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From waste to fertilizer: The impact of rose-waste compost on cut rose cultivation in Kenya

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ABSTRACT

The impact of compost amendment on crop yield and quality in cut rose cultivation under large-scale commercial conditions was examined near Lake Naivasha, Kenya. The experiment, conducted between August 2022 and February 2024, involved over 7500 rose plants. Growers often hesitate to incorporate compost due to limited knowledge about its long-term effects on yield and quality, highlighting the importance of this research. Three mature rose-waste-based composts were incorporated into the soil prior to seedling planting: (i) pure rose waste compost, (ii) compost made of 80 % rose waste and 20 % tomato waste, and (iii) compost made of 90 % rose waste and 10 % mature compost. Standard fertigation was applied to all treatments, except for one additional treatment where fertigation was halved to evaluate compost as a fertilizer substitute. Crop performance was assessed through daily harvest records, cumulative yield analyses, and economic profitability based on auction prices. Soil and plant quality parameters were assessed every 3–6 months. Compost amendment combined with full fertigation increased the number of harvested stems by 3.2–4.7 % over 18 months. This resulted in an economical yield increase of approximately €22,000 per hectare ($9600 per acre) for the first 18 months of cultivation. The halved fertigation treatment yielded a comparable harvest to the control with fertigation only. Compost amendment improved soil organic matter content with ca. 30 % throughout the experiment and enhanced short-term nutrient availability, while facilitating long-term nutrient release without compromising vase life, stem length, or bud size. In conclusion, rose-waste compost significantly enhanced soil quality by e.g. increasing nutrient availability, which in turn enhanced crop performance during the growth phase of cut roses, with sustained differences thereafter. These findings underline the potential of compost amendment to sustainably close the cycle of resources within Kenyan rose cultivation, while boosting crop yields and improving soil health.

1. Introduction

Globally, nutrient recycling and efficient waste management are important for sustainable agriculture, maintaining production, minimizing environmental impact, and ensuring long-term soil health (Phiri et al., 2024). In this context, the Kenyan rose cultivation sector, with over 3000 ha under cultivation, can make significant steps to improve sustainability. Over recent decades, cut flower production, especially roses, has shifted from the Global North to the Global South, with Kenya emerging as a dominant player. In 2017, cut flower export accounted for almost 14 % of Kenya's export products and over 70 % of its horticultural exports (Gemählich, 2022). Perennial crops like roses generate substantial amounts of valuable green wastes (de Nijs et al., 2024) and are known to deplete soil over time (Atoloye et al., 2022), highlighting the importance of nutrient recycling. The high nutrient demand of roses reinforces these challenges, emphasizing the need for a sustainable crop management approach that closes the cycle of resources. Additionally, the availability of various fertilizers is not always guaranteed due to import challenges, sea freight delays and other logistical problems. As a results, many companies are increasingly considering alternative

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sources for nutrient inputs. Moreover, the cost of fertilizers is relatively high, further increasing the sectors' interest in sustainable practices.

Kenyan roses are mainly grown in polythene greenhouses using either substrate or soil cultivation (Lan et al., 2022). Our study focuses on soil cultivation. Optimal rose cultivation requires well-drained, aerated soil with high soil organic matter (OM) content (Idrovo-Novillo et al., 2019). Monitoring soil nutrient levels and crop performance is essential, as deficiencies in key elements can directly impact yield and harvest quality (Franco-Hermida et al., 2020). For example, copper deficiency affects stem lignification, resulting in hollow stems (Hawrylak-Nowak et al., 2022). Soil pH is crucial for regulating the bioavailability of micronutrients. Additionally, the quality of commercial cut roses is important for growers, assessed by appearance, including stem length, bud diameter, and vase life (Gemählich, 2022; Idrovo-Novillo et al., 2019).

The cultivation of cut roses generates substantial volumes of green waste from crop maintenance, rejected produce, and grading. This waste, characterized by high nutrient levels, represents a valuable waste stream that can be converted into compost, with high fertilizing potential and compliance with international sanitation requirements (Idrovo-Novillo et al., 2019; de Nijs et al., 2024). However, growers remain hesitant to use compost extensively due limited understanding of its effects on crop production, particularly for long-term crops like cut roses, which have a lifespan of six to ten years (Case et al., 2017). Consequently, the implications of compost incorporation have effects for several years, making it an important consideration. Additionally, there is a concern about the potential risks associated with the use of compost of inferior quality, which may introduce pathogens, viruses or other harmful agents into the cultivation system. So far, research on the longer-term effects of rose waste compost amendment on yield and quality is limited.

The effects of compost amendment on soils have been studied across diverse conditions, showing enhancing effects for both soil quality and plant production. Compost amendment has shown to improve soil quality by increasing soil organic matter (SOM) levels (Bernal et al., 2017; Doan et al., 2014; Lerch et al., 2019), thereby improving soil structure (Lim et al., 2016; Villa et al., 2021), enhancing water holding capacity (Villa et al., 2021), and increasing microbial abundance and diversity (Cáceres et al., 2018; Guerini et al., 2007; Lim et al., 2016). These improvements help enhancing the natural suppressiveness of soils against soil-borne plant pathogens following compost amendment (De Corato, 2021). Compost also acts as a slow-release fertilizer, although its soil improvement functions are often more significant than its fertilizing effects (Bergstrand, 2022; Bernal et al., 2017). The combined use of organic and mineral fertilizers can create a synergistic effect, reducing reliance on mineral fertilizer. Furthermore, Cáceres et al. (2018) highlighted that compost amendment can also enhance the availability of immobilized nutrients by lowering soil pH, thereby reducing fertilizer loss.

Compost has been shown to increase yield and quality in various production systems, including carrots (Cucci et al., 2020), maize, wheat, potato, and faba beans (Bedada et al., 2014), wheat and maize (Bouhia et al., 2023; Mohamed et al., 2019), saffron flowers and corms (Daneshmandi et al., 2024), and cucumber and summer squash (Rashwan et al., 2021). However, most studies focus on short-term effects, with few examining long-term impacts. Particularly, the effects of compost amendment on cut rose cultivation systems have been understudied. Idrovo-Novillo et al. (2019) studied the effects of rose compost on cut roses in a small-scale experiment (24 plants per treatment) and found that combining compost amendment with fertigation significantly improved soil fertility, yield and crop quality.

