Research Article

Received: 8 July 2010 Revised: 19 November 2010 Accepted: 22 December 2010

(wileyonlinelibrary.com) DOI 10.1002/jsfa.4306

Yield and fruit quality of four sweet corn hybrids (*Zea mays*) under conventional and integrated fertilization with vermicompost

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Abstract

BACKGROUND: Vermicompost has been proposed as a valuable fertilizer for sustainable agriculture. The effects of vermicompost on yield and quality of sweet corn were evaluated in this study. In two field trials, sweet corn plants were grown under (i) a conventional fertilization regime with inorganic fertilizer, and integrated fertilization regimes in which 75% of the nutrients were supplied by the inorganic fertilizer and 25% of the nutrients were supplied by either (ii) rabbit manure, or (iii) vermicompost. All three types of fertilization regime were supplied at two doses. Two pairs of nearly isogenic sweet corn hybrids homozygous for *sugary1* and *shrunken2* mutants were included in the trials to explore fertilizer × genotype interactions. Growth, yield and ear quality of the plants were evaluated in relation to the three fertilization regimes.

RESULTS: In general, the integrated regimes yielded the same productivity levels as the conventional treatment. Moreover, both vermicompost and manure produced significant increases in plant growth and marketable yield, and also affected the chemical composition and quality of the marketable ear. Nevertheless, most of the observed effects of the organic fertilizers were genotype-dependent.

CONCLUSION: The results confirm that the use of organic fertilizers such as vermicompost has a positive effect on crop yield and quality. Nevertheless, these effects were not general, indicating the complexity of the organic amendment–plant interactions and the importance of controlling genetic variation when studying the effects of vermicompost on plant growth.

Keywords: crop yield; vermicomposting; genotype × environment interaction; organic fertilizers; soil fertility; sustainable agriculture

INTRODUCTION

In recent years, increasing consumer concern about issues such as food quality, environmental safety and soil conservation has led to a substantial increase in the use of sustainable agricultural practices. Sustainable agriculture can be defined as a set of farming practices that conserve resources and environment without compromising human needs.[1]

The use of organic fertilizers, such as animal manures and composted materials, has been proposed as one of the main pillars of sustainable agriculture. Animal manure is a valuable resource as a soil fertilizer because it provides large amounts of macro- and micronutrients for crop growth and is a low-cost, environmentally friendly alternative to mineral fertilizers.[2]

Vermicomposting involves the breakdown and mineralization of an organic substrate by the joint action of earthworms and microorganisms. During vermicomposting, earthworms strongly modify the biochemical properties of the raw organic material and also shape its microbial communities,[3] thus producing a stabilized, finely divided peat-like material called vermicompost.[4]

The use of organic fertilizers such as vermicompost helps maintain soil fertility, and has evident environmental benefits as it enables on-farm recycling of organic waste. However, it is not yet clear whether organic amendments can maintain crop human demands at the same levels as inorganic fertilization.[5] Vermicompost increases growth, yield and tomato quality when used as a soil supplement[6] or as an alternative to mineral fertilizers in rice–legume intercropping.[7] The addition of vermicompost to field strawberries was found to produce significantly higher yields than the addition of equivalent amounts of mineral fertilizers, and the presence of plant growth regulators in the vermicompost was suggested.[8] Nonetheless, the lack of consistent results regarding the effects of vermicompost on crop yield and nutritional quality[9] shows that it is not yet clear whether hormonal effects are produced under all conditions, and suggests that many of the reported effects may be more closely related to nutrient

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supply. In addition, several plant-dependent factors, including plant developmental stage, age and genotype, determine the efficiency of the fertilization.[10] In particular, plant genotype determines important differences in both nutrient use efficiency[11] and resource allocation within plants.[12] In other words, for the same amounts of nutrients supplied, rather different yields and nutrient concentrations in leaves and grains will be produced by different genotypes of the same plant species. It has also been shown that different plant genotypes produce different root exudates and therefore establish different relationships with the microbial community at the rhizosphere level.[13,14] The inconsistent effects of vermicompost between and even within species[15] may therefore be due to genotype-dependent effects of this type of organic fertilizer.

Sweet corn is an annual crop of great economic importance in the USA, and also increasingly in Europe, where 500 000 tons of grain were produced in 2004.[16] As large areas of land are dedicated to production of this crop and as its nutrient requirements, especially for N, are high, the use of sustainable agricultural practices is particularly important. The name sweet corn, as opposed to field corn, is used to designate a series of varieties with natural recessive mutations that determine the differential accumulation of carbohydrates in the endosperm. Two main types of endosperm mutants can be distinguished on the basis of differences in endosperm carbohydrate biochemistry: class 1 mutants (e.g. *shrunken2* or *sh2*), which accumulate sugars at the expense of starch, thus decreasing the total carbohydrates in the grain, and class 2 mutants (e.g. *sugary1* or *su1*), which alter the types and amounts of polysaccharides, with a slight decrease in the starch content.[17] These types of mutations are found in a wide range of corn hybrids with completely different genetic backgrounds. Variations in nutrient uptake, allocation and transformation by the different endosperm mutants and hybrids may cause different responses to the type of nutrient source provided as fertilizer, in terms of yield and nutritional quality. Certain varieties will therefore be more adequate for sustainable or organic production than others.

The present study evaluated the feasibility of substituting part of the inorganic fertilizer input to a sweet corn crop, with vermicompost or manure. In order to explore the interactions between the type of fertilizer and plant genotype, two pairs of nearly isogenic sweet corn hybrids were included in the fertilizer trials.

