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REGULAR ARTICLE

Short-term and long-term effects of vegetable, fruit and garden waste compost applications in an arable crop rotation in Flanders

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Abstract
Aims Substantial amounts of VFG-compost are produced annually in Flanders. Our objective was to analyse the effects of VFG-compost applications in a common crop rotation.
Methods Data from a long-term (1997 – present) field trial were analysed. Simulations with the RothC-model were performed to get a better insight into the dynamics of the underlying soil organic matter.
Results VFG-compost applications (15 $t.ha^{-1}$ 3-yearly up to 45 $t.ha^{-1}$ yearly) can replace a substantial part of the mineral nitrogen fertilisation. Nitrogen recovery rates ranged from 6 to 22 %. Plots fertilised according to the nitrogen advice had comparable yields, whether this advice had been provided (partially) through VFG-compost or not. Long-term VFG applications resulted in carbon accumulation in the top soil. The RothC-model gave a good prediction of the carbon change with low to moderate VFG applications, but tended to overestimate the carbon change with high applications. The simulation results indicated that the carbon accumulation was mainly due to an increase of the more resistant carbon fractions. In the long term, compost applications increased the nitrogen supplying capacity of the soil, as illustrated by the gradual increase of the mineral nitrogen stocks in spring over the years.
Conclusions VFG-compost applications had a positive effect both on crop yields and soil organic matter. The RothC-model was used to simulate long-term effects, but its calibration should be improved for long-term compost applications.

Keywords VFG · Compost · Soil organic carbon · Nitrogen supply · Modelling

Abbreviations

VFG	Vegetable fruit and garden waste
SOC	Soil organic carbon
DPM	Decomposable plant material
RPM	Resistant plant material
BIO	Microbial biomass
HUM	Humified organic matter
CEC	Cation exchange capacity

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Introduction

In the Flanders area of Belgium vegetable, fruit and garden waste (VFG) as well as green waste are collected selectively and the majority of the collected waste is then composted, which results in an annual production of more than 300 000 tonnes of VFG compost and approximately 500 000 tonnes of green compost (Anon 2011).

In other European countries, the production of biowaste compost and interest in its possible use on agricultural land is increasing (Erhart et al. 2005 (Austria); Fagnano et al. 2011 (Italy); Lillywhite et al. 2009 (UK); Odlare et al. 2011 (Sweden)). Agriculture and horticulture are generally considered as obvious markets for the disposal of these waste products.

Compost is considered as a valuable fertiliser, supplying nutrients (especially nitrogen) for the crop and hence saving substantial amounts of mineral fertiliser (Erhart et al. 2005; Lillywhite et al. 2009; Nevens and Reheul 2003; Odlare et al. 2011; Paterson et al. 2011). Generally, compost applications result in high total nutrient supplies, but the supply of crop-available nutrients during the first growing season after application is limited. The average percentages of nutrients in VFG and green compost that would be available for the crops during the next growing season are estimated as 10–20 % for nitrogen, 50 % for phosphorous, 80 % for potassium and 20 % for magnesium (source: www.vlaco.be).

In addition, the use of compost in agriculture and horticulture could contribute significantly to the improvement of the soil organic carbon content in the long term (Barral et al. 2009; Nevens and Reheul 2003) and hence to the chemical (nutrients), physical (structure and moisture retention) and biological (soil life) quality of the soil (Emmerling et al. 2010; Fagnano et al. 2011; Herencia et al. 2011; Laudicina et al. 2011; Odlare et al. 2011; Ozores-Hampton et al. 2011). In Flemish conditions, this is an important aspect since results of thousands of soil analyses carried out annually by the Soil Service of Belgium have shown that carbon stocks in Flemish agricultural land have decreased in the past decades (Boon et al., 2009).

Moreover, on a global scale, agricultural soils are considered to be a major sink of carbon dioxide. The application of compost can contribute to the carbon storage in the soil and hence to the reduction of greenhouse gases (CO_2) in the atmosphere (Fabrizio et al. 2009; Fagnano et al. 2011). Taking into account the average carbon content and the humification coefficients of VFG and green compost when applied to arable land (Anon. 2011), the amounts of compost produced in Flanders correspond to a significant potential carbon sequestration.

However, in order to limit the potential losses of nitrates to ground and surface water according to the European Nitrates Directive (EC European Commission 1991), the use of organic fertilisers on agricultural land in Flanders is limited by the Flemish manure legislation (Mestdecreet - Manure Decree) (Anon. 2006). This legislation limits the amounts of nitrogen and phosphorous that can be applied by organic and mineral fertilisers, depending on the crop and soil type. However, because of the slow release of nutrients in compost, exceptions are made for the use of certified compost, allowing in certain conditions (low soil organic matter content in respect of the nitrate residue norm) the application of higher amounts.

In terms of application, few data are yet available on the long-term effects of the use of different types of compost, such as the VFG and green composts produced in Flanders, on agricultural land, including the effects on carbon sequestration, on soil quality (different aspects), on plant nutrition, on environmental aspects (e.g. nitrate leaching during winter) and on soil organic matter dynamics. Long-term effects can be studied in different ways: long-term field trials combined with intensive laboratory analyses, incubation tests in the laboratory or simulation models.

The aim of the present study was to analyse both the short-term and the long-term effects of VFG compost applications in a typical arable crop rotation in Flanders, using field trial measurements and computer simulations. In the short term, the direct impact of VFG compost applications through its nitrogen fertilising value and its effect on crop yields was measured. In addition, the long-term effect on the change of the soil organic carbon content, composition and dynamics was studied as well as the effect of this change on the nitrogen supplying capacity of the soil.

Materials and methods

Field trial setup

A long-term field trial with VFG compost was set up by the Soil Service of Belgium in 1997 on a loamy soil in Flanders. The site has a maritime temperate climate, with significant precipitation in all seasons (no dry season) and a warm summer (according to the Köppen climate classification: Cfb) (Peel et al. 2007). The average temperature during the trial period was 11.0 °C and the average annual precipitation 760 mm.

The trial was set up as a randomised complete block design. The field was divided into 48 plots, each one having a surface of about 100 m². Twelve treatments were laid out in four replicates (Table 1), including an unfertilised control treatment, a control treatment with only mineral fertilisation, treatments with three-yearly applications of VFG-compost (15, 30 and 45 tonnes per hectare), with two-yearly applications of VFG compost (15, 30 and 45 tonnes per hectare), with yearly applications of VFG compost (15, 30 and 45 tonnes per hectare) and an unfertilised fallow plot. Starting from 1998, in treatments 5 and 11 (respectively 45 tonnes VFG/ha 3-yearly and yearly), the plant cover (crop and weeds) was removed in part of the plots (5×5 m²), in order to study the mineralisation of the applied compost. These fallow mini-plots were named treatment 13 and treatment 14.

Since 1997, the following crop rotation was applied: sugar beet (1997), winter wheat (1998), potatoes (1999), carrots (2000), sugar beet (2001), winter wheat (2002), potatoes (2003), carrots (2004), winter wheat (2005), sugar beet (2006), winter wheat (2007), winter wheat (2008), potatoes (2009) and winter wheat (2010).

The VFG compost was applied according to the scheme in Table 1, before the growing season (in spring for the root crops and just before sowing for the winter cereals).

Soil analyses and mineral fertilisation in the field trial

Each year, at the end of the winter period (start of the growing season) a soil sample was taken in the ploughing layer (0–23 cm) of the field trial for the analysis of pH, carbon content (C%), phosphorous (P_2O_5), potassium (K_2O), magnesium (MgO), calcium (CaO) and sodium (Na_2O). Based on this analysis, a standard fertilisation and liming recommendation was calculated using the BEMEX expert system of the Soil Service of Belgium (Vandendriessche et al. 1996). The basic fertilisation (P, K, Mg, Ca, Na) and lime applications in the trial were always performed according to these recommendations.