The study by Idrovo-Novillo et al. (2019) showed promising results regarding compost use in horticulture but it was limited by its small scale and infrequent yield sampling. Building on these findings, our study aimed to address these limitations by conducting a long-term, field-scale experiment to evaluate the incorporation of compost into the production cycle of cut roses in a commercial setting. This study followed the transition from seedlings to mature plants at the commercial production level, providing comprehensive insights into compost's potential for rose cultivation, including economic viability. Specifically, this study focussed on (1) evaluating the effects of three different rose-waste composts on the yield and quality of *Rosa* sp. Royal Athena grown in a greenhouse over 18 months, (2) investigating the potential of compost to partially substitute mineral fertilizer by testing a reduced dose of standard fertilizer and monitoring the resulting effects and finally (3) providing insights into the economic viability of compost use in commercial rose cultivation. The experiment was conducted on a rose farm in Naivasha, Kenya, where rose waste co-composting was previously studied (de Nijs, et al., 2024). The experiment involved over 1500 plants per treatment, frequent monitoring (Fig. 1), and daily yield assesments, alongside quality evaluations and physicochemical soil analyses conducted every three to six months. By following the transition from seedlings to mature plants, this study offers comprehensive insights into the potential of compost to enhance sustainable rose cultivation in commercial greenhouse production systems.

2. Materials and methods

2.1. Field site and resources

The field experiment was conducted in a commercial greenhouse of Bilashaka Flowers located in Naivasha, Kenya, between August 2022 and February 2024. The region experiences an average annual temperature of 18.1 °C and receives a yearly rainfall of 1100 mm. The polythene greenhouses span 60 ha, and 23 varieties of cut roses are cultivated. Soil cultivation is practiced on more than half of the planted area, while substrate cultivation is used on the remainder. Baseline soil samples were collected before compost application. Ten randomly distributed composite samples ($n = 6$) were taken using a corer to a depth of 25 cm. Samples were stored at 4 °C, freeze-dried, and sieved (<2 mm) within two weeks. Fertigation (irrigation + fertilizer) and irrigation water samples were collected every 3–6 months and stored at −20 °C until analysis (see Section 2.5).

The composts used in this experiment were obtained from the farm and described in detail in de Nijs et al. (2024). In short, piles of approximately 4000 kg per replicate were composted for nine months, including maturation, following the turned windrow approach (Fig. 1). In this experiment, the resulting three compost mixtures were tested in triplicate: (1) rose waste only (R), (2) 80 % rose waste + 20 % tomato waste (T) and (3) 90 % rose waste + 10 % mature rose compost (C). These mixtures were tested as soil amendment together with a halved fertigation and control treatment. Tomato waste was chosen as a local waste stream with no current usage. All compost mixtures resulted in mature and stable compost which met international sanitation requirements and showed high fertilizing potential (de Nijs et al., 2024). The greenhouse soil has a loam texture (32.1 % sand, 48.2 % silt & 19.8 % clay), a neutral pH of 6.9 ± 0.1, an organic matter (OM) percentage of 3.4 ± 0.1 and a C/N ratio of 7.5 ± 0.3. Soil and compost characteristics are summarized in Table 1. Fertigation, based on a mixture of lake water, collected rainwater and recycled drain water from the hydroponics greenhouses, was prepared daily (Table 2). Lake water was used for the beds treated with 50 % fertilizer, pH was adjusted in the greenhouse using nitric acid to match the fertigation solution pH.

Rose seedlings were obtained from Stockman Rozen Ltd. The *Rosa* sp. cv. Royale Athena was crafted on Natal Briar rootstock and propagated in porous pots (diameter 5 cm) for six weeks in cocopeat medium. Seedling height at planting was approximately 20 cm.

2.2. Experimental design

The 3.9 ha greenhouse was replanted at the start of the experiment. The experimental site of approximately 24 m by 44 m was located in the

Fig. 1. Conceptual presentation of this study. The large amounts of rose wastes generated during rose cultivation were composted and subsequently amended to the soil prior to planting the rose seedlings. Compost amendment has a positive effect on crop yield and soil quality.

Table 1
Characteristics of the initial greenhouse soil (n = 10) and of the three mature composts (n = 3), mean ± SE.

	Greenhouse soil	Compost R	Compost T	Compost C
Characteristics				
pH	6.9 ± 0.1	8.1 ± 0.0	8.0 ± 0.1	8.3 ± 0.1
EC (uS cm^{-1})	283 ± 44	5400 ± 400	5900 ± 800	5700 ± 900
OM (%)	3.4 ± 0.1	18.3 ± 0.5	14.0 ± 0.3	18.1 ± 1.7
C/N	7.5 ± 0.3	9.5 ± 0.4	8.4 ± 0.2	9.7 ± 0.2
C (%)	1.1 ± 0.1	9.3 ± 0.3	6.8 ± 0.1	9.5 ± 1.1
N (%)	0.2 ± 0.0	1.0 ± 0.1	0.8 ± 0.0	1.0 ± 1.1
DOC (mg g^{-1})	0.2 ± 0.0	1.8 ± 0.0	1.1 ± 0.0	2.0 ± 0.2
CEC (cmol kg^{-1} OM)	-	348 ± 7	397 ± 8	363 ± 11
Total macro- and micro-nutrients (mg g^{-1})				
P	0.62 ± 0.03	1.7 ± 0.0	1.4 ± 0.0	2.4 ± 0.1
K	5.7 ± 0.12	9.9 ± 0.4	9.0 ± 0.6	10.0 ± 0.4
Mg	2.6 ± 0.08	4.3 ± 0.2	4.5 ± 0.1	4.7 ± 0.2
Fe	34.0 ± 0.26	24.6 ± 0.4	25.6 ± 0.5	22.4 ± 0.3
Mn	1.0 ± 0.03	0.68 ± 0.06	0.65 ± 0.03	0.76 ± 0.00
Cu	0.013 ± 0.001	0.010 ± 0.001	0.016 ± 0.003	0.014 ± 0.001
Zn	0.13 ± 0.00	0.22 ± 0.01	0.17 ± 0.01	0.22 ± 0.01

Table 2
Characteristics of fertigation solution and acidified clear water used for irrigation, mean ± SE (n = 4).