MATERIAL AND METHODS

Site description

Field trials were carried out in Pontevedra (NW Spain) (42° 24′ N, 8° 38′ W), in 2007 and 2008. The climate at the site (20 m above sea level) is mild and humid, with an annual rainfall of ∼1600 mm. The soil at the experimental site is sandy loam; the main physicochemical characteristics of the soil are summarized in Table 1.

Fertilizing materials

Rabbit manure was collected from a rabbit farm in Ourense (NW Spain). The manure was used to produce vermicompost, in 1 m^3 vermireactors with the earthworm species *Eisenia fetida*, at a commercial vermicomposting facility. Five 500 mL samples of vermicompost and manure were collected from the stockpiled materials at the facility and analyzed for determination of their physicochemical properties (Table 1). In addition, commercial nitrogen (10.5% $N\text{-}NO_3^-$, 10.2% $N\text{-}NH_4^+$, 6.5% MgO), phosphorous (28% P_2O_5) and potassium (K_2O) mineral fertilizers were used.

Table 1. Main physicochemical properties of bulk soil at the experimental site, vermicompost and manure used in the experiment. Values are means ± standard error

	Bulk soil	Vermicompost	Manure
Moisture (%)	12.33 ± 0.05	55.50 ± 0.15	66.31 ± 4.88
Organic matter (%)	9.00 ± 0.00	55.00 ± 1.67	69.00 ± 1.00
pH	6.57 ± 0.02	7.23 ± 0.11	7.75 ± 0.08
EC (mS cm^2)[a]	0.02 ± 0.00	0.31 ± 0.02	0.27 ± 0.01
C (%)	3.01 ± 0.08	23.42 ± 0.48	30.38 ± 0.27
N (%)	0.35 ± 0.01	2.16 ± 0.01	2.24 ± 0.01
P (%)	0.004 ± 0.00	0.034 ± 0.00	0.033 ± 0.00
K (%)	0.007 ± 0.00	0.143 ± 0.00	0.110 ± 0.00

[a] Electrical conductivity.

Plant material

The plant material consisted of two pairs of nearly isogenic sweet corn hybrids produced at the Misión Biológica de Galicia by crossing the *su1* and *sh2* nearly isogenic versions of the sweet corn inbred lines I453 × 101t and P39 × C23. The two isogenic versions for each genetic background were the hybrid homozygous for the endosperm mutant *sugary1* (*su1*) and the hybrid homozygous for *shrunken2* (*sh2*). The four resulting hybrids are hereinafter denoted as I453*su1*×101t*su1*, P39*su1*×C23*su1*, I453*sh2*×101t*sh2* and P39*sh2*×C23*sh2*. Comparisons among endosperm mutants and among genetic backgrounds enabled evaluation of the magnitude of gene-dependent and whole-genotype-dependent effects on plant yield.

Experimental design

Three types of fertilization regimes were compared: (i) *inorganic*: sweet corn plants were supplied with simple N, P and K mineral fertilizers; (ii) *integrated fertilization with manure*, in which 75% of the nutrients were supplied as N, P and K mineral fertilizers and 25% of the nutrients were supplied as rabbit manure; and (iii) *integrated fertilization with vermicompost*, in which 75% of the nutrients required were supplied as N, P and K mineral fertilizers and 25% were supplied as vermicompost derived from rabbit manure. All three fertilization regimes were supplied at two different doses: a *normal* dose (80 : 24 : 20 kg ha^{-1} N : P : K) for an expected final crop yield of 4 Mg ha^{-1} of dry weight grain, and a *high* dose of 120 : 36 : 30 kg ha^{-1} N : P : K for an expected final yield of 6 Mg dry grain ha^{-1}, according to the dry grain yield reported for sweet corn.[16] The amounts of vermicompost, manure and mineral fertilizers required to supply these nutrient requirements (Table 2) were calculated taking into account the nutrient status of the soil at the experimental site and the N, P and K content of each fertilizer (Table 1).

Trial plots were sown on 16 May, in 2007 and 2008. In both years, fertilizers were applied manually to the plots 1 week before sowing, and incorporated by mixing into the first 20 cm of the soil. For all treatments and doses, 40% of the total nitrogen was supplied before sowing, and the remaining 60% – corresponding to inorganic N fertilizer – was provided as top dressing during stalk formation, 2 months after sowing (Table 2).

Table 2. Total amounts of each of the fertilizers used in the different fertilization regimes for normal and high doses

		Sowing				Top dressing
Dose	Fertilizing treatment	Organic fertilizer (kg ha^{-1})[a]	N fertilizer (kg ha^{-1})	P fertilizer (kg ha^{-1})	K fertilizer (kg ha^{-1})	N fertilizer (kg ha^{-1})
Normal (80 : 24 : 20)	Conventional	0	156	102	48	234
	Integrated with manure	5438	96	102	36	234
	Integrated with vermicompost	4186	111	102	36	234
High (120 : 36 : 30)	Conventional	0	234	154	72	351
	Integrated with manure	8157	145	154	54	351
	Integrated with vermicompost	6279	167	154	54	351

[a] Dry weight.

The *su1* and *sh2* mutants were assayed adjacently but were separated by border rows to avoid cross-pollination. Experimental units consisted of 10 m^2 plots each with one combination of mutant, genetic background, fertilizer and dose. Each plot contained two central and two border rows spaced 0.80 m apart, with 25 two-plant hills spaced 0.21 m apart; plots were overplanted and thinned to a final density of approximately 60 000 plants ha^{-1}. Plots were arranged in the field following a randomized complete block design with two replications per year. Trial location within the experimental field was changed each year to avoid any residual uncontrolled cumulative effects of the fertilizers. Plots were hand-weeded. The plants were not treated with pesticides or fungicides and were not given any supplemental water.