In the different treatments of the trial, soil samples were taken each year in the soil layers 0–30 cm, 30–60 cm and 60–90 cm for the analysis of mineral nitrogen (N) (3 layers), pH and carbon content (only top layer 0–30 cm). The samples were taken in the four replications and mixed per treatment for the analysis. This was done several times a year: at the end of the winter period, in order to determine the available mineral nitrogen stock for the following crop and to calculate a nitrogen fertilisation recommendation with the N-INDEX expert system (Geypens et al. 1994) (Table 2); in autumn, in order to determine the residual nitrogen after the harvest of the main crop; and a few times during the growing season in most of the treatments. The nitrogen fertilisation of the different trial treatments was applied as follows: treatment 1 received no nitrogen fertilisation; treatment 2 always received mineral nitrogen fertilisation according to the nitrogen fertilisation recommendation. Treatments 3 to 11 received no mineral nitrogen fertilisation during the first trial years (1997–2002). However, starting from 2003, the expected amount of nitrogen released by the applied compost during the growing season was supplemented each year with mineral N fertiliser up to the recommended level.

For the analyses of the soil samples, the following methods were used. After drying and sieving the soil samples, the pH was measured in a KCl-solution. The C% was measured with the modified Walkley & Black method (oxidation with potassium dichromate and back titration with Fe^{2+}, AFNOR 1985). The elements P, K, Mg, Ca and Na were extracted in an ammonium lactate extract and analysed with ICP (Inductive coupled plasma) (BELAC accredited method, BELAC 2011). Mineral N was analysed spectrophotometrically with a continuous flow system after KCl extraction (BELAC accredited method, BELAC 2011).

VFG and crop analyses and calculations in the field trial

The compost used in this study was VFG compost, provided by Ecowerf, a professional company in the compost industry in Flanders. Prior to each compost application, a representative sample was taken and analysed. Each year, the composition of the applied composts approached the average composition of VFG compost (Vlaco 2011), the heavy metals were far below the legal standards and the composts contained very low amounts of stones and impurities and no viable seeds.

Crop yields were determined as follows. For sugar beets, four beet rows of 4 m length were manually harvested and topped. The harvested beets and the leaves were weighed. Winter wheat was harvested with a small trial combine harvester and at least 20 m² per plot were harvested and grain and straw yield was determined. For potatoes, four rows of 3 m length per plot were manually harvested and fresh and dry tuber and leaf yields were determined. For carrots, two rows of 3 m+one row of 1.5 m length per plot were manually harvested and weighed. Root and leaf fresh and dry yields were

Table 1 Treatments in the VFG field trial

Treatment		Application of VFG compost													
		'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10
1	Control (no fertilisation)														
2	Yearly mineral fertilisation according to advice														
3	3-yearly application of 15 tonnes VFG/ha	x			x			x			x			x	
4	3-yearly application of 30 tonnes VFG/ha	x			x			x			x			x	
5	3-yearly application of 45 tonnes VFG/ha	x			x			x			x			x	
6	2-yearly application of 15 tonnes VFG/ha	x		x		x		x		x		x		x	
7	2-yearly application of 30 tonnes VFG/ha	x		x		x		x		x		x		x	
8	2-yearly application of 45 tonnes VFG/ha	x		x		x		x		x		x		x	
9	yearly application of 15 tonnes VFG/ha	x	x	x	x	x	x	x	x	x	x	x	x	x	x
10	yearly application of 30 tonnes VFG/ha	x	x	x	x	x	x	x	x	x	x	x	x	x	x
11	yearly application of 45 tonnes VFG/ha	x	x	x	x	x	x	x	x	x	x	x	x	x	x
12	Fallow														
*13**	*Fallow, 3-yearly application of 45 tonnes VFG/ha*	*x*			*x*			*x*			*x*			*x*	
*14**	*Fallow, yearly application of 45 tonnes VFG/ha*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*

x : application of VFG compost

13* and 14*: fallow mini-plots: in part of the plots of treatments 5 and 11, the plant cover was eliminated starting from 1998.

determined. For each crop, dry matter content and nitrogen content (Kjeldahl) were determined on the different plant parts (leaves, beets, roots, tubers, grain, straw). Multiplying dry matter yield and corresponding nitrogen content gave a value for the nitrogen taken up by the harvested plant parts. The percentage nitrogen recovered by the crop at harvest from the applied VFG compost was calculated by subtracting the uptake in the control (treatment 1) from the treatment uptake and expressing the difference as a percentage of the total nitrogen applied in the compost.

The yield data (except for treatments 13 and 14) were analysed by ANOVA as a randomised complete block design. Means were compared by the Tukey-HSD-test.

Table 2 N-recommended levels in the different treatments in the VFG field trial

	Treatment:	1	2	3	4	5	6	7	8	9	10	11
1997	Sugar beet	-	163	163	163	163	163	163	163	163	163	163
1998	Winter wheat	-	188	-	-	-	-	-	-	-	-	-
1999	Potatoes	-	230	-	-	-	-	-	-	-	-	-
2000	Carrots	-	70	-	-	-	-	-	-	-	-	-
2001	Sugar beet	-	175	-	-	-	-	-	-	-	-	-
2002	Winter wheat	-	165	-	-	-	-	-	-	-	-	-
2003	Potatoes	-	200	200	210	210	200	220	200	200	200	180
2004	Carrots	-	85	85	86	80	96	88	68	93	75	78
2005	Winter wheat	-	188	190	167	153	110	93	60	130	99	54
2006	Sugar beet	-	161	158	154	141	137	168	149	144	126	126
2007	Winter wheat	-	200	190	175	160	169	163	162	159	148	131
2008	Winter wheat	-	192	171	165	176	166	174	136	99	66	66
2009	Potatoes	-	212	220	209	213	199	205	205	208	190	186
2010	Winter wheat	-	198	189	188	184	168	196	151	162	126	84

Simulations with the RothC model

In order to get a better insight into the effect of long-term applications of VFG compost on soil organic matter dynamics, the organic matter mineralisation in the different treatments of the long-term field trial was simulated with the RothC model. The RothC model simulates soil organic carbon (SOC) turnover and was developed at Rothamsted Research (UK), using results of several long term experimental fields at the institute (Jenkinson et al., 1987).

The RothC model is based on the interaction between five conceptual SOC fractions. Out of these five fractions, four are considered to be active: decomposable (DPM) and resistant (RPM) plant material, microbial biomass (BIO), and humified organic matter (HUM). The fifth fraction is a small amount of inert organic matter (IOM), usually <20 %, that does not turnover (age >50 000 years). Each active fraction decomposes by first-order kinetics into BIO, HUM or carbon dioxide (CO_2). The proportions between the quantity of CO_2 and BIO+HUM produced are determined by the cation exchange capacity (CEC) or clay content of the soil. The rate constants were set by tuning the model to long-term field data at Rothamsted. The decomposition rates are modified as a function of temperature, soil moisture deficit and the presence of a plant cover. Input of carbon from plant material is divided between DPM and RPM. The RothC model takes into account the amount and the composition of the organic matter present and added (as fertiliser or plant residues), soil type, temperature, soil moisture and soil cover.

This model was used in the present study because it was developed in comparable agro-ecological conditions and has been calibrated for Belgian and Flemish conditions during previous studies (Anon. 2009; van Wesemael et al. 2005). Van Wesemael et al. (2005) estimated the local parameters by fitting the model to SOC values from a long-term experiment in central Belgium. After calibrating the plant input, the model reasonably represented the observed SOC-stocks with uncertainties that were in the same order of magnitude as the ones reported for long-term experiments in the United Kingdom, Hungary and Sweden (5.8 % to 8.4 % RMSE).

