A prominent role for precision composting in sustainable agriculture

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Abstract

Compost use in agriculture has the potential to increase the productivity and sustainability of food systems and to mitigate climate change. But the use of diverse compost types in unsuitable biophysical conditions cause uncertain outcomes for crop yields, soil organic carbon (SOC) and nitrous oxide (N_2O) emissions. Here, we performed a global meta-analysis with over 2000 observations to determine whether a Precision Composting Strategy (PCS) that aligns suitable composts and application methods with target crop and environment can advance sustainable food production. Eleven key predictors of compost (carbon-to-nutrient ratios, pH, salt content), management (nitrogen supply) and biophysical settings (crop type, soil texture, SOC, pH, temperature, rainfall) determined 80% of the effect on crop yield, SOC, and N_2O emissions. We estimate that a PCS could increase global cereal production by 354.5 Tg annually, approximately 1.7-times Africa's current cereal yield. We further estimate that annual Carbon sequestration could increase by 170.4 Tg Carbon, approximately 20% of the global potential of croplands. This points to a central role of PCS in current and emerging agriculture consistent with the United Nations' Sustainable Development Goals.

Introduction

Conventional agriculture relies on the intensive use of mineral fertiliser that returns only small amounts of carbon to soil[1]. Crop yields are impacted by declining soil fertility[2], and fertiliser losses from soil contribute much to the accumulation of excess reactive nitrogen (N) and phosphorus (P) in the biosphere[3]. Agriculture and associated land-use change generates almost one-quarter of global greenhouse gas (GHG) emissions[4]. Over the past two centuries, approximately 133 Pg of carbon has been lost from the organic carbon stores of agricultural soils[5]. Around one-third of agricultural soils are degraded[6], which contributes to global yield gaps of 32% for maize and 60% for wheat[2]. Action is needed to achieve the dual goals of doubling food production by 2050 from the 2010 production level and keeping global warming below the 1.5-2°C target of the Paris Agreement for Climate Change Mitigation[7].

Compost use is often considered an avenue to regenerate soil organic carbon (SOC) in croplands, to reduce the need for mineral fertilizers, improve yield[8–9], and to transition towards Circular Agriculture and the Sustainable Development Goals (SDGs)[10]. However, compost use can cause considerable trade-offs with large uncertainties for crop yields[11–14] and increased nitrous oxide (N_2O) emissions from soil[15–17]. Hence, a strategic approach is needed to deliver consistent and multiple benefits.

The often-unsatisfactory performance of compost can be attributed to three major changes when compared to its historical use. The first is compost type; in the past, locally derived compost feedstock comprised manure, agricultural residue, and household waste[18], while today's feedstock include food processing and industrial wastes, and sewage sludge[19–20]. The second change concerns agricultural systems and their biophysical context. High intensity cropping characterizes most global regions[1], which results in overfertilized (especially Europe and East Asia) and carbon depleted soils (especially Africa and global tropics)[1,6]. Climate variability is intensifying with more pronounced drought, flood and temperature extremes impacting agriculture[21]. The third change concerns the application methodology. Historically, compost was often the only input into cropping systems, while today compost is often accompanied by mineral fertilizers and soil with a profoundly altered physical, chemical, and biological makeup[22].

The changing and diversity of global cropping system is at odds with compost as an often generic product that does not target specific crop needs or biophysical settings. Previous research has generally focused on providing an optimal amount of compost for a single effect (e.g., crop yield, SOC, water relations, low N_2O emissions)[23–25], with complex interactions receiving less attention. Diagnosing the configurations that generate unsatisfactory or desirable outcomes will form the basis for designing precision composts that deliver multiple benefits.

This need motivated our study, and we chose the response indicators (i) crop yield, (ii) SOC and (iii) N_2O emissions to examine compost use with view of food security, soil fertility and GHG footprint. We hypothesized that matching specific composts with specific biophysical conditions and application methods generates superior outcomes, which we termed "Precision Composting Strategy (PCS)". To test this, we built a global database of over 2000 observations to quantify the effects of compost use with meta-analysis methodology by comparing the use of mineral fertilizer and two categories of compost (compost-only, compost + mineral fertilizer). The meta-analysis demonstrated strong variability and uncertainty of compost effects. To address the determinants of PCS, we used boosted regression tree statistics to quantify the relative importance of contributing factors including compost characteristics, fertilization regime, crop type, soil, and climate. Lastly, we established a theoretical concept of PCS and estimated regional and global benefits for yield and SOC.

Main Text

The current compost agronomy carries uncertainties

Variable rather than comprehensive benefits were identified by our global synthesis of current compost use. While compost application in croplands can be effective for SOC sequestration, it carries large uncertainty for crop yield and N_2O emissions. Overall, 90% of all experiments detected improved SOC (Extended data Fig. 2b). Compost only (CO) or compost+mineral fertilizer (CM) increased SOC by 36.8% and 32.0% when compared to mineral fertilizer (MF) (Fig. 1a). This sharpens findings of previous meta-analyses with smaller sample sizes and geographic range that calculated SOC increase of over 40% (Extended data Table 2). The average crop yield in 61% of CO experiments was negatively affected with 10% lower yields than with MF (Fig. 1a, Extended data Fig. 2a). Although CM generated on average 15.7% higher yield than MF, 24% of experiments had lower yield (Fig. 1a, Extended data Fig. 2a). Of the 82 and 109 experiments with CO and CM that quantified yield and SOC, only 30.5% and 70.6% (25 and 77 experiments), respectively, found that both yield and SOC improved (Extended data Fig. 3).

Many studies contest the notion that organic soil amendments can mitigate GHG emissions because N_2O emissions can increase in the presence of labile organic C[26-27]. Our results indicated that compost (CO, CM) did not stimulate N_2O emissions in line with a previous meta-analysis based on a relatively small number of observations (Fig. 1a, Extended data Table 2). Compost strongly influences the variability of N_2O emissions when compared to MF, ranging from 13.4% lower to 20.5% higher (CO, 95% CI) and from 8.0% lower to 26.6% higher (CM, 95% CI) (Fig. 1a). Together, these findings are evidence that the potentially comprehensive benefits derived from compost use are not being realized.

Uncertainties at regional and temporal scales were detected. CO had lower yield than MF in most regions, except in Africa and South America where CO and MF had similar yields (Fig. 1b). CM improved crop yield in most regions, but the effect size varied greatly from a 48.6% increase in Africa to a 4.7% increase in Europe. CO increased SOC similarly across regions while the effect size of CM spanned from 86.5% SOC increase in Africa to 6.4% in Australia (only 6 observations, Fig. 1c). Strong regional variation was also observed for N_2O emissions with lower emissions in Africa (CO), similar (CO, CM) in most regions (Asia, Europe, North America) and higher emissions in Australia (CM) compared to MF (Fig. 1d). It is worth noting that except for Asia (CM, 41 observations), most regions had few (6-15) observations for N_2O emissions.

Our analysis did not confirm the often-reported positive relationship between the duration of compost application and crop yield (Extended data Fig. 4a). CO generated 10.9% lower yield than MF in short term use (<3 years) but produced similar yield as MF in medium-term (3-10 years) and long-term use (>10 years, only 12 observations) (Fig. 1e). In contrast, CM significantly increased yield in short-term (16.3%) and medium-term use (12.3%), while long-term use had similar yield as MF. Although CO and CM increased SOC, there was no obvious net accumulation of SOC in the longer term (Fig. 1f, Extended data Fig. 4b). Short-term compost use of CO had similar N_2O emissions than MF, while long-term compost use appeared to stimulate N_2O emissions by 22.8% (Fig. 1g). With CM, N_2O emissions matched those of MF in short-term use and increased (26.9%) in medium-term use but were lower in long-term use (-19.2%).

