First-Season Crop Yield Response to Organic Soil Amendments: A Meta-Analysis

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ABSTRACT

Organic soil amendments are increasingly promoted as a sustainable alternative to synthetic fertilizers and as a tool for building soil quality through improved chemical, physical, and biological properties. However, short-term yield response to organic amendments is highly variable. A meta-analysis of 53 studies was conducted to (i) develop a global estimate of first-season crop yield response to organic amendments, and (ii) determine the effect of crop type, amendment characteristics, soil properties, cultural practices, and climate on the magnitude of this yield response. Yield response ratios were calculated (organic amendment yield compared to a non-fertilized control) and differences among groups were determined using 95% bootstrap confidence intervals (CI). Across all studies, crop yield increased 43±7% (95% CI) in the first-season after an organic amendment. Yield response was greatest for leafy crops (71±26% increase) and lowest for root/tuber/bulb crops (29±10% increase). Poultry manure/compost was the most commonly used amendment and provided a yield increase of 76±21%. In contrast, plant-based amendments increased yield by only 27±9%. Amendment application rate alone was not an effective predictor of yield response, and there were not enough studies available to explore the possible interaction between amendment type and rate. Yield benefits of organic amendments were muted in soils with high organic matter and in arid climates. These results help identify options for maximizing the agronomic value of organic amendments, and suggest research is needed to improve agronomic efficiency of amendments in arid regions with poor soil quality.

Core Ideas

- Organic amendments are promoted as sustainable alternatives to synthetic fertilizer.
- Crop yield increased by an average of 43% in the first season after organic soil amendment.
- Yield benefit from organic amendments was greater in leafy crops than root crops.
- Poultry manure was commonly used and provided the greatest agronomic benefit.
- Yield benefit of organic amendment was lower in arid regions with poor soil quality.

Organic soil amendments are often promoted as a tool for building soil quality through improved chemical, physical, and biological properties. Manure and compost application to arable soils can lead to long-term increases in plant essential nutrients (e.g., P, K, and Mg; Bulluck et al., 2002; Wortman et al., 2012a), soil organic matter content, aggregate stability, and water-holding capacity (Goyal et al., 1999; Diacono and Montemurro, 2010), and microbial abundance and activity (Goyal et al., 1999; Pérez-Piqueres et al., 2006). Crop yield can also increase over time with regular application of manure or compost to the same field (Jiang et al., 2006), and yields are often similar between fields with a long-term history of organic soil amendment compared to inorganic fertilization (Edmeades, 2003). These long-term benefits of organic amendments have been well documented; however, many farmers use manure and compost as substitutes for synthetic fertilizer, and the short-term agronomic value of organic amendments remains unclear.

At a variety of production scales, there is growing interest in meeting crop nutrient demands with organic amendments, and better understanding of factors influencing potential yield responses is critical. Reliance on organic amendments is already common among certified organic farmers, who are prohibited from applying synthetic fertilizers, and small-holder farmers in developing countries who may lack access to synthetic inputs either due to limited resources or inadequate markets (Hamilton et al., 2014). Many conventional farmers in developed countries also consider using organic amendments to replace, or at least supplement, synthetic fertilizer inputs when an economical amendment is available. Manure application costs can be as low as 18% of the cost of synthetic fertilizer, but replacing synthetic fertilizers with organic amendments is only economical when the manure or compost can be sourced on or very near the farm (e.g., less than 35 km; Araji et al., 2001). At a broader scale, it has been discussed that shifting to integrated crop–livestock systems in the United States and throughout the world may create future opportunities for farmers to use animal manure as a sole crop nutrient input, which could provide additional environmental and economic benefits (Russelle et al., 2007). Rapid global urbanization may increase the use

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Published in Agron. J. 109:1210–1217 (2017)
doi:10.2134/agronj2016.10.0627
Supplemental material available online
Available freely online through the author-supported open access option

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Abbreviations: CI, confidence intervals; SOM, soil organic matter content.

of organic amendments as farmers in or adjacent to cities will have greater access to composted urban organic waste products including yard waste, food waste, and municipal biosolids (Beniston and Lal, 2012).

