. Jarana F1) from June to October. Treatments applied before the potatoes, chard and cabbage included: (i) green manure (GM); GM with (ii) 20 t $ha^{-1}$ or (iii) 40 t $ha^{-1}$ of farmyard manure compost (C20 and C40); GM with (iv) 1 t $ha^{-1}$ or (v) 2 t $ha^{-1}$ of a commercial organic fertiliser (CF1 and CF2), and (vi) a control treatment without soil amendments (T0). This crop rotation was set up as a randomised block design with four blocks, each block was divided in 6 plots and the size of each plot was 15 $m^2$.

Composting piles, approximately 1.8 m wide, 1.5 m high and 6 m long, were prepared outdoors from farmyard manure (cow manure mixed with wheat straw used as bedding material and accumulated for 1 year in the cattle shed). The feedstock was composted for approximately 7 months and manually turned at 2 and 4 months after the start of the composting process. The compost piles were covered with a double shade net to protect from rain and from excessive drying of the external parts of the piles. The commercial organic fertiliser (Dix from Crimolara) was based on granulated fermented poultry manure and feathers and was certified for use in organic agriculture. The characteristics of the compost and the organic fertiliser are shown in Tables 1 and 2, respectively. The green manure yields and nutrient concentrations are shown in Table 3.

The organic fertiliser had not been composted so contained high concentrations of $NH_4^+$-N (7272, 17557 and 5309 mg $kg^{-1}$ in the 1st, 2nd and 3rd year, respectively) far above the maximum recommended value (400 mg $kg^{-1}$ DM) for mature compost by Zucconi and de Bertoldi (1987) and the ratios $NH_4^+$-N/$NO_3^-$-N were extremely high compared to the suggested upper limit value of 1 for matured compost by Larney and Hao (2007). In contrast, the farmyard manure composts were matured, as indicated by the $NH_4^+$-N concentrations (69, 338 and 81 mg $kg^{-1}$ DM[1] in the 1st, 2nd and 3rd year, respectively), which were below the maximum recommended value. The organic and total N applied by the organic amendments in the three growing seasons are shown in Table 4.

## *Cultural practices*

Soil preparation for the cover crop was carried out with a deep tine cultivator and the surface was levelled with a spike tooth harrow. Dolomite lime (88% $CaCO_3$ and 5% $MgCO_3$) was applied at the

**Table 2.** Dry matter content (DM) and chemical characteristics of commercial organic fertiliser applied before potato (1st year), chard (2nd year) and cabbage (3rd year) (mean ± standard deviation).

| Nutrients | | 1st year | 2nd year | 3rd year |
|---|---|---|---|---|
| DM | (%) | 91.5 | 91.7 | 90.5 |
| pH ($H_2O$) | | 6.6 ± 0.1 | 6.9 ± 0.04 | 6.9 ± 0.01 |
| EC | (ds $m^{-1}$) | 5.9 ± 00.2 | 6.8 ± 0.2 | 6.9 ± 0.2 |
| C | (g $kg^{-1}$) | 461 ± 7 | 410 ± 3 | 423 ± 5 |
| N | (g $kg^{-1}$) | 99.9 ± 1.5 | 97.4 ± 4.0 | 99.6 ± 5 |
| C/N | | 4.6 | 4.2 | 4.3 |
| $NH_4^+$-N | (mg $kg^{-1}$) | 7272 ± 545 | 17557 ± 3095 | 5309 ± 150 |
| $NO_3^-$-N | (mg $kg^{-1}$) | 2.1 ± 1.0 | 1.2 ± 0.2 | 135 ± 9.4 |
| Soluble C | (g $kg^{-1}$) | 42.7 ± 3.0 | 50.4 ± 1.7 | 52.2 ± 1.3 |
| Soluble N | (g $kg^{-1}$) | 36.6 ± 2.8 | 20.6 ± 0.7 | 21.2 ± 0.3 |
| P | (g $kg^{-1}$) | 8.8 ± 0.5 | 12.6 ± 0.5 | 12.8 ± 0.6 |
| K | (g $kg^{-1}$) | 42 ± 3.5 | 28.1 ± 10.9 | 25.8 ± 9.5 |
| Ca | (g $kg^{-1}$) | 9.3 ± 1.5 | 32.8 ± 3.4 | 32.8 ± 8.9 |
| Mg | (g $kg^{-1}$) | 8.0 ± 2.6 | 3.1 ± 0.2 | 3.3 ± 0.3 |

Note: Nutrient concentrations are expressed on a dry matter basis.

**Table 3.** Fresh weight (FW), dry matter content (DM) and chemical characteristics of green manure incorporated before potato (1st year), chard (2nd year) and cabbage (3rd year) (mean ± standard deviation).

| Nutrients | | 1st year | 2nd year | 3rd year |
|---|---|---|---|---|
| FW | (t $ha^{-1}$) | 17.4 ± 1.3 | 28.1 ± 2.7 | 22.1 ± 2.4 |
| DM | (%) | 20 ± 0.4 | 23.9 ± 0.2 | 20.1 ± 0.5 |
| C | (g $kg^{-1}$) | 460 ± 3.3 | 393 ± 18 | 399 ± 22 |
| N | (g $kg^{-1}$) | 12.1 ± 1.9 | 13.3 ± 0.9 | 20.6 ± 2.2 |
| C/N | | 38 | 30 | 20 |
| Soluble C | (g $kg^{-1}$) | 62.4 ± 3.8 | 78.4 ± 7.3 | 70.4 ± 1.5 |
| Soluble N | (g $kg^{-1}$) | 3.2 ± 0.2 | 4.4 ± 0.5 | 6.1 ± 0.2 |
| P | (g $kg^{-1}$) | 3.7 ± 0.1 | 3.1 ± 0.1 | 3.9 ± 1.1 |
| K | (g $kg^{-1}$) | 29.7 ± 2.2 | 11.2 ± 1.1 | 23.6 ± 3.6 |
| Ca | (g $kg^{-1}$) | 5.8 ± 0.4 | 5.0 ± 0.8 | 6.9 ± 1.1 |
| Mg | (g $kg^{-1}$) | 1.6 ± 0.1 | 0.9 ± 0.1 | 1.9 ± 0.2 |

Note: Nutrient concentrations are expressed on a dry matter basis.