	Fertigation	Clear water acidified
pH	5.4 ± 0.3	5.2 ± 0.5
EC (uS cm^{-1})	1154 ± 55	363 ± 19
Nutrients & heavy metals (mg L^{-1})		
NO_3	491 ± 35.4	56.2 ± 27.1
NH_4	10.5 ± 6.40	0.51 ± 0.16
PO_4	53.1 ± 18.6	1.13 ± 0.59
SO_4	80.3 ± 10.6	6.54 ± 1.56
P	14.3 ± 4.49	0.44 ± 0.19
Na	43.4 ± 3.78	28.3 ± 2.05
K	89.0 ± 7.00	21.7 ± 0.61
Ca	86.1 ± 8.77	24.5 ± 1.56
Mg	17.7 ± 2.21	5.24 ± 0.12
Fe	0.62 ± 0.07	0.02 ± 0.00
Mn	0.56 ± 0.16	0.43 ± 0.12
Cu	0.23 ± 0.10	0.02 ± 0.00
Zn	0.18 ± 0.09	0.02 ± 0.00
Mo	0.09 ± 0.03	< lod[a]
B	< lod	< lod
S	28.5 ± 4.23	2.0 ± 0.52

[a] < lod = below limit of detection

Table 3
Field treatments as used in this experiment.

ID	Treatment (including raw material compost composition)
control	Control, no compost amendment with full fertigation
R	100 % rose-waste compost with full fertigation
T	80 % rose waste + 20 % tomato waste compost with full fertigation
C	90 % rose waste + 10 % mature compost with full fertigation
R 50 %	100 % rose-waste compost with halved fertigation

centre of the greenhouse to minimize edge effects. Prior to planting, the soil was prepared with a ripper followed by a harrow. Roses were grown on elevated beds of 44 m long, 90 cm wide and 60 cm high. The experimental area was divided into paths and planting beds using rope, with each 44 m bed representing one experimental plot. A total of 15 beds were prepared, including three replicates for the three compost mixtures (treatments R, T and C), three beds with 100 % rose-waste compost receiving half of the standard fertigation (treatment R 50 %) and three control beds (control) (Table 3). Treatments were randomly allocated following a three-time repeated randomized block design. Beds were constructed manually, and compost was added in five equal layers during bed preparation (Fig. 2A) to ensure uniform distribution and minimize cross-contamination. To increase the OM % by approximately one percent point, each bed received 1.35 m^3 compost, equivalent to approximately 1080 kg by wet weight, applied at a rate of 27 kg m^{-2} and incorporated to a depth of 60 cm.

After a stabilization period of four weeks, two driplines for fertigation were installed per bed (Fig. 2B). Beds assigned to the R 50 % treatment were equipped with one dripline for fertigation and another for clear water irrigation. The latter was acidified using nitric acid and a dosage pump to adjust the pH to approximately 5.5, ensuring comparable conditions for nutrient uptake.

Rose seedlings were planted in two rows per bed, spaced 25 cm apart between rows and 18 cm apart between plants, resulting in approximately 500 plants per bed and a planting density of 8.1 plants per m^2 (Fig. 2B). With exception of the beds assigned to the R 50 % treatment, all beds followed the standard fertigation regime involving three to eight cycles per day depending on solar radiation. Standard crop management and crop protection regime were followed such as defoliation and spraying. To promote ground shoot development, primary shoots were

Fig. 2. Set-up of the field experiment in the greenhouse. A) raised beds (44 ×0.9 ×0.6 m) amended with the different compost treatments. B) The top of a raised bed with two rows of rose seedling and two driplines for either fertigation or irrigation, depending on the treatment. The two rows per bed resulted in a total of approximately 500 plants per bed.

bent down along the beds seven weeks after planting. The first shoots were harvested 12 weeks post-planting, and subsequently, flowering shoots were harvested daily as buds reached the desired cut stage.

Soil and plant quality assessments were conducted five times: 0, 3, 6, 13 and 18 months after planting. Composite topsoil samples (n = 10) were taken per experimental bed using a corer to a depth of 25 cm, stored at 4 °C, freeze-dried and sieved (<2 mm) within two weeks after sampling. Additionally, 10 harvested stems measuring 45 + cm were randomly selected for leaf analysis and a vase life experiment. After cooled transport to the Netherlands, bud height was measured before further processing. All leaves from five stems were collected, rinsed with deionized water, and air-dried at 40 °C. Daily yields were recorded for each bed starting from the first harvest, detailing the total number of stems and their distribution over length categories, as well as the total weight harvested in kg's using an electronic scale.

2.3. Economical yield

To calculate theoretical economical yield, daily auction prices per length category for Royale Athena were averaged over seven days to adjust for irregular harvest to sale intervals. The number of stems harvested each day per length category was then multiplied by the corresponding seven-day average auction price at Royal FloraHolland in Aalsmeer, the Netherlands, reflecting the typical five-day delay between harvest and auction. This approach considers variations in stem distribution across length categories within treatments as well as the market dynamics of supply and demand influenced by seasonal fluctuations, and thus climatic conditions and demand in Kenya and in Europe. However, this approach assumes that all harvest stems will pass all quality checks and reach the auction. In reality, there is a loss rate of 5–10 % and certain market conditions can lead to unsold produce that is discarded.

2.4. Vase life experiment

Vase life experiments were conducted in a controlled climate condition greenhouse in Amsterdam, the Netherlands, at crop ages of 3, 6, 13 and 18 months, following VBN (Dutch Flower Auctions Association) standards (NBV, n.d.). After arrival in the Netherlands, roses were treated with a preservative and nutrient solution for 24 h at 4 °C, similar to those prepared for auction. Five stems per experimental bed were cut to 40 cm with all but the top three leaflets removed. These were placed in 1 L plastic bottles containing 1000 ml tap water supplemented with 10 g flower food (Crysal Ltd.). Every seven days, the water was refilled to 1 L with tap water. Vase life was monitored daily, ending when any of the senescence symptoms described by In and Lim (2018) and VBN (Beoordelingskaart, 2010) were observed: pedicel bending, wilting, bluing, petal or leaf abscission, or yellowing. The greenhouse climate was maintained at 20 ± 2 °C temperature, 60 ± 5 % relative humidity, and 18 h of (simulated) natural daylight.