Assessment of plant yield and quality of the marketable ears

Final plant growth was evaluated at commercial harvesting stage, 20 days after mean female flowering. Five plants were selected at random from the two central rows of each plot and their heights recorded. These plants were subsequently cut to soil level and the dry mass of the shoots and leaves was calculated after drying at 60 °C for 1 week. Data were averaged to a single value per plot.

The number of ears produced in each of the harvested plants was determined. More resources are normally allocated to the uppermost ear because of apical dominance,[18] resulting in one large ear that is considered marketable, and other smaller ears that are discarded. In each plant, the marketable ear was separated for subsequent quality analysis and the remaining non-marketable ears were dried for 1 week at 60 °C for biomass determination. Mean biomass per ear and total ear biomass produced per plant were calculated.

The quality of the marketable ear was estimated by qualitative evaluation of the appearance and also by determination of some quantitative parameters. The quantitative measures included the size (length and diameter), total weight and grain percentage of the marketable ear in each plant, as well as the chemical quality of the grain (concentration of soluble solids, N, P and K).

Marketable appearance of the unhusked ears was determined visually, on a scale ranging from 1 (imperfect ears) to 9 (perfect ears), on the basis of size, husk coverage, husk color intensity and presence of damage by pathogens; the scores were assessed following the usual criteria used for the fresh market, as described elsewhere.[19] Husks were subsequently removed, and the length, diameter and fresh weight of the ears were recorded. Grain was separated from stover and weighed. Subsamples were separated for analysis of grain dry matter, soluble solids and nutrient content. Dry matter was determined by drying at 60 °C until constant weight. Soluble solids were determined in grain juice – obtained by pressing the grain subsample in a syringe – by use of a hand refractometer, and was expressed in °Brix.

Chemical analyses of soil, manure and vermicompost

Moisture and organic matter content of the soil samples, vermicompost and manure were calculated gravimetrically after drying samples at 105 °C for 24 h and ashing at 450 °C for 6 h, respectively. The pH and electrical conductivity (EC) were determined in samples diluted in water (1 : 20). Total N and C contents were determined in dried and milled samples, with a Carlo Erba 176 1500C/N analyzer (Carlo Erba Instruments, Milan, Italy). Total P and K contents were determined by X-ray fluorescence after drying, grinding and pelleting the samples.

Chemical analysis of plant samples

Composite leaf samples were taken from the plants harvested in each plot. Immediately after harvest, leaf samples were rinsed in distilled water and dried at 60 °C for 1 week. Grain subsamples extracted from the marketable ears were dried at 60 °C for 1 week until constant weight. Total N and C contents were determined in dried and milled samples, with a Carlo Erba 176 1500C/N analyzer. Total P and K contents in leaf and grain were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES), in a PerkinElmer Optima 4300 DV analyzer (Waltham, MA, USA), after microwave-assisted digestion of the samples. Determination of total C, N, P and K was performed in the central laboratory facilities (CACTI) at the University of Vigo.

Data analysis

Data were analyzed on a plot mean basis with linear mixed models, by use of SAS software, version 9.1.[20] The type of fertilizing treatment, dose, genetic background and endosperm mutants were considered as fixed effects. The years and the interaction between year and endosperm mutant within the blocks were introduced as random factors in order to account for climatic and spatial variability. Because of the low germination rates in some plots, which were mainly due to genetic factors (interaction: endosperm mutant × genetic background: $P < 0.01$), and given that plant density has an important influence on corn growth and yield,[21] the number of plants per plot was included in the model as a covariate in subsequent analyses. Normality of distributions was assessed by Kolmogorov–Smirnov criteria, and the homogeneity of variances by Levene's test. In all cases, specific comparisons among treatments were tested for significance by the LSMEAN