Taken together, our global analysis robustly demonstrates that underperformance and variability, rather than comprehensive benefits, characterize compost use across regional and temporal scales. To innovate the use of compost, we propose a Precision Compost Strategy (PCS) that requires understanding of compost characteristics and their interactions with crop and biophysical settings.

Determinants of a Precision Compost Strategy

A boosted regression tree (BRT) analysis quantified 11 factors that impact the effect size of compost on yield and SOC (Fig. 2). To predict the effects, we considered site biophysical traits (crop type, soil texture, SOC, pH, temperature, precipitation), nitrogen (N) supply (relative supply with CO or CM to MF) and compost characteristics (C/N, C/P, pH, electrical conductivity EC). The correlation coefficient (R^2) of the relationships between the model-predicted effects, and the measured effects on yield and SOC with CO or

CM *versus* MF exceeded 0.80; i.e., together these factors explain over 80% of effects (Fig. 2c, f). A less comprehensive analysis was performed on N_2O with fewer data available.

Effect of nitrogen. Nitrogen supply was the primary yield-determining factor, contributing 17.8% (CO) and 37.2% (CM) (Fig. 2a-b), in line with the notion that optimal N supply guarantees yield[28]. To match the yields achieved with MF, CO demands up to 50% more N than MF, and CM up to 50% less N. At similar N supply, CO generated 9.7% lower yield than MF, and CM 4.9% higher yield (Extended data Fig. 5a). The strong yield-enhancing effect of CM at similar N supply can be attributed to a higher N use efficiency when combining slower and faster release organic and inorganic N, respectively (Extended data Fig. 6). To generate higher yield than MF, overall, the proportion of compost-N to total-N supply may range from 10 to 80% (Extended data Fig. 7a). Soils with different SOC demand different N regimes; for example for greatest benefits, the proportion of compost-N should be no more than 30% in very low SOC soil (<5.0g SOC/kg soil), but can approach 50% in high SOC soil (>15.0g/kg) (Extended data Fig. 7b,e).

Nitrogen supply was the third strongest factor for increasing SOC, contributing 15.4% (CO) and 13.1% (CM) (Fig. 2d-e). Nitrogen supply determines the rates of SOC accumulation and decomposition[29], and both insufficient[30] and excess N[31] can prevent SOC accumulation. SOC benefits with CM peaked when 6.5-times more N than MF was supplied (Extended data Fig. 8b), highlighting that optimal N supply will maximize net SOC accumulation. The balance between C and N input is an important factor for SOC accumulation[32], and the highest relative SOC benefit was observed with a ratio of C:N input of around 5.0 in very low SOC soil (<5.0g C/kg soil), 10-15 in low SOC soil (5.0-10.0g/kg), and 15-20 in moderate and high SOC soil (>10.0g/kg) (Extended data Fig. 9).

Effective reduction of N_2O emissions also relies on optimal N supply[33]. IPCC Tier 1[34] accounting assumes that 1.0% of N fertilizer is emitted as N_2O, similar to our calculated average of MF (0.9%) but twice the calculated averages of CO (0.44%) and CM (0.49%) (Extended data Table 3). Rather than assuming a linear increase of N_2O emissions with N supply, exponential increases can occur[35]. To lower N_2O emissions below those of MF, CO should supply 2.9-times less, and CM 1.2-times less N, than MF (Extended data Fig. 8c). Promisingly, at similar N supply CM resulted in 17.0% lower N_2O emissions than MF (Extended data Fig. 5c).

In summary, N is a strong determinant of the effects of compost on yield, SOC and N_2O emissions and trade-offs with higher N supply have to be considered. Sufficient N supply guarantees yield benefits but carries uncertainties for SOC and N_2O emissions mitigation. Optimal N supply with compost use must be accurately identified for different cropping systems (e.g., paddy *vs* upland production), application methods (e.g., subsurface *vs* surface) and compost characteristics (e.g., cattle *vs* poultry manure feedstocks). Similarly, initial soil SOC must inform the ratio of C and N input and the proportion of compost N to total N input.

Effects of crop and site characteristics. Compost effects depend on crop type, soil properties (texture, initial SOC, pH) and climate (mean annual temperature MAT, mean annual precipitation MAP), which together contribute almost 50% to yield (CO 45.8, CM 46.0%, Fig. 2a-b) and 60% or more to SOC (CO 60.0, CM 65.0%, Fig. 2d-e).

CO effects on yield differed significantly between crop types (Extended data Table 5) with lower yields compared to MF in vegetable (-18.8%), grain (-12.6%) and feed crops (-10.1%), variable yields in root and tuber crops (-6.6 to 4.9%), and higher yield in fruit crops (11.6%, only 7 observations) (Fig. 3a). Thus, CO benefits crops with longer growing periods and/or lower nutrient demand but not fast growing and nutrient demanding crops. The consistent yield increases achieved with CM, ranging from 13.1% in grain crops to 24.6% in fruit crops (Fig. 3a), confirm that the nutrient limitations observed with CO are preventable in all major crops. SOC benefits with CO depended on crop types with highest SOC gains observed in root and tuber (101.2%), feed (98.8%) and fruit crops (56.4%), and lower gains in grain (28.4%) and vegetable crops (27.2%). SOC benefits with CM were similar in root and tuber (36.9%), fruit (36.2%) and grain crops (32.1%), and greater than in vegetable crops (15.8%) (Extended data Table 5, Fig. 3g). The relatively lower SOC benefits with vegetable crops can be attributed to higher initial SOC content in soils under vegetable production[36], and potentially accelerated SOC decomposition in the presence of high N supply[37].

Yield and SOC were strongly influenced by soil properties (*P*<0.001; Extended data Tables 5-6). Compost benefited crops more on poorer textured soils (sandy, clay) and less on favorably textured soils (clay-loam, loam). While CO generated similar yield as MF on poorer textured soils, it strongly reduced yield on more favorably textured soils (clay-loam -16.1%; loam -32.5%) (Fig. 3b). CM strongly boosted yield (41.3 and 39.2%) on sandy and clay soils, but not on clay-loam and loam. The beneficial effects of compost on poorer textured soils can be attributed to improved soil physico-chemical properties (Extended data Fig. 6). SOC increased in the order sandy soil (CO 83.0%, CM 155.1%) > clay soil (CO 37.0%, CM 40.1%) > clay-loam soil (CO 24.1%, CM 23.5%) > loam soils (CO 20.8%, CM 16.3%) (Fig. 3h). The pronounced effect on sandy soils is expected as these soils generally have low initial SOC and therefore much potential for SOC gain. The strong SOC benefit on clay soil may be explained by the mineral matrix protecting organic C from microbial degradation[38].

We detected notable trade-offs of compost benefits on yield and SOC. In very low SOC soil (<5.0 g C/kg soil), compost resulted in the lowest yield (CO -19.9%, CM 15.6%), but the largest SOC benefits (CO 58.7%, CM 55.8%) (Fig. 3c,i). In high SOC soil (>15.0 g C/kg), compost generated comparatively the highest yields (CO -5.5%, CM 25.7%), but lowest SOC benefits (CO 23.7%, CM 10.9%). The low yield benefit in low SOC soil can be explained by low microbial activity resulting in slow decomposition and nutrient release[39]. The lowest SOC benefits occurred on high SOC soil possibly due to the negative relationship between the initial SOC of soil, a primary driver (CO 19.2%, CM 24.2%, Fig. 2d-e), and SOC benefits[40]. Thus, depending on initial SOC levels, specific compost must be chosen to achieve synergistic benefits as outlined below.