2.5. Analytical methods

The air-dried and ground samples were used for all analyses. Fertigation and irrigation samples were filtered over 0.2 μm prior to analysis. The methods detailed in de Nijs et al., (2023) were followed and are summarized below. Organic Matter (OM) was determined via loss on ignition at 550 °C for 16 h (Nelson and Sommers, 1996). Carbon (C) and Nitrogen (N) were measured using an elemental analyser (Vario El cube, Elementar). pH and EC were measured in an ultrapure-H_2O extract prepared at 1:20 (w:v) on dry weight equivalent (Manu et al., 2017). Soil available micronutrients (Cu, Fe, Mn, Zn) and heavy metals (Ni, Pb, Cd) were analysed according to the FAO DTPA-extraction method (FAO, 2022) and measured using ICP-OES (Optima 8000, PerkinElmer). Inorganic N (NH_4^+, NO_3^-, NO_2^-) and plant-available K, and P were measured in a 1:10 (w:v) 0.01 M $CaCl_2$ extract using an auto-analyzer (Segmented flow SAN++, Skalar). Total nutrient and heavy metal concentrations were determined by ICP-OES (Optima 8000, PerkinElmer) after microwave digestion. Approximately 100 mg of milled material was dissolved in 9 ml HNO_3 and 3 ml HCl for the soil samples, and 2.5 ml HNO_3 and 7.5 ml HCl for the leaf samples (Multiwave Pro, Anton Paar).

2.6. Data analysis

Daily yield recordings per raised bed were used to calculate cumulative yields per treatment as number of stems harvested and economical yield (see 2.5). Cumulative values were compared at day 189, 393 and 550, corresponding to the periodical sampling moments. At the end of the 18-month experiment, average stem length was calculated and compared across treatments. Yield in the floricultural sector is often expressed as stems harvested per m^2 per year. These metrics were calculated for the 12–18 month period post-planting and extrapolated to a one-year period. This period was chosen because rose plants are considered mature from 12 months. Dividing the greenhouse area over the raised beds resulted in an area of 60.34 m^2 per bed, which was subsequently used to calculate yield per m^2 per year for each treatment. Vase life (days) and bud height (mm) of sampled cut roses were assessed for each periodical sampling moment and compared between treatments.

Soil and leaf characteristics over time were expressed as dry weight equivalent. Linear Mixed Modelling (LMM) was used to assess soil characteristics over time using the base model: $lmer(parameter) \sim treatment + /* \, day + day^2 + (1|bed))$ (Crawley, 2007; de Nijs et al., 2023). Treatment differences over time were evaluated using Anova type *III* analysis (Table A.2). Leaf nutrient levels were benchmarked against the commercial standard range as provided by Crop Nutrition Laboratory Services Ltd. (Cropnuts).

All analyses and visualizations were performed using R version 4.0.4 (R Core Team, 2021). Statistical significance was determined at $p < 0.05$. Treatment differences at specific timepoints were tested performing one-way Anova followed by post hoc LSD-test when significant differences were found. The dataset and scripts are available online (de Nijs et al., 2024).

3. Results and discussion

3.1. Yield affected by compost treatment

3.1.1. Cut rose yield

Compost amendment significantly increased total yield over the 18-month period following planting, as measured by the number of stems harvested (Fig. 3). Roses were first harvested 91 days after planting, followed by daily harvesting at optimal cut stages. While pronounced production flushes occurred initially, with periods of no harvest in

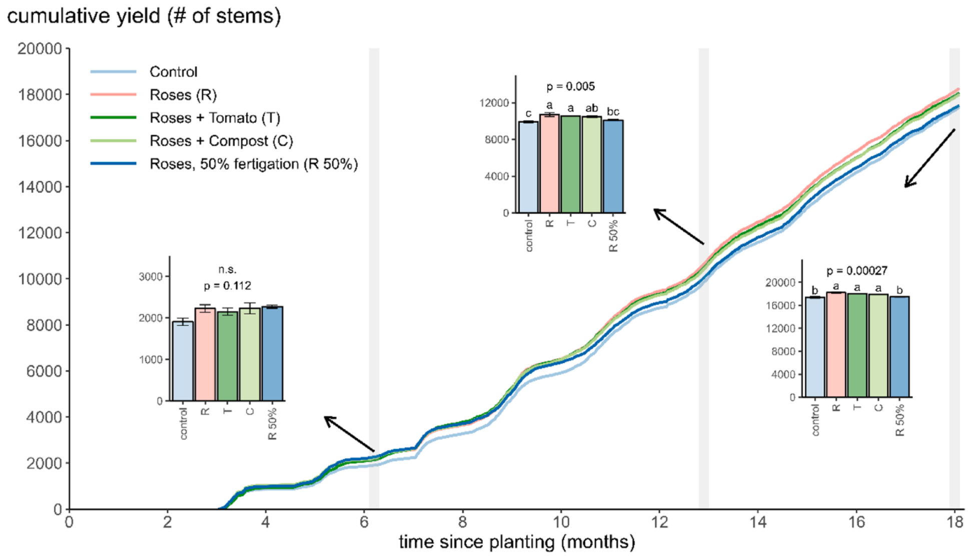

Fig. 3. Cumulative yield in number of stems harvested for the five different treatments. Treatments were compared at 6.2, 12.9 and 18.1 months after planting (day 189, 393 & 550). Boxplot-insets shows cumulative means ± SE (n = 3 per treatment), with letters indicating statistical differences according to a post-hoc LSD test, note that the Y-axes have different scales.

between, variations among individual plants mitigated this pattern over time.

At 6.2-months, approximately at the end of the second flush, no significant differences in total yield as number of stems harvested were observed between the treatments ($p = 0.112$, Fig. 3). Significant yield differences emerged at 12.9 months ($p = 0.005$). By the end of the study, at 18 months, all three compost treatments (R, T & C) with 100 % fertigation significantly outperformed both the R 50 % and the control treatment ($p = 0.005$), the R 50 % treatment showed intermediate yields (Fig. 3).