rate of 5 t $ha^{-1}$ of $CaCO_3$ equivalent before the beginning of the crop rotation in October 2011. Soil samples from the top 20 cm layer were collected for analyses at the beginning of the crop rotation and in each experimental plot at the end of the crop rotation. The cover crop was sown in October 2011 (120 kg $ha^{-1}$ rye and 60 kg $ha^{-1}$ vetch), October 2012 (100 kg $ha^{-1}$ rye and 100 kg $ha^{-1}$ vetch) and October 2013 (75 kg $ha^{-1}$ rye and 150 kg $ha^{-1}$ vetch). Plants for analyses were manually harvested in each plot by using two 0.5 × 0.5 m quadrats to determine above ground biomass. The green manure was chopped when most of the vetch was flowering, using a breaker hammer attached to the tractor and left as mulch *in situ* 158, 194 and 189 days after sowing in 2012, 2013 and 2014, respectively. After drying on the soil surface for 2 days, the green manure was incorporated into the soil to the depth of 15 cm together with the compost, the commercial fertiliser, or on its own, in the respective plots, using a rotary tiller. Nine days after incorporation of the organic amendments, potatoes were planted at a spacing of 25 cm between plants in the row and 60 cm between the rows. The potato was the only crop in which measures were applied to control pest and diseases. Two applications of Bordeaux mixture (Bouille bourdelaise) (20 kg $ha^{-1}$) and copper hydroxide (2 kg $ha^{-1}$) were used to control late blight (Phytophtora infestans) and two applications of Spintor (Lusosem) based on the fermented bacteria *Saccharopolyspora spinose* were used to control Colorado potato beetle (Leptinotarsa decemlineata). The chard and the cabbage were transplanted in the experimental plots at 5 and 6 days, respectively, after the incorporation of the organic amendments, at a plant spacing of 40 × 40 cm. After harvesting the potatoes, chard and cabbage, soil preparation was carried out with a tine cultivator. Lettuce seedlings were transplanted at 35 × 35 cm plant spacing. Turnip and carrot were sown with a manual

**Table 4.** Organic N ($N_{org}$, mg kg$^{-1}$ soil) and total N ($N_{tot}$, kg ha$^{-1}$) applied during the growing seasons for compost, commercial fertiliser and green manure.

| | 1st year | | 2nd year | | 3rd year | |
|---|---|---|---|---|---|---|
| | $N_{org}$ | $N_{tot}$ | $N_{org}$ | $N_{tot}$ | $N_{org}$ | $N_{tot}$ |
| Organic amendments | (mg kg$^{-1}$) | (kg ha$^{-1}$) | (mg kg$^{-1}$) | (kg ha$^{-1}$) | (mg kg$^{-1}$) | (kg ha$^{-1}$) |
| 20 t ha$^{-1}$ compost | 76 | 102 | 79 | 107 | 89 | 125 |
| 40 t ha$^{-1}$ compost | 152 | 204 | 159 | 214 | 179 | 250 |
| 1 t ha$^{-1}$ fertiliser | 64 | 91 | 55 | 89 | 64 | 90 |
| 2 t ha$^{-1}$ fertiliser | 128 | 182 | 110 | 178 | 129 | 180 |
| Green manure | 32 | 42 | 67 | 89 | 69 | 91 |

Note: The total N (organic N + mineral N; kg ha$^{-1}$) was calculated based on a soil depth of 15 cm and a density of 1.04.

sower with spacings of 30 × 20 cm and 30 × 10 cm, respectively. Crops were sprinkler irrigated with a system of mini-sprinklers (200 L h$^{-1}$), placed 6.5 m apart, so that the water content in the soil was not limiting for plant growth. Hoe blade weeding was carried out frequently to avoid weed competition. At the end of the growing season, four plants from each replicate were harvested for analyses to quantify fresh and dry weight.

Mean daily air and soil temperatures were automatically registered with thermistores (Delta-T devices). Soil temperature was measured at 10 cm depth and the air temperature at 30 cm height. For the potato, chard and cabbage, average daily air temperature ranged between 6.6–27.5, 6.3–27.0 and, 7.2–24.4 °C, respectively. For lettuce, turnip and carrot, average daily air temperature ranged between 10.9–24.5, 15.6–28.1 and, 14.6–25.1 °C. Soil temperature ranges were about 4.7 °C lower compared to air temperature.

### *Field incubation*

The field incubation was set up on the 28th of March 2012, 7th of May 2013 and 16th of April 2014 immediately after the organic amendments had been incorporated into the soil during the three spring/summer vegetable growth seasons based on the methodology described by Raison et al. (1987). Samples were taken every 14 days during the incubation period except for the first sampling, which was performed after 7 days. At the start of each incubation period, 5 pairs of samples were taken randomly from each plot pushing the perforated PVC cores (15 cm long and 4 cm of diameter) into the soil to avoid soil disturbance. One from each pair of samples was frozen and the other was enclosed in a micro-perforated polyethylene bag and buried at 20 cm depth. Net N mineralisation was calculated by the difference between the amounts of inorganic N ($NH_4^+$-N + $NO_3$-N) of initial and incubated samples. Accumulated N mineralisation per kg of soil was calculated by the sum of mineralised N in each period of incubation. The apparent net N mineralisation of compost and of organic commercial fertiliser was estimated by the difference between the net N mineralisation in treatments C20, C40, CF1 and CF2 and the net N mineralisation in treatment GM. The apparent net N mineralisation for the green manure was calculated by the difference between the net N mineralisation in treatments GM and T0.

### *Analytical methods*

Dry matter content (DM), pH and electrical conductivity (EC) were determined by standard procedures (CEN 1999). Crop and green manure samples were dried at 65 °C until constant weight. Compost and commercial fertiliser samples were freeze-dried to reduce moisture content. Subsequently, the samples were milled using a rotor mill with a 2 mm sieve (Retschmühle type SM1, Retsch). Total C was determined by near-infrared detector in an elemental analyser (Primacs SC analyser, Skalar) after combustion at 950 °C. Total N and P were measured by molecular spectrophotometry (San Plus System, Skalar) and K was quantified by flame photometry (PFP7 Flame Photometer, Jenway) after digestion with sulfuric acid. Total Ca and Mg were measured by atomic spectrophotometry (iCE 3000 Series AA Spectrometer, Thermo Scientific) following nitro-perchloric digestion. Mineral N was extracted from 6 g fresh samples of soil, compost and commercial fertiliser samples using KCl 1 M 1:5 solution ratio and $NH_4^+$-N and $NO_3$-N concentrations were determined by molecular absorption spectrophotometry with a segmented flow analyser system (San Plus system, Skalar). For green manure, compost and commercial fertiliser, soluble C and N were extracted from 4 g dry sample with $CaCl_2$ 0.01 M at a ratio of 1:20. Then, soluble C and N were determined by near-infrared detector and chemiluminescence, respectively, in an elemental analyser (Formacs analyser, Skalar) after combustion at 950 °C. The available contents of $P_2O_5$ and $K_2O$ in the soil were determined by Egner-Riehm method (Balbino 1968).