Compost benefitted yield more on acidic soil (pH<6.0) than alkaline soil (pH>8.0) or more neutral soil (pH 6.0-8.0). CO generated similar yield as MF on acidic and alkaline soil, and lower yield on neutral soil (-18.7%, Fig. 3d), while CM had the strongest benefit on acidic (27.8%) and neutral soil (11.0%) and similar yield as MF on alkaline pH soils. SOC benefits ranged from acidic soil (CO 77.6%, CM 60.5%), alkaline soil (CO 37.8%, CM 41.7%) to neutral pH soil (CO 27.2%, CM 22.2%) (Fig. 3j). Together, this confirms a pH amelioration effect of compost on soils with non-optimal pH for crops (Extended data Fig. 6), which is most pronounced for acidic soil as compost is generally alkaline (Extended Data Table 1).

Compost benefits were greater in tropical climate (MAT>20°C) with comparatively higher yields (CO -7.1%, CM 20.1%), than in cool climate (MAT<10°C; CO -20.1%, CM 8.8%) (Fig. 3e). SOC showed a similar trend with highest benefits in tropical (CO 44.2%, CM 35.9%) and warm climates (10°C <MAT<20°C) (CO 41.1%, CM 33.4%) than in cool climate (CO 24.5%, CM 21.9%) (Fig. 3k). The lower benefits of yield and SOC with compost use in cool climates is likely due to the slower nutrient release[39] and relative higher initial SOC in these soils[41].

Compost generated higher benefits in arid (MAP <500mm y^{-1}) and semi-arid climates (MAP 500-1000mm y^{-1}) than humid climate. CO produced similar yield as MF in arid climate, but lower yields in semi-arid (-10.6%) and humid climate (-16.7%; MAP >1000mm y^{-1}, (Fig. 3f). In contrast, CM benefitted yield more in semi-arid (21.3%) and humid climates (12.5%) than in arid climate (3.9%). CO benefitted SOC more in arid (55.3%) than in semi-arid (31.9%) and humid climates (34.3%) (Fig. 3l). SOC benefits with CM were higher in arid and semi-arid (34.2, 40.4%) than in humid climates (18.6%). The stronger benefits of compost in drier climate can be largely explained by improved soil water relations (Extended data Fig. 6), and SOC depleted agricultural soils[41]. In humid regions, compost only (CO) had lowest yield with possible reasons including fast growth of tropical crops and associated high nutrient demand, and heavy nutrient leaching form high rainfalls[42].

N_2O emissions were not significantly impacted by the factors outlined above. Emissions were mostly lower or matched those with MF (Extended data Fig. 10), likely because compost mostly generates less inorganic N which limits nitrification and denitrification[43].

We show that the properties of the crop-soil-climate system significantly influence how composts benefit yield and SOC, and how current compost use generates most benefit in crop systems with long growing periods, poorly textured and/or acidic soils, or warm, dry climates (Extended data Fig. 11). Questions remain about how to achieve the best outcomes with compost use. SOC gains in low SOC soil seem easily achieved but can SOC levels also be improved in high SOC soil and realize synergistic effects for yield and SOC? To address these questions, we explored the effects of compost characteristics.

Effects of compost characteristics. Together, compost characteristics (C/N, C/P, pH, EC) contributed 36.3% (CO) and 17.1% (CM) to yield (Fig. 2a-b) and 24.5% (CO), 21.9% (CM) to SOC (Fig. 2d-e).

The C/N ratio of CO emerged as the second most important factor (14.8% contribution) for crop yield (Fig. 2a). Generally, CO with low C/N ratio (<10.0) generated the same yield as MF and a high C/N ratio (>10.0) reduced yield (-7.5 to -16.9%, Fig. 4a). In contrast, CM with high C/N ratio produced 10.8-18.1% higher yields than MF (Fig. 4a), confirming that nutrient limitation imposed by CO can be offset by mineral fertilizer addition. Notably, the effect of compost C/N ratio on yield was impacted by initial SOC. In soil with very low initial SOC (<5.0g/kg soil), low C/N compost had the strongest yield benefits (CO 11.5%, CM 35.8% above MF), while in soil with high initial SOC (>15.0g/kg) high C/N compost achieved best outcomes with similar (CO) and 32.8% higher (CM) yield than MF (Fig. 4i-j). Low SOC soils generally have a lower inherent nutrient status and low C/N compost supplies more N to crops[44], while high SOC soils with higher nutrient status and higher C/N compost benefit N relations, including initial N immobilization by microbes[45-46].

Similarly, SOC benefit of compost was impacted by the initial soil SOC. Low C/N compost nearly doubled SOC on very low initial SOC soil (CO 106.2%, CM 88.3%) compared to high C/N compost (CO 40.3%, CM 34.7%) (Fig. 4k). On high SOC soil, this reversed as high C/N compost benefitted SOC more (CO 41.8%, CM 21.7%) than low C/N compost (CO 20.6%, CM 4.2%) (Fig. 4l). This confirms that depending on SOC status, soils require compost with different C/N stoichiometry. Nitrogen limitation in low SOC soil demands compost with lower C/N ratio, whereas C limitation in higher SOC soil requires higher C/N compost[47-48]. A further consideration is that higher SOC soil with higher C/N ratio has a higher fungal/bacterial ratio, which is favoured by higher C/N compost which in turn can favour SOC build up[49].

Acidic (pH<6.0) compost often resulted in less benefit, while neutral (pH 6.0-8.0) and alkaline (pH>8.0) compost tended to have better outcomes. Acidic compost had the lowest benefits with -24.3% yield (CO) and similar yield (CM) as MF (Fig. 4c), while alkaline (pH>8.0) CO and neutral (pH 6.0-8.0) CM generated best outcomes with similar (CO) and 25.7% higher (CM) yield than MF. Immature compost generally has higher acidity due to the presence of organic acids which can negatively affect crops, while mature compost is often weakly alkaline with a higher content of soluble N and other yield-benefitting substances (e.g., humic compounds)[9]. Overall, alkaline compost benefitted SOC more (CO 52.2%, CM 46.4%) than acidic compost (CO 23.0%, CM 25.2%) (Fig. 4g), in line with greater yield with alkaline compost (Fig. 4c). On acidic soil, a higher pH of CO had a significant (P<0.01) positive relationship with yield and SOC (Fig. 4m), confirming the pH amelioration effect. We examined if acidic compost has most benefits on alkaline soil, and while the limited data did not support this notion, recommend further exploration.

Compost EC significantly affected crop yield with CO (Extended data Table 5). CO with low EC (<2mS/cm) increased yield by 16.8%, while high EC (>4mS/cm) reduced yield (-26.5%) (Fig. 4d). The use of high EC compost, especially in larger amounts and over longer times as often practiced when compost is the only nutrient source (e.g., some organic production systems), causes salt accumulation in soil and diminishes yield as crops suffer water stress and salt toxicity[50]. High EC compost also negatively impacted the soil biological community and nutrient cycling[51]. Compost EC weakly affected SOC (CO

P=0.058, CM *P*=0.078, Extended data Tables 5-6) with low EC compost more strongly benefitting SOC (CO 66.9%, CM 30.5%) than high EC compost (CO 28.7%, CM 12.5%, Fig. 4h). Reasons for declining SOC benefits with increasing EC include reduced crop growth (Fig. 4d) and associated lower input of crop residues and negative impact on soil aggregation and protection of SOC from microbial degradation[52].