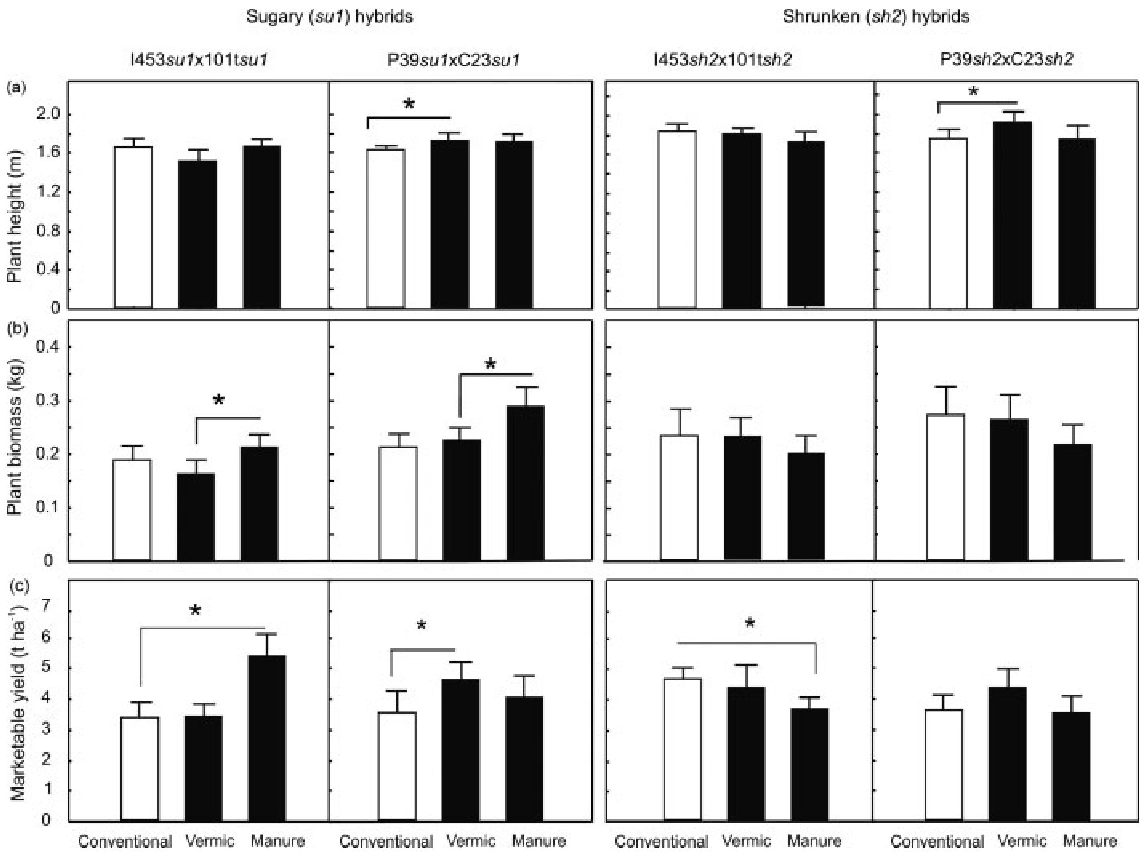

Figure 1. Height, biomass and marketable yield of the four sweet corn hybrids as affected by the three fertilization regimes evaluated: conventional (inorganic), integrated with vermicompost, and integrated with manure. Bars represent least square means ± standard error for the two replicates, two doses of fertilizer and 2 years ($n = 8$). Asterisks and bars below indicate significant differences between treatments at $P < 0.05$.

statement, at $P \leq 0.05$. The relationships between variables were analyzed by Pearson correlation analysis.

RESULTS

Plant growth and yield

Final growth and marketable yield of the sweet corn hybrids grown under the different fertilization treatments are shown in Fig. 1. For all fertilization regimes and doses assayed, the hybrids with P39×C23 genetic background were taller and of significantly higher biomass at harvest than the other hybrids (Table 3). In addition, the height of the hybrids with P39×C23 genetic background was further increased by the integrated fertilization regime with vermicompost as compared to the conventional fertilization regime (Table 3) (Fig. 1(a)). The fertilization regimes containing either manure or vermicompost did not produce significant differences in plant biomass relative to the conventional fertilizer. However, the integrated fertilization regimes produced differences in the plants with the *su1* mutant (Table 3), as the biomass of plants grown with manure was greater than with plants grown with vermicompost (Fig. 1(b)).

The different fertilization treatments did not affect the leaf N content of the plants, at either the normal or the high dose, and this parameter only differed among the different hybrids (Table 3); the leaf N content in P39*su1*×C23*su1* hybrids was higher than in P39*sh2*×C23*sh2*, and was higher in I453*sh2*×101t*sh2* than in I453*su1*×101t*su1* hybrids. Potassium leaf content was not affected by the type of fertilizer and there were no differences among the hybrids assayed (Table 3). On the contrary, P leaf content was higher in the plants cultivated with vermicompost than in those cultivated under conventional fertilization regime, independently of the hybrid considered (Tables 3 and 4). This parameter was also significantly affected by genetic background (Table 3); the I453×101t plants had significantly higher leaf P content than the P39×C23 plants, irrespective of the endosperm mutation, fertilization treatment and dose applied.

There were no differences among the corn hybrids assayed in terms of marketable yield, when averaged across fertilization treatments. Nevertheless, there were significant differences in the marketable yields of the corn plants in relation to the different fertilization treatments (Table 3). In general, the integrated fertilization regimes maintained similar yields to conventional fertilization at both normal and high doses (Fig. 1(c)). In addition, marketable yield was significantly higher in the *su1* endosperm mutants grown with manure (I453*su1*×101t*su1*) or vermicompost (P39*su1*×C23*su1*), and significantly lower in I453*sh2*×101t*sh2* hybrids grown under combined fertilization with manure, relative to conventional fertilization. The increase in the dose of fertilizer produced an increase in the final marketable yield of the plants, independently of the genotype and fertilization treatment considered (Table 3). The number of ears per plant ranged between two and three and was only affected by plant genotype, while the type of fertilizing treatment did not have a significant effect on number of ears per plant (Tables 3 and 5). Total ear biomass per plant was significantly higher with the high dose of fertilizer, independently of the type of fertilization treatment (Tables 3 and 5).