For using the model in the present study, the model was calibrated using, as much as possible, the field trial data of the different treatments, in addition to the parameters determined by Anon (2009):

- The input organic matter DPM/RPM-ratio was adjusted for each type of organic input (Table 3), based on the results of a previous project (Anon. 2009). In this project, the OC content in crop residues was estimated from data in the literature. The DPM/RPM-ratios of the crop residues, which in the original Roth-C-model are assumed to be 1.44, was adapted for each crop residue type. The DPM/RPM-ratio of VFG-compost, as well as those of the different crop residue types, were estimated from the humification coefficient (i.e. the proportion of the fresh organic matter that is still present in the soil after one year). These humification coefficients were derived from the results of a number of field trials and incubation experiments. The relationship between DPM/RPM-ratio and humification coefficients was established via linear regression.
- The amount of carbon added via VFG compost was calculated based on the analysis results of each VFG-application (Table 4).
- To estimate the amounts of carbon applied to the soil through crop residues at harvest, average data for each crop were used (Anon 2009) and were adapted proportionally using the yield and crop residue data of the trial (Table 5). For each crop, the average yields (crop residue yields if available) of all the treatments and the whole trial period were calculated. These averages were used as reference values and linked to the average carbon inputs per crop listed in Table 3. For each treatment*crop*year, the carbon input was then calculated as follows:

$$C-input_{(t)} = C-input_{(avg)} * \frac{yield_{(t)}}{yield_{(avg)}} \qquad (1)$$

where

$C\text{-}input_{(t)}$	C-input per treatment*crop*year
$C\text{-}input_{(avg)}$	Average C-input per crop (Table 5)
$yield_{(t)}$	Measured yield (or crop residue yield) per treatment*crop*year
$yield_{(avg)}$	Average yield (or crop residue yield) per crop

- For the estimation of the amounts of carbon applied to the soil through root exudates (rhizodeposition), the figures proposed by Anon (2009) were used:

Table 3 General average C-input and composition of the different fresh organic inputs used in the VFG field trial (source: Anon 2009)

Type of organic matter input	Average C-input	DPM/RPM ratio
Crop residues	t/ha	
Winter wheat (straw removed)	2.08	1.35
Sugar beet (crop residues incorporated)	2.30	1.54
Potatoes	1.76	1.52
Carrots	1.21	1.48
Yellow mustard	1.36	1.37
Organic fertilisation	t/10 t applied product	
VFG compost	1.54	0.15

0.4 t/ha/year for all crops, with a fixed DPM/RPM-ratio of 1.72.

– For the estimation of temperature and moisture deficit the monthly weather data of a nearby weather station (Beauvechain, Belgium) were used.
– The sowing and harvesting dates of each crop were used to determine the period of soil coverage.
– For each treatment, the simulation started from the same initial situation, based on the measurement of the initial carbon content (0.9 %) and soil texture (light loam with a clay content of 14 % and a specific gravity of 1.4) of the field.
– The field cropping and fertilisation history (arable field without significant organic fertilisation) was taken into account in order to *estimate the initial distribution of the soil carbon* over the conceptual SOC fractions. This was done according to the initial distributions set up by Anon (2009).

Table 4 Carbon content and application date of the different VFG applications in the VFG field trial

	Application date	C-content (%)
1997	26/03/1997	16.1
1998	14/10/1997	16.9
1999	1/04/1999	9.7
2000	26/01/2000	17.2
2001	20/02/2001	12.5
2002	16/10/2001	13.3
2003	17/03/2003	12.6
2004	19/02/2004	13.9
2005	16/11/2004	16.7
2006	30/01/2006	18.7
2007	9/11/2006	17.3
2008	2/11/2007	14.5
2009	16/03/2009	19.4
2010	1/10/2009	15.9

The simulated carbon contents were then plotted. The average simulated and measured carbon contents per year were calculated for each treatment and used to evaluate the performance of the simulations by calculating the R^2-values of the simulation curves as defined in Kvalseth (1985) and the RMSE (root mean square error) and correlation coefficient (r) used by Smith et al. (1997):

$$R^2 = 1 - \frac{\sum (y - \hat{y})^2}{\sum (y - \bar{y})^2} \tag{2}$$

where y is the measured C% (average per year), $\hat{y}$ is the predicted C% based on the average simulated carbon content per year and $\bar{y}$is the average of the measured C% over the whole trial period.

$$RMSE = \frac{100}{\overline{O}} \sqrt{\sum_{i=1}^{n} (P_i - O_i)^2 / n} \tag{3}$$

and

$$r = \frac{\sum_{i=1}^{n} (O_i - \overline{O})(P_i - \overline{P})}{\left(\sum_{i=1}^{n} (O_i - \overline{O})^2 \right)^{1/2} \left(\sum_{i=1}^{n} (P_i - \overline{O})^2 \right)^{1/2}} \tag{4}$$

where O is the measured C% (average per year), P is the predicted C% based on the average simulated carbon content per year, $\overline{O}$ is the average of the measured C% over the whole period, $\overline{P}$ is the average of the predicted C% over the whole period and n is the number of paired values.

Results

Impact of VFG applications on crop yields

The effect of the VFG-applications on crop yields is shown in Table 6: the yield results of the winter wheat in 2010 are listed. The treatments with the highest VFG applications (treatment 10 and 11) gave the highest yields (more than 9 t/ha) but, except for treatment 5, these results were not significantly different from the

Table 5 Yields or crop residues per crop (all years) and per treatment*year in the VFG field trial

Year	Crop		Yield/Crop residue levels (t/ha)											
			Average	Per treatment										
				1	2	3	4	5	6	7	8	9	10	11
1997	Sugar beet	Leaves	38.0	37.4	58.9	40.7	43.0	49.9	40.7	43.0	50.0	40.7	43.0	49.9
1998	Winter wheat	Grains+straw	12.1	10.7	14.9	12.5	13.2	13.9	12.5	13.2	13.9	12.5	13.3	14.2
1999	Potatoes	Fresh tubers	54.0	49.1	65.3	51.1	55.1	57.7	57.0	61.1	63.8	62.2	63.3	66.3
2000	Carrots	Leaves	21.6	22.3	28.6	25.9	26.8	28.6	24.3	24.4	25.4	26.3	29.3	31.0
2001	Sugar beet	Leaves	38.0	17.7	46.0	23.4	24.3	31.0	22.3	24.4	28.6	24.2	28.4	32.6
2002	Winter wheat	Grains+straw	12.1	8.0	15.2	9.1	8.9	11.0	9.4	9.2	10.4	9.7	11.3	12.6
2003	Potatoes	Fresh tubers	54.0	31.0	47.4	49.9	49.7	48.8	49.0	48.8	49.6	48.0	53.2	48.6
2004	Carrots	Leaves	21.6	12.3	18.3	16.8	15.6	14.9	15.9	16.0	18.0	18.0	18.0	18.2
2005	Winter wheat	Grains+straw	12.1	7.2	14.1	13.7	13.9	14.4	14.2	14.1	14.2	13.9	14.9	14.8
2006	Sugar beet	Leaves	38.0	20.4	51.4	47.9	42.7	47.0	51.8	43.5	43.9	48.4	46.3	50.7
2007	Winter wheat	Grains+straw	12.1	6.8	10.1	11.4	11.7	11.7	11.6	11.9	11.1	11.4	11.8	10.9
2008	Winter wheat	Grains+straw	12.1	5.9	13.1	13.9	13.9	13.6	13.6	14.1	14.0	12.9	14.1	13.0
2009	Potatoes	Fresh tubers	54.0	34.1	56.0	54.6	60.5	57.3	55.6	56.3	56.7	56.7	58.2	59.7
2010	Winter wheat	Grains+straw	12.1	10.9	12.6	13.3	13.1	11.5	12.5	12.8	12.5	12.7	14.1	14.1

other fertilised treatments (treatment 2 to 9). None of the VFG-treatments differed in yield significantly from the treatment fertilised with minerals. The non-fertilised plots gave significantly the lowest yields, but, even after 14 years without N fertilisation, the yield levels (7.3 t/ha) were still acceptable. In the straw yield results, no significant differences were observed. From a qualitative point of view, the protein content of the grains was significantly higher in the fertilised treatments than in the non-fertilised treatment.

In Fig. 1, the relative yields of the treatments with VFG application are compared to the yield of the

Table 6 N-fertilisation and yield results of winter wheat in 2010 (VFG field trial)

Treatments		N-fertilisation from VFG (crop available N)	N-fertilisation from min. fertiliser	N-fertilisation total	Yield quantitative		Yield quality protein content
					Grains (15 % humidity)	Straw (*)	
		kg N/ha	kg N/ha	kg N/ha	t/ha	t DM/ha	%
1	Control (no fertilisation)	0	0	0	7.348 a	2.045	8.2 a
2	Min. fertilisation (advice)	0	188	188	8.258 ab	5.744	12.5 b
3	15 tonnes VFG/ha. 3-yearly	0	192	192	8.752 ab	4.88	12.5 b
4	30 tonnes VFG/ha. 3-yearly	0	179	179	8.583 ab	2.999	12.3 b
5	45 tonnes VFG/ha. 3-yearly	0	175	175	7.493 a	5.762	13.3 b
6	15 tonnes VFG/ha. 2-yearly	0	167	167	8.219 ab	3.231	12.2 b
7	30 tonnes VFG/ha. 2-yearly	0	163	163	8.405 ab	5.013	12.2 b
8	45 tonnes VFG/ha. 2-yearly	0	151	151	8.189 ab	4.684	12.8 b
9	15 tonnes VFG/ha. yearly	20	143	163	8.358 ab	6.154	12.5 b
10	30 tonnes VFG/ha. yearly	39	100	139	9.265 b	6.439	12.6 b
11	45 tonnes VFG/ha. yearly	59	76	135	9.343 b	5.967	12.4 b

Different letters in a column indicate statistically significant differences ($P \leq 0,05$) based on the Tukey-HSD-test.