### Statistical analysis and kinetic models

Analysis of variance (ANOVA) was performed by the general linear model procedure, and a probability level of $p = 0.05$ was applied to determine statistical significance between treatment means. All statistical calculations were performed using SPSS v. 17.0 for windows (SPSS Inc.). The first-order kinetic model with one mineralisation pool (Bonde and Lindberg 1988) was fitted to the N mineralisation of compost, commercial fertiliser and green manure determined from incubated soils (Equation (1)).

$$\mathrm{Nm} = \mathrm{N}_0\left[1 - \exp\left(-k_1 t - k_2 t^2\right)\right] \tag{1}$$

The Nm (mg kg$^{-1}$ of soil) is the accumulated mineralised N at time $t$; $k_1$ and $k_2$ are mineralisation constant rates, whereas the amount of potentially mineralisable N is given by $N_0$ (mg kg$^{-1}$). The immobilisation time-period was determined based on the mineralisation constant rates of the one pool model ($t = -k_1/k_2$). Model equations were fitted by the non-linear least-square curve-fitting technique (Marquardt–Levenberg algorithm), to minimise the sum of the squared differences between the observed and predicted values of the dependent variable. The Pearson correlation test was performed to relate crop yield with the sum of mineralised N (Hauke and Kossowski 2011).

## Results

### Crop yields

Increased soil N availability and crop yields were found for both rates of either compost or organic fertiliser, compared to the control or the treatment with only green manure. Potato yields were not significantly different between C40 (36 t ha$^{-1}$), CF1 and CF2 (36 and 42 t ha$^{-1}$ respectively). However, potato yield increased for CF2 compared to T0, GM and C20 (Figure 1). Compared with all other treatments: (i) lettuce yields were significantly higher for treatments C20 and C40 (18 and 19 t ha$^{-1}$ respectively); (ii) chard yield increased for CF2 (46 t ha$^{-1}$) and (iii) turnip yield was clearly enhanced for C40 (38 t ha$^{-1}$). The differences between treatments C20, C40 and CF2 for cabbage yield (20, 26 and 24 t ha$^{-1}$, respectively) were not significant. The apparent increase in the carrot yield between treatments C20 and C40 was not significant. However, carrot yield was significantly higher for treatment C40 compared to treatments T0, GM, CF1 and CF2. In contrast to the first crop of the season, the application of 40 t ha$^{-1}$ of compost and green manure (C40) increased crop yields by 89, 115 and 56% for lettuce, turnip and carrot (second season crops), respectively, compared with the application of 2 t ha$^{-1}$ of commercial organic fertiliser and green manure (CF2).

### Nitrogen mineralisation

A positive correlation was found between crop yield and N mineralisation determined from soil incubations, being particularly clear for the first crop of the season: potato ($R^2 = 0.90$, $p < 0.01$), chard