Table 3. Results of the linear mixed models showing the effects of the main factors analyzed (mutant, genetic background, fertilization regime and dose) on plant growth and yield, as well as the significant interactions among them (non-significant interactions have been removed to obtain the minimal model)

Independent variable	Dependent variable	Degrees of freedom	*F*	*P*
Plant biomass	Mutant	1, 6	1.12	0.32
	G. background	1, 80	4.86	0.03
	F. regime	2, 80	0.09	0.91
	Dose	1, 78	3.39	0.06
	F. regime × mutant	2, 80	3.48	0.03
Height	Mutant	1, 1	1.26	0.46
	G. background	1, 79	6,45	0.01
	F. regime	2, 79	0.71	0.49
	Dose	1, 78	1,87	0.17
	F. regime × g. background	2, 78	5.65	0.00
Leaf N	Mutant	1, 7	0.05	0.83
	G. background	1, 83	0.08	0.77
	F. regime	2, 83	2.36	0.10
	Dose	1, 81	0.20	0.65
	Mutant × g. background	1, 83	4.71	0.03
Leaf P	Mutant	1, 1	0.22	0.68
	G. background	1, 87	29.68	<0.01
	F. regime	2, 86	2.97	0.05
	Dose	1, 86	2.38	0.12
Leaf K	Mutant	1, 6	1.23	0.30
	G. background	1, 82	0.76	0.38
	F. regime	2, 82	0.56	0.57
	Dose	1, 81	0.33	0.56
Marketable yield	Mutant	1, 77	0.04	0.84
	G. background	1, 77	0.23	0.63
	F. regime	2, 77	1.22	0.30
	Dose	1, 77	3.74	0.05
	F. regime × mutant	2, 77	5.27	<0.01
	F. regime × mutant × g. background	2, 77	4.09	0.02
N° ears/plant	Mutant	1, 85	5.43	0.02
	G. background	1, 85	1.04	0.31
	F. regime	2, 85	0.17	0.84
	Dose	1, 85	1.86	0.17
	Mutant × g. background	1, 85	4.64	0.03
Ear biomass/plant	Mutant	1, 86	2.36	0.12
	G. background	1, 86	1.40	0.24
	F. regime	2, 86	0.28	0.75
	Dose	1, 86	7.45	<0.01

Quality of marketable ears

The hybrids differed slightly in the appearance of the marketable ear. In general, appearance of *su1* ears was rated lower than *sh2*, although this varied according to the genetic background of the plants. In addition, the type of fertilization regime had a significant effect on the appearance of the marketable ear, depending on the dose (Table 6). At the normal dose, the appearance of the marketable ear with the three types of fertilizers was similar, whereas at the highest dose the appearance of the ears of plants grown with manure was rated significantly lower than those of plants grown with the mineral fertilizer (Table 5).

The biomass of the marketable ear did not differ in relation to the type of fertilization regime applied either at high or at low doses (Tables 5 and 6). Differences in ear biomass were only observed between the two types of endosperm mutants (Table 6).

Similarly, fertilization did not have any effect on the diameter of the main ear (Table 5), which was determined by the genetic background, with significantly larger ear diameter for P39×C23 than for I453×101t. Length of the marketable ear varied among the different plant genotypes assayed; the type of fertilization regime also had an effect, which was independent of the plant genotype but dependent on the dose used (Table 6). At normal doses of fertilizer, the plants grown with the fertilizer containing manure yielded significantly longer marketable ears than the plants grown with the fertilizer containing vermicompost, whereas at high doses the length of the ears grown with the fertilizer containing manure was significantly lower, resulting in similar values to those obtained with the other fertilizers (Table 5). Grain yield in the ears was mainly determined by the type of endosperm mutant (Table 6), with *su1* mutants having a higher proportion of grain than the *sh2* mutants. The fertilization regime had significant effects on this

Table 4. Leaf nutrient content of sweet corn hybrids subjected to normal and high doses of the different fertilization regimes. Values represent least square means ± standard error for the two replicates, four sweet corn hybrids studied and the 2 years of the study ($n = 16$)

	Normal			High		
Nutrient	Conventional	Vermicompost	Manure	Conventional	Vermicompost	Manure
N (mg kg^{-1} dw)	30 751 ± 1 206	30 931 ± 1 222	29 950 ± 1 206	31 394 ± 1 206	31 574 ± 1 206	29 545 ± 1 212
P (mg kg^{-1} dw)	2 625 ± 167b	3 044 ± 171a	2 908 ± 167ab	2546 ± 168b	2 766 ± 168a	2 737 ± 168ab
K (mg kg^{-1} dw)	13 875 ± 3 809	14 634 ± 3 816	13 976 ± 3 810	12 987 ± 3 809	13 960 ± 3 809	14 262 ± 3 813

Different letters within the same row indicate significant differences at $P < 0.05$.

Table 5. Effects of the fertilization regimes on yield and quality of marketable ears of sweet corn plants. Values represent least square means ± standard error for the two replicates, four sweet corn hybrids studied and the 2 years of the study ($n = 16$)

	Normal			High		
Trait	Conventional	Vermicompost	Manure	Conventional	Vermicompost	Manure
No. ears per plant	2.06 ± 0.23	2.12 ± 0.23	2.17 ± 0.23	2.35 ± 0.23	2.29 ± 0.23	2.12 ± 0.23
Total ear biomass per plant (g)	66.27 ± 11.17a	65.53 ± 11.17a	71.61 ± 11.16a	86.82 ± 11.19b	79.38 ± 11.19b	82.66 ± 11.19b
Biomass of marketable ear	39.18 ± 3.06	37.21 ± 3.14	40.76 ± 3.05	43.91 ± 3.06	37.65 ± 3.06	42.78 ± 3.07
Length of marketable ear (cm)	20.37 ± 0.41ab	19.84 ± 0.42b	20.93 ± 0.41a	20.30 ± 0.41ab	20.73 ± 0.41ab	19.42 ± 0.41b
Diameter of marketable ear (cm)	3.82 ± 0.23	3.90 ± 0.23	3.93 ± 0.23	3.85 ± 0.23	3.83 ± 0.23	3.88 ± 0.23
Appearance of marketable ear	5.00 ± 0.88ab	4.82 ± 0.88b	4.79 ± 0.87c	5.55 ± 0.87a	5.05 ± 0.87abc	4.79 ± 0.87b

Different letters within the same row indicate significant differences at $P < 0.05$.

parameter, although it depended on the genetic background of the plants (Table 6). The fertilization regime containing manure and vermicompost produced a significant increase in grain yield in the marketable ear of the I453×101t plants relative to the conventional fertilizer, while the regime containing vermicompost produced a significant decrease in this parameter in the P39×C23 plants (Fig. 2(b)).