(*) Straw yields are indicative because of late lodging.

treatment with only mineral fertilisation during the whole period (treatment 2=100 %). Starting from 2003, the N-fertilisation in all the treatments with VFG-compost was supplemented with mineral fertiliser to the recommended amount. In previous years, these treatments only received VFG compost according to the trial setup, mostly resulting in a sub-optimal N-fertilisation. Figure 1 shows clearly that, since 2003, all the treatments with VFG compost showed equivalent yields with treatment 2 (mineral fertilisation according to recommendation). In these treatments, the VFG compost provided a partial implementation of the N-fertilisation recommended amount but even before 2003, the yields in the compost-fertilised treatments were higher than those in the non-fertilised treatment (treatment 1).

Nitrogen fertilising value of VFG compost

Generally, the applications of VFG compost in the trial resulted in high total N-applications (Table 7). However, the supply of crop-available N during the first growing season after application is considered as limited to 10–20 % of the total supplied N (Vlaco 2011). This is confirmed by the N recovery results in the first six trial years (when VFG compost applications were not supplemented with mineral N fertilisers); except for the first trial year (1997) and the lowest VFG dose in 2002, N recovery percentages varied between 10 and 22 % (Table 8). There was no indication of immobilisation of existing soil mineral nitrogen (negative N recovery rate) with application of low doses of VFG compost.

During this period (1997–2002), the N-uptake by the crops increased with increasing VFG-doses, although it never reached the level of N-uptake with mineral N-fertilisation according to fertilisation advice (Fig. 2).

Starting from 2003 (when for all the treatments with VFG compost the N-supply through compost was supplemented with mineral N-fertilisation up to the recommended amount), the percentage of the recommended amount of N that was supplied by the compost was calculated for each treatment and each trial year. For this, only the plant available N during the first growing season was taken into account, i.e. 15 % of the total N-amount applied by the compost. In Fig. 3, the total N-uptake by the crop (kg N/ha) is shown in relation to the % of the N-advice supplied by VFG-compost. There was no relationship found between any of the crops or trial years. From this it can be concluded that the N-uptake by the plants remains the same whether the N is provided by mineral fertilisers or by VFG-compost. Thus, N supplied to the crop by mineral fertilisation can be (partially) replaced by N supplied by VFG-compost.

Note that, with the extreme VFG applications, the N-supply through compost often exceeded the fertilisation recommendations, resulting in increased risks of nitrate leaching at the end of the growing season.

Change of the C-content of the top soil layer (0–30 cm)

In 2010, after 14 years, the influence of long-term application of VFG compost was obvious (Fig. 4). In the plots fertilised with minerals, without VFG application, the C-content in the 0–30 cm soil layer was 1 %. As the frequency and dosage of VFG application increased, the C-content of the soil increased as well. The highest C-contents were observed with a yearly application (since 1997) of 30 tonnes and 45 tonnes VFG per

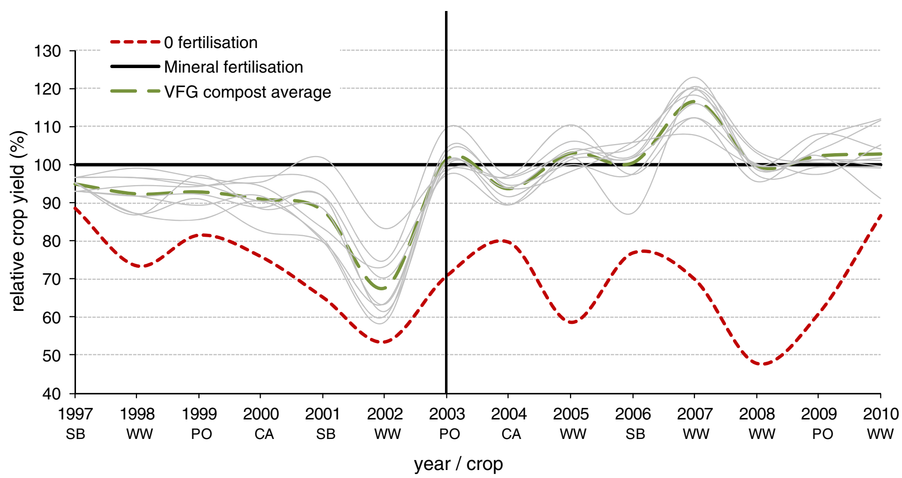

Fig. 1 Yields of the VFG field trial during the period 1997–2010, relative to the treatment with only mineral fertiliser (treatment 2). SB= sugar beets; WW=winter wheat; PO=potatoes and CA=carrots

Table 7 N-content of the applied composts and total N-application from VFG compost per treatment (VFG field trial)

Year	N-content VFG			Total N applied (kg/ha)													
				Treatment													
	NO_3-N mg/l	NH_4-N mg/l	Total N (kg/tonne)														
				1	2	3	4	5	6	7	8	9	10	11	12	13	14
1997	70	643	15.4	0	0	231	462	693	231	462	693	231	462	693	0	693	693
1998	15	694	14.8	0	0	0	0	0	0	0	0	222	444	666	0	0	666
1999	38	391	12.2	0	0	0	0	0	183	366	549	183	366	549	0	0	549
2000	7	448	10.7	0	0	161	321	482	0	0	0	161	321	482	0	482	482
2001	0	338	17.9	0	0	0	0	0	269	537	806	269	537	806	0	0	806
2002	1	1199	16.0	0	0	0	0	0	0	0	0	240	480	720	0	0	720
2003	2	905	15.2	0	0	228	456	684	228	456	684	228	456	684	0	684	684
2004	26	711	17.3	0	0	0	0	0	0	0	0	260	519	779	0	0	779
2005	8	825	12.6	0	0	0	0	0	189	378	567	189	378	567	0	0	567
2006	1.9	327	13.5	0	0	203	405	608	0	0	0	203	405	608	0	608	608
2007	1.8	648	12.7	0	0	0	0	0	191	381	572	191	381	572	0	0	572
2008	<3,1	150	12.5	0	0	0	0	0	0	0	0	188	375	563	0	0	563
2009	<3,1	261	13.7	0	0	206	411	617	206	411	617	206	411	617	0	617	617
2010	<3.1	372	13.1	0	0	0	0	0	0	0	0	197	393	590	0	0	590

hectare. With the application of low dosages of VFG compost (15 tonnes/ha), the increase of the C-content was limited, even with yearly applications.

Treatment 12 shows the change of the C-content in a fallow soil with no external C-supply, either from crop residues or from application of compost. The C-content (0–30 cm) measured in these plots shows a decreasing trend over the years (Fig. 5). C-supplies from moderate compost applications (treatment 13: 45 tonnes/ha 3-yearly, no crop) provided a compensation for this decrease in the long term; the C-content of the soil remained stable and increased even slightly. C-supply from high compost applications (treatment 14: 45 tonnes/ha yearly, no crop) caused a marked increase of the C-content in the soil.

The change of the C-content (0–30 cm) in the different non-fallow treatments (treatments 2 to 11) is given in Figs. 6 and 7. The changes of the C-content are shown with increasing VFG doses (Fig. 6) and increasing frequencies of application (Fig. 7). Over a 14-year period, the C-content in the plots with only mineral fertilisation showed no significant change. From 2007 (after 10 years of trial), the effect of increasing VFG doses and application frequencies became obvious in the measurements. The yearly application of 45 ton VFG per hectare induced an increase of the C-content with up to 1,8 % in 2010.

