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William J Parton, Robin H Kelly, Melannie D Hartman, Agathe Revallier, Ana Barbara Bisinella de Faria, Gabriela Naves-Maschietto, Marie Orvain, Sabine Houot, Maria Albuquerque, Sebastian Kech

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Agricultural and municipal organic waste amendments to increase soil organic carbon: How much, how often, and to what end?

William J. Parton[1] | **Robin H. Kelly**[1] | **Melannie D. Hartman**[1] | **Agathe Revallier**[2] | **Ana Barbara Bisinella de Faria**[2] | **Gabriela Naves-Maschietto**[2] | **Marie Orvain**[2] | **Sabine Houot**[2] | **Maria Albuquerque**[2] | **Sebastian Kech**[2]

[1]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, USA

[2]Veolia Environnement SA, Aubervilliers, Paris, France

Correspondence
William J. Parton, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, USA.
Email: William.Parton@colostate.edu

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Abstract

A new version of the Century ecosystem model, modified to better represent chemically and physically recalcitrant organic amendments by allowing the addition of organic waste products (OWP) as a mixture of plant material and surface slow soil organic matter (SOM) controlled by the Indicator of Residual Organic Carbon (IROC), and field observations from a 16-year wheat corn rotation experiment near Paris, France, were used to assess the long-term impacts of applying agricultural and municipal organic waste products (OWP) on soil carbon (C) sequestration, grain C and nutrient content, and soil nutrient status. Sixteen years of observed grain C, nitrogen (N), phosphorus (P), and potassium (K) and soil C and nutrient data were used to calibrate and validate the performance of IROC-Century. A suite of future management scenarios, simulated using this calibrated model, explored multiple frequencies of applications of OWP and fertilizer to evaluate their long-term impacts on grain C and nutrient content, soil C sequestration, and NO_3^- leaching. The model effectively simulated the impact of biennial additions of four OWP types on soil C, N, P, and K during the 16-year experiment. Measured and simulated OWP +fertilizer resulted in higher soil C (highest for well-decomposed [55%] vs. less-decomposed [37%] OWP) and N content, while total soil accumulation of N, P, and K was determined by the content of the OWP, regardless of IROC, and OWP greatly reduced the need to add chemical fertilizer while increasing crop production and N, P, and K uptake by the crop. Simulation scenarios using IROC-Century for future management suggest that the optimal cropping management system to maintain high corn and wheat production and reduce NO_3^- leaching is to apply OWP biennially for 12 years along with

Abbreviations: BIO, biowaste compost made from green waste and organic municipal waste; CON, control treatment with no OWP added; FYM, farmyard manure; GHG, greenhouse gas(es); GWS, composted green waste mixed with wood chips and sewage sludge; IROC, indicator of residual organic carbon; MSW, composted municipal solid waste; OWP, organic waste products; PASTIS, predicting agricultural solute transport in soil (model); ROTHC, Rothamsted carbon (model); SOC, soil organic carbon; SOM, soil organic matter.

fertilizer and then reduce OWP to every fourth year while continuing to add fertilizer to the wheat crop only. However, reducing the number of OWP additions in these scenarios did decrease the rate of soil carbon sequestration.

1 | INTRODUCTION

Humans demand a great deal from the 11% of Earth's land surface (Ballayan & DeSantis, 2003) allocated to croplands—to produce food and fiber, provide long-term resilience to wind and water erosion, to retain fertility, and, increasingly, to act as a sink for atmospheric carbon (C) (Kane, 2015). This amelioration of anthropogenic climate change requires not only reductions in greenhouse gas emissions via better management strategies but identification and exploitation of CO_2 sinks (Pachauri et al., 2014). Croplands have been subject to soil disturbance through mechanical cultivation, a regular harvest of a significant fraction of plant material, and fallow periods; all processes shown to cause large losses of soil organic carbon (SOC) compared to undisturbed soils (Rasmussen & Parton, 1994 and reviewed extensively in Lal et al., 2020). These degraded soils present an opportunity as large potential sinks for atmospheric C.

Europe is a region of high historic losses of SOC due to land use and, therefore, presents a large capacity for soil sequestration moving forward (Sanderman et al., 2017). Angers et al. (2011) mapped the C saturation deficit in France at the national scale, based on climate, soil characteristics, and land use significantly for SOC storage with a median saturation deficit of 8.1 g C kg^{-1} soil and this generally increased with increasing clay content. In France, the potential rate of soil C sequestration was estimated to average 0.55 ton C ha^{-1} year for the whole depth or 0.28 ton C ha^{-1} year for the topsoil (reviewed by Minasny et al., 2017) with the greatest sequestration potential in cropland soils in Northern and Southwestern France, totaling ∼ 20 million hectares (Arrouays et al., 2002). The size of this potential C sink, coupled with an established commitment to addressing environmental challenges (Wendling et al., 2020), positions France as a valuable proof of concept in agriculturally based climate change solutions.

One strategy for mitigating climate change is to divert agricultural and municipal organic waste products (OWP) to croplands, a practice that benefits agricultural productivity by reducing reliance on chemical fertilizer and improving soil structure and water holding capacity (Dadashi et al., 2019; Lal, 2016; Oldfield et al., 2018; Picariello et al., 2021; Smith et al., 2008). Long-term studies of applications of farmyard manure (FYM) have shown SOC increases of 47% (Blair, Till, Poulton , 2006a) to 161% (Blair et al., 2006b). The use of composted OWP made from agricultural and municipal wastes has been shown to restore SOC (Peltre et al., 2012) and lower greenhouse gas emissions relative to noncomposted material (Ryals et al., 2015). Ryals et al. (2015) found that applying compost to annual grasslands in California substantially increased plant production(>50%) with only a minor increase in soil N_2O flux. In an experiment near Paris, France, applying OWP greatly increased SOC, soil N mineralization, and plant production with the increases in plant production largely due to increases in soil N mineralization rates (Chalhoub et al., 2013).

Ecosystem modeling is a valuable tool to extrapolate results from isolated field experiments to longer time scales and larger geographical extents (Chalhoub et al., 2013; Ryals et al., 2015). Long-term agricultural experiments have been used extensively to test the ability of the Century model (Parton et al., 1994), RothC (Jenkinson et al., 1992), and other ecosystem models to simulate plant production, SOC dynamics, and nutrient cycling (Smith et al., 1997). Century simulations by Ryals et al. (2015) indicate long-term plant production (20–50 years) increased substantially, following large compost applications to an annual grassland site due to increased soil N mineralization rates and that SOC increased by >1000 g C m^{-2} during that period via increased plant production.

The aim of this study is to assess the ecosystem impact of adding OWP to a wheat-corn cropping system near Paris, France. We modified version 4.7 of the Century model to better represent compost management by allowing the addition of OWP as a mixture of plant material (structural SOM) and surface slow SOM (SOM2C pool), partitioned based on the Indicator of Residual Organic Carbon (IROC). We then used this model, IROC-Century, to evaluate a suite of future management scenarios with different amounts and frequencies of OWP and fertilizer additions to determine optimal management strategies to maintain plant production, maximize soil C storage, reduce inorganic fertilizer additions, and limit soil NO_3^- leaching relative to current management practices.

2 | MATERIALS AND METHODS

2.1 | Experimental site description

The joint French National Research Institute for Agriculture, Food and Environment (INRAE)—Veolia (water, waste, and energy management company) long-term (1998–present) field experiment, QualiAgro, was designed to explore the benefits and potential environmental impacts of manure and three municipal waste composts (Houot et al., 2002) on soil fertility and crop production. The site, managed cooperatively by INRAE and Veolia, is located in Feucherolles, a commune in the Yvelines department in the Île-de-France in the north-central part of the county (48.8727˚ N, 1.9726˚ E). The mean annual temperature of the site is 11.7˚C and the mean annual precipitation is 571 mm. The study includes 10 experimental treatments for a winter wheat/corn maize crop rotation system. The experiments include four different types of OWP: biowaste compost made from green waste (prunings, leaves, and grass) and organic municipal waste (BIO, biowaste compost made from green waste and organic), composted municipal solid waste composed of dry and clean packaging and lawn waste (MSW, composted municipal solid waste), composted green waste (mainly prunings and refuse screenings) mixed with wood chips and sewage sludge (GWS), and farmyard manure (FYM) (Annabi et al., 2007) with an organic matter content of between 34% and 57% (BIO < GWS < FYM < MSW). Based on laboratory incubations of each OWP type, the proportion of OWP likely to be incorporated into the SOM due to its chemical and physical composition, ranges from 33% to 54% (MSW < FYM < BIO < GWS). For each OWP type, plus a control treatment with no OWP (CON), there are fertilized (+N) and unfertilized/minimally fertilized treatments (−N) where the amount of N fertilizer (solutions of urea and ammonium nitrate, containing 39% nitrogen) added varied as a function of the soil mineral N content on a winter wheat (*Triticum aestivum* L.) and corn maize (*Zea mays* L.) rotation on a silt loam Glossic Luvisol (7% sand, 79% silt, 14% clay). The simulated fertilizer additions for the +N and −N treatments varied annually to match the timing and amount of fertilizer additions in the field experiments. The mean fertilizer addition (N only) for the +N corn was 3.9 g N m^{-2} (range: 0.0–7.9), while the mean fertilizer addition for +N wheat was 12.9 g N m^{-2} (range: 8.2–20.0). The mean fertilizer addition for the -N corn was 0.4 g N m^{-2} (range: 0–3.3) and the mean fertilizer rate for −N wheat was 5.8 g N m^{-2} (range: 0.0–8.7). All OWP types were applied based on the same rate of C addition, averaging 400 g organic C m^{-2} at each application, an amount ~2–3 times greater than traditionally applied by local farmers, selected for this study with the intent to explore maximum impacts over a limited period of time (Table 1). The OWP, applied every 2 years, was incorporated to a depth of 14 cm by chisel plowing the day after application. The soil was also mechanically cultivated every year in mid-October to mid-November to a depth of 30 cm with a moldboard plow. The wheat crop residues (70%) were exported but the corn maize residues were plowed into the soil after grain harvest.