Similarly, the chemical composition of the grain was strongly influenced by the plant genotype. Nevertheless, the type of fertilization regime also had important effects on this parameter. The soluble solid content of the grain was different in the hybrids assayed and in addition, this parameter was influenced by the type of fertilization regime, although the effects differed depending on the genetic background (Table 6). Application of the fertilizer containing vermicompost resulted in a decrease in the soluble solids in the grain of the plants with P39×C23 genetic background relative to conventional fertilization (Fig. 2(a)). The N content of the grain also differed among hybrids, but the concentration of this nutrient increased in hybrids with P39×C23 genetic background grown with vermicompost, relative to hybrids under conventional fertilization (Fig. 2(b) and Table 6). The K content of the grain was different in the different genotypes, with the plants with I453×101t genetic background having significantly higher K content than plants with P39×C23 background, although the type of fertilizer did not have any effects on this parameter (Table 6). Conversely, the P concentration in the grain was influenced by the type and dose of fertilizer, and the effects varied depending on the endosperm mutant considered (Table 6). Although the integrated fertilization treatments did not produce significant differences in this parameter relative to the conventional treatments, fertilizers containing vermicompost or manure had different effects on the *sh2* mutants at normal and high doses (Fig. 3).

DISCUSSION

Previous studies of the effects of organic fertilizers have shown substantial decreases in sweet corn growth and yield under both organic[22] and integrated cropping systems.[23] Nevertheless, we found that replacement of 25% of the nutrients supplied by mineral fertilizers, with organic nutrient sources (vermicompost or manure), yielded the same level of productivity as with the conventional inorganic fertilization. Moreover, the organic fertilizers produced some improvements in plant yield and grain quality relative to inorganic fertilizers, although the effects varied with the type of organic fertilizer and plant genotype. For instance, reductions in marketable yield were only observed in one of the four hybrids assayed, in relation to use of the fertilizer containing manure.

As reported by Atiyeh *et al.*,[24] Arancon *et al.*[25] and Singh *et al.*,[26] vermicompost produced an increase in plant growth and marketable yield relative to the inorganic fertilizer. Nevertheless, the observed increases in plant growth and yield were small, and they were not general as they varied substantially with plant genotype. It has been suggested that vermicompost promotes plant growth via biologically mediated mechanisms, such as the production of bioactive substances (i.e. phytohormones) and inoculation of plant growth-promoting microorganisms that increase nutrient supply.[27] These effects will therefore be independent of the amount of macronutrients supplied to the plant. In order to verify that the effects of vermicompost were nutrient independent, we included a high dose that provided a saturating amount of N, P and K. Nutrient saturation of the plants was confirmed since no increases in leaf or grain content of these nutrients were observed with the high dose of fertilizer (inorganic, vermicompost and manure). Interestingly, increases in sweet corn growth and marketable yield were produced by both the normal and the high doses of vermicompost and manure,

Table 6. Results of linear mixed models showing the effects of the main factors analyzed (mutant, genetic background, fertilization regime and dose) on quality of the marketable ear, as well as significant interactions among them (non-significant interactions have been removed to obtain the minimal model)

Independent variable	Dependent variable	Degrees of freedom	*F*	*P*
Appearance	Mutant	1, 1	2.13	0.38
	G. background	1, 79	1.74	0.19
	F. regime	2, 80	1.54	0.22
	Dose	1, 77	0.09	0.76
	Mutant × g. background	1, 79	3.81	0.05
	F. regime × dose	2, 79	4.61	0.01
Length	Mutant	1, 2	8.83	0.11
	G. background	1, 82	157.49	<0.001
	F. regime	2, 81	0.61	0.54
	Dose	1, 81	2.54	0.11
	Mutant × g. background	1, 83	6.84	0.01
	F. regime × dose	1, 81	3.58	0.03
Diameter	Mutant	1, 1	10.84	0.18
	G. background	1, 80	4.85	0.03
	F. regime	2, 80	0.91	0.40
	Dose	1, 77	0.50	0.48
	Mutant × dose	1, 77	4.54	0.03
Grain (%)	Mutant	1, 1	15.50	<0.001
	G. background	1, 84	0.09	0.77
	F. regime	2, 84	0.07	0.79
	Dose	1, 84	1.34	0.27
	F. regime × g. background	1, 84	4.54	0.01
Soluble solids	Mutant	1, 1	21.38	0.13
	G. background	1, 77	34.75	<0.001
	F. regime	2, 77	1.13	0.33
	Dose	1, 76	1.71	0.19
	Mutant × g. background	1, 78	4.72	0.03
	F. regime × g. background	2, 76	4.33	0.01
N	Mutant	1, 81	9.23	<0.01
	G. background	1, 81	29.00	<0.001
	F. regime	2, 81	1.02	0.36
	Dose	1, 81	1.31	0.25
	Mutant × g. background	1, 81	5.57	0.02
	F. regime × g. background	2, 81	4.50	0.01
P	Mutant	1, 1	0.80	0.53
	G. background	1, 74	1.84	0.18
	F. regime	2, 74	0.43	0.65
	Dose	1, 72	0.53	0.47
	F. regime × dose × mutant	2, 73	3.68	0.03
K	Mutant	1, 1	1.25	0.46
	G. background	1, 86	5.37	0.02
	F. regime	2, 85	0.95	0.38
	Dose	1, 86	0.90	0.34