These results indicate that compost amendment can substitute for 50 % of standard mineral fertilizer rate over this timeframe. Approximately 10 months after planting, yields of the halved fertigation treatment decreased and stabilised at production rates similar to the control (Fig. 3), suggesting depletion of easily available nutrients that initially boosted yields compared to the control, despite the lowered fertilizer dosage. Relative to the control, treatment R showed a 4.7 % increase to 18268 ± 110 stems, treatment T showed a 3.7 % increase T to 18184 ± 134 stems and treatment C showed a 3.2 % increase to 17996 ± 36 stems (Table 4). No significant differences were found among these three treatments. When analysing the kg of harvested stems, less pronounced but similar patterns were observed compared to number of stems harvested, with higher yield for the compost amended beds receiving full fertigation (Table 4). Only the R and C treatments significantly outperformed the control treatment over the 18-month period, with an increased harvest of 5.0 and 4.1 %, respectively. This suggests that, although the number of stems and their distribution across length categories are similar between compost treatments, there may be variations in stem thickness and bud size, which are important quality criteria. However, no evidence of differences in bud size was found (Section 3.2).

Table 4
Cumulative yield after 18 months, projected yield per m^2 per year and cut rose quality after 18 months, mean ± SE (n = 3 per treatment). Compost treatments: R = 100 % roses, T = 80 % roses + 20 % tomato, C = 90 % rose waste + 10 % mature rose compost, R 50 % = 100 % rose waste which received 50 % of the fertilizer dosage. Superscript letters (e.g., a, ab, abc) indicate statistical differences between means, as determined by a post-hoc LSD test at $p < 0.05$. Means sharing the same letter are not significantly different.

	Total yield			Mature yield	Cut roses
	# stems	kg's	euro's	# stems m^{-2} $year^{-1}$	mean length (cm)
Control	17443^{b} ± 125	543^{bc} ± 8.2	2742^{c} ± 30	285 ± 6.7	52.4 ± 0.1
R	18268^{a} ± 110	570^{a} ± 4.9	2876^{a} ± 37	288 ± 6.0	52.4 ± 0.1
T	18184^{a} ± 134	562^{abc} ± 9.4	2841^{ab} ± 31	290 ± 7.1	52.3 ± 0.1
C	17996^{a} ± 36	565^{ab} ± 6.4	2848^{ab} ± 21	285 ± 2.0	52.4 ± 0.1
R 50 %	17527^{b} ± 82	541^{c} ± 3.9	2770^{bc} ± 14	280 ± 1.0	52.2 ± 0.1
p-value	0.0005	0.0431	0.0299	0.763	0.968

In standard rose cultivation practices (control treatment), approximately 2.89 million stems are harvested per hectare during the first 18 months after planting. Compost amendment could potentially increase this yield to over 3 million roses (3.01 m). Across various studies spanning different crops, durations, and application rates, compost amendments have shown an average yield increase of up to 17 %, with the greatest benefits observed in finer-textured soils (Luo et al., 2018). A study similar to ours by Idrovo-Novillo et al. (2019) in Ecuador observed significant yield differences as early as two months after initial harvest, representing one flowering flush. They reported higher yields with combined compost and full fertigation treatments compared to treatments that used either compost alone or non-stabilised rose waste with full fertigation (Idrovo-Novillo et al., 2019). Our study addressed potential nutrient availability limitations by acidifying irrigation water to a pH similar to that of the fertigation (Table 2), in contrast to their use of alkaline water. Similar yield increases with compost amendments were found in studies on roses by Barbosa et al. (2019) and millet by Meena et al. (2016). Both studies highlighted the positive impact of integrating organic amendments and mineral fertilizers on yield, suggesting opportunities to reduce mineral fertilizer rates. The combination organic and mineral fertilizers often synergistically enhance crop productivity, reducing dependency on mineral inputs (Bernal et al., 2017). The lasting effects of compost amendment across multiple production cycles are attributed to nutritive and non-nutritive benefits, both associated with OM amendment (Reeve et al., 2012).

In floriculture, yields are typically evaluated by the number of stems or kg's harvested per m^2 per year. Mature yields ranged from 280 to 290 per m^2 per year across all treatments and did not show significant differences ($p = 0.763$, Table 4). This suggests a shift in the effects of compost amendment from the growth phase to the mature phase of the rose crop. Initial production differences due to compost amendment with full fertilization persisted as the crops matured beyond the first 12 months.

These results suggests that young rose crops are particularly sensitive to improved soil conditions resulting from compost amendment during their growth phase. This phase may also coincide with the early depletion of readily available nutrients from the compost, as observed in the R 50 % treatment, in which production declined earlier. In this study, no significant effect of compost on yearly mature yield was observed, but this could change over time as differences in soil functioning become more pronounced. Previous studies have shown yield increases up to 24 years after a single compost application (Atoloye et al., 2022; Reeve et al., 2012). A meta-analysis of Luo et al. (2018) indicated that crop yield responses to organic fertilization are modest in the first three years, after which they gradually increased due to the slow release of nutrients from organic amendments. Bernal et al. (2017) emphasized that compost's direct fertilizing effects may be less pronounced compared to its broader soil improvement functions, which might become more significant in later stages post-planting.

Over the 18-month period, the average length of all harvested roses did not significantly differ among treatments ($p = 0.968$, Table 4). Idrovo-Novillo et al. (2019), on the other hand, observed that average stem length increased with combined compost and full fertigation treatments compared to compost alone, suggesting a synergistic effect of compost application when used with mineral fertilizer.

3.1.2. Economical yield

Patterns of cumulative economical yield varied slightly compared to total stems harvested (Fig A.1). By the end of the experiment, all three compost treatments (R, T & C) with 100 % fertigation yielded significantly higher returns than the control treatment ($p = 0.0299$, Table 4). The R, T and C treatment showed respective yield increases of 4.9 %, 3.6 % and 3.8 % compared to the control. This resulted in a theoretical economic yield increase of approximately €22,000 ($23,800) for the combined compost and fertigation treatments over the 18-month period. R 50 %, with halved fertigation, did not significantly influence economic yield based on post-hoc LSD test (Table 4). It is important to note that our approach assumes all harvested stems reach the auction. However, practical experience learned that a loss rate of 5–10 % is more realistic. This loss is likely consistent across treatments, as shown by the similar vaselife duration across treatments (Section 3.2) and does therefore not influence the observed differences.