N_2O emissions were lower or matched those with MF and were not significantly impacted by compost characteristics (Extended data Fig. 12). We could not perform a group heterogeneity (QB) analysis for EC, with only one subgroup with CO and no studies with CM. However, CO with high EC stimulated N_2O emissions (25.4% above MF) (Extended data Fig. 12d), likely owing to a combination of factors that include inhibited crop growth, resulting N surplus, reduced soil aggregation and poorer soil aeration, all of which enhance the processes leading to N_2O emission[50-52].

In summary, the findings confirm our hypothesis that compost characteristics significantly affect the responses of the tested response variables in cropping systems. Matching the initial soil SOC, pH, EC with a specific compost is crucial to obtain the desired outcomes, and further research has to fill the knowledge gaps where current data cannot examine all scenarios.

A Precision Compost Strategy for sustainable agriculture

PCS is a conceptual innovation to advance the effective use of diversified composts in today's cropping systems that demand inputs of organic matter and nutrients. We envisage PCS to guide a systematic approach to achieve superior outcomes by matching compost characteristics, cropping system properties and application methodology (Fig. 5). Three principal steps in a PCS comprise (i) diagnosing local biophysical conditions, (ii), designing and producing specific composts targeting crop-soil-climate, (iii) supplying composts with optimal carbon and nutrient supplies (N, P, other essential and beneficial nutrients). Based on these principles, we estimated the potential benefits across global regions (Table.1, Supplementary Information).

In Africa, especially Sub-Saharan regions, yield and SOC are generally low and heavily constrained by nutrient input. Developing compost as a source of nutrients could be a critical strategy to improve soil fertility and crop productivity with best yield achieved with the combined input of organic matter and nutrients[53]. To deliver nutrients and build SOC, low C/N compost should be a priority. Suitable feedstocks for low C/N compost include crop residues (N-rich legume biomass), animal manure (poultry, pig), and municipal wastes (food waste, humanure). Low-cost composting techniques, such as open compost rows, can be implemented with limited infrastructure. Compost is likely to have most impact in drier regions where increased SOC can partially mitigate the impacts of climate change induced altered rainfall and temperatures[21]. We estimate that precision composting in Africa's croplands can increase cereal productivity by 82.5 Tg (40% of current production) and that annually 46.7 Tg C can be sequestered into SOC, which amounts to a 3.9‰ rate that approximates the "4 per 1000 initiative" for climate change mitigation (Table 1).

In Asia, we focus on China where most research on compost has been performed, crop yield is moderate, and low SOC and high N_2O emissions demand action. Contrary to Africa, China suffers nutrient excess[28]. To maximize compost benefits, reducing N input in cropping systems should be the first step, as this negatively impacts SOC buildup and stimulates N_2O emissions (Extended data Fig. 8b-c). Toxins in compost are derived from intensive livestock and industrial wastes, and high-quality compost requires clean feedstocks (separating clean and contaminated feedstocks) and controlling composting processes (e.g., adding heavy metal fixatives, ensuring adequate maturation periods[22]). For example, northeast China's high SOC soils demand high C/N compost and Southern China's acidic soils need alkaline compost. Since China has a considerable soil phosphorus (P) surplus[54], a P-based strategy should be adopted for compost use to avoid P oversupply[55]. We estimated that compost use in China can increase cereal production by 24.8 Tg (4% of current production) and annually sequester 27.9 Tg C into SOC, which amounts to a sequestration rate of 3.3‰ (Table 1).

Europe and USA have high crop yield and SOC, with moderate, stable or declining N_2O emissions. These regions have globally the most advanced nutrient and crop management[28] but can further benefit from an advanced compost agronomy (e.g., crop rotation, conservation tillage, manure recycling), to lead the way towards a Precision Compost Strategy to accurately match the needs of crops and avoid current N excess and pollution. Developing high C/N compost could be an important strategy to increase SOC. Suitable techniques and feedstocks for high C/N compost can be solid-liquid separation of livestock slurries that favor solid fractions with high C/N ratio, adding C-rich wastes (municipal green waste, forest industry wastes) as well as considering nutrient-dense food waste for nutrient delivery[56]. We estimate that compost use can increase crop productivity by 9% (Europe 47.0 Tg) and 14% (USA 60.6 Tg) above current production, and that annually 20.7 Tg C (Europe) and 19.6 Tg C (USA) can be sequestered into SOC, amounting to annual C sequestration rates of 1.0‰ (Europe, USA) (Table 1).

We estimate that globally, a Precision Composting Strategy can increase cereal production by 354.5 Tg, which is 1.7-times Africa's current production (Table 1). Composts in cropping lands could annually sequester 170.3 Tg C into soils, which achieves 17.0-22.7% of the total C sequestration potential of global croplands (0.75–1.0 Pg yr^{-1})[57]. Our estimated compost benefits on climate mitigation did not consider the wider environmental impact that include GHG emissions in upstream mineral fertilizer producing and composting processes. However, recent life cycle assessments (LCA) have demonstrated GHG savings with compost use based on manufacturing less mineral fertilizer, sequestering more SOC and curbing N_2O emissions[58-60].

Recycling biowastes into cropland soil is attracting attention as a win-win strategy for mitigating environmental impacts of cropping and enabling sustainable high production agriculture. The challenge is how to recycle and use biowaste efficiently. We present evidence that a global Precision Composting Strategy is a vital component of sustainable agriculture. This strategy could be accepted worldwide but has to after overcome various barriers (Supplementary Information) to advance circular agriculture with

greater crop productivity, higher soil fertility, greater resilience against climate change, and circularity of material flows in support of Sustainable Development Goals.

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Tables

Table. 1 Global Precision Composting Strategy (PCS) priorities and their estimated benefits for cereal production and SOC stocks of croplands. Detailed assumptions and calculations are shown in Supplementary Information.

Region	Priorities for PCS	Estimated benefits			
		Cereal production (Tg)	% change to current production	Cropland SOC stocks (Tg C y^{-1})	‰ change to current SOC stocks
Africa	• Low C/N compost for nutrient and SOC deficient soils • Compost to reduce climate change impact in drylands • Suitable low-cost composting techniques	82.5	40.4	46.7	3.9
China	• Lower N input to reduce current N excess • Lower P input to reduce existing P accumulation in soil • Clean feedstocks to avoid toxins	24.8	4.0	27.9	3.3
Europe	• High C/N compost for higher SOC soils • Design advanced compost strategies	47.0	8.7	20.7	1.0
USA		60.6	14.4	19.6	1.0
Global	• Compost+mineral fertilizer for optimized N supply • Prioritize compost use on poorly textured and/or acidic soils • Prioritize compost use in warmer or drier climate • Prioritize alkaline and lower EC compost • Low C/N compost for low SOC soil • High C/N compost for high SOC soil	353.5	11.9	170.4	1.3

Methods

Data selection

Peer-reviewed papers were searched for using ISI Web of Science, Google Scholar and China National Knowledge Infrastructure (CNKI, http://www.cnki.net) from Jan 1980 to Feb 2020. Search terms included “compost”, “compost addition”, “organic fertilization”, “organic amendment” or “manure” in combination with “mineral fertilizer”, “synthetic fertilizer”, “field application”, “long-term fertilization”, “crop yield”, “productivity”, “SOC”, “nitrous oxide”, “greenhouse gas emissions”, “nitrogen uptake”, “soil fertility” or “soil physical-chemical properties” in the article title, abstract, or keywords.