Simulation of the C-evolution in the top soil layer (0–30 cm)

In Fig. 8, the results of the RothC-simulations are given for the most important treatments. Each graph shows the average C-measurements per year, with a linear regression fitted through the measurements, and the SOC simulation results. On the left side, from top to bottom, the graphs are shown for increasing VFG-applications

Table 8 N recovery rates of the applied composts with different VFG doses, from 1997 to 2002 (VFG field trial)

VFG-dose t/ha	1997 sugar beet	1998 winter wheat	1999 potatoes	2000 carrots	2001 sugar beet	2002 winter wheat
15	6.9	13.5	21.7	16.1	14.1	6.3
30	4.5	10.2	10.4	15.9	10.6	9.7
45	6.9	9.8	9.1	11.4	10.2	9.3

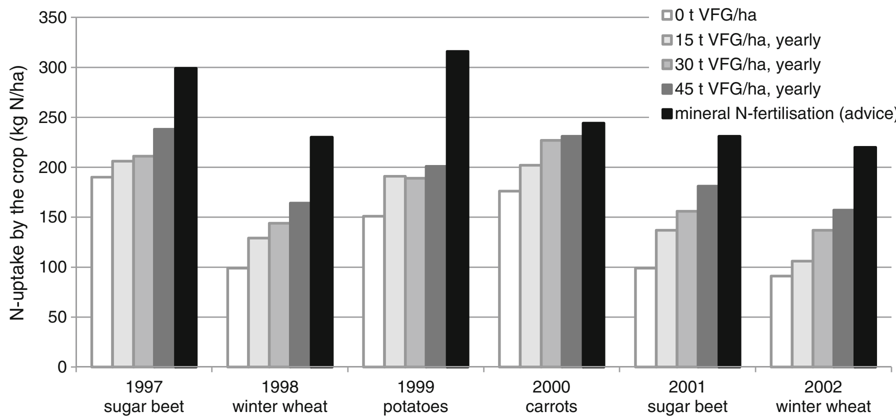

Fig. 2 N-uptake by the crop in relation to VFG-dose, compared to N-uptake with mineral N-fertilisation according to fertilisation advice, from 1997 to 2002 (VFG field trial)

(from 0 to 45 tonnes/ha yearly) on the normal crop rotation. On the right side, the graphs are shown for the same VFG-applications, but without crop (fallow plots).

With no VFG application, the simulation results tended to underestimate the real C-contents on the fallow plots. With intermediate VFG applications (15 t/ha yearly), the simulation results gave a relatively good prediction of the real C-contents. This was also the case for the other intermediate treatments (15 to 30 t/ha, 3-yearly to yearly, data not shown), but with extremely high VFG applications (45 t/ha yearly) the simulations tended to overestimate the C-contents.

The performance of the model predictions were evaluated by the calculation of the R^2-values (Eq. 2), the RMSE (Eq. 3) and the correlation coefficients (r, Eq. 4). The R^2-values ranged from −1.28 to +0.32, the RMSE from 9.1 % to 20.8 % and the correlation coefficients from −038 to +0.73 (Table 9).

In Fig. 9, the R^2-values of the simulations as well as of the linear regressions were plotted vs. the average yearly amount of VFG applied on the crops (e.g. 45 tonnes/ha 3-yearly represents an average of 15 tonnes/ha yearly). For the linear regressions, the R^2-values increase with increasing VFG applications. For the RothC simulations, the R^2-values follow a quadratic curve: they reach a maximum with average VFG-applications, but with low and high applications the R^2 is poor.

Analysis of the C-fractions in the top soil layer (0–30 cm)

Figure 8 demonstrates clearly that the long-term application of VFG compost results in an accumulation of C in the top soil layer. To study the effect on C-composition (fractions) and organic matter dynamics, two extreme trial treatments were compared: treatment 2 (only mineral fertilisation) and treatment 11 (45 t VFG/ha yearly). Although it was observed that the RothC simulations tend to overestimate the C-accumulation in the top soil for extremely high VFG applications, the simulation results could still be used to evaluate the distribution of the SOC over the different fractions DPM, RPM, BIO and HUM. It appeared that the strong

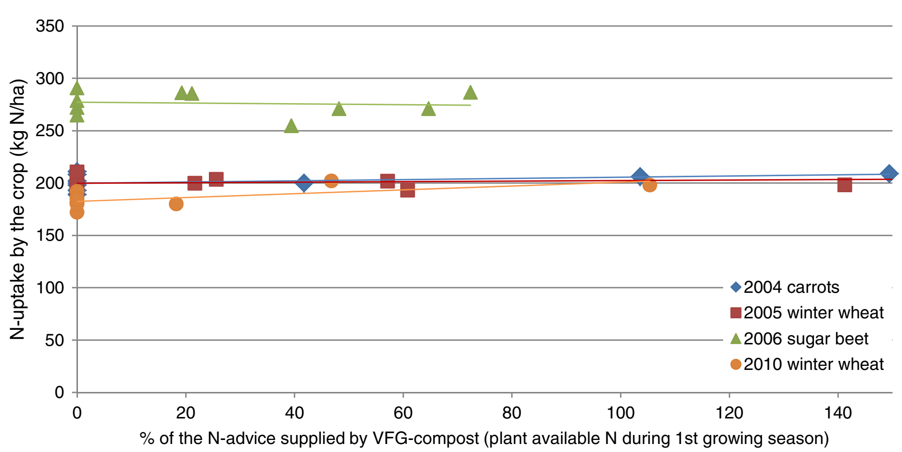

Fig. 3 N-uptake by the crops in relation to the percentage of the N-advice supplied by VFG compost (plant available N during the 1st growing season after application), from 2003 to 2010 (VFG field trial)

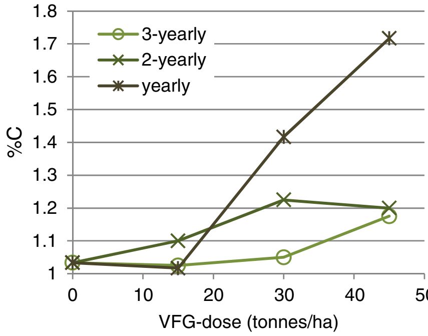

Fig. 4 Influence of long-term application of VFG compost on the C-content in the soil (0–30 cm) in 2010: effect of VFG dose and frequency of application (VFG field trial)

C-accumulation induced by high VFG-applications were mainly due to an increase of the RPM-fraction. Figure 10 shows that, with only mineral fertilisation, the total C-content remained more or less the same, but the HUM-fraction decreased slightly. With long-term applications of high amounts of VFG (45 t/ha/year), the RPM-fraction increased significantly, but also the HUM- and the BIO-fractions increased.

Soil N-supplying capacity

The evolution of the N-stocks (0–90 cm) in spring was analysed in the different trial treatments (Fig. 11). Without VFG applications (treatment 2), the mineral N-stocks after winter remained on average at the same level during the whole trial period. With long-term yearly applications of VFG (treatments 9 to 11), the mineral N-stocks after winter increased gradually over the years and this increase was more pronounced with higher VFG doses (increasing slopes and R^2-values of the linear regressions).

Discussion

Fertilising value and effect on crop yield

Generally, compost is considered as a valuable fertiliser, especially with respect to nitrogen. The VFG compost applications in the trial resulted in high total nitrogen supplies. However, not all the nutrients in VFG compost are directly available for the crops. Compost should in general be considered more as a slow-release source of nitrogen (Erhart et al. 2005; Odlare et al. 2011). The average percentages of nitrogen in VFG compost that are available for the crops during the next growing season after application are generally estimated at 10–20 % (Vlaco 2011). Our trial results confirm these percentages. Furthermore, Lillywhite et al. (2009) indicated that, with lower application rates of some compost types, nitrogen uptake could be reduced compared to a control treatment without compost application, due to immobilisation of existing soil mineral nitrogen. In our study, however, there was no indication of this immobilisation effect with application of low doses of VFG compost, the nitrogen recovery rates ranging from 6 to 22 % in these treatments.