The significant increase in economical yield in compost-amended treatments highlight the potential financial benefits of integrating composting practices into rose cultivation. Halving fertigation dosage did not affect economical yield compared to standard practice, yet it significantly reduced costs by decreasing minerals fertilizer use. While this study did not factor in compost preparation costs, Idrovo-Novillo et al., (2019) did. They showed that combined compost and fertigation treatments yielded the highest net income for rose cultivation, suggesting that increased economic yield offsets compost production costs. Without accounting for raw material purchase and transport costs, the production costs for compost could potentially be even lower, thereby increasing net profitability. Moreover, implementing composting practices enhances waste management and reduces the environmental footprint of rose cultivation, making it an attractive option for growers seeking both economic benefits and sustainable practices (Atoloye et al., 2022; Villa et al., 2021).

3.2. Quality affected by compost treatment

The effect of compost treatment on consumer quality of cut roses was assessed based on vase life and bud height. Vase life is a crucial quality criterion for customer satisfaction and indicates the longevity of cut flowers in days. No negative effect of compost amendment on vase life was observed, as shown by the no-effect line (Fig A.2). Compost treatment showed a significant positive effect on vase life at the six-month mark after planting ($p = 0.015$). Post-hoc LSD testing indicated that roses from treatment R and C had significantly prolonged vase life compared to controls. Main senescence criteria were wilting and petal abscission (data not shown). Variations in the average vase life observed across timepoints may be attributed to numerous pre-harvest factors related to seasonal fluctuations, like relative humidity, draft, solar radiation, water availability and post-harvest handling such as variations in transport conditions and duration (In and Lim, 2018).

Bud height showed no significant variations across treatments over time. Idrovo-Novillo et al. (2019) similarly found consistent bud sizes and vase life durations across treatments, supporting that compost amendment does not compromise cut rose quality, providing an added incentive for growers to adapt composting practices.

3.3. Regulating factors

3.3.1. Soil characteristics

Compost amendment significantly increased initial organic matter (OM) levels by approximately 1 percent point from 3.3 ± 0.04 % to a range between 4.1 % and 4.7 % (Table A.1), as indicated by Linear Mixed Model (LMM) analysis ($p < 0.0001$, $R^2m = 0.77$, Table A.2). Throughout the 18-month experiment, OM levels remained stable ($p = 0.16$, Table A.1). Idrovo-Novillo et al. (2019) reported a slight OM increase with combined compost and fertilizer treatments. The limited mineralization observed in this study could be attributed partly to root exudation of soluble OM, compensating for compost degradation (Atoloye et al., 2022). Moreover, compost application increased substrate diversity, enhancing microbial activity and thus necromass production, contributing to stable OM levels (Atoloye et al., 2022; Scotti et al., 2016; Wu et al., 2019). Incorporating new OM into finer-textured soils, such as the loamy soil in this study, enhances soil fertility by increasing cation exchange capacity, thereby reducing nutrient leaching and precipitation (Reeve et al., 2012; Villa et al., 2021). Furthermore, the improved moisture retention capacity of compost has been shown to reduce nutrient leaching by approximately 30 % (Balaganesh et al., 2020).

Similar trends were observed for C % and N % (Fig. 4 A&B), with compost amendment showing a significant impact ($p < 0.0001$ & $p < 0.0001$, $R^2m = 0.84$ & 0.72, Table A.2). No time effect was observed ($p = 0.17$ & $p = 0.35$, Table A.2). The initial C/N ratio was elevated in compost treatments, ranging between 8.1 and 8.4, compared to the control's 6.9 ± 0.43, indicating a slightly lower relative N contribution ($p < 0.0001$, $R^2m = 0.48$, Table A.2). Perennial crop systems have a high potential for C sequestration due to their long crop cycles and minimal tillage (Baldi et al., 2018). Compost amendment in this study increased soil organic carbon (SOC) by about 80 % and N by about 40 %, explaining the observed increase in C/N ratio (Table A.1). Atoloye et al. (2022) demonstrated significant SOC enhancement in dryland topsoils post-compost application, suggesting potential long-term sequestration.

Initial nitrate (NO_3) levels, around 1.3 mg g^{-1} for all treatments, declined gradually to around 0.25 mg g^{-1} by the end of the 18-month experiment. The 50 % fertigation treatment showed a faster decline within the first 3 months post-planting (Fig. 4C). Both treatment and time significantly influenced NO_3 evolution through nitrification ($p < 0.05$ & $p < 0.0001$, $R^2m = 0.70$, Table A.2), without time interaction. Conversely, phosphorus (PO_4) rose from 0.04 mg g^{-1} to about 0.12 mg g^{-1} across all treatments except R 50 %, which reached only 0.07 mg g^{-1} after 18 months. The interaction term between treatment and time was significant ($p < 0.0001$, $R^2m = 0.89$, Table A.2), indicating PO_4 evolution varied among treatments over time. These patterns indicate that although compost amendment initially enhanced NO_3 and PO_4 availability, these nutrients were gradually depleted over the study duration. A study on almond orchards observed similar short-lived increases in inorganic N post-compost application, suggesting that sustained nutrient availability may require more time or repeated compost