Relevant papers in our meta-analysis had to meet the following criteria: (1) the focus had to be field studies comparing mineral fertilizer (MF) and compost use; (2) to reflect the conventional use of mineral fertilizer by farmers, MF had to be applied as traditional mineral fertilizer (e.g., urea, ammonium nitrate, superphosphate, potassium sulfate or potassium chloride) and studies using eco-friendly and enhanced efficiency N fertilizers (e.g., inhibited/coated urea) were excluded; (3) to reflect farmer practices of compost use, compost had to be used only (CO) or combined with MF (CM), the MF in combination with compost was NPK fertilizer (Compost-NPK), or only one or two of NPK fertilizer; (4) the control (MF) and treatment (CO or CM) could have equal or unequal (lower or higher) total N, which can be used to determine the effect of fertilizer supply; (5) detailed descriptions of crops and field sites were provided (crop type, location, soil properties, climate conditions); (6) detailed information on management was provided including the application quantities of MF and CO/CM (some studies reported the application amount of compost by weight, we translated to nutrient input according to the nutrient content of compost) and duration fertilization; (7) compost characteristics were detailed (e.g., feedstock, total C, total N, total P, pH or EC); (8) target variables were reported (crop yield, SOC in topsoil, N_2O emissions), or other variables (e.g. N uptake, NUE, soil physical-chemical properties after the end of field trials) to confirm or explain compost effects; (9) data had to be used only once if same data appeared in in multiple papers. A total of 257 studies was selected (see Supporting Information with meta-analysis reference list).

Database

We extracted mean value and replications (n) of crop yield (kg ha^{-1}), soil organic carbon content (SOC, g kg^{-1}) and nitrous oxide (N_2O) emissions (kg N ha^{-1}) for treatments with MF and treatments with CO/CM in 257 selected publications. We compiled information on field site location and climate, background soil property, cropping system, fertilizer supply and duration, and compost characteristics that may have influenced the compost response, as well as information on NUE (%, defined as ratio of difference in crop aboveground uptake N with and without fertilization to total N supply), N uptake (kg ha^{-1}) that was used to calculate NUE (thus treatments with no fertilizer in relevant studies were also extracted), and some soil physical-chemical properties after experimentation that may confirm the compost effects.

Field site location included studying country, latitude and longitude. Climate included mean annual temperature (MAT, °C) and mean annual precipitation (MAP, mm). Background soil properties included studying topsoil depth (cm), soil texture (clay-silt-sandy content (%)), soil carbon content (SOC) and pH. Cropping system included open field and closed cultivation (e.g., greenhouse vegetables) and crop type (e.g., rice, wheat, maize, tomato). For fertilizer supply (kg ha^{-1} y^{-1}), we focus N supply as N is quantitatively the most important nutrient for many crops. We further calculated the relative N supply of CO/CM to MF, aiming to address the effect of N supply with compost use. Fertilization duration indicated number of years since compost use (for studies with only one crop season field trait that lasted less than one year, we recorded 1 year). Compost characteristics included total C, total N, total P content (%) (to calculate C/N ratio and C/P ratio), pH and EC (mS/cm). Soil physical-chemical properties after experimentation included soil bulk density (g cm^{-3}), water content (%) and pH.

These data were extracted from the main text, tables or figures (obtained from GetData Graph Digitizer software) in relevant publications, when available. If not available, latitude and longitude (28% of total observations) coordinates were derived from Google Maps using the name of field site (in cases where only a country name was reported, we extracted its capital city's coordinates), MAT (45% of total observations) and MAP (40% of total observations) were derived from a website that showing the world temperatures-weather (https://www.timeanddate.com/weather/) using site location coordinates (latitude, longitude), replication for treatments (9% of total observations) was derived from mean value for total studies (n=3). Data were left blank when information could not be obtained. The complete global compost effect database is available in Supporting Information, and the general description was as followed:

Studies were performed in 34 countries in all inhabited continents (most in Asia, followed by Europe, North America, Africa, South America and Australia) across a wide range of locations (36.6°S-56.5°N, 121.7°W-152.6°E), climates (MAT 16-4000 mm; MAT 2-45°C), and crop type (grain, feed, vegetable, fruit, roots and tubers), with most reports (64%) from grain cropping. Most studies (74%) had an experimental duration of less than 4 year. Mineral NPK (71%) dominated in MF treatment, and compost combined with mineral NPK (CNPK, 69%) dominated in CM treatment. Cattle manure dominated (30%) in compost feedstocks, followed by pig manure (14%), municipal sludge (12%), green waste (12%), crop straw (10%), poultry manure (9%), by-production (e.g., olive pomace, millet glume, spent mushroom, 8%) and others (5%). Most compost (75%) had processing durations between 50 and 90 days, with water content between 26.0% and 60.0%, total C content between 13.0% and 31.0%, total N content between 1.0% and 2.2%, total P content between 0.5% and 1.9%, C/N ratio between 9.5 and 18.5, C/P ratio between 11.6 and 37.2, pH between 7.2 and 8.9, and EC between 3.2 and 5.7 mS/cm (Extended Data Table 1).

Meta-analysis

The natural log of the response ratio (lnRR)[61] was calculated as the effect size: lnRR = ln (X_t / X_c), where X_t and X_c are the mean response value in treatment with compost (CO or CM) and treatment with mineral fertilizer (MF). As most studies did not show standard deviations (SD), individual effect size was not weighted by the inverse of the pooled variance, but weighted by replication[62], with weight = (n_t × n_c)/(n_t + n_c), where X_t and X_c are the number of replication in treatment with CO or CM and treatment with MF.

To explore the factors that affect compost effect, possible factors were grouped into different categories. Countries were classified into six categories: Asia, Europe, Africa, Australia, North America and South America. MAT was classified into three categories: cool (<10 °C y^{-1}), warm (10-20 °C y^{-1}) and tropical (>20 °C y^{-1}). MAP was classified into three categories: arid (<500 mm y^{-1}), semi-arid (500-1000 mm y^{-1}) and humid (>1000 mm y^{-1}). The thresholds for the classification of MAT and MAP were following previously described[63-64]. Background soil texture was classified into four categories: sandy, loam, clay loam and clay, following the international standard for soil texture classification[65]. Background soil SOC was classified into four categories: very low (<5 g kg^{-1}), low (5-10 g kg^{-1}), moderate (10-15 g kg^{-1}) and high (>15 g kg^{-1}). The thresholds for soil SOC were set by distribution of data, with ~23% of data for very low SOC soil, ~30% of data for low SOC soil, ~26% of data for moderate SOC soil, and ~21% of data for high SOC soil. Background soil pH was classified into three categories: acidic (<6), neutral (6-8) and alkaline (>8). Crop type was classified into six categories: grain, feed, vegetable, fruit, roots and tuber, and others, according to classification in FAOSTAT[66]. N supply with CO/CM was classified into five categories: lower N supply (≥50% reduced and <50% reduced), similar N supply and higher N supply (<50% increased and ≥50% increased) with CO/CM than MF. Fertilization duration was classified into three categories: short (≤3 y), moderate (3-10 y) and long (>10 y) term duration, following previously described[67]. Compost C/N ratio was classified into three categories: low (<10), moderate (10-20) and high (>20). The C/N ratios of 10 and 20 was set as criterion for low and high C/N compost based on previous study[68]. Compost C/P ratio was classified into three categories: low (<15), moderate (15-30) and high (>30). We chose lower (15) and upper (30) thresholds for C/P ratio because most data were distributed in this range, with ~30% of data <15, and ~70% of data <30. Compost pH was classified into three categories: acidic (<6), neutral (6-8) and alkaline (>8.0). Compost EC was classified into three categories: low (<2 mS/cm), moderate (2-4 mS/cm) and high (>4 mS/cm). The EC maximum level of 4 mS/cm was previously stated as the safe limitation in field compost use[9], thus was set a threshold for high EC compost.