Despite the slow-release effect of compost applications, the trial results indicate that VFG compost can replace a significant part of the mineral nitrogen fertilisation already in the first growing season after application. When only taking into account the plant available nitrogen during the first growing season, compost applications of 15 t/ha provided 20 to 25 % of the recommended nitrogen fertilisation, applications of 30 t/ha provided 40 to 60 % of the recommended amount and applications of 45 t/ha provided 65 to 157 % of the recommended amount. The nitrogen uptake by the

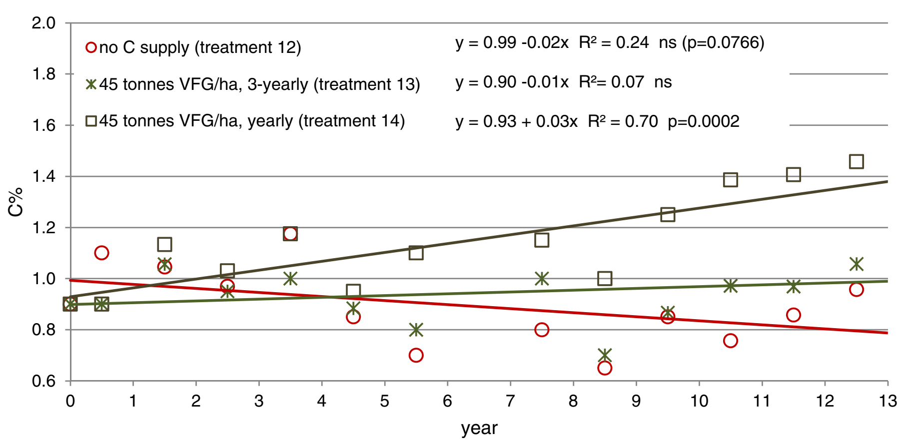

Fig. 5 Changes of the C-content on fallow plots, without external C-supply or with supply of VFG compost (45 tonnes/ha 3-yearly or yearly) (VFG field trial)

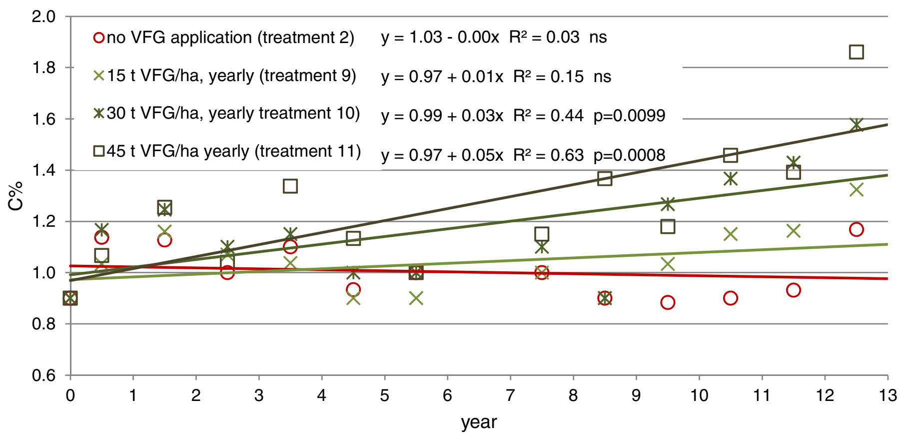

Fig. 6 Influence of long-term application of VFG compost on the C-content in the soil (0–30 cm): change of the C-content with yearly application of increasing VFG doses (VFG field trial)

plants remained the same whether the nitrogen was provided by mineral fertilisers or by VFG-compost. However it should be noted that the extreme compost applications of 45 t/ha often corresponded to an important excess fertilisation and could therefore induce risks of nitrate leaching at the end of the growing season. These risks were also reported by Gerke et al. (1999), especially in sandy sites.

The nitrogen fertilising effect of compost applications on crop yields was already reported before in different studies (Lillywhite et al. 2009; Nevens and Reheul 2003; Erhart et al. 2005; Fagnano et al. 2011; Paterson et al. 2011) and is confirmed in the present study. All the plots fertilised according to the recommended nitrogen fertilisation had comparable yield levels, whether this had been provided (partially) through VFG-compost or not. But already during the period 1997–2003, the fertilising value of the VFG compost appeared from the yield data: the yields in the compost-fertilised treatments were clearly higher than those in the non-fertilised treatment.

Effect on soil organic carbon content

In the fallow plots with no external carbon supply (no crop residues and no application of compost), measurements in the ploughing layer showed that the carbon content decreased over the years, due to natural degradation of the soil organic matter (mineralisation). This was also observed in the RothC simulations executed with the field trial data, although the simulation results appeared to underestimate the carbon contents (overestimate the organic matter degradation). The field measurements showed also that carbon supplies from crops only (only mineral fertilisation) provided compensation for this decrease in the long term; the carbon content of the soil remained more or less stable. Again, this trend was slightly underestimated by the RothC simulations. Extra carbon supplies from compost applications induced an increase of the carbon content in the soil, which was stronger as the frequency and dosage of VFG applications increased. These results confirm the results of

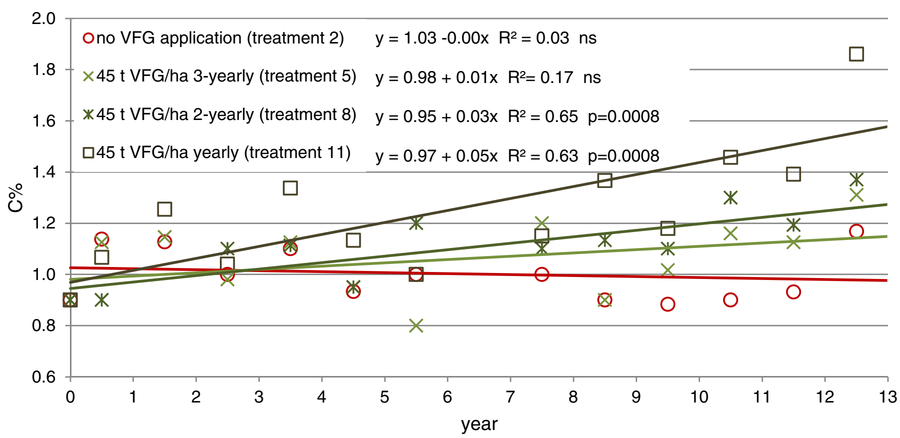

Fig. 7 Influence of long-term application of VFG compost on the C-content in the soil (0–30 cm): change of the C-content with increasing frequencies of application of 45 tonnes/ha VFG compost (VFG field trial)