Core Ideas

- Observed and simulated biennial addition of organic waste products (OWP) increased grain carbon (C), nitrogen, phosphorus, and potassium by >40%.
- Observed and simulated biennial additions of OWP during a 16-year period increased soil C by >38%.
- Maximum corn grain C occurred after biennial OWP applications over 16 years.
- Soil carbon stabilization is greater for composted OWP than fresh manure and increases with compost age.

2.2 | The IROC-Century model

The Century model (version 4.7, developed from the version described in detail by Parton et al., 1994) was selected for this study because it has been used extensively to simulate SOM dynamics, crop growth, and nutrient (N, P, K) cycling for long-term agricultural experiments around the world (Baethgen et al., 2021; Parton & Rasmussen, 1994; Paustian et al., 1992; Smith et al., 1997). The SOM model simulates the flow of C and nutrients (N, P, K) for the soil surface and mineral soils (0–30 cm depth) using five SOM pools (structural and metabolic litter, and active, slow, and passive SOM); all but the passive pool are also represented in surface organic matter (Figure 1). Century also simulates the mineralization of N, P, and K from decomposing dead plant material and SOM pools, leaching of organic and inorganic N, P, and K, and uptake of N, P, and K by live plants. Temperature and moisture control many of the C and nutrient flows in the model. Plant production is based on a plant-specific maximum growth rate, solar radiation, plant water stress, air temperature, and calculated nutrient (N, P, and K) demand of the plant, which varies as a function of the soil mineral nutrient content. This plant production is allocated to the different plant parts (roots, leaves, and grain) as a function of soil moisture and nutrient stress. Dead plants and externally added organic material are incorporated into the different surface litter and SOM pools as a function of the soil texture and the decomposition rates are calculated as a function of soil water stress and soil temperature.

While previous versions (Baethgen et al., 2021; Rasmussen & Parton, 1994) of Century allowed for the addition of organic matter to be partitioned only into the metabolic and structural surface litter, Ryals et al. (2015) found that the majority of compost in a California grassland experiment had a decay rate most similar to the slow SOM pool in Century. Results from

TABLE 1 Mean and variability of QualiAgro experiment organic waste product (OWP) additions from 1998 to 2013 for the four different types of OWP: Biowaste compost made from green waste (prunings, leaves, and grass) and organic municipal waste (BIO), composted municipal solid waste comprised of dry and clean packaging and lawn waste (MSW), composted green waste (mainly prunings and refuse screenings) mixed with wood chips and sewage sludge (GWS), and farmyard manure (FYM).

	GWS		BIO		MSW		FYM	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
IROC	65.32–95.34	76.82	67.37–89.43	75.11	26.79–61.33	48.46	52.51–75.66	65.39
g C m^{-2} added as compost	291.91–645.41	434.04	255.72–484.79	392.64	262.35–600.16	374.50	290.25–539.43	405.76
C:N ratio	9.08–14.45	10.65	9.14–14.88	11.78	12.78–22.02	15.74	10.05–18.48	14.43
C:P ratio	6.65–14.46	9.58	11.34–26.9	20.64	21.38–69.17	40.48	16.86–47.2	26.55
C:K ratio	7.94–38.75	20.23	7.17–13.72	9.98	15.91–54.44	32.54	5.71–12.34	9.25
Fraction inorganic N	0.11–0.25	0.17	0.02–0.13	0.07	0.07–0.32	0.14	0.02–0.20	0.07
Fraction inorganic P	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fraction inorganic K	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88

Note: Values for the Indicator of Residual Organic Carbon (IROC), organic C:N, C:P, C:K ratios, and fraction of added OWP N, P, and K that is inorganic.
Abbreviations: C, carbon; K, potassium; N, nitrogen; P, phosphorus.

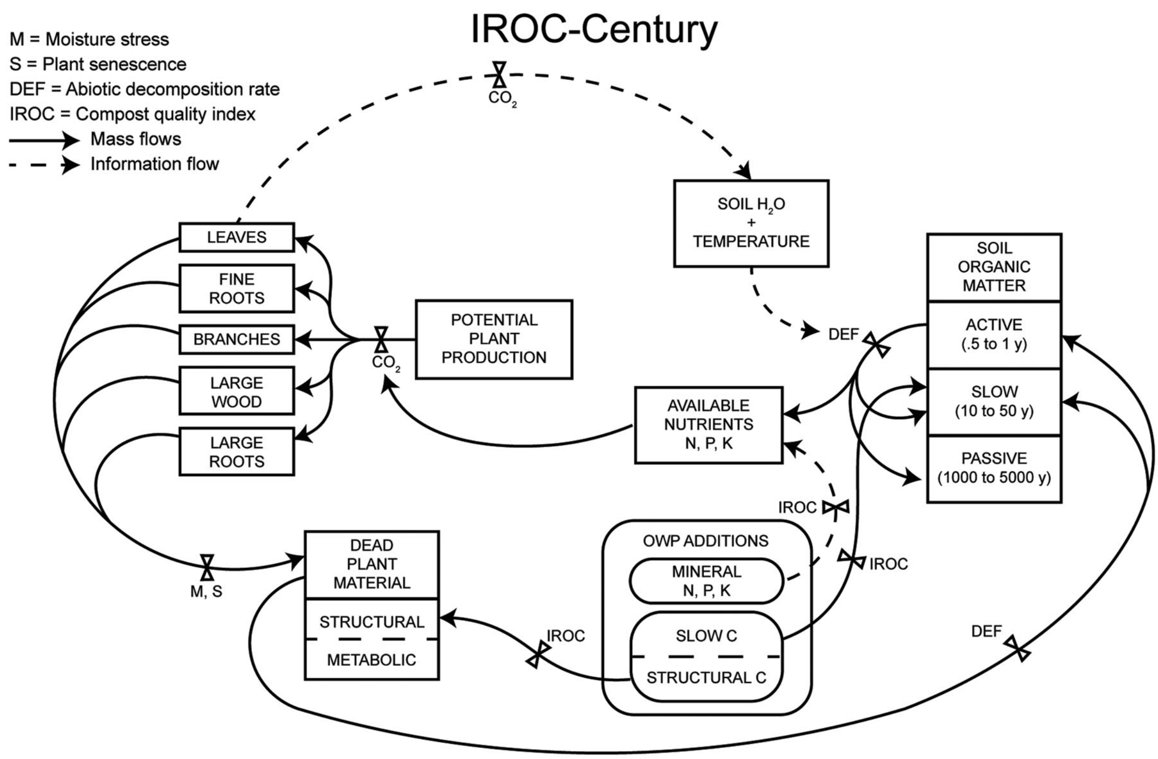

FIGURE 1 Flow diagram for Indicator of Residual Organic Carbon (IROC)-Century model with organic waste product (OWP) addition flows.

the Chalhoub et al. (2013) experiment showed that some OWP types with less-decomposed material contained a mixture of slow SOM and undecomposed plant material.

In response to these results, we added functionality to Century 4.7 to allow the addition of OWP as a mixture of plant material (structural SOM) and surface slow SOM (SOM2C pool) controlled by the Indicator of Residual Organic Carbon (IROC = 44.5 + 0.5 SOL—0.2 CEL + 0.7 LIC—2.3 C_{min3}, where SOL is soluble, CEL is cellulose, LIC is lignins and cutins as percent of total dry matter as determined by

Van Soest (1968) fractionation, and C_{min3} is the percentage of organic C remaining after 3 months of laboratory incubation), a control parameter (Lashermes et al., 2009) that has been successfully used to calculate the partitioning of organic carbon within the organic pools of the RothC model (Peltre et al., 2012). Higher values of IROC are associated with higher rates of SOC stabilization, while low values of IROC and higher C:N ratios are associated with N immobilization during the initial decay period of the OWP. This modified model, IROC-Century (Figure 1), employs a new driver file, COMP.100, that incorporates this index to control the fraction of added OWP that is partitioned to the slow versus structural pool using a linear equation with the fraction of OWP in the slow pool increasing linearly from 0.08 (IROC ≤ 35) to 0.93 (IROC ≥ 95) based on QualiAgro data.

2.3 | IROC-Century parameterization and validation

Field observations from the +N and −N CON, MSW, FYM, and BIO OWP experiments were used to parameterize the model inputs and crop growth parameters for wheat and corn, while observations from the GWS ±N OWP treatments (not used for calibration) were used to validate the model performance. Soil texture (sand/silt/clay percent), weather data (observed average monthly maximum and minimum air temperature and cumulative monthly precipitation), and soil texture-based approximations of field capacity and wilting point (Saxton et al., 1986) were used to drive the model. Long-term Paris, France weather data (1900–1998) were used to drive the equilibrium simulation, but it was necessary to adjust the weather data set during the experimental period since, when recent limited data from the site were compared to the Paris long-term dataset, minimum temperatures were 2.5°C warmer in Paris than the minimum temperatures at the research site, likely due to the urban heat island effect (Oke, 1997).