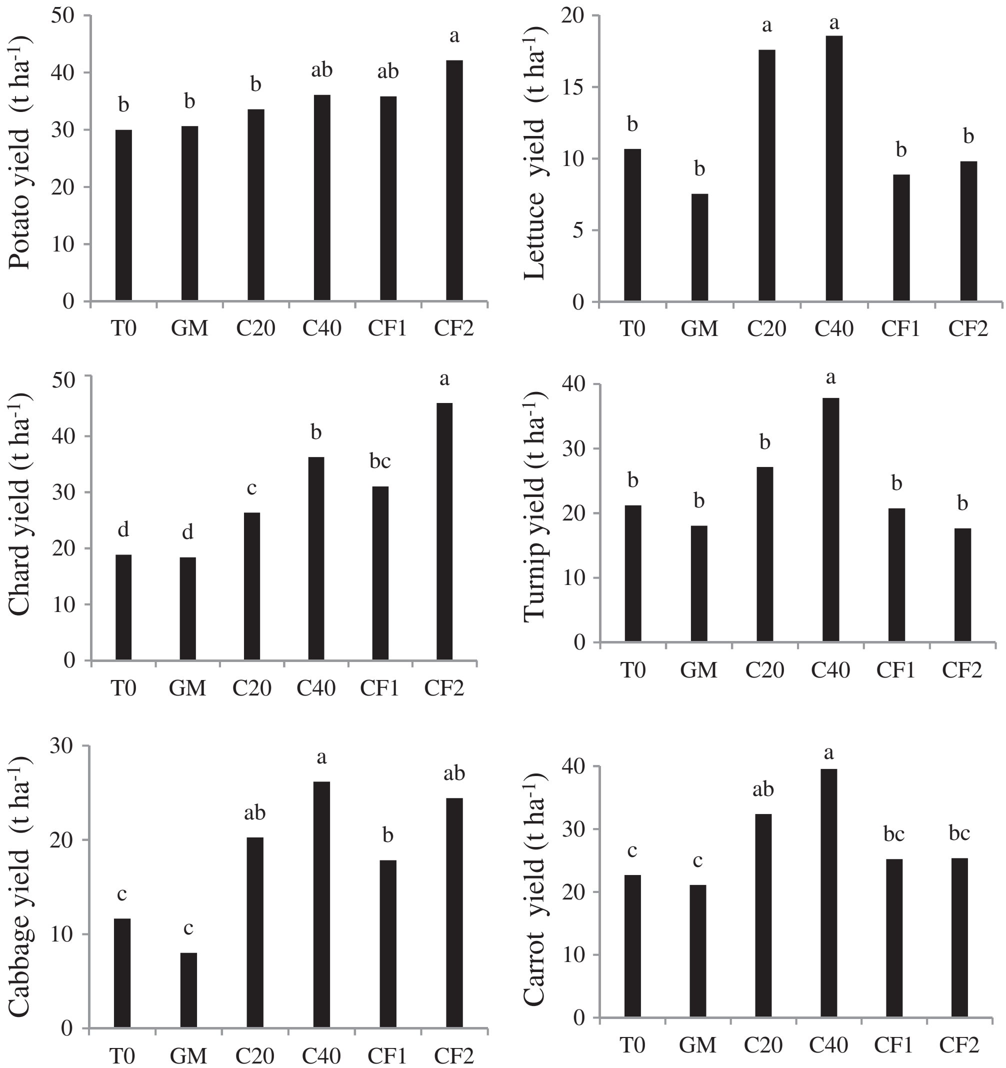


**Figure 1.** Crop yields (t ha$^{-1}$) of potato and lettuce (1st year), chard and turnip (2nd year) and cabbage and carrot (3rd year) for the control treatment without fertilisation (T0) and for the treatments with green manure (GM), GM with 20 or 40 t ha$^{-1}$ of compost (C20 and C40), and GM with 1 or 2 t ha$^{-1}$ of commercial fertiliser (CF1 and CF2).
Note: Bars, within each crop, with different letters are significantly different ($p < 0.05$).

($R^2 = 0.84$, $p < 0.01$) and cabbage ($R^2 = 0.79$, $p < 0.05$). Mineralised N was apparently higher for CF2 in comparison with all other treatments during the first crop of the season (potato, chard and cabbage), though the differences were only significant for chard. However, the amounts of mineralised N for C40 during the second crop season for lettuce (84 kg ha$^{-1}$), turnip (63 kg ha$^{-1}$) and carrot (166 kg ha$^{-1}$) were apparently greater than that for treatment CF2 (60, 33 and 149 kg ha$^{-1}$, respectively), though the differences were not significant (Table 5).

The commercial organic fertiliser was rapidly mineralised (Figure 2). During the first 7 days of incubation, 23 and 49% of the total organic N was mineralised in the 1st year, 60 and 44% in the 2nd year, and 30 and 44% in the 3rd year, in the treatments with 1 (CF1) and 2 t ha$^{-1}$ (CF2) organic fertiliser application, respectively. In contrast, the organic N in compost was mineralised at a slower rate throughout the crop rotation.

**Table 5.** Accumulated mineralised N (kg ha$^{-1}$) during each crop growing season for green manure (GM), GM with 20 and 40 t ha$^{-1}$ compost (C20 and C40) and GM with 1 or 2 t ha$^{-1}$ organic fertiliser (CF1 and CF2) and for the control without fertilisation (T0).

| | | N mineralisation (kg ha$^{-1}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Crops | T0 | | GM | | C20 | | C40 | | CF1 | | CF2 | |
| 1st year | Potato | 104 | ab | 88 | b | 152 | ab | 160 | ab | 148 | ab | 201 | a |
| | Lettuce | 59 | ab | 49 | b | 62 | ab | 84 | a | 59 | ab | 60 | ab |
| 2nd year | Chard | 67 | b | 67 | b | 96 | b | 99 | b | 123 | b | 199 | a |
| | Turnip | 61 | a | 47 | a | 55 | a | 63 | a | 42 | a | 33 | a |
| 3rd year | Cabbage | 71 | b | 78 | ab | 112 | ab | 160 | ab | 142 | ab | 187 | a |
| | Carrot | 112 | b | 123 | ab | 179 | a | 166 | ab | 144 | ab | 149 | ab |

Notes: Values within a row followed by different letters are significantly different ($p < 0.05$). The mineralised N (kg ha$^{-1}$) was calculated based on a soil depth of 15 cm.

## *Nitrogen synchrony*

The amounts of the accumulated mineralised N (Nm) for the first crop in each season (potato, chard and cabbage) were largest with the addition of 2 t ha$^{-1}$ of organic fertiliser, whereas the amount of Nm for the second crop season (lettuce, turnip and carrot) was largest with the addition of 40 t ha$^{-1}$ of compost (Table 6). The application of 40 t ha$^{-1}$ of compost caused an initial N immobilisation for 71 days during the potato crop growing season, and 31 days during the chard season, promoting N re-mineralisation during the last period of potato and lettuce growth (Nm = 57 and 23 mg kg$^{-1}$, respectively) and during chard and turnip growth (Nm = 21 and 10 mg kg$^{-1}$, respectively). In the third year of the crop rotation N immobilisation was not detected with the application of 40 t ha$^{-1}$ compost and mineralised N increased during the growing period of cabbage (58 mg kg$^{-1}$) compared to chard (21 mg kg$^{-1}$), although the length of the growing period for cabbage (56 days) was similar to that of chard (54 days) (Figure 2 and Table 6).

In the 1st and 2nd years of the crop rotation, green manure incorporation into the soil caused N immobilisation. The amount of Nm during the growth period of potato and lettuce (196 days) was −20.6 mg N kg$^{-1}$ and during the growth period of chard and turnip (110 days) was −7.7 mg N kg$^{-1}$. On the contrary, in the 3rd year of crop rotation, the green manure incorporation, after an initial short period of N immobilisation of 32 days, increased net N mineralisation. The amount of Nm during the growth period of the cabbage and the carrot (168 days) was 13.9 mg N kg$^{-1}$ (Figure 2).

## *Soil characteristics*

The average soil mineral N concentrations for the growing seasons of potato (48.9 kg ha$^{-1}$), chard (85.7 kg ha$^{-1}$) and cabbage (74.5 kg ha$^{-1}$) were higher for the CF2 treatment in comparison to all other treatments (Figure 3). This data was determined based on the mineral N concentrations of the samples taken in the beginning of each incubation period. Soil mineral N concentrations decreased in CF1 and CF2 for potato between 7 and 35 days after commercial organic fertiliser incorporation (from 89.2 to 25.1 kg ha$^{-1}$ for CF1 and from 130.8 to 49.2 kg ha$^{-1}$ for CF2), for chard between 7 and 47 days after organic fertiliser incorporation (from 92.5 to 17.7 kg ha$^{-1}$ for CF1 and from 158.1 to 30.4 kg ha$^{-1}$ for CF2) and for cabbage between 20 and 48 days after organic fertiliser incorporation (from 59.0 to 19.7 kg ha$^{-1}$ and from 136.0 to 20.5 kg ha$^{-1}$, respectively for CF1 and CF2).