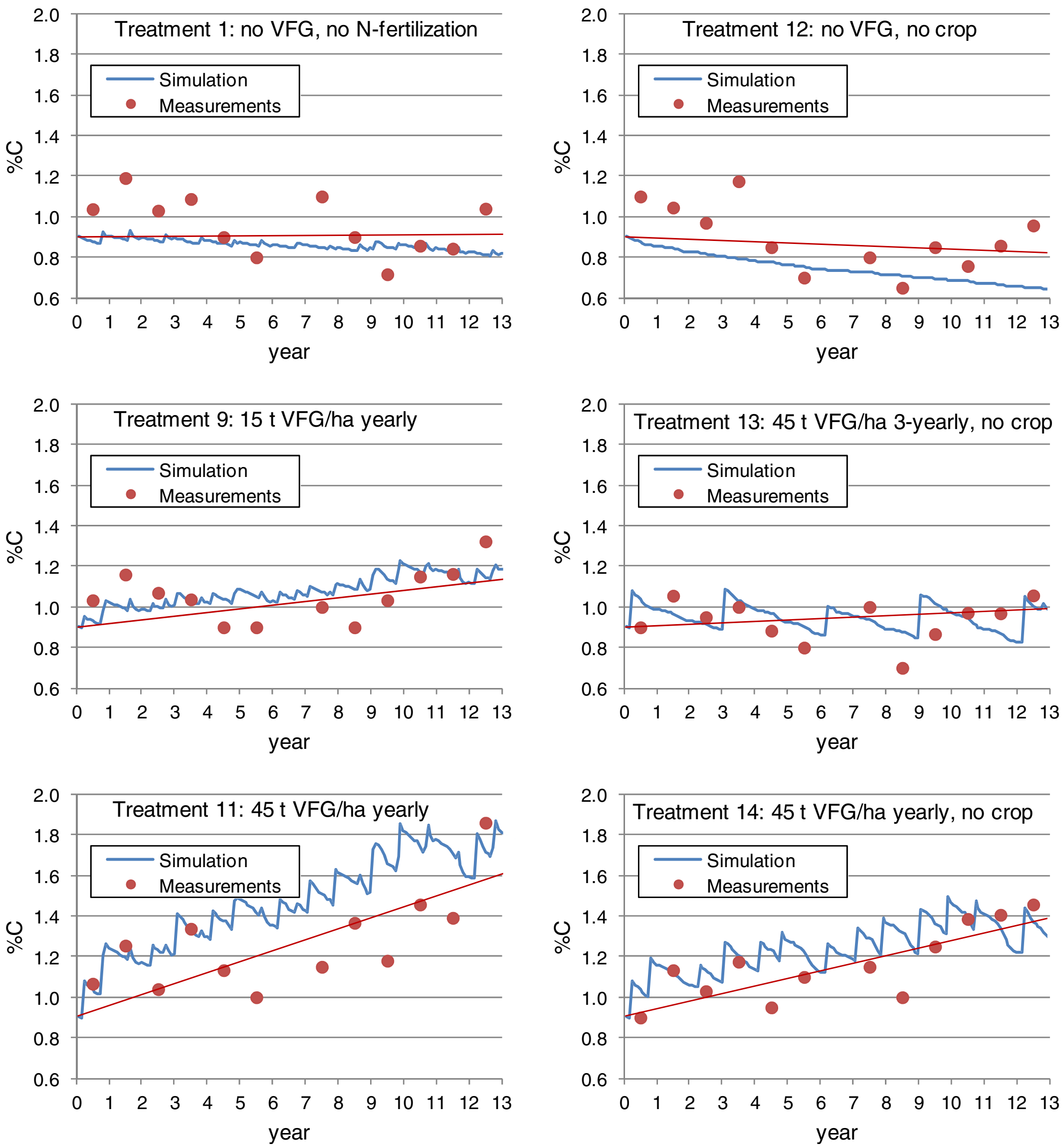

Fig. 8 RothC simulation of the SOC-evolution in different treatments in the VFG field trial: irregular line=simulation results; dots=measurements; straight line=linear regression on the measurements

several other studies with different compost types (Fagnano et al. 2011; Nevens and Reheul 2003; Delschen 1999; Arthur et al. 2011; Herencia et al. 2011; Emmerling et al. 2010; Odlare et al. 2011). After 14 years, the highest carbon contents were measured in the plots with a yearly application of 30 tonnes and 45 tonnes VFG per hectare (1.8 %C). With the application of low dosages of VFG compost (15 tonnes/ha), the increase of the carbon content was limited, even with yearly applications. The RothC model appeared to give a good prediction of carbon evolution with low to moderate VFG applications, but tended to overestimate the carbon evolution with extremely high VFG applications (45 t/ha yearly). This could be due to an overestimation of the resistant carbon fraction of the VFG compost or to an incorrect estimation of the carbon supply by the crops (residues and rhizodeposition). Indeed, it was observed by Anon (2009) that the RothC model was highly sensitive to the amounts of carbon supplied by crop residues and organic fertilisation. Further research is needed to improve the parameterisation of the RothC model with respect to the

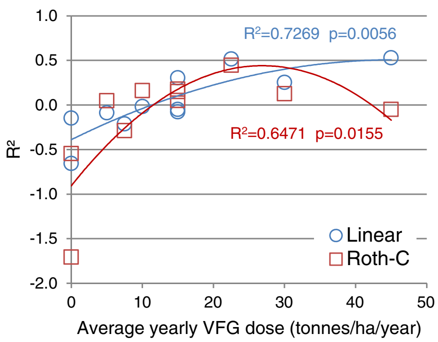

Fig. 9 R^2 of the linear regressions (*dots*) and the RothC-simulations (*squares*) of the C-content (0–30 cm) in function of the average yearly VFG applications (VFG field trial)

carbon fractions of VFG compost and the carbon supply by different agricultural crops in Flemish conditions.

The performance of the model predictions were evaluated by the calculation of the R^2-values (Kvalseth 1985), the RMSE and the correlation coefficients r (Smith et al. 1997). The calculated R^2-values corresponded to the EF-values (model efficiency) proposed by Smith et al. (1997). They can be positive or negative. A perfect fit of the simulation corresponds to an R^2 of 1. An R^2 between 0 and 1 indicates that the simulated values give a better prediction of the measured values than their average. A negative value indicates that the simulated values give a less good prediction of the measured values than their average. The RMSE calculates the total difference between the simulated and the measured values and can range from 0 to ∞. For a perfect fit it equals 0. The correlation coefficient (r) evaluates how well the simulated trend matches the trend of the measured values. However, if the measured values show no clear trend, the usefulness of this statistic is limited.

Table 9 Statistics describing the model performance for the different treatments of the VFG field trial

Treatment	R^2	RMSE	r
1 (no fertilisation)	−0.36	16.34	0.43
2 (mineral fertilisation)	−1.28	14.15	−0.38
3 (15 t VFG/ha, 3-yearly)	0.04	13.96	0.21
4 (30 t VFG/ha, 3-yearly)	0.12	16.81	0.39
5 (45 t VFG/ha, 3-yearly)	0.06	12.11	0.46
6 (15 t VFG/ha, 2-yearly)	−0.21	15.43	−0.08
7 (30 t VFG/ha, 2-yearly)	0.17	15.03	0.42
8 (45 t VFG/ha, 2-yearly)	0.32	9.05	0.73
9 (15 t VFG/ha, yearly)	−0.10	11.79	0.30
10 (30 t VFG/ha, yearly)	0.05	15.33	0.55
11 (45 t VFG/ha, yearly)	−0.19	20.77	0.68
12 (no fertilisation, fallow)	−0.70	21.78	0.58
13 (45 t VFG/ha, 3-yearly, fallow)	0.09	11.72	0.32
14 (45 t VFG/ha, yearly, fallow)	0.31	12.4	0.70

In the simulation results of this study, the R^2-values ranged from −1.28 to +0.32. These values are relatively low, in contrast with, for example,the results of Ludwig et al. (2007), who obtained values of more than 0.80. However, Smith et al. (1997) also found negative EF-values for 9 out of 11 field experiments studied for the RothC-model. The RMSE-values in the present study were relatively high, ranging from 9 to 22 %, indicating a poorer performance of the simulation model, compared with values of Ludwig et al. (2007), 6.1 and 7.0, and with van Wesemael et al. (2005), 5.8 % to 8.4 %. Nevertheless, except for the extreme VFG applications of 45 t/ha, the simulation curves seem to follow fairly closely the visual trend of the measurements and the correlation coefficients were positive for most of the treatments. The negative R^2-values and the high RMSE-values could be attributed partly to the variation in the SOC measurements caused by sampling (one mixed sample per treatment) and by the precision of the laboratory analysis (Walkley&Black method).

Effect on soil organic carbon composition and nitrogen supplying capacity of the soil

The trial measurements demonstrated clearly that long-term applications of VFG compost result in an accumulation of carbon in the top soil layer. Furthermore, long-term organic fertilisation such as compost applications have an influence on the distribution of organic carbon in the different soil carbon fractions (Kader et al. 2010; Sleutel et al. 2006; Heitkamp et al. 2009) and hence on the mineralisation capacity of the soil (Odlare et al. 2011; Pedra et al. 2007) and the N-supplying capacity of the soil. Besides quickly decomposable organic matter (DPM fraction), ensuring an amount of nitrogen that becomes available for the crop during the first growing season, VFG compost supplies more resistant organic matter fractions (RPM and HUM fractions) as well, which accumulate in the soil and mineralise gradually in the following years, increasing the N supplying capacity of the soil. These organic matter conversions and accumulations are simulated with the RothC model.