indicating that these effects were independent of the amount of N, P and K provided. Foliar analyses revealed that the differences in macronutrient content between the plants cultivated with the three types of fertilizers were almost negligible. However, there was a slight increase in leaf P in the plants cultivated with the fertilizer containing vermicompost, relative to those cultivated with the inorganic fertilizer and with the fertilizer containing manure. Considering that, for each dose, the same amounts of nutrients were provided to the plants, regardless of the type of fertilizer, the higher leaf P presumably corresponds to a higher availability of this nutrient in vermicompost amended plots. Vermicompost therefore increased P availability and plant uptake. A higher P content in plants treated with vermicompost may explain the higher growth and yield in plants cultivated with this type of fertilizer. Nevertheless, there was no correlation between P leaf content and plant height ($P = 0.91$) or marketable yield ($P = 0.43$). Moreover, increased yield and growth in plants treated with manure cannot be explained by different nutrient concentrations in the plants, as shown by the leaf contents of N, P and K, confirming our hypothesis that increased growth and yield of the plants with fertilizer containing manure or vermicompost were not due to differences in macronutrient availability and uptake.

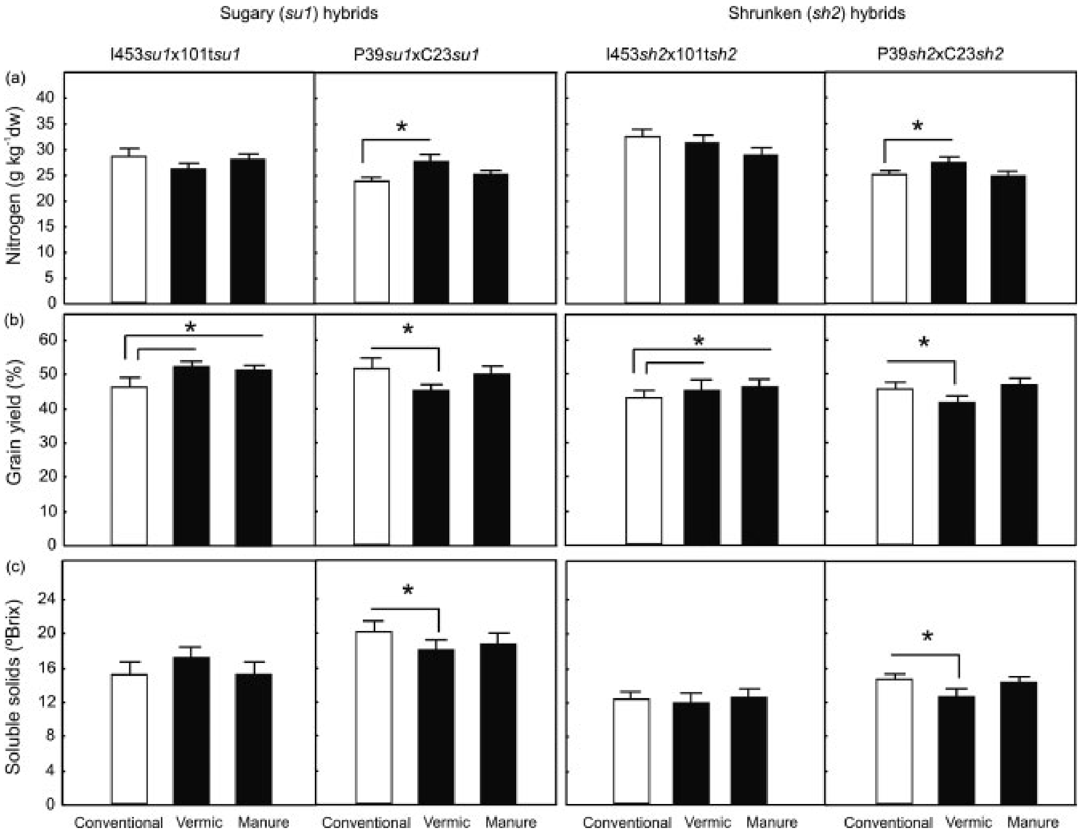

Figure 2. Nitrogen content, grain yield and soluble solid content of marketable ears of the four sweet corn hybrids as affected by the three fertilization regimes evaluated: conventional (inorganic), integrated with vermicompost and integrated with manure. Bars represent least square means ± standard error for the two replicates, two doses of fertilizer and 2 years ($n = 8$). Asterisks and bars below indicate significant differences between treatments at $P < 0.05$.