To initialize the model, we assumed the experimental site was a grazed grassland-clover pasture prior to 1960 and was managed as a fertilized, conventionally cultivated wheat/corn rotation from 1960 to 1998. Management practices during the experimental period (± OWP, ±N fertilizer, quantity and timing of each, crop planting and harvest dates, and type, intensity, and timing of cultivation events), varied annually based on the actual management practices for the QualiAgro experiment from 1998 to 2013, which were specified in IROC-Century schedule files. We assumed that disking, seed drill, and plow events were of relatively similar and low-to-moderate intensity typical of well-managed corn/wheat cropping systems in the United States (Delgrosso et al., 2016). Actual C, N, P, and K content and IROC (different for each year and OWP type) of OWP applied during the experimental period were reflected in simulation input files.

Extensive field observations of plant production and nutrient uptake from low and high soil fertility treatments allowed us to calibrate the simulated crop growth. The key parameters that were altered in the IROC-Century crop growth model include maximum seasonal growth rate (1180 g C m^{-2} for corn and 680 g C m^{-2} for wheat), allocation of C to roots, grain, and straw, and C:N, C:P, and C:K ratios for roots, grain, and straw. Carbon allocation to grain was 50% of aboveground plant production for corn and 60% for wheat. Data from the −N CON treatment, where nutrients were most limited, and data for the OWP treatments with N additions (high available nutrient content) were used to determine maximum and minimum respective values for the plant C:N, C:P, and C:K ratios for roots, shoots, and grain. As in the Century model, IROC-Century then allows the plant C:N, C:P, and C:K ratios to float between the lowest and highest values as a function of the soil nutrient content while limiting plant growth when nutrient availability is low.

During refinement of the 2000 year equilibrium simulations, we adjusted vegetation parameters (C:N, C:P, C:K, plant N fixation rate), the decay rate of the slow and passive SOM pools, the starting C:N, C:P, and C:K of the SOM pools, rate of P weathering (0.3 g P m^{-2} year), and rates of atmospheric N deposition to result in SOC levels comparable to measurements taken in 1999. Available soil P measurements were limited. With total P measured only in 2013 and annual Olsen P (similar to labile P in the IROC-Century model) to test and calibrate the P submodel, we employed methods established by Parton et al. (2005) to parameterize the soil P submodel. We calibrated the soil K model by adding a fixed amount of K (0.2 g K m^{-2} year) during the equilibrium simulation and adjusted the K leaching parameter and the equilibrium coefficient between the labile mineral K and secondary K, employing very high soil C:K ratios to best approximate K cycling in the soil (Paul, 2014) in absence of a robust soil K dataset. These calibration techniques are based on widely held biogeochemical assumptions and, while imperfect, are standard procedure in ecosystem modeling studies, as accurate long-term detailed soil and plant observations are sparse and rarely exist before the last 50–100 years (Baethgen et al., 2021).

Root mean square error (RMSE, a statistic commonly used in climatology, forecasting, and regression analysis to verify experimental results) quantifies the standard deviation of model prediction error. A high RMSE indicates greater spread around the line of best fit. In addition, we compare means for observations and simulations, and where the mean ± SD of the simulations overlaps that of the observations, the modeled parameters sufficiently follow the observations (Kenney & Keeping, 1962).

2.4 | IROC-Century scenario experiments

To assess the potential of OWP to maximize plant production, enhance SOC sequestration, minimize soil NO_3^- leaching rates, and reduce the need to add N fertilizer, we completed a series of IROC-Century model runs. The first set of runs looked at the impact of biennial additions of OWP (FYM, GWS, BIO, and MSW) for 30 years while adding fertilizer for the first 6 years. For the second set of runs, we looked at the impact of adding N fertilizer the first 6 , 12, 18, 24, and 30 years from the beginning of the experiment while adding MSW biennially during the model runs (impacts of reducing fertilizer additions were found to be similar for all OWP additions, as shown in Figure 8). We also simulated the impact of adding OWP and fertilizer for the first 16 years and then reducing the OWP frequency to 4, 8, and 12 years while continuing +N. In addition, we simulated the impact of fertilizing wheat and adding OWP every 2, 4, or 8 years, with and without N fertilizer. These simulations examined the interactive impact of altering fertilizer and OWP and determined how rapidly land managers may be able to reduce OWP and fertilizer application rates after 12 years of biennial OWP additions, with the goal of determining the optimum minimal amounts of N fertilizer and OWP additions needed to maintain maximum crop productivity.

3 | RESULTS

3.1 | Observations and IROC-Century modeling (1998–2013)

3.1.1 | Grain C, N, P, and K

Observed and simulated mean corn and wheat grain C, N, P, and K were the highest in the +OWP +N treatments, followed by +OWP −N and −OWP +N (both 5%–15% lower than +OWP +N treatments), and substantially decreased (~50%) for the CON −N treatments (Figure 2; Tables 2 and 3). There was a consistent pattern of increased corn and wheat grain C, N, P, and K resulting from the +N treatment and the +OWP treatments all greatly increased corn and wheat grain C, N, P, and K compared to the CON −N. The GWS treatment (data not used in IROC-Century parameterization) simulated mean grain C, N, P, and K (Tables 2 and 3) are within 15% of the observed means for most of the comparisons (62% for GWS vs. 72% for model calibration treatments). Across-treatment mean wheat and corn simulated versus observed C, N, P, and K, RMSE for C, N, P, and K, the ratio of RMSE to observed mean C, N, P, and K, and percent difference (observed minus simulated) of simulated C, N, P, and K to observed C, N,

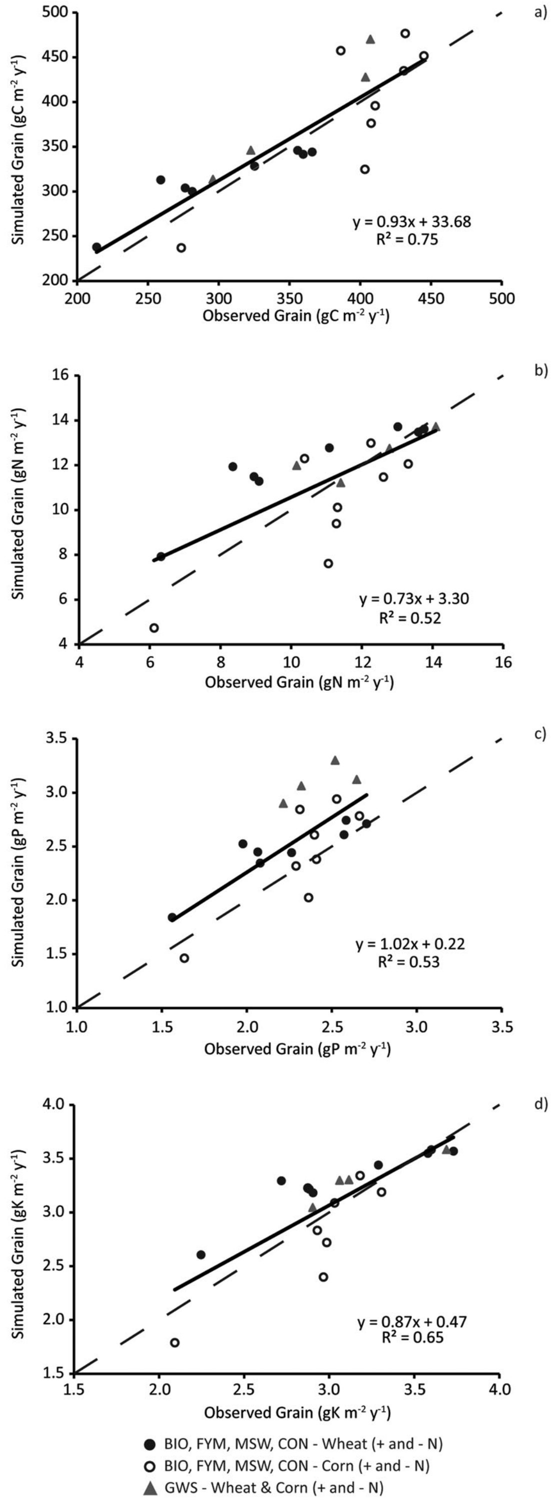

FIGURE 2 Comparison of combined wheat and corn observed versus simulated grain C (a), grain N (b), grain P (c), and grain K (d) for all treatments (± organic waste product (OWP) and ± N fertilizer). The solid line is the best fit regression line, and the dashed line is the 1:1 line.

TABLE 2 Comparison of observed (obs) versus index of residual organic carbon (IROC)-Century-simulated (sim) mean (1998–2013) corn grain carbon (C), nitrogen (N), phosphorus (P), and potassium (K) for the four different types of organic waste products (OWP): Biowaste compost made from green waste (prunings, leaves, and grass) and organic municipal waste (BIO), composted municipal solid waste composed of dry and clean packaging and lawn waste (MSW), composted green waste (mainly prunings and refuse screenings) mixed with wood chips and sewage sludge (GWS), and farmyard manure (FYM).