At the end of the crop rotation, significant differences were not found for total soil C and N between the different treatments (Table 7). Concentrations of extractable P and K were higher in the treatments C40 compared to all the other treatments ($p < 0.05$). The EC was higher for treatment C40 and CF2 compared with T0, GM, C20 and CF1, probably because EC values for the composts (between 3.6 and 6.9 dS m$^{-1}$) were above the recommended values for composts used as soil amendments (3 dSm$^{-1}$) (Soumaré et al. 2003).

There were no significant differences for total C between the beginning and the end of the crop rotation for all treatments. Total N and extractable P and K concentrations were lower at the end of

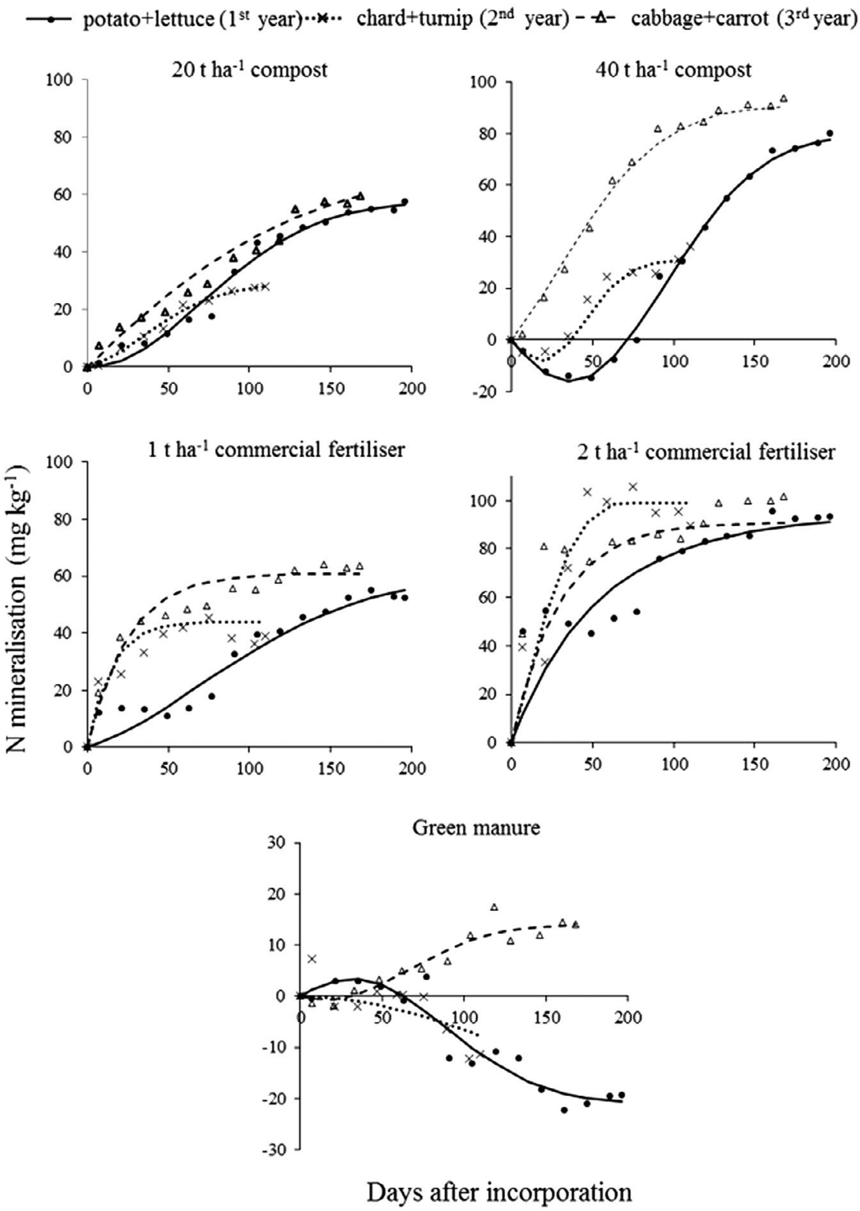


**Figure 2.** Accumulated mineralised N (mg kg$^{-1}$) from soil incubation during the growing seasons for the three years of crop rotation. Note: N mineralisation equations are described in Table 6.

the crop rotation in all treatments except for C40 (Table 7). However, there were significant differences in EC values between the beginning (0.032 dS m$^{-1}$) and the end of the crop rotation (0.038 dS m$^{-1}$) after three years of applying 40 t ha$^{-1}$ compost or 2 t ha$^{-1}$ of commercial organic fertiliser together with the green manure. The pH value increased in the first year from 4.9 to 6.7 (data not shown), and gradually declined to values of 6.1 in the end of experiment (Table 7).

**Table 6.** Apparent N mineralisation equations and accumulated mineralised N (Nm) during the growing seasons, for compost, commercial fertiliser and green manure from soil incubation.