We used MetaWin 2.1 to calculate the mean effect sizes and 95% bootstrapped (4999 iteration) confidence intervals (95% CI), and the heterogeneity between groups (QB), with random effects model[69]. Treatment effects were considered significant if the 95% CI does not include 0. A significant (**P*<0.05, ***P*<0.01 and ****P*<0.001.) QB indicates treatment effects was significantly affected by a given explanatory factor (e.g., N supply, background soil SOC) (Extended Data Table 4-7). When we calculated the effect of MAT and MAP, only outdoor field production studies were included and closed cultivation systems (e.g., greenhouse vegetables) excluded as not aligned with outside MAT and MAP.

The results were back-transformed and reported as percentage change of response variables (e.g., crop yield, SOC and N_2O emissions) with CO/CM relative to MF, according to $(e^{\ln RR}-1)\times 100\%$. A significant positive percentage change indicated that compost use increased the response variables.

Boosted regression tree analysis

Boosted regression tree (BRT) analysis[70] was performed to quantify the relative importance of crop type, background soil property (texture, SOC and pH), climate (MAT and MAP), N supply, and compost characteristics (C/N ratio, C/P ratio, pH and EC) on crop yield and SOC. We did not test the effect of N_2O emissions with BRT because of the paucity of data (only 40 observations with CO, 54 observations with CM). With the expectation for crop type and soil texture which were discrete variables, other factors were using continuous variables to fit BRT model (only open field system was checked as it may influence predictors with MAT and MAP).

Parameter values used for the BRT analysis referred to a previous study[71]. Cross validation (CV) was set as 10. A Gaussian error was used. Tree complexity, learning rate, step size and bag fraction was set as 2, 0.01, 50 and 0.75, respectively. To obtain the best model with minimum error, we set a range number of regression tree from 2000 to 8000 to train this model, and the final best model had number of regression tree at 5600 for yield with CO, 6750 for SOC with CO, 4150 for yield with CM, and 2600 for SOC with CM. The relative importance of each factor indicated a percentage of the total variation explained by the models. The BRT analyses was performed in R version 3.6.3 with "*gbm*" package plus the "*dismo*" package[72], with available R code given in Code Availability.

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Declarations

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Author contributions W.Z. conceived the research and established the methodology. W.Z. S.Z. proposed the PCS concept. S.Z. collected and analyzed the data. S.Z. S.S. W.Z. illustrated the figures and tables. S.S. S.Z. G.H. T.L. C.X. Y. H. D.C. J.T. Z.D. W.Z. and F. Z. wrote the manuscript.

Competing interest declaration The authors declare no competing interests.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to W.Z. (wfzhang@cau.edu.cn).

Figures

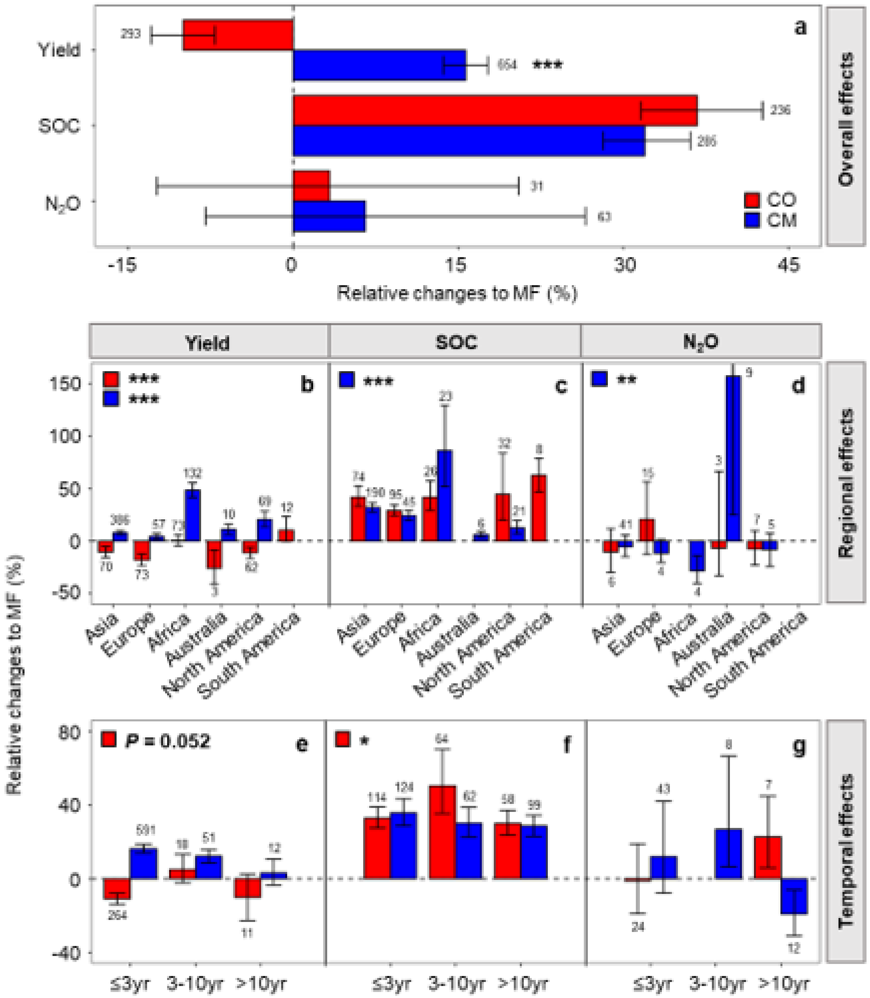

Figure 1

Effect of compost use in global and regional contexts, and length of time of -space scale. a Overall effects of compost (CO) and compost+mineral fertilizer (CM) relative to mineral fertilizer (MF) on crop yield, soil organic carbon (SOC) and N2O emissions from soil (a). b-d Regional effects on yield (b), SOC (c) and N2O emissions (d). e-g Effects of duration of compost use on yield (e), SOC (f) and N2O emissions (g). Values are mean effect sizes with 95% confidence intervals (CI). The number of observations is shown above bars. Mean effect sizes (i.e., relative change in yield, SOC or N2O emissions compared to MF) are considered significant if the 95% CI does not include 0. A ratio of 0 (dotted line) indicates no difference between CO or CM and MF. Values larger (>0) or smaller (<0) than zero indicate higher or lower values with CO or CM than with MF. *P<0.05, **P<0.01 and ***P<0.001 indicate significant differences between CO and CM (a), between regions (b-d) and duration of compost use (e-g).