OWP	N	obs C	sim C	%	obs N	sim N	%	obs P	sim P	%	obs K	sim K	%
BIO	+	432	477	10.4	12.3	13	5.7	2.53	2.94	16.2	3.18	3.34	5.0
BIO	−	386	457	18.4	10.4	12.3	18.3	2.31	2.85	23.4	2.87	3.23	12.5
GWS	+	407	470	15.5	12.8	12.7	−0.8	2.52	3.3	31.0	3.12	3.3	5.8
GWS	−	404	428	6.0	11.4	11.2	−1.8	2.32	3.06	31.9	2.9	3.05	5.2
FYM	+	445	452	1.5	13.3	12.1	−9.0	2.66	2.79	4.9	3.31	3.19	−3.6
FYM	−	408	376	−7.7	11.3	9.4	−16.8	2.41	2.38	−1.2	2.99	2.72	−9.0
MSW	+	431	435	1.0	12.6	11.5	−8.7	2.4	2.61	8.8	3.03	3.09	2.0
MSW	−	403	325	−19.5	11.1	7.6	−31.5	2.36	2.03	−14.0	2.97	2.4	−19.2
CON	+	411	396	−3.6	11.3	10.1	−10.6	2.29	2.32	1.3	2.93	2.83	−3.4
CON	−	274	237	−13.4	6.1	4.7	−23.0	1.63	1.46	−10.4	2.09	1.79	−14.4

Note: The normalized difference (difference/mean) between observed and simulated mean C, N, P, and K as g m^{-2} year quantify model efficiency.
Abbreviation: CON, control treatment with no OWP added.

TABLE 3 Comparison of observed (obs) versus simulated (sim) mean (1998–2013) wheat grain carbon (C), nitrogen (N), phosphorus (P), and potassium (K) (all g m^{-2}) for the four different types of organic waste products (OWP): Biowaste compost made from green waste (prunings, leaves, and grass) and organic municipal waste (BIO), composted municipal solid waste comprised of dry and clean packaging and lawn waste (MSW), composted green waste (mainly prunings and refuse screenings) mixed with wood chips and sewage sludge (GWS), and farmyard manure (FYM).

OWP	N	obs C	sim C	%	obs N	sim N	%	obs P	sim P	%	obs K	sim K	%
BIO	+	356	346	−2.8	13.0	13.7	5.4	2.6	2.8	6.2	3.6	3.6	−0.6
BIO	−	259	313	6.0	8.4	11.9	41.7	2.0	2.5	27.8	2.7	3.3	21.0
GWS	+	323	346	7.3	14.1	13.7	−2.8	2.7	3.1	17.7	3.7	3.6	−3.0
GWS	−	296	314	6.0	10.2	12.0	17.6	2.2	2.9	30.6	3.1	3.3	7.8
FYM	+	366	344	−6.0	13.8	13.6	−1.4	2.7	2.7	0.0	3.7	3.6	−4.3
FYM	−	276	304	9.9	9.0	11.5	27.8	2.1	2.5	18.4	2.9	3.2	11.8
MSW	+	360	342	−5.0	13.6	13.5	−0.7	2.6	2.6	1.6	3.6	3.6	−0.8
MSW	−	281	300	6.6	9.1	11.3	24.2	2.1	2.4	13.0	2.9	3.2	9.3
CON	+	325	328	0.9	11.1	12.8	15.3	2.3	2.4	8.0	3.3	3.4	4.6
CON	−	214	234	11.2	6.3	7.9	25.4	1.6	1.8	17.9	2.3	2.6	16.0

Note: The normalized difference between observations and simulations (difference/observed mean) as g m^{-2} year quantify model efficiency.
Abbreviation: CON, control treatment with no OWP added.

P, and K are shown in Table 4. The RMSE of wheat C, N, P, and K diverges from the 1:1 line comparing simulations to observations by 21.7%–31.4%, and corn RMSE C, N, P, and K diverge by 13.6% –25.8% and the percent difference (observed-simulated) for wheat and corn mean C, N, P, and K was +13.4% and − 7% (Table 4). The major bias was a model overestimate of grain P for wheat and corn. Simulated and observed wheat and corn grain C, N, P, and K for all treatments (Figures S1 and S2) fall within 1 SD of the mean, suggesting no statistically significant difference in the comparison of observed and simulated mean values. Comparison of observed and simulated corn grain C, N, P, and K over time (Figures S3–S6) for the −N +OWP treatments show initial reductions in grain C, N, P, and K during the first 2 years followed by an increase in the C in grain with grain C, N, P, and K values similar to +OWP +N by the end of the experiment. The time series of wheat grain C, N, P, and K (Figures S7–S10) for the −N +OWP treatments show a general pattern of increasing grain C, N, P, and K with time; however, the values are always less than the +OWP +N treatments after 16 years. These results contrast with the corn grain C, N, P, and K for the +OWP +N and −N treatments where grain C, N,

TABLE 4 Across-treatment observed (obs) and simulated (sim) wheat and corn grain mean carbon (C), nitrogen (N), phosphorus (P), and potassium (K) (g m^{-2} year), root mean squared error (RMSE), ratio of RMSE to observed mean, and the normalized difference (difference/observed mean) between observed and simulated mean C, N, P, and K as g m^{-2} year quantify model efficacy.

Crop	Quantity	Grain C	Grain N	Grain P	Grain K
Wheat	Mean obs. (g m^{-2} per year)	318.22	10.84	2.27	3.17
Corn	Mean obs. (g m^{-2} per year)	402.52	11.25	2.34	2.94
Wheat	Mean sim. (g m^{-2} year)	282.01	10.85	2.29	2.97
Corn	Mean sim. (g m^{-2} year)	405.22	10.46	2.57	2.89
Wheat	RMSE (g m^{-2} year)	86.34	3.40	0.54	0.69
Corn	RMSE (g m^{-2} year)	54.87	2.29	0.61	0.59
Wheat	RMSE (% obs)	27.13	31.38	23.72	21.74
Corn	RMSE (% obs)	13.63	20.35	25.84	20.08
Wheat	Mean sim. (% difference from obs)	−11.38	0.03	0.90	−6.42
Corn	Mean sim. (% difference from obs)	0.67	−7.00	9.79	−1.52

P, and K content are similar for +N and −N treatments at the end of the experiment.

3.1.2 | Soil C, N, P, and K

The IROC-Century model effectively simulated the observed pattern of increasing SOC with time for all +OWP treatments, with SOC increasing more rapidly for BIO, FYM, and GWS than for the lower IROC MSW treatment, and a general pattern of higher SOC for the +N +OWP treatments (Figures 3a,b and 4). Soil organic C was relatively constant for CON +N and decreased with time for CON −N, as did total soil N. Total simulated soil carbon changes from 1998 to 2013, cumulative compost C inputs, and the ratio of carbon change to compost C inputs show the highest carbon storage for GWS (mean IROC = 76, 2242–2346 g C m^{-2}) and the lowest carbon storage for OMR (mean IROC = 45, 1376–1590 g C m^{-2}) and that soil C inputs are higher with +N OWP treatments compared to −N OWP treatments (Table 5). The ratio of carbon change to compost carbon inputs (Table 5) decreases from 0.52 to 0.55 for GWS and BIO with high IROC values (IROC = 76) to 0.37–0.45 for MSW (IROC = 45). The model performed similarly (Figure 4a) for the validation and calibration data sets (R^2 = 0.92 for GWS vs. 0.90 for the combined CON, FYM, MSW, and BIO treatments), while combined across treatment RMSE equals 211 g C m^{-2} (<5% of mean soil C).

The cumulative compost organic N input, inorganic N input, simulated change in soil organic N (from 1998 to 2013) and the ratio of total N inputs (organic compost N plus inorganic N) for all of the experiments show a clearly reduced accumulation of soil organic N from GWS to MSW (195–120) driven by reduced N added in the different composts (C:N ratio increasing from 14 in GWS to 22 for MSW) (Table 5). A comparison of the +N and −N treatments shows a clear pattern of greater accumulation in soil N for +N treatments. The control treatments show a pattern of carbon loss for the −N treatment (25 g N m^{-2}) and a slight increase for +N. The ratios of changes in soil organic N to total N inputs (organic plus inorganic N) are slightly lower for +N OWP treatments (0.42 vs. 0.36, respectively, for GWS −N and GWS +N) and are similar for the OWP additions except for slightly lower value for MSW (0.39 and 0.33) while the inorganic N CON +N treatment has only 8% of the N was found in the organic N pool (ratio = 0.08). The IROC-Century model explained most of the variability in observed organic N (Figure 4b, R^2 = 0.90 for GWS and 0.74 for CON, FYM, MSW, and BIO treatments combined) and the combined RMSE for organic N is equal to 27.5 g N m^{-2} (<7% of the mean soil N). A detailed comparison of the observed and simulated soil organic N for the different OWS treatments (not shown) shows that the model tended to overestimate soil organic N by 40–50 g N m^{-2} in 2013 for the +N and −N FYM and MSW treatments (no bias for BIO and GWS).

Observed and simulated total P, mineral P, organic P, and Olsen P for all the experimental treatments (Figure 5) increase with time for +OWP treatments with small differences for the +N and −N compost treatments. The GWS treatments had the highest P content because GWS compost P concentration was two to three times greater than for the other OWPs. Total P and mineral P decreased slowly with time for the CON treatments with and without fertilizer. Comparison of the simulated versus observed total P (have an R^2 = 0.93) (observed total P is only measured at end of experiment) and observed Olsen P versus model Olsen P (has an R^2 = 0.79). Simulated total P for the +OWP treatments was slightly higher (20–30 g P m^{-2}) for −N compared to +N treatments, while field observations followed an opposite pattern. Simulated mineral P for GWS (validation treatment) was higher than measured Olsen P, while total P simulations matched observations more closely (Figure 5).