| Organic amendments | Model equation | Nm ($mg\ kg^{-1}$) | |
|---|---|---|---|
| 1st year | | Potato | Lettuce |
| 20 $t\ ha^{-1}$ compost | $Nm = 58\ [1-\exp(-0.0001t-0.0001t^2)]^{***}$ | 48 | 9 |
| 40 $t\ ha^{-1}$ compost | $Nm = 80\ [1-\exp(0.01t-0.00014t^2)]^{***}$ | 57 | 23 |
| 1 $t\ ha^{-1}$ fertiliser | $Nm = 60\ [1-\exp(-0.003t-0.00005t^2)]^{***}$ | 43 | 12 |
| 2 $t\ ha^{-1}$ fertiliser | $Nm = 101\ [1-\exp(-0.018t-0.000031t^2)]^{***}$ | 85 | 6 |
| Green manure | $Nm = -21\ [1-\exp(-0.018t-0.00015t^2)]^{***}$ | | |
| 2nd year | | Chard | Turnip |
| 20 $t\ ha^{-1}$ compost | $Nm = 30\ [1-\exp(-0.005t-0.00025t^2)]^{***}$ | 20 | 8 |
| 40 $t\ ha^{-1}$ compost | $Nm = 36\ [1-\exp(0.022t-0.0007t^2)]^{***}$ | 21 | 10 |
| 1 $t\ ha^{-1}$ fertiliser | $Nm = 44\ [1-\exp(-0.068t-0.000006t^2)]^{***}$ | 43 | 1 |
| 2 $t\ ha^{-1}$ fertiliser | $Nm = 99\ [1-\exp(-0.023t-0.0006t^2)]^{***}$ | 97 | 2 |
| Green manure | $Nm = -20\ [1-\exp(-0.00001t-0.00004t^2)]^{**}$ | | |
| 3rd year | | Cabbage | Carrot |
| 20 $t\ ha^{-1}$ compost | $Nm = 70\ [1-\exp(-0.008t-0.00002t^2)]^{***}$ | 31 | 29 |
| 40 $t\ ha^{-1}$ compost | $Nm = 91\ [1-\exp(-0.0085t-0.00013t^2)]^{***}$ | 58 | 32 |
| 1 $t\ ha^{-1}$ fertiliser | $Nm = 61\ [1-\exp(-0.04t-0.000003t^2)]^{***}$ | 56 | 5 |
| 2 $t\ ha^{-1}$ fertiliser | $Nm = 91\ [1-\exp(-0.034t-0.000006t^2)]^{***}$ | 80 | 11 |
| Green manure | $Nm = 14\ [1-\exp(0.0064t-0.0002t^2)]^{***}$ | | |

$^{**}p < 0.01$; $^{***}p < 0.001$.

## Discussion

Nitrogen mineralisation increased in fertilised treatments both with compost and with the commercial organic fertiliser (C20, C40, CF1, CF2). A positive correlation was found between crop yield and the amount of mineralised N measured by incubation of soil cores during the growth period, showing that field incubation may be a suitable method for predicting mineralisation rates. Other authors found a close agreement between N mineralisation determined by field incubation and crop yield (Yan et al. 2006; Monaco et al. 2010).

The information about N mineralisation and immobilisation after compost incorporation is useful to find the best strategies and timing for compost application to maximise crop yields. With farmyard manure composts, an initial soil N immobilisation followed by net N re-mineralisation may occur if the compost has a high C/N ratio and is not mature (Probert et al. 2005). Antil et al. (2011) reported N immobilisation during the first three weeks after poultry/cattle manure compost incorporation (C/N = 9.2) and Mubarak et al. (2010) observed N immobilisation in the first four weeks of incubation after farmyard manure incorporation (C/N = 18.6). In the experiment reported here, the incorporation of 40 $t\ ha^{-1}$ compost in the 1st and 2nd years of the crop rotation caused an initial N immobilisation for 71 and 31 days, respectively.

Lettuce, turnip and carrot yields (the second crop in each year) were higher when the compost had been applied compared to the commercial fertiliser. This was thought to be due to the rapid N mineralisation from the commercial fertiliser during the previous crop, probably as the result of its high concentration of total N (97–100 $g\ kg^{-1}$), low C/N ratio (4.2–4.6) and high concentration of soluble C and N (43–52 and 21–37 $g\ kg^{-1}$, respectively). Indeed, these chemical characteristics have been reported to increase the microbial activity with the release of high amounts of mineral N in a short period of time (Antil et al. 2011). In addition to the rapid N mineralisation after the application of 2 $t\ ha^{-1}$ of commercial organic fertiliser in the second year of the crop rotation, its high $NH_4^+$ concentration (17557 $mg\ kg^{-1}$) probably also accounted for short-term N availability. On the other hand, the application of farmyard manure compost promoted the slow release of N providing longer lasting supplies of N. Therefore, to increase all crop yields the commercial organic fertiliser should be applied immediately before each crop in the rotation.