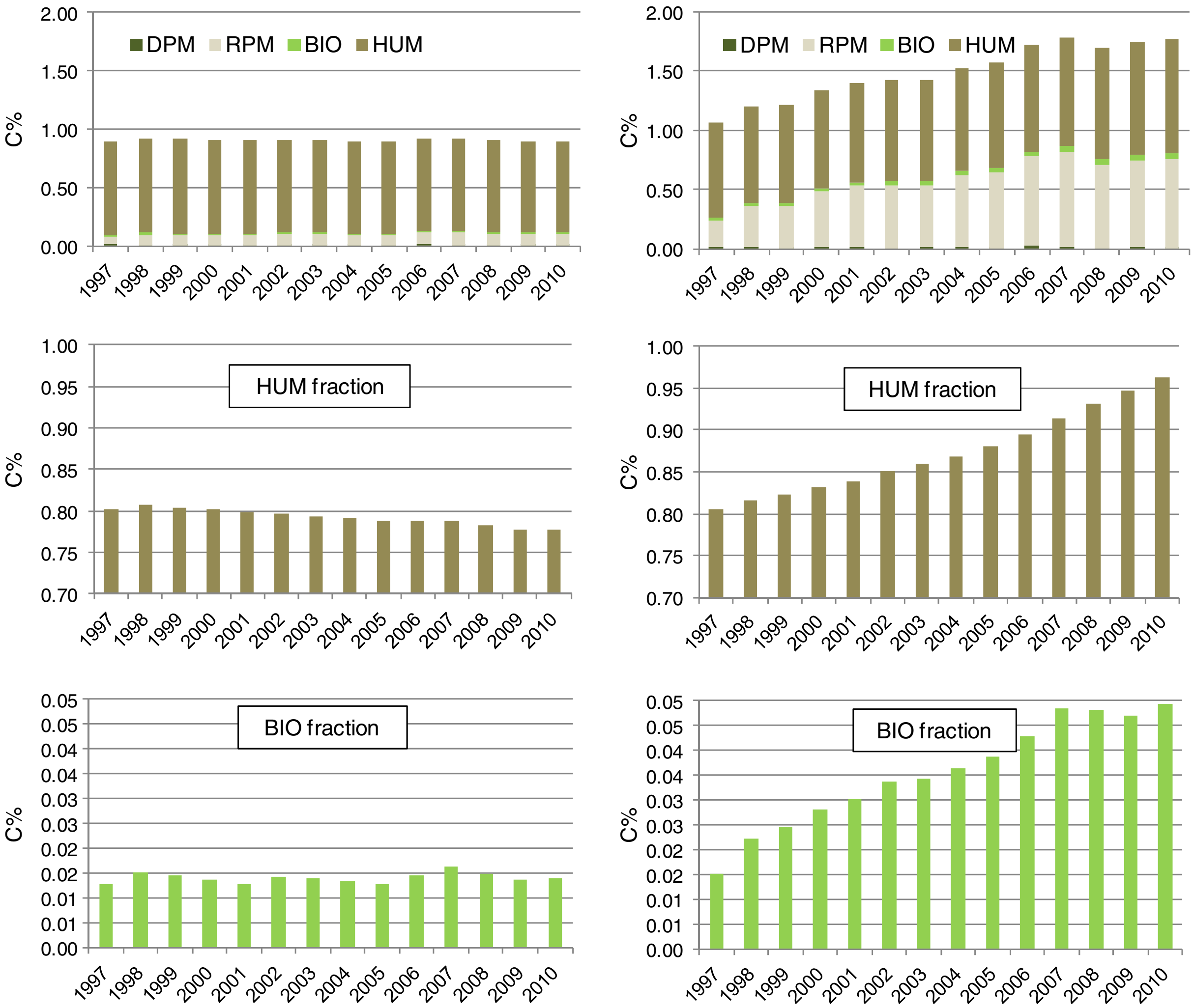

Fig. 10 RothC simulated C-fractions in the top soil (0–30 cm), after long-term mineral fertilisation (*left*) and after long-term VFG application (45 t/ha.year) (*right*). From top to bottom: top: all C-fractions, centre: HUM-fraction, bottom: BIO-fraction

Although the RothC simulations appeared to overestimate the total carbon accumulation in the top soil for extremely high VFG applications, the simulation results could be used to evaluate the distribution of the soil organic carbon over the different fractions DPM (degradable plant material), RPM (resistant plant material), BIO (microbial biomass) and HUM (humified organic matter). From the simulation results it appeared that the carbon accumulation with high VFG-applications was mainly due to an increase of the more resistant carbon fractions; in the plots receiving only mineral fertilisation, the total carbon content remained more or less the same, but the HUM fractions decreased slightly. In the treatments with long-term applications of high amounts of VFG (45 t/ha/year), the RPM-fractions increased significantly, but the HUM-and the BIO-fractions also increased. These observations seem to correspond to the conclusions of Emmerling et al. (2010) and Laudicina et al. (2011), who found that microbial biomass increased significantly after application of biowaste compost. Also Fabrizio et al. (2009) considered that with the application of compost, the recalcitrant C content of the compost was mainly sequestered in the soil, increasing the more resistant C-fractions in the soil. However, these observations need to be confirmed by laboratory measurements of the different fractions.

An increase of the nitrogen supplying capacity of the soil can be deduced from the measurements of mineral nitrogen stocks (0–90 cm) in spring in the different trial treatments. Without VFG applications,

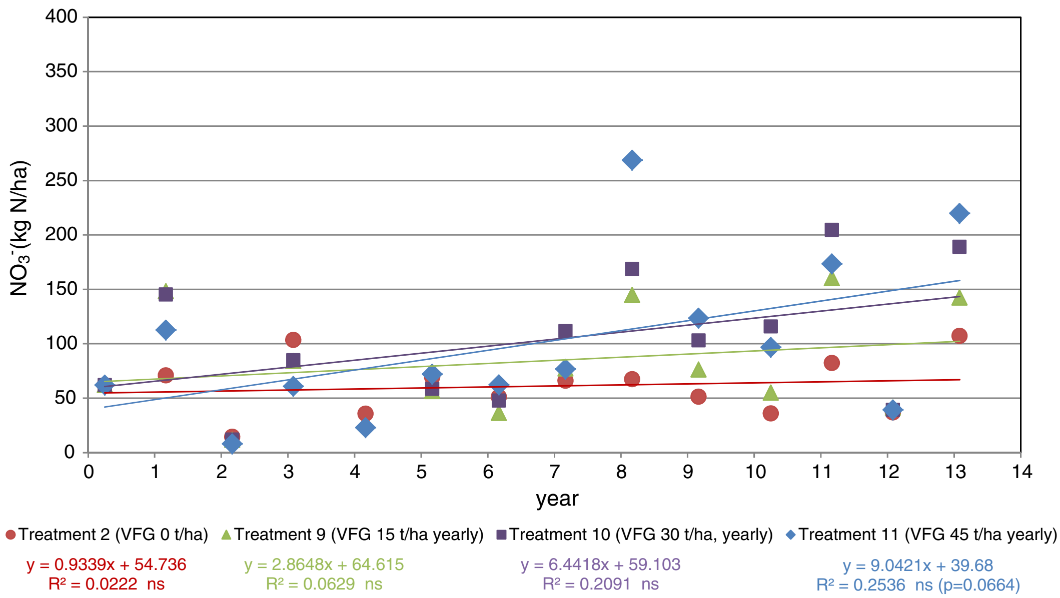

Fig. 11 Change in the mineral N-stocks over the years in relation to long-term application of increasing amounts of VFG compost (VFG field trial)

the mineral nitrogen stocks in spring remained on average at the same level during the whole trial period. With long-term yearly applications of VFG, the mineral nitrogen stocks after winter increased gradually over the years and this increase was more pronounced with higher VFG doses.

Conclusions

The trial results indicate that VFG-compost applications can replace a significant part of the mineral nitrogen fertilisation in the following growing season. Nitrogen recovery rates ranged from 6 to 22 %. The plots fertilised according to the nitrogen recommendations had comparable yields, whether this had been provided (partially) through VFG-compost or not. Measurements and simulations demonstrated that long-term VFG applications resulted in a carbon accumulation in the top soil. The RothC-model gave a good prediction of the carbon changes with low to moderate applications, but tended to overestimate the carbon change with high applications. From the simulation results it appeared that the carbon accumulation was mainly due to an increase of the more resistant carbon fractions. The effect of long-term compost applications on the nitrogen supplying capacity of the soil appeared from the gradual increase of the mineral nitrogen stocks in spring over the years.

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