TABLE 5 Simulated changes in soil carbon (C) and nitrogen (N) from 1998 to 2013 (all g m^{-2}), cumulative C and N inputs as organic waste products (OWP), cumulative inorganic N added as fertilizer, ratio of total change in soil C and N during the experiment to cumulative OWP C input and OWP+N N inputs, respectively

	BIO		GWS		FYM		MSW		CON	
	−N	+N	−N	+N	−N	+N	−N	+N	−N	+N
Compost C inputs	3918	3918	4343	4343	4064	4064	3757	3757	–	–
Soil C change (2013–1998)	2013	2165	2242	2346	1827	1983	1376	1590	–	–
Ratio of soil C change to compost input	0.5	0.55	0.52	0.54	0.45	0.49	0.37	0.45	—	—
Compost N inputs	340	340	410	410	295	295	242	242	—	—
Inorganic N input	55	156	55	156	55	156	55	161	55	192
Soil N change (2013–1998)	176	189	193	201	149	162	115	133	−85	+8
Ratio of soil N change to total inorganic plus organic N inputs	0.45	0.38	0.42	0.36	0.43	0.36	0.39	0.33	−0.50	+0.08

Abbreviations: BIO, biowaste compost made from green waste and organic municipal waste; CON, control treatment with no OWP added; FYM, farmyard manure; GWS, composted green waste mixed with wood chips and sewage sludge; MSW, composted municipal solid waste comprised of dry and clean packaging and lawn waste.

Total simulated soil K, secondary K, organic K, and mineral K and observed exchangeable soil K all increased with time for the +OWP treatments, with the highest soil K for BIO and FYM since the K content in the BIO and FYM was two to three times higher than GWS and MSW (Figure 6). Modeled mineral K and observed exchangeable K were the highest for FYM and BIO and decreased with time in exchangeable K for the CON treatments (both +N and −N). IROC-Century underestimated exchangeable K relative to observed mineral K for +N and −N CON and MSW treatments relative to observations ($R^2 = 0.59$) (Figure 6).

Figure 7 shows the cumulative (1998–2013) simulated NO_3^- leaching for the +N OWP and −N OWP treatments. IROC-Century-simulated annual NO_3^- leaching (Figure 7) was the lowest for CON and much higher for the +OWP +N treatments with the highest leaching rates in the GWS treatment followed by the BIO, FYM, and MSW treatments, consistent with the observed decrease in organic N cumulative additions going from GWS to MSW (410 g N m^{-2} for GWS to 242 g N m^{-2} for MSW; Table 5). Comparison of +N and −N +OWP cumulative (156 g N m^{-2} vs. 55 g N m^{-2} cumulative inorganic N additions) treatment NO_3^- leaching rates (Figure 7) showed that the +N treatments had NO_3^- leaching rates that are 20%–40% higher than the −N treatments. Nitrate leaching was not measured at the site; however, Chalhoub et al. (2013) simulated NO_3^- leaching (GWS > FYM > BIO > MSW > CON). Like the Chalhoub et al. (2013), PASTIS simulations were from the same field experiment.

3.2 | Simulated impact of fertilizer and compost types

IROC-Century simulations were conducted to figure out the optimal way to add OWP and N fertilizer (Figures 8–10) to maintain maximum crop production while adding the least amounts of OWP and N fertilizer. Comparison of simulations of biennial additions of GWS, BIO, FYM, and MSW with +N ending in year 6 shows that corn (Figure 8a) and wheat grain C (Figure 8b) are the highest for the GWS treatment followed by BIO, FYM, and MSW. The results for corn C show little change for GWS after fertilizer application is stopped (year 6); however, corn grain C decreases for BIO, FYM, and MSW immediately after fertilizer is stopped, with the largest drop in MSW. All the OWP treatments show similar corn grain C after 12 years of adding OWP. The wheat results (Figure 8b) show that dropping the fertilizer after 6 years results in substantially reduced wheat grain C for all OWP types (40%–50% with highest drop for MSW), a general upward trend in wheat

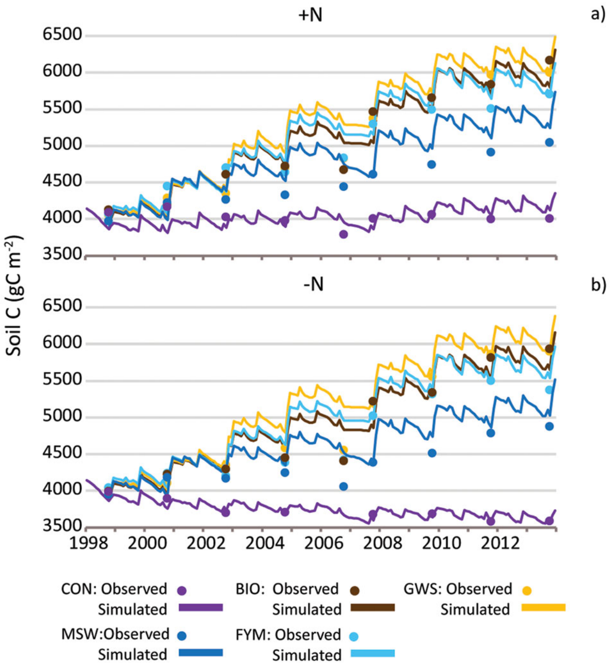

FIGURE 3 Simulated changes in soil carbon (C) for the four different types of organic waste products (OWP) (biowaste compost made from green waste (prunings, leaves, and grass) and organic municipal waste—biowaste compost made from green waste and organic (BIO), composted municipal solid waste composed of dry and clean packaging and lawn waste—composted municipal solid waste (MSW), composted green waste (mainly prunings and refuse screenings) mixed with wood chips and sewage sludge—composted green waste mixed with wood chips and sewage sludge (GWS), and farmyard manure—FYM) +N and −N treatments. Observed soil C data are compared with results from Indicator of Residual Organic Carbon (IROC)-Century simulations.

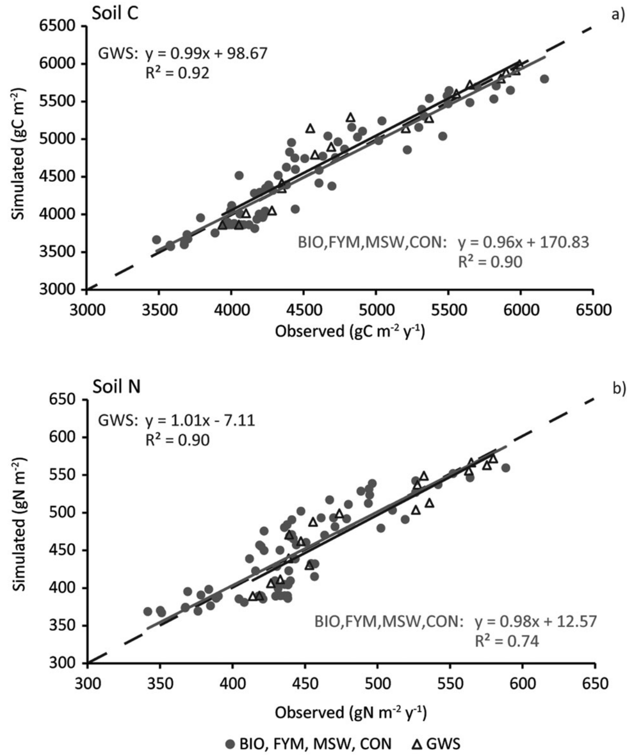

FIGURE 4 Comparison of observed versus simulated soil carbon (C) for all treatments (a), the combined treatment C R^2 point comparison of the observed versus simulated soil C and the combined R^2 comparison of the observed versus simulate soil nitrogen (N) (b). The data for the validation site composted green waste mixed with wood chips and sewage sludge (GWS) are shown in red, while the data from all the other sites are shown in blue. The solid line is the best fit regression line, and the dashed line is the 1:1 line.

grain with time after year 6 for all treatments but never reach maximum grain C values. Soil C increases with time for all the OWP treatments with GWS and BIO having the highest increases in soil C (Figure 8c). Soil NO_3^- leaching is also the greatest with GWS and BIO (Figure 8d). The drop in wheat grain C for the OWP treatments after stopping N fertilizer additions is consistent with the results from Table 2 which show that N fertilizer additions are needed to maintain maximum wheat grain C for all OWP treatments. The higher grain C for the GWS and BIO OWP additions can be explained by the higher N additions associated with these treatments (Table 5).

IROC-Century scenario simulations of the impact of adding N fertilizer (+N) for different time periods in combination with adding OWP biennially are shown in Figure 9. We chose the MSW OWP additions since the results from Figure 8 showed that it was highly responsive to reducing N fertilizer additions to the system. For the MSW treatment (Figure 9a) ratio of corn grain C with periodic +N to corn grain C with continuous +N drops to 0.8 initially for the −N simulation and then approaches 1.0 after 12 years of adding OWP. The ratio for 6-year fertilizer addition shows that the ratio drops to 0.9 for corn initially, after stopping the fertilizer additions, and then approached 1.0 after 12 years of adding OWP. Figure 9b shows that results for wheat grain C (0, 6, 12, 18, and 24 years of adding fertilizer) with the ratio of wheat grain C to maximum wheat grain C dropping to around 0.6 after fertilizer additions are stopped for all the simulations. The ratio is slightly higher for the simulations with longer time periods of adding fertilizer but does not change substantially with longer time periods with added OWP.