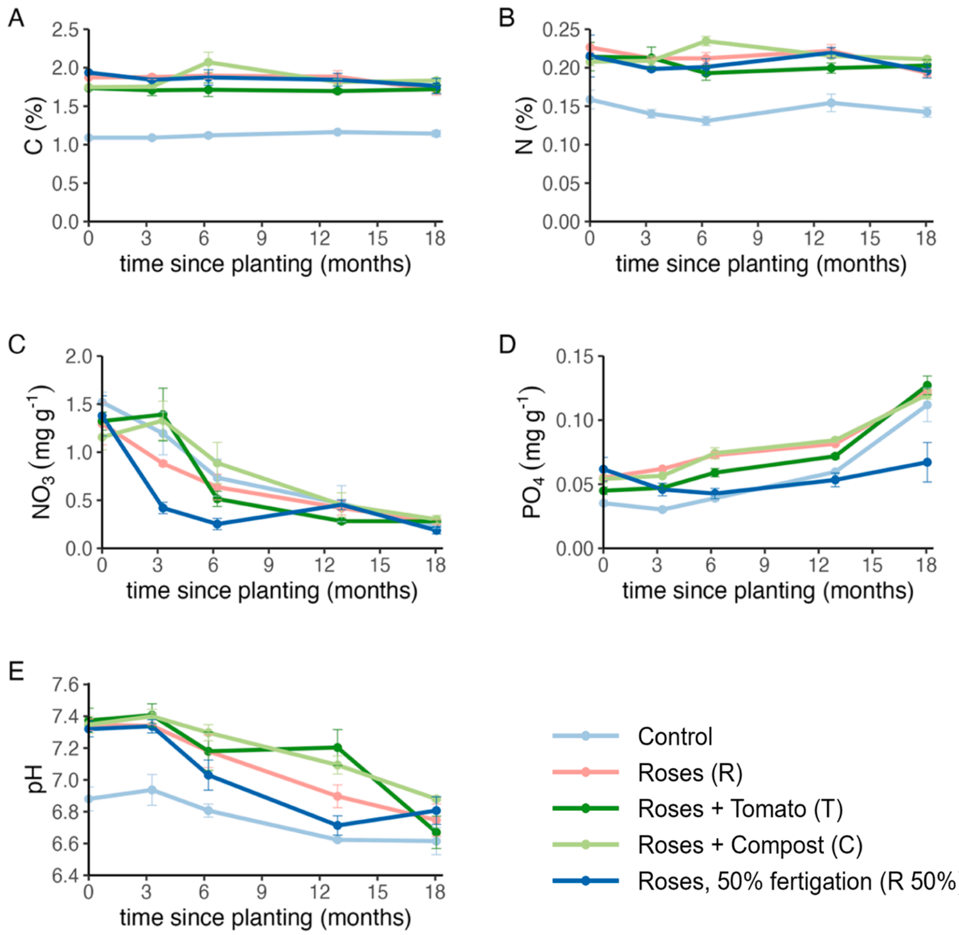

Fig. 4. Changes in physicochemical parameters throughout the 18-month experiment for the five treatments. (A) C (%), (B) N (%), (C) NO_3 (mg g^{-1}), (D) PO_4 (mg g^{-1}), (E) pH. Mean ± SE, n = 3, expressed on dry weight basis.

application due to the slow mineralization rate (Villa et al., 2021). Ethiopian smallholder farms reported increased phosphorus levels following compost amendment compared to unfertilized controls (Bedada et al., 2014). The observed decrease in easily available macronutrients in the R 50 % treatment may have contributed to the declining yields observed 10 months after planting.

Compost initially raised soil pH from 6.9 ± 0.1–7.3–7.4 ($p < 0.0001$, $R^2m = 0.79$, Table A.2), consistent with the high pH (>8) of the compost compared to the baseline soil pH (Table 1). Initial increased soil pH is a well-documented effect of compost amendment due to alkaline substances present in compost (Bedada et al., 2014; Farrell et al., 2010; Idrovo-Novillo et al., 2019). Over 18 months, pH levels declined significantly across all treatments, deceasing by approximately 0.5 pH units to 6.5–6.9 (Fig. 4E), with time being a driving factor ($p = 0.04$, Table A.2). Compost-amended beds showed a more pronounced pH decline, likely due to increased plant growth and thereby root exudation, which lowered soil pH (Cacini et al., 2020; Farrell et al., 2010). The incorporation of approximately 33 % new OM from compost, with a unique molecular composition, likely contributed to mineral associated organic matter (MAOM) formation. This involves acid groups (R-COOH), further contributing to lowering soil pH. Atoloye et al. (2022) observed increased MAOM stocks three years after compost amendment, pH evolvement was not reported. This decrease in soil pH enhances plant nutrient uptake potential, critical for nutrient-sensitive plants like roses (Barbosa et al., 2019; Ehret et al., 2005). Idrovo-Novillo et al. (2019) noted rose chlorosis due to alkaline water irrigation, leading to a soil pH (7.8–8.0) insufficient for micronutrient supply. Soil pH levels in our study remained below this critical level.

While data suggested a decline in EC over time, considerable replicate variation (Table A.1) led to significant treatment effects, but not for time, based on LMM analysis ($p < 0.05$ & $p = 0.15$, $R^2m = 0.53$, Table A.2). Idrovo-Novillo et al. (2019) similarly observed EC reductions, likely due to crop nutrient uptake and deeper soil leaching. Compost-amended beds showed EC levels similar to the control, while compost having relatively high EC levels (Table 1), approaching upper safe limits for agricultural application (de Nijs et al., 2024). The observed soil EC levels, however, posed no adverse effects, even though Onwosi et al. (2017) recommends to lower amendment rates to prevent soil salinization. From three months onward, R 50 % treatment showed low EC values (<140 μs cm^{-1}) due to reduced fertigation dosage, supplemented by acidified clearwater with a naturally lower EC (Table 2). Such low salinity levels benefit rose cultivation, as salt stress hampers growth and flower production (Cai et al., 2014).

Compost amendment provides nutrients, but may also introduce or alter the bioavailability of heavy metals due to changes in soil pH, microbial activity, and OM interactions. (De Corato, 2020). Additionally, excessive soil nutrient concentrations can inhibit the uptake of other nutrients, potentially leading to deficiencies (Yeo et al., 2016). To assess this, patterns of total vs. plant-available micronutrients and heavy metals were evaluated. General patterns between full and half fertigation treatments drove temporal variations in plant-available nutrient levels (Fig A.3). While Farrell et al. (2010) noted a short-term leaching pulse of heavy metals due to altered biochemistry, and Cacini et al. (2020) reported increased concentrations in pot roses following compost amendment, no significant influence of these dynamics were found in this study (Fig A.3). Initially, compost amendment increased plant-available Fe and Mn levels, which reached control levels at the six-month mark, similar to depletion of easily available nutrients like NO_3 and PO_4 from the compost. Total Fe levels were approximately 33 g kg^{-1}, over 500 times higher than the plant-available fraction. Plant-available Zn was consistently higher in the compost-amended beds compared to the controls, suggesting enhanced long-term availability. Both total and plant-available Cu levels increased across treatments, attributed to higher fertigation Cu concentrations aimed at mitigating stem hollowing, linked to Cu deficiency (Hawrylak-Nowak et al., 2022). Cu's strong binding to OM may amplify this effect (Farrell et al., 2010). Mg concentrations showed a declining trend with plant-available fractions dropping from approximately 13–10 % over time across all treatments. No significant differences in total or plant-available Cd, Ni and Pb levels between treatments indicated that no heavy metal pollution was introduced by compost amendment. The decline of several essential plant-available nutrients between 6- and 13-months post-amendment might explain reduced yields observed in the R 50 % treatment from around 10 months after planting. Mineralization of compost-bound nutrients is relatively slow, and their release may have delayed visible effects (Luo et al., 2018).