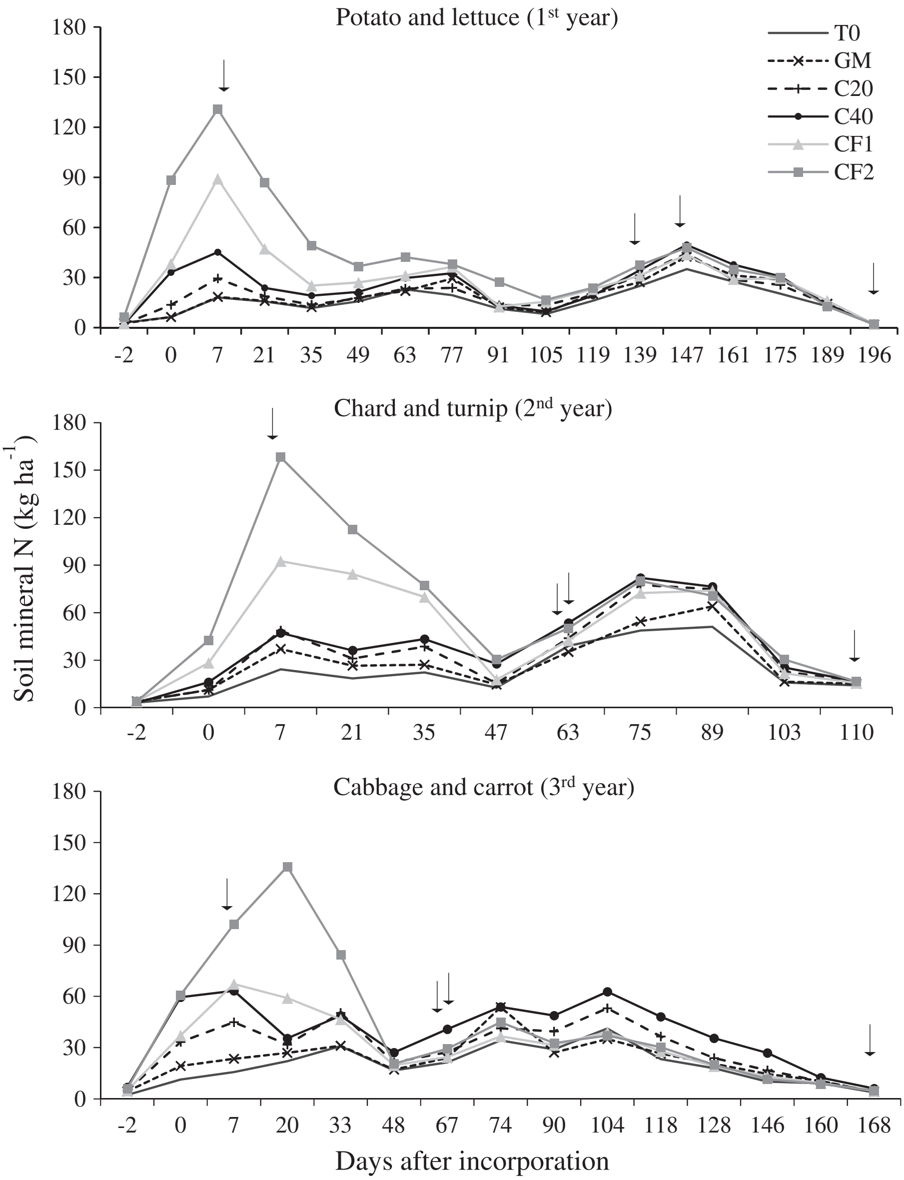


**Figure 3.** Soil mineral N (kg ha$^{-1}$) during the crop growing seasons for the green manure (GM), GM with 20 or 40 t ha$^{-1}$ of compost (C20 and C40), GM with 1 or 2 t ha$^{-1}$ of commercial organic fertiliser (CF1 and CF2), and for the unfertilised control treatment (T0). Note: The arrows represent the beginning and the end of crop growing period.

The highest levels of mineral N released during the second crop of each year, occurred with the addition of 40 t ha$^{-1}$ of compost. However, lettuce yield with the application of 40 t ha$^{-1}$ compost (19 t ha$^{-1}$) was below that reported by Brito et al. (2012) for the same variety (33 t ha$^{-1}$) with the application of 40 t ha$^{-1}$ compost, probably because the lettuce here had less available N at planting. An early season potato crop (90–120 days) instead of the late-season potato crop (120–150 days) would probably have resulted in increased amounts of organic N available for the lettuce growth. The amount of available N for the turnips and the carrots with the addition of 40 t ha$^{-1}$ of compost, was sufficient to achieve average yields for Portuguese conditions, as reported by Almeida (2006) at 33 and 30 t ha$^{-1}$, respectively. This may be explained because both crops, turnip and carrot, were planted after two

**Table 7.** Soil chemical characteristics at the beginning and the end of the crop rotation for the control treatment (T0) without soil amendments and in response to green manure (GM), GM with 20 or 40 t ha$^{-1}$ of compost (C20 and C40), GM with 1 or 2 t ha$^{-1}$ of commercial organic fertiliser (CF1 and CF2).

| | | pH | EC (dS m$^{-1}$) | C (g kg$^{-1}$) | N (g kg$^{-1}$) | Extractable phosphorus ($P_2O_5$)* (mg kg$^{-1}$) | Extractable potassium ($K_2O$)* (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Beginning | | 4.9 b | 0.032 b | 29.0 a | 1.9 a | 208 a | 215 b |
| End | T0 | 6.2 a | 0.032 b | 29.1 a | 1.4 b | 133 c | 124 c |
| | GM | 6.1 a | 0.030 b | 29.6 a | 1.4 b | 135 c | 131 c |
| | C20 | 6.1 a | 0.032 b | 31.8 a | 1.5 b | 152 b | 184 b |
| | C40 | 6.2 a | 0.038 a | 32.4 a | 1.6 ab | 173 a | 272 a |
| | CF1 | 6.1 a | 0.030 b | 31.7 a | 1.5 b | 144 bc | 133 c |
| | CF2 | 6.1 a | 0.036 a | 31.8 a | 1.4 b | 129 c | 134 c |

Notes: Values in columns followed by different letters are significantly different ($p < 0.05$).
*Egner-Riehm method.

short-cycle crops, chard (54 days) and cabbage (56 days). Thus, crop rotations need to be optimised considering the potential yields of both crops in the season, based on crop duration and N supply.

There were no significant differences on potato yield between the application of 2 t ha$^{-1}$ of commercial fertiliser and the application of 40 t ha$^{-1}$ of compost, because the long potato growing season (124 days) allowed N mineralisation (57 mg kg$^{-1}$) to increase with the application of 40 t ha$^{-1}$ compost together with green manure as opposed to the short period for chard growth (54 days), which was not long enough to provide readily available N (21 mg kg$^{-1}$). Consequently, chard yield was highest with the application of 2 t ha$^{-1}$ of commercial organic fertiliser and green manure compared to the application 40 t ha$^{-1}$ of compost and green manure.

In the third year of the crop rotation, cabbage yields were similar with the application of 2 t ha$^{-1}$ organic fertiliser and green manure or 40 t ha$^{-1}$ compost and green manure because N mineralisation increased with the application of 40 t ha$^{-1}$ compost and green manure, although the growing period of chard and cabbage were similar. This can be explained by the lower C/N ratio (C/N = 12) of the compost and higher total N concentration (25 g kg$^{-1}$) compared to the C/N ratio and total N of the composts applied in the first and second year of the crop rotation and by the effect of continuous application of compost, increasing soil organic N content and consequently net N mineralisation and crop yields in the long-term (Kuo and Jellum 2000). D'Hose et al. (2012) found that crop yields of beet, maize, potato and Brussels sprouts increased after the fourth year of farm compost application with a mean C/N ratio of 18.2. Bonanomi et al. (2014) also reported that crop yields of lettuce, melon and pepper increased after the second year of municipal solid waste compost application with C/N ratios of 15 and 25.

The time between compost incorporation and planting the chard was 5 days whereas N remineralisation took place for 26 days after planting the chard. Therefore, to increase the synchronisation between chard N uptake and net N mineralisation it would be advantageous to increase the interval between compost incorporation and planting the chard. Nevertheless, chard yield with the application of 40 t ha$^{-1}$ compost and green manure (36 t ha$^{-1}$) was above to the value reported by Brito et al. (2012) with 40 t ha$^{-1}$ compost and green manure (25 t ha$^{-1}$) for similar environmental conditions.