The simulated impact of the fertilizer treatments on SOC (Figure 9c) shows SOC increase with time for all treatments with SOC increasing more rapidly for the simulations with longer time periods of applying fertilizer, because of increases in the amount of C added to the soil (wheat and corn production are higher for the 24 years fertilizer simulation vs. the −N simulation). The greater the duration of fertilizer addition, the higher the cumulative NO_3^- leaching (Figure 8d).

Following 12 years of biennial additions of MSW with annual fertilizer additions, corn grain C show little change

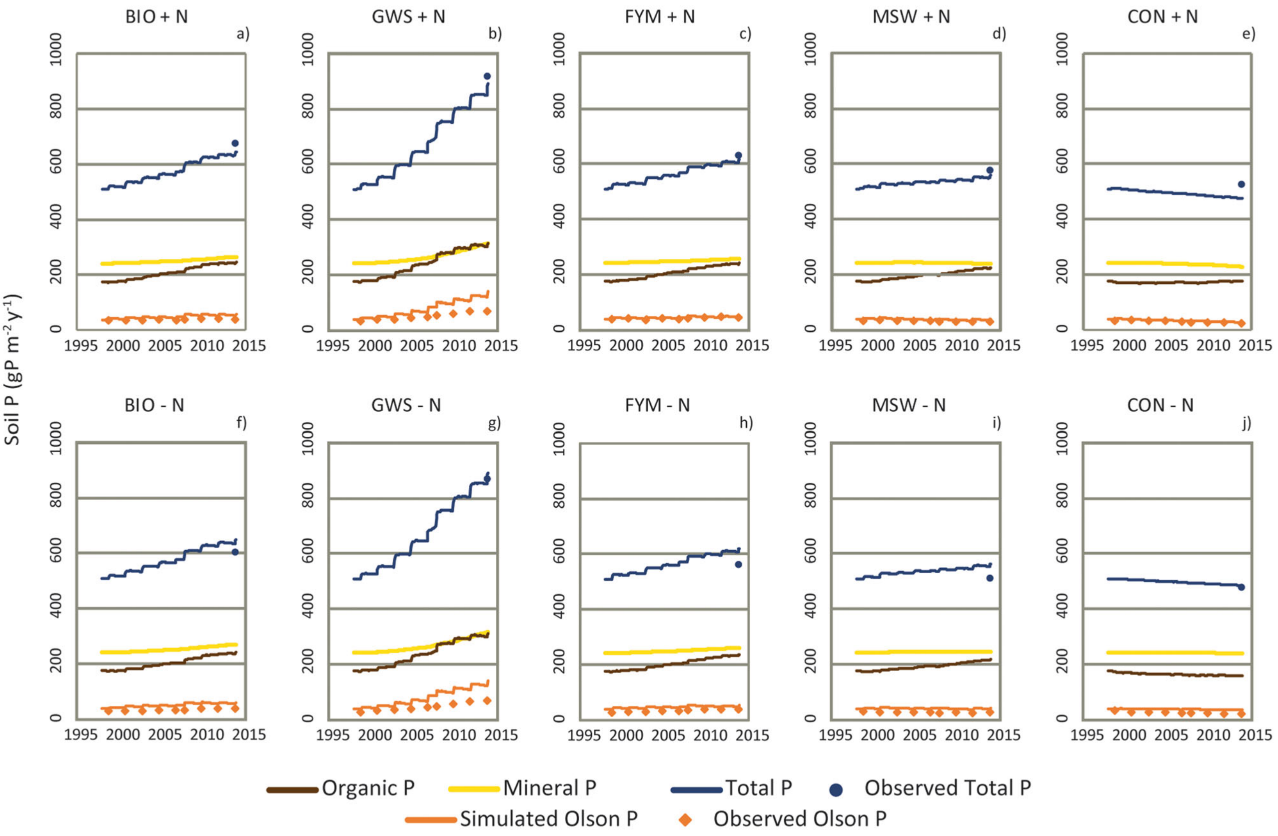

FIGURE 5 Comparison of observed versus simulate time series of observed total phosphorus (P), secondary P and mineral P with observed total P and Olsen extractable P for all the different treatments.

when continuing biennial additions of MSW whether fertilizer is applied or not (Figure 10a), while wheat grain C are much higher for the +N simulation compared to the −N (Figure 10b). Soil C remains relatively stable with biennial MSW additions whether fertilizer is applied or not, but soil NO_3^- leaching is higher for the +N simulations. Reducing the frequency of MSW addition from every 2 to every 8 years (−N, Figure 10) reduced corn and wheat grain C (more impact on wheat), and reduced soil NO_3^- leaching and SOC. For the 4-year +MSW treatments (+N and −N), adding fertilizer greatly enhances wheat grain C (slightly lower than 2-year +MSW +N simulation), has a minor impact on corn grain C, and increases soil NO_3^- leaching and SOC. Therefore, combining the addition of fertilizer for the wheat crop with the 4-year OWP additions can result in stable soil C and maintain wheat and corn grain C near maximum grain C, achieved under maximum fertilizer addition.

4 | DISCUSSION

Extensive, high-quality data, like those coming out of the QualiAgro experiment, are rarely available for model calibration of plant production (grain, roots, and straw) and crop nutrient uptake for N, P, and K. In addition, QualiAgro maintains detailed chemical composition measurements for four OWP types that allowed us to robustly parameterize and validate a new IROC-Century model, which allows added OWP to be partitioned into slow versus structural pools based on the biodegradability of the material (measured by the IROC). Rasmussen and Parton (1994) found that Century effectively simulated the impact of adding manure to wheat production systems in Oregon with increases in soil C and N, nutrient mineralization, and plant production, as did Paustian et al. (1992) for wheat production systems in Sweden. Similarly, a comparison of observations from the QualiAgro experiment with the IROC-Century model shows that model correctly simulates the impact of adding OWP every 2 years, the separate impact of adding fertilizer, the interactive impact of combining fertilizer with OWP, and the impact of OWP quality, as quantified by IROC, on grain C content and nutrient uptake (R^2 = 0.77, 0.65, 0.53, 0.52 for C, N, P, and K, respectively), soil C (R^2 = 0.92) and soil mineral N, P, and K (R^2 = 0.79, 0.93, and 0.59 for N, P, and K). Mean grain C, N, P, and K for all of the experiments showed that the observed means for grain wheat and corn C, N, P, and K are not statistically different from the simulated mean values, that the across-site maximum difference between the simulated mean

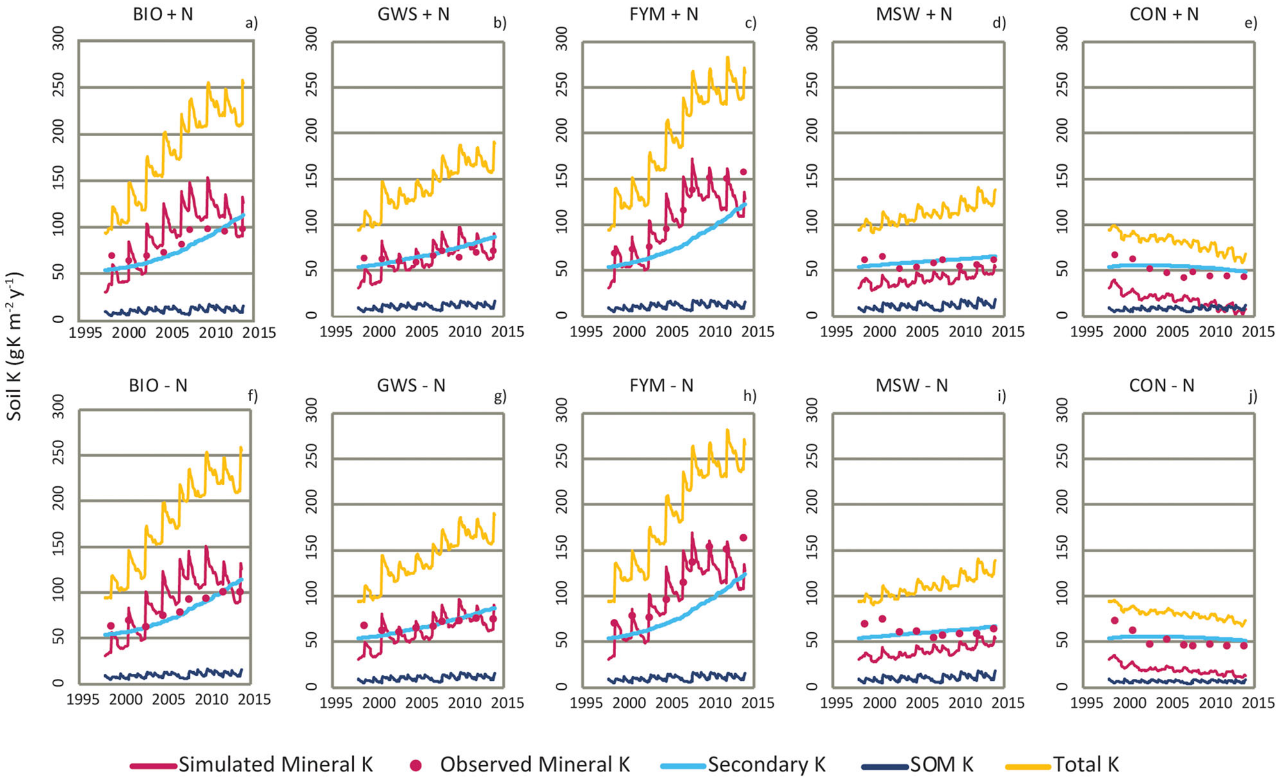

FIGURE 6 Comparison of observed versus simulated time series of total potassium (K), secondary K, and mineral K with the observed extractable K for all treatments.