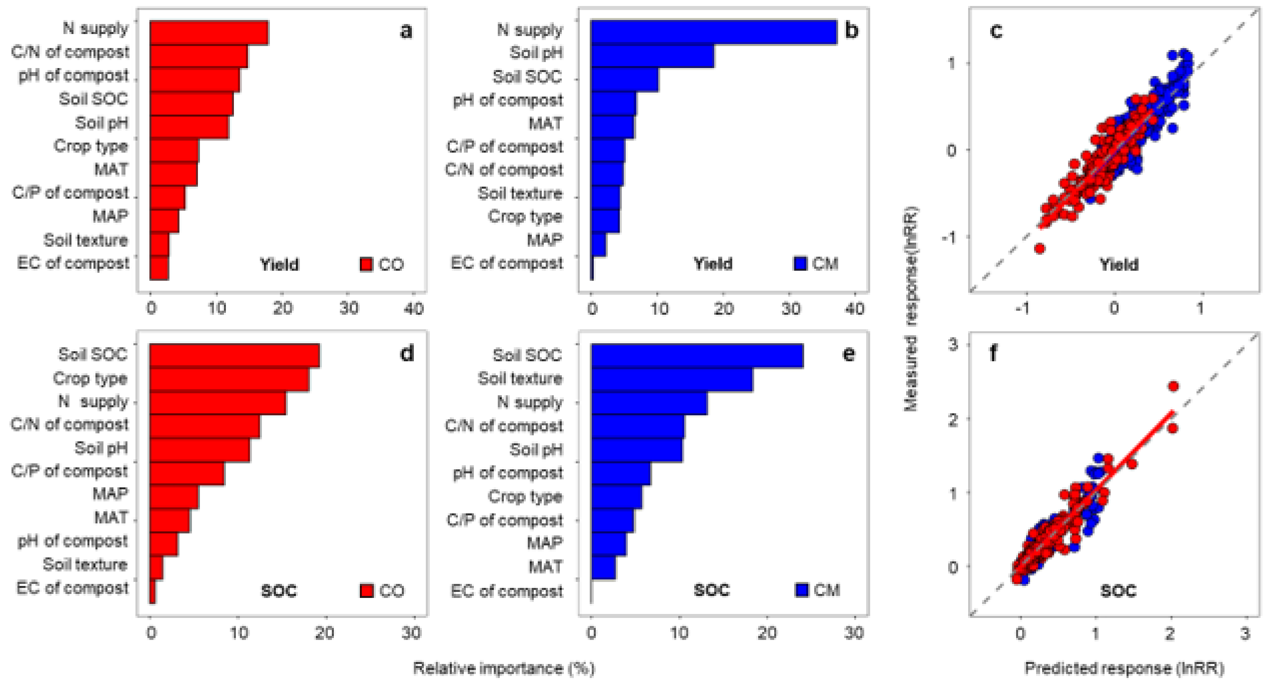

Figure 2

Boosted regression tree analysis (BRT) identifying the relative importance of contributing factors that drive the effects of compost on yield and SOC. a-b Relative importance of the main factors on yield with compost (CO, a) or compost+mineral fertilizer (CM, b). Relationship between model predicted and measured effect on yield (c); Relationship with CO: measured response of yield (response ratio lnRR) = 1.076 × predicted response of yield (lnRR) + 0.007, $R2=0.83$, $P<0.001$, $n=292$; Relationship with CM: Measured response of yield (lnRR) = 1.055 × predicted response of yield (lnRR) - 0.008, $R2=0.79$, $P<0.001$, $n=639$. d-e Relative importance of factors on SOC response of CO (d) or CM (e). The relationships between model-predicted and measured effect of SOC (f); Relationship with CO: measured response of SOC (LNRR) = 1.044 × predicted response of SOC (lnRR) - 0.014, $R2=0.90$, $P<0.001$, $n=231$; Relationship with CM: Measured response of SOC (lnRR) = 1.040 × predicted response of SOC (lnRR) - 0.011, $R2=0.83$, $P<0.001$, $n=280$. MAT, mean annual temperature, MAP, mean annual precipitation. Dashed line is 1:1 parity.

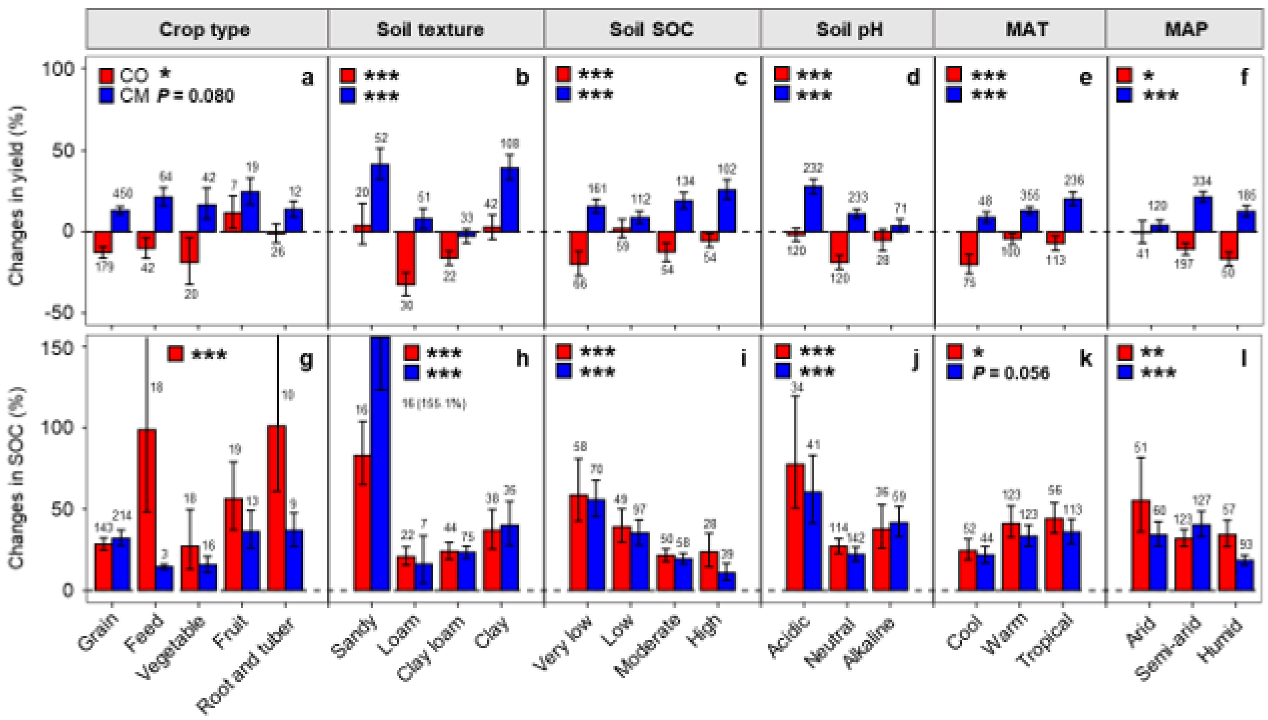

Figure 3

Influence of site-biophysical conditions on yield and SOC with compost or compost+mineral fertilizer. a-f Influence of crop type (a), soil texture (b), initial SOC (c), soil pH (d), mean annual temperature (MAT), (e) mean annual precipitation (MAP) (f) on the relative change with CO or CM compared to MF on yield (%). g-l Influence on SOC (%). For categories ‘crop type’ and ‘soil texture’ see Methods. Categories for soil SOC: very low (soil SOC with≤5g/kg); low (soil SOC with 5-10 g/kg); moderate (soil SOC with 10-15g/kg); high (soil SOC with >15g/kg). Categories for soil pH: acidic (soil pH <6); neutral (soil pH 6-8); alkaline (soil pH >8). Categories for MAT: cool (MAT with <10°C); warm (MAT with 10-20°C); tropical (MAT with >20°C). Categories for MAP: arid (MAP with <500mm); semi-arid (MAP with 500-1000mm); humid (MAP with >1000mm). CO (compost only) and CM (compost amended with mineral fertilizer). Values are mean effect sizes with 95% confidence intervals (CI) and number of observations above bars. Mean effect sizes (i.e., changes in yield, SOC or N2O emissions) are considered significant if the 95% CI does not include 0. A ratio of 0 (dotted line) indicates no difference between CO or CM and MF. Values larger or smaller than zero indicate higher (>0) or lower (<0) values with CO or CM than with MF. *P<0.05, **P<0.01 and ***P<0.001 indicate significant differences between crops and site biophysical conditions.