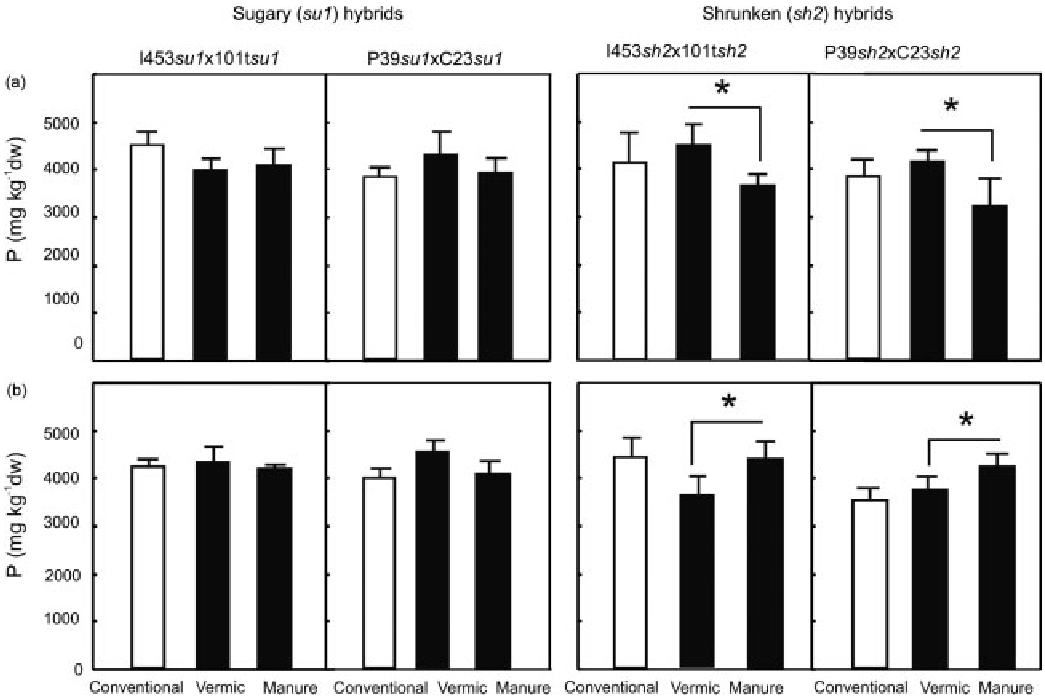

Figure 3. Phosphorus content in marketable ears of the four sweet corn hybrids as affected by the three fertilization regimes evaluated (conventional (inorganic), integrated with vermicompost and integrated with manure) at normal (a) and high doses (b). Bars represent least square means ± standard error for the two replicates, and 2 years ($n = 4$). Asterisks and bars below indicate significant differences between treatments at $P < 0.05$.

Both manure and vermicompost had a significant effect on the quality and chemical composition of the ears. Vermicompost increased the N content of the grain and decreased grain yield and soluble solids in the hybrids with P39 × C23 genetic background. In general, marketable ears of the plants treated with the high dose of fertilizer containing manure had a poorer appearance and were smaller than those grown under the other fertilization regimes, although manure increased the grain yield in the marketable ear of the hybrids with I453 × 101t genetic background. Previous studies have shown that the use of organic fertilizers, both alone or in combination with inorganic fertilizers, can increase ear quality and grain nutrient content of sweet corn further than with inorganic fertilization alone[28] and that the nutritional quality of vermicompost-treated crops is superior.[6] However, other studies have shown no such differences[23] or even decreased nutrient content as a result of organic fertilization.[22,29] As far as we know, the effects of vermicompost on sweet corn nutrient content have not been evaluated until now. Here, we observed that vermicompost had highly variable effects on the quality of the marketable ear, and that the effects depended on the dose supplied and the sweet corn hybrid considered. Again these results show that the large contradictions in the reports regarding the effects of vermicompost and other organic fertilizers on fruit quality may largely depend on the species and genotypes tested.[9,15,30]

The present study demonstrated that different responses to the fertilizer supplied are determined by variations in the whole genotype or even in single genes. This makes sense if we consider that different maize hybrids can adopt different strategies in order to increase nutrient uptake efficiency, such as: (i) increasing the surface area of roots that are in contact with soil, by modifying root morphology; (ii) modifying the composition and amount of root exudates; and (iii) modifying rhizosphere microflora, by promoting mycorrhizal associations.[31–33] The different types of fertilizer supplied may play a key role in the relationships between the corn plants and their most immediate environment in the rhizosphere. In fact, a parallel study revealed that the different fertilization treatments produced significant changes in the rhizosphere microbial communities of sweet corn plants and that these changes largely depended on the plant genotype.[33]

CONCLUSIONS

Organic fertilizers have often been reported to produce considerably lower crop yields than inorganic fertilizers. Extensive research on inorganic fertilization and plant breeding, carried out within the framework of conventional agriculture, has allowed agricultural producers to fine-tune nutrient inputs and plant needs in order to maximize crop yields. However, such detailed knowledge has not yet been attained as regards the interactions between plants and organic fertilizers in sustainable agriculture. In order to maximize crop yields, the importance of all the sources of variability that may determine crop productivity under these production systems must be investigated. Here we observed that, when the same amount of NPK was supplied to the plants, both of the integrated fertilization regimes assayed produced similar or even higher crop yields than inorganic fertilizer alone. Increases in plant growth and yield in response to combined inorganic–organic fertilizers appeared to be independent of nutrient supply. Moreover, both types of integrated fertilization had rather different effects on plant growth and yield, so that plants may respond differently to the 'quality' or degree of mineralization of the organic matter. Furthermore, the thorough study of the interactions between plant genotype and fertilization strategy demonstrated that most of the effects of organic fertilizers were genotype dependent. This confirms that within a given crop certain genotypes or varieties may be more suitable for organic or combined inorganic–organic cropping systems than others. The results obtained here provide a better understanding of the effects of organic fertilizers on plant growth. Such advances will enable crop producers to achieve the desired results and therefore maintain confidence in sustainable agricultural practices.

ACKNOWLEDGEMENTS

This research was financially supported by a grant from the Xunta de Galicia (07MRU023383PR). Cristina Lazcano is in receipt of an Ángeles Alvariño research fellowship from the Xunta de Galicia.

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