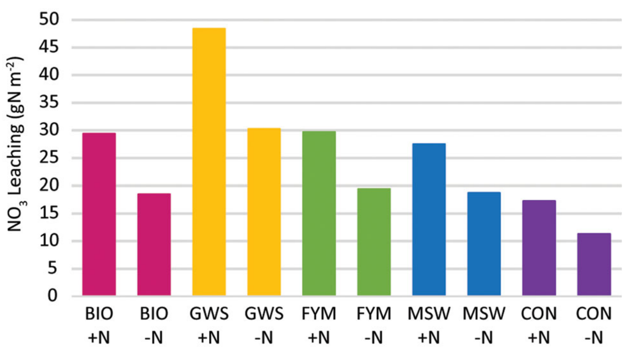

FIGURE 7 Indicator of Residual Organic Carbon (IROC)-Century Annual soil NO_3^- leaching (g N m^{-2} per year) for the fully fertilized (+N) (a) and unfertilized/minimally fertilized (−N) treatments (b) for all organic waste products (OWP) types.

grain C, N, P, and K and observed mean grain C, N, and K is less than 14%, and the RMSE for the soil C and N is less than 7% of the mean soil C and N levels. As mechanical cultivation is identical across treatments, and fertilizer (N) additions were designed to virtually eliminate N limitation in the system, crop production is maximized and not impacted by cultivation effects. Model results show higher total P for the −N treatments likely because crop P uptake is lower for the −N treatments (Tables 2 and 3) compared to the +N treatments, as fertilizer increases crop production and uptake of P from the soil, added via OWP. It is unclear why the observations show the opposite. The IROC-Century model effectively simulates ecosystem impacts (soil C and N, NO_3^- leaching, and grain C, N, P, and K content) of adding OWP and inorganic N fertilizer on this agricultural system and may be used to elucidate possible future impacts of altering the frequency of OWP and fertilizer (N) amendments.

Major conclusions about the simulated ecosystem impacts of adding different types of OWP (GWS, BIO, MSW, and FYM) are that the soil carbon stabilization of added OWP declines with higher values of IROC and that the N, P, and K concentration of the added OWP is the major factor controlling the amount of N, P, and K stabilized in the soil. The fraction of added GWS compost was the highest (0.55 with IROC = 76) and decreased with lower IROC 0.37 for MSW (IROC = 49) likely, as a result of adding more structural plant material and less stable, chemically and physically recalcitrant slow SOM (Figure 1) with decreasing IROC. The model results and observed experimental results showed that the amount of N, P, and K stabilized in the soil was positively correlated to the N, P, or K content of the added OWP (Tables 1 and 5 and Figures 5 and 6). Additionally, the amount of N stabilized in the soil was much greater when it was added as organic N (>30%) compared to inorganic N (<10%). Long-term organic matter experiments in Sweden and Oregon (Paustian et al., 1992; Rasmussen et al., 1996) show the

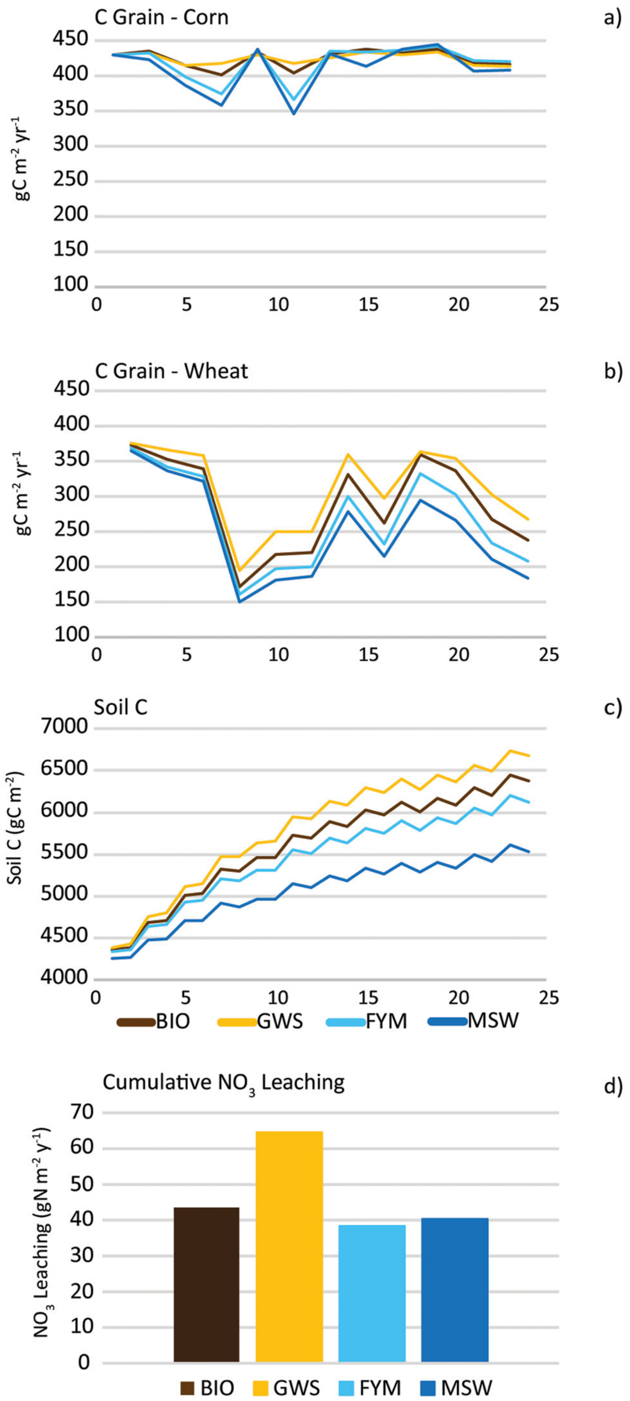

FIGURE 8 Indicator of Residual Organic Carbon (IROC)-Century simulated 24 years time series of corn grain carbon (C) relative to maximally fertilized corn grain C (a), wheat grain C relative to maximally fertilized wheat grain C (b), soil C (c), and soil NO_3^- leaching (d) for the biowaste compost made from green waste and organic municipal waste (BIO), farmyard manure (FYM), composted green waste mixed with wood chips and sewage sludge (GWS), composted municipal solid waste (MSW) + organic waste products (OWP) simulations where fertilizer was added for the first 6 years.

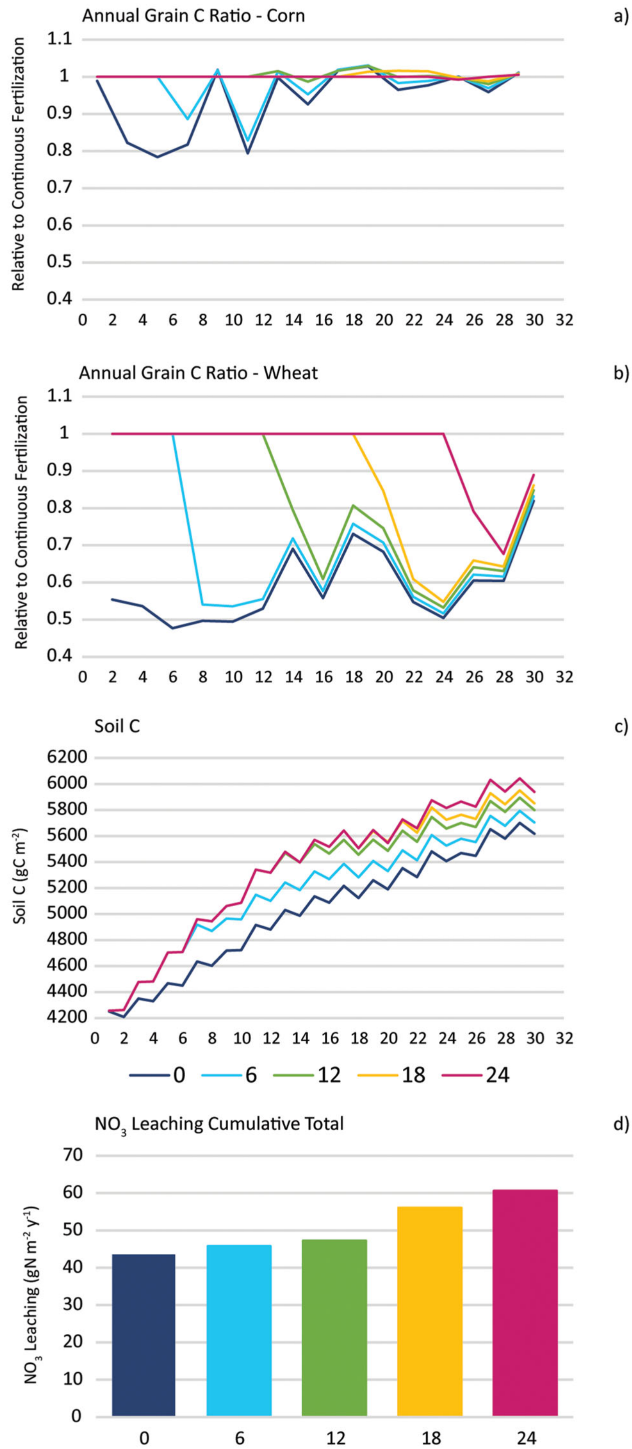

FIGURE 9 The effects of 30 year Indicator of Residual Organic Carbon (IROC)-Century scenarios for different fertilizer addition time periods (0, 6, 12, 18, and 24 years) on the ratio of corn grain carbon (C) to maximum fully fertilized corn grain C (a), the ratio of wheat grain C to maximum fully fertilized wheat grain C.