Differences in crop yields from plots where the green manure was applied on its own compared with the control treatment were not significant. This was likely to be due to the fact that less of N was incorporated into the soil when the green manure was incorporated on its own in comparison to where it was incorporated together with compost or organic fertiliser ($N_{org}$ applied in Table 4). Probably, the green manure should be sown earlier in order to increase the growing period and consequently enhance N accumulation. Several studies reported yield reductions when nonleguminous green manures (Kumar and Goh 2002) or even leguminous green manures (Salmeron et al. 2011) were incorporated into the soil. These were explained by the lack of synchrony between N crop demand and N mineralisation (Sainju et al. 2006), which depends mainly on the balance between

N mineralisation and immobilisation largely determined by the C/N ratio (Tejada et al. 2008). Although an optimal C/N ratio is difficult to define, Rosecrance et al. (2000) suggested that net N mineralisation would be expected with a rye/vetch mixture used as green manure, whereas other authors reported that N immobilisation occurred for rye/vetch with C/N ratio > 10 (Kuo and Sainju 1998). Here, the C/N ratio of the green manure in the 1st and 2nd year of the crop rotation (C/N = 38 and C/N = 30, respectively) promoted N immobilisation (0.11 and 0.02 mg N $kg^{-1}$ $day^{-1}$ respectively). This was also a consequence of the high concentration of soluble C in the 1st and 2nd year (62.4 and 78.3 g $kg^{-1}$, respectively) in relation to the soluble N of the green manure (3.2 and 4.4 g $kg^{-1}$ respectively) which stimulated the microorganisms to immobilise N from soil to decompose the easily soluble C from green manure (Kuo and Sainju 1998).

In the third year of the crop rotation, the C/N ratio (C/N = 20) of the green manure, as well as the total N concentration (21 g $kg^{-1}$) and the soluble C to soluble N ratio (C/N = 12) were expected to stimulate N immobilisation, as suggested by Kuo and Sainju (1998). These authors reported total N concentration <32 g $kg^{-1}$ and the soluble C to soluble N ratio >9 as indicative of possible N immobilisation, after green manure application to soil. Here, after an initial minor N immobilisation, net N mineralisation increased, probably because of continuous green manure incorporation over the three years of the crop rotation.

Previous crop rotation studies showed that soil incorporation of green manure might increase yields in later years (Kumar and Goh 2002). For example, cereal yields increased close to 30% after 4 years of rye and clover application (Loes et al. 2011). The net N mineralisation in the third year, when the seed sowing rate for the green manure was 75 kg $ha^{-1}$ rye and 150 kg $ha^{-1}$ vetch suggested that this green manure seeding density was probably advantageous to promote the yield increase of the following crop. However, the differences in crop yield in the third year of the crop rotation were not significant with the application of green manure on its own (Figure 1). This was probably explained by the timing of green manure incorporation into the soil (Baggs et al. 2000), since the time between green manure incorporation and cabbage transplantation was 6 days, whereas N re-mineralisation took place for 19 days after cabbage plantation. Under these conditions, it may be advantageous to increase the timing between the green manure incorporation into the soil and the plantation of cabbage to match the cabbage N demand with the net N mineralisation from green manure.

After 3 years of repeated applications of organic materials into the soil, there were no significant differences in total C and N between the treatments. However, for the same treatments, Fraga et al. (2015) detected significant differences between treatments based on the permanganate oxidizable carbon pool. These authors found that the application of 40 t $ha^{-1}$ of compost and green manure increased soil permanganate oxidizable carbon compared to all other treatments, having the most pronounced effect on soil C sequestration. This is a method that seems to be a more sensitive indicator to evaluate the evolution of soil C sequestration under alternative management practices (Weil et al. 2003).

Soil mineral N increased in the first seven days after commercial organic fertiliser incorporation, but decreased in the next few days. This mineral N decrease was not caused only by N uptake from the crops since it occurred before planting the potato and 2 days after planting the chard in 2012 and 2013, respectively. These mineral N losses from the system probably occurred as a result of N leaching, because rainfall can be responsible for high N losses in the presence of high soil mineral N content (Zhu et al. 2005). Xin-Qiang et al. (2011) suggested that higher potential leaching would be engendered when the rainfall intensity was over 5.9 mm $day^{-1}$. In the study reported here, between day 7 and day 42 after commercial organic fertiliser application the daily rainfall intensity was over 5.9 mm $day^{-1}$ for 14 and 9 days in 2012 and 2013 respectively (data obtained from the nearest weather station). These mineral N losses with commercial fertiliser incorporation might also be due to denitrification induced by oxygen depletion under anaerobic conditions (Calderón et al. 2005). Aulakh et al. (2000) reported that nearly saturated soils, supported greater nitrification of applied ammonia fertiliser, resulting in higher rates of denitrification.

More than 83% of the potential mineralisable N ($N_0$) was mineralised during spring/summer crops. Therefore, the risk of leaching during autumn and winter was small. In addition, the sowing of a combination of rye and vetch in October is advantageous to minimise N losses (Rosecrance et al. 2000). The risk of leaching was even smaller during autumn and winter after one long and one short cycle crop (potato and lettuce or carrot and cabbage) compared to two short cycle crops (chard and turnip) because the concentration of soil mineral N after the long and short cycle crop (1.9–6.0 kg ha$^{-1}$) was below the concentration of soil mineral N after the two short cycle crops (14.1–16.6 kg ha$^{-1}$).

## Conclusions

The results of this study suggested that: (i) field incubation can be used to assess mineralisation rates; (ii) application of farmyard manure compost together with green manure (rye/vetch) contributed to increased yields of both crops in each year, whereas the commercial organic fertiliser only increased yields for the first crop of the year; (iii) the commercial organic fertiliser was rapidly mineralised, increasing the risk of early spring leaching and/or denitrification, as opposed to the farmyard manure compost, which after an initial N immobilisation released mineral N slowly over all crop growing seasons; (iv) if the first crop is a short season crop, organic fertiliser should be applied or the incorporation of compost should be earlier in order to match crop N uptake with net N mineralisation, whereas a long-cycle crop may be planted immediately after compost and green manure incorporation; (v) the application rate of 40 t ha$^{-1}$ year$^{-1}$ of farmyard manure compost (average of 223 kg N ha$^{-1}$ year$^{-1}$) with 22.5 t ha$^{-1}$ year$^{-1}$ of rye/vetch as green manure (average of 74 kg N ha$^{-1}$ year$^{-1}$) was suitable to fertilise a three-year organic horticultural rotation; (vi) organic growers can rely on applications of farmyard manure compost together with a rye/vetch green manure to increase crop yields during organic horticultural rotations in the short-term but with stronger outcomes in later years.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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