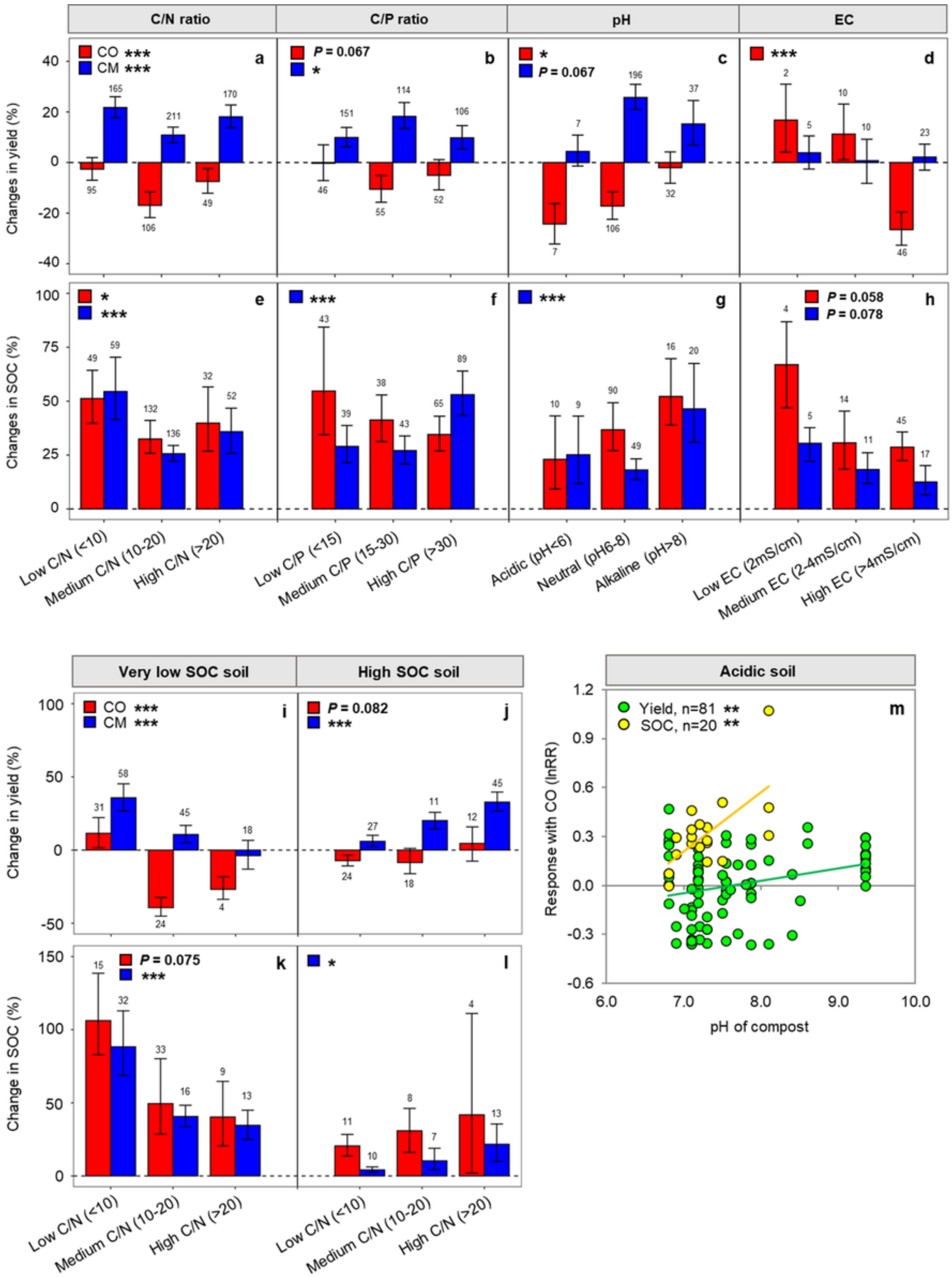

Figure 4

Influence of compost characteristics and their interactions with soil factors on compost effects. a-d Influence of C/N ratio (a), C/P ratio (b), pH (c) and electric conductivity (EC) (d) on relative change of CO or CM to MF in yield (%). e-h Influence of these factors on SOC (%). CO (compost) and CM (compost amended with mineral fertilizer). Values are mean effect sizes with 95% confidence intervals (CI) and number of observations above bars. (See Fig. 3 for details). i-j Effect of compost C/N ratio on relative change of CO (compost) or CM (compost amended with mineral fertilizer) to MF (mineral fertilizer) on yield (%) with soils that have very low SOC (<5g/kg soil, i) or high SOC (>15g/kg soil, j). k-l Influence on SOC (%). m The relationships between pH of compost and CO response (lnRR) in yield and SOC on acidic soils (pH<6). CO response in yield (lnRR) = 0.076 × pH of compost-0.579, R2=0.08, P=0.009, n=81; CO response in SOC (lnRR) = 0.362 × pH of compost-2.320, R2=0.44, P=0.001, n=20. *P<0.05, **P<0.01 and ***P<0.001 indicate significant differences between different compost characteristics (a-l), and significant relationships with pH (m).

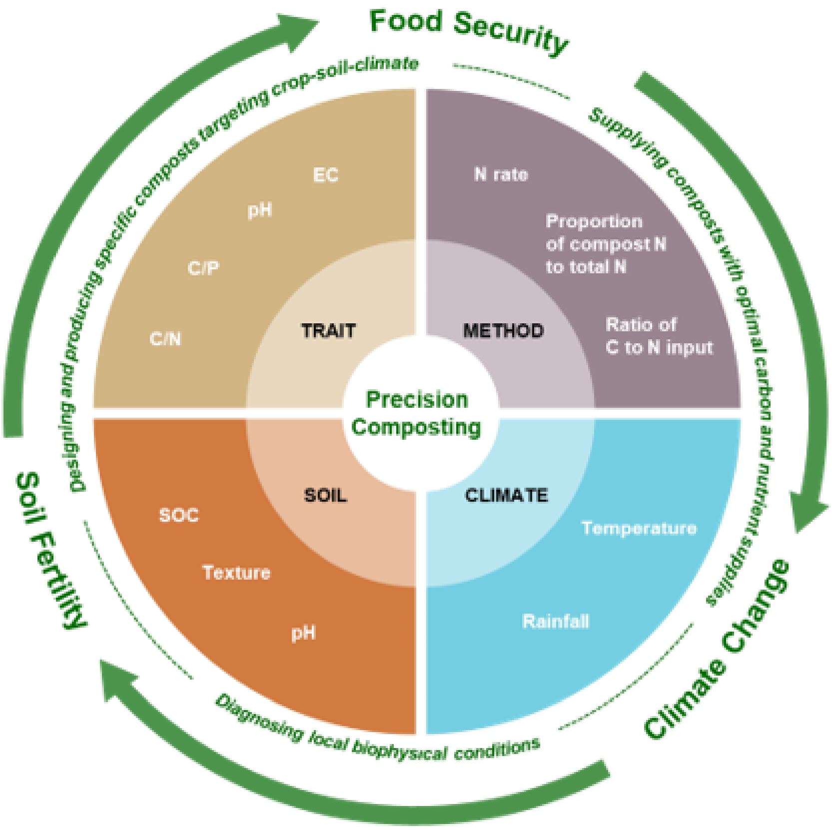

Figure 5

Conceptual framework for a Precision Composting Strategy (PCS). It represents a systematically approach matching compost characteristics (carbon-to-nutrient ratios, pH and EC) with cropping system properties (soil texture, SOC and pH, temperature and rainfall) and application methods (N rate, proportion of compost N to total N, ratio of C to N input, other nutrients) to optimise outcomes. The comprehensive benefits of PCS are detailed in Extended data Fig. 11, 13.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- PRISMAflowchart.docx

- Supplement.docx