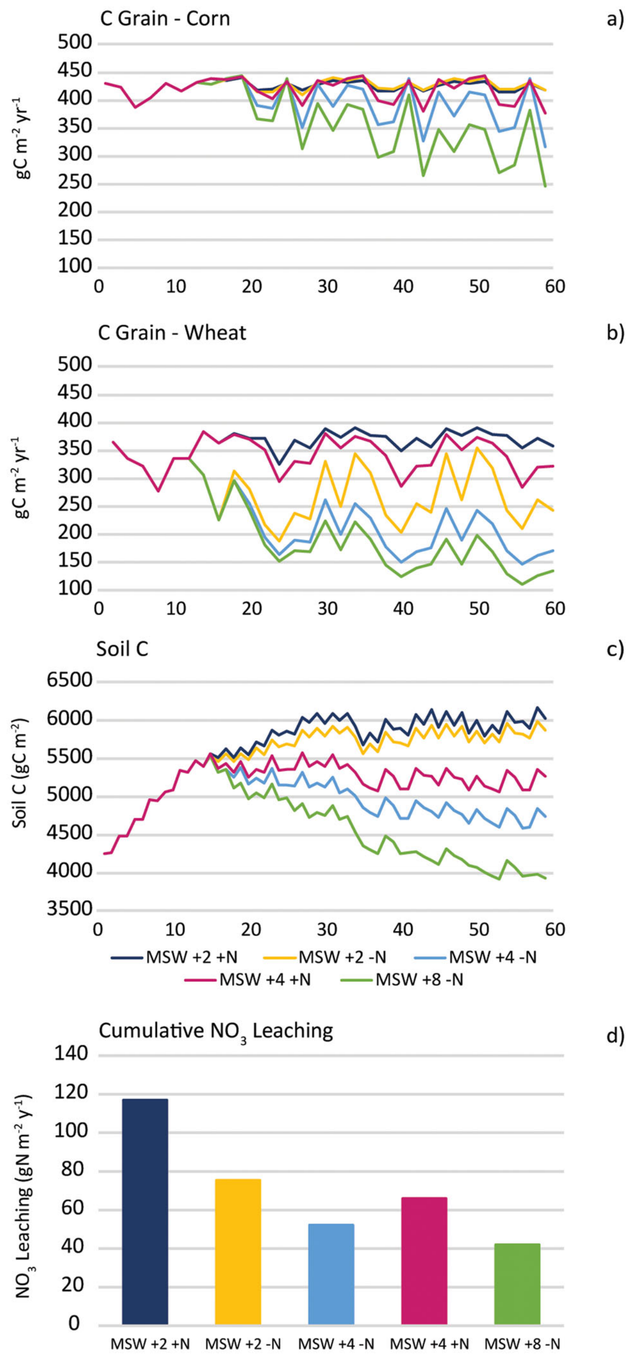

FIGURE 10 Simulated management scenarios using Indicator of Residual Organic Carbon (IROC)-Century for a 60 year corn/wheat rotation showing (a) corn grain carbon (C), (b) wheat grain C, (c) soil C, and (d) soil NO_3^- leaching for composted municipal solid waste (MSW) organic waste products (OWP) addition where MSW OWP was added biennially for the first 12 years with fertilizer (+N) followed by different frequencies (every 2, 4, or 8 years) of OWP addition with (+N) and without (-N) N fertilizer.

same patterns of higher N stabilization for organic matter additions with higher N organic matter and higher N stabilization for organic N additions compared to inorganic N additions.

Amending soils with OWP will, in most cases, result in increases in soil C and N, available soil N, and plant production, as shown in both the long-term results from the QualiAgro study (Chalhoub et al., 2013; Levavasseur & Obriot, 2021) and our IROC-Century model results. The QualiAgro OWP experiment and IROC-Century results indicate that adding OWP biennially for 12 years increases soil C and N levels, grain C, and NO_3^- leaching, and that adding higher IROC OWP results in higher C in grain and soil C and N levels. Model results and observed data suggest that combining +N with OWP additions will increase corn grain C during the first 6–10 years, that maximum corn grain C can be maintained without +N after 10 years of adding OWP biennially, and that +N is needed to maintain maximum wheat grain C. Further, our simulated scenarios indicate that N fertilizer additions can be reduced after 12 years of adding OWP biennially without reducing corn grain C, and that continued +N is necessary for the wheat crop to maintain high winter wheat production, as the N demand of wheat versus corn grain is 50% higher (Tables 2 and 3). The model results suggest that the optimal long-term +N and OWP addition management is to add OWP biennially for 12 years, end +N after 10 years for corn production, maintain +N for wheat production, and reduce OWP additions to a 4 year frequency after 12 years. The combination of these practices maintains near maximum C in grain, and high levels of soil C, N, and P, and soil nutrient mineralization (N, P, and K), while also lowering NO_3^- leaching. Reducing the OWP addition frequency to one every 8 years causes a substantial reduction in grain C and soil C and N levels and would require adding more N fertilizer to maintain high grain C.

IROC-Century simulations and the QualiAgro experiments did not address the impact of compost and N additions on soil N_2O fluxes directly. However, Xia et al. (2020) performed a meta-analysis of the impact of adding manure to croplands and found that soil N_2O fluxes were similar for manure additions (similar levels of C and N additions to this study) and inorganic N fertilizer. This suggests that soil N_2O fluxes would be highest for the +N OWP addition treatments and lowest for the −N CON treatment, with the +N −OWP and −N +OWP landing somewhere in between. Given this, it is likely that the net greenhouse gas budget would be more favorable for the +OWP treatments than the +N treatments since +OWP treatments accumulated SOM during the treatment period. Ryals et al. (2015) showed that large compost additions (similar in magnitude to this study) to grasslands resulted in a net decrease in the greenhouse gas budget (with the impact being more favorable for higher C:N compost) because soil C storage increased much more rapidly than the increase in soil N_2O fluxes, suggesting that the net greenhouse budget could potentially be negative for the plus OWP treatments without N additions. Measurement of soil N_2O fluxes at the INRA-Veolia experiments would add a robust new validation point for global study of the impacts of compost and waste diversion projects on net GHG budgets.

The NO_3^- leaching rates for this experiment estimated by the PASTIS model (Chalhoub et al., 2013) and these IROC-Century simulations were similar with both studies suggesting that NO_3^- leaching rates were highest for GWS (highest IROC but highest N content and lowest C:N) and FYM. Ryals et al. (2015) found that adding compost to annual grasslands in California increased SOM by amounts that exceeded C from compost additions by increasing plant production (by more than 40% for 25 years after a single large compost addition). Palmer et al.'s (2017) soil modeling study similarly found that the major impact of higher SOC and N results from increases in OWP while increasing soil N mineralization and plant production (also seen in Paradelo et al., 2019).

The addition of OWP, especially composted, high-IROC materials, therefore, seems to be beneficial. Material that would otherwise become part of the waste stream, when treated appropriately to minimize pathogens and phytotoxic compounds (Sayara et al., 2020) and managed in conjunction with fertilizer (for wheat), can, as suggested by Paustian et al. (2016), increase soil C storage, thus mitigating climate change (although future studies must address potential impacts of increased trace gas production more directly [Verdi et al., 2018]), improve soil fertility and nutrient content, enhance grain C and nutrient status, and reduce dependence on commercial fertilizer while having little to no increase in NO_3^- leaching to groundwater relative to existing agricultural practices. This project directly addresses a number of pressing issues, including climate change and the municipal waste stream. Effective methods of combating both are badly needed, and this study provides a hopeful merging of solutions.

AUTHOR CONTRIBUTIONS

William J. Parton: Conceptualization; funding acquisition; investigation; methodology; supervision; writing—original draft; writing—review and editing. **Robin H. Kelly**: Conceptualization; data curation; formal analysis; supervision; validation; writing—original draft; writing—review and editing. **Melannie D. Hartman**: Formal analysis; methodology; software; writing—review and editing. **Agathe Revallier**: Conceptualization; data curation; investigation; methodology; writing—review and editing. **Ana Barbara Bisinella de Faria**: Data curation; formal analysis; validation; visualization; writing—review and editing. **Gabriela Naves-Maschietto**: Data curation; writing—review and editing. **Marie Orvain**: Resources; writing—review and editing. **Sabine Houot**: Writing—review and editing. **Maria Albuquerque**: Funding acquisition; project administration **Sebastian Kech**: Methodology.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

William J. Parton https://orcid.org/0000-0003-4151-7869
Robin H. Kelly https://orcid.org/0000-0002-9721-267X
Melannie D. Hartman https://orcid.org/0000-0002-0675-2292

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