3.3.2. Leaf nutrient levels

Eighteen months post-planting, leaf nutrient contents did not significantly differ between treatments, except for Cu, where only the R treatment showed higher levels (Table A.3). Halving the fertigation (R 50 % treatment) did not result in leaf nutrient deficiencies compared to the control treatment. Most nutrients remained within the recommended range provided by Crop Nutrition Laboratory Services Ltd. (Cropnuts) (Table A.3), with Ca levels slightly elevated across all treatments except R 50 %. N and P levels approached the upper limit of the recommended range. Cu levels were consistently low (3.6–5.7 mg kg^{-1}) across treatments, below the reference range of 7.0–15 mg kg^{-1}, possibly influenced by high P levels antagonizing Cu availability (Rietra et al., 2017). Lignification problems associated with Cu deficiency shortly after planting led to increased Cu fertigation concentrations across treatments. Leaf Fe levels exceeded the reference range in the R and T compost treatments, likely influenced by soil Fe levels rather than compost amendment, as initial soil Fe levels were higher than those in the compost used (Table 1). While OM addition might affect soil Fe bioavailability, no differences in plant-available Fe among treatments were observed. Elevated Fe levels may inhibit the uptake of other micronutrients like Cu and Zn, contributing to the observed nutrient dynamics (Rietra et al., 2017).

3.4. Compost application potential

Amending with compost increased cut rose yield during the first 12 months but had no significant effect once the crop reached maturity (Table 4). However, improved soil quality and increased OM % from compost might play a more pronounced long-term role. Over time, soils without compost may become compacted, forming a hard pan due to regular drip irrigation. This limits water infiltration and oxygen availability, particularly in fine-textured soils like the loamy soil in this experiment (Villa et al., 2021). Additionally, in greenhouse soils that have been in production for over 10 years, the loss of soil structure can lead to the beds collapsing on the sides, significantly reducing the rooting zone. Initially, soil structure might not yet significantly hinder crop production, but over the ears, compost can mitigate soil compaction, maintaining higher production compared to non-amended soils.

Compost incorporation improves soil structure by increasing SOM levels, which prevents compaction, and enhances both water infiltration and aeration (Atoloye et al., 2022; Luo et al., 2018; Villa et al., 2021). These benefits facilitate deep root growth, particularly for roses with rooting zones up to 60 cm, enhancing crop performance through improved soil structure. Additionally, compost serves as a slow-release fertilizer, ensuring short-term nutrient availability while supporting long-term nutrient release. In intensively cultivated lands with perennial crops like cut roses, compost amendments help maintain or increase OM levels, preventing soil depletion of nutrients and sequestering carbon by increasing SOC stocks. Although this study was limited to 18 months, our findings suggest that compost amendment can provide lasting agronomic benefits, such as maintaining soil health and structure, which are critical for sustaining high productivity over the roses' full lifespan (6–10 y). Future research should explore these benefits over the entire lifecycle of perennial crop systems.

Beyond agronomic improvements, compost amendment contributes significantly to circular economy principles by enabling on-farm waste stream recycling, reducing dependency on mineral fertilizer, and promoting environmental sustainability (Balaganesh et al., 2020; Hamedi et al., 2022; Scotti et al., 2016; Villa et al., 2021). The compost used in this study was produced from rose waste and other agricultural residues, demonstrating its role in closing resource cycles and mitigating waste (Mangottiri et al., 2024). In this study, a relatively high compost application rate of 27 kg per m^2 to a depth of 60 cm was used to increase OM to 4–5 %. This rate not only prevents soil exhaustion but also enhances soil carbon sequestration and improves sustainability in intensively cultivated land. In most studies, typical application rates range from 1 to 10 kg per m^2, irrespective of incorporation depth (Atoloye et al., 2022; Bedada et al., 2014; Scotti et al., 2016). The chosen rate in this study is similar to the amendment rates used by Idrovo-Novillo et al. (2019) and Meena et al. (2016). This rate was a compromise between commercial feasibility and maximized observable effects, both positive and negative, which might have been less apparent at lower rates.

For growers, integrating compost with mineral fertilizer holds promise for reducing dependency on the latter. Halving mineral fertilizer application may be overly ambitious, as synergistic effects diminished after about 10 months. However, the R 50 % treatment maintained performance levels comparable to the control after an initial decline, achieving significant savings in mineral fertilizer costs. Adoptive fertilization strategies are essential to optimize these outcomes. Using integrative nutrient diagnosis methods, as advocated for roses by Franco-Hermida et al. (2020), can identify specific nutrient surpluses or deficiencies for tailored corrective measures. Additionally, annual topdressing of compost in between the rose crops might enhance sustained nutrient availability. Aligning mineral fertilization with compost application can enhance yield potential, while reducing costs and promoting sustainable agricultural practices.

4. Conclusion

This study showed, for the first time, the significant positive effect of compost amendment on rose crop yield during the growth phase. An initial productivity boost in the first year was followed by stabilized production as the crop matured. Over the initial 18 months, compost amendment combined with full fertigation increased the number harvested stems by an average of 3.9 %, translating to an economic yield increase of 4.1 % (€22,000 per hectare). The addition of compost improved soil structure through a 30 % increase in compost-derived organic matter, which facilitated short-term nutrient availability and sustained long-term nutrient release. These improvements not only enhanced crop performance and supported consistent yields over time without compromising key quality parameters such as vase life, stem length, or bud size, but are also expected to sustain high production rates throughout the roses' lifecycle. By integrating compost with mineral fertilization, growers can effectively manage waste streams, optimize yield, reduce costs, and promote sustainable agricultural practices. The synergistic effect of compost and full fertigation underscores its potential to enhance both yield and profitability while promoting soil health. Overall, compost amendment contributes to closing the cycle of resources within Kenyan rose cultivation, making it both environmentally and economically beneficial.

CRediT authorship contribution statement

Evy de Nijs: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Roland Bol:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Rosaline Zuurbier:** Writing – review & editing, Methodology, Conceptualization. **Albert Tietema:** Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2025.100208.

Data availability

Data and scripts have been published online and are referenced in the text.

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