A transition to organic amendments as the primary nutrient source could contribute to a number of ecosystem services including suppression of soil-borne pathogens (Noble and Coventry, 2005) and reduced crop–weed interference (Liebman and Davis, 2000), in addition to the soil quality benefits discussed previously. However, using fresh animal manures to meet all crop nutrient demands can increase groundwater nitrate leaching and surface runoff of P (Kleinman et al., 2002; Basso and Ritchie, 2005). In most cases, it is not recommended that farmers use manure alone to meet crop N demand because over time P will accumulate well beyond crop sufficiency levels and potentially contribute to pollution of surface waters (Wortman et al., 2012a). Instead, best management practices for calculating organic soil amendment rates should include consideration of N/P ratio of the amendment, baseline soil nutrient levels, crop nutrient demands, and potential mineralization rate of the amendment. Nonetheless, over-application of soil amendments is common and the potentially negative consequences can be mitigated by using composted organic amendments, instead of fresh manures (Basso and Ritchie, 2005), and by incorporating amendments in the soil shortly after application (Kleinman et al., 2002).

The primary agronomic challenge in replacing synthetic fertilizer with organic amendments is that nutrients from organic amendments must be mineralized in the soil before becoming plant available–a process influenced by a complex suite of environmental and management factors. These factors, which will largely determine the potential short-term yield benefit of an organic amendment, may include: the source of organic amendment and the rate and method of application (El-Haris et al., 1983; Bernal et al., 2009), chemical and biological properties of the organic amendment (Hartz and Giannini, 1998; Thangarajan et al., 2015), site-specific soil chemical, physical, and biological properties (Sørensen and Jensen, 1995; Hadas et al., 1996; Thangarajan et al., 2015), local climate and weather (Sims, 1986), and cultural practices (e.g., irrigation and tillage; El-Haris et al., 1983; Agehara and Warncke, 2005). Given that nutrient availability following organic amendment application is difficult to predict, short-term yield responses may vary considerably, especially among crop functional groups and species with different nutritional requirements (Antonious et al., 2012). Thomsen et al. (2008) observed wheat yield increases between 164 and 336% in the first season after cattle manure application. In contrast, Alvarez et al. (2006) reported a 14% yield loss in potato (*Solanum tuberosum* L.) in the first season following soil application of dairy manure. Because these two studies were conducted with different crops and organic amendments in different soil, climatic, and management conditions, it is difficult to compare results and pinpoint the factors that may contribute to or limit crop yield after application of an organic amendment. However, synthesis and meta-analysis of these yield responses in the literature may prove useful for parsing out potentially important factors influencing the short-term yield benefits of organic amendments.

Previous review articles on organic amendments have discussed long-term impacts on soil properties and crop yield (Edmeades, 2003; Diacono and Montemurro, 2010) or yield response to individual amendment types (Choudhary et al., 1996). However, there have been no previous attempts to aggregate and systematically quantify short-term yield responses to a broad range of organic amendments reported in the scientific literature. Because organic amendments are increasingly used as a substitute for synthetic fertilizer, it is important to understand crop yield response and the primary factors driving the response. It is generally understood that organic amendments enhance yield, but a meta-analysis of previous studies will help to establish quantitative benchmarks for this potential yield benefit. This information could inform strategies for improving the agronomic efficiency and management of organic amendments. Within this context, the aims of this meta-analysis were to (i) develop a global estimate of first-season crop yield response to organic amendments, and (ii) determine the effect of crop type, amendment characteristics, soil properties, cultural practices, and climate on the magnitude of this yield response.

MATERIALS AND METHODS

Article Search and Selection Process

The effect of organic amendments on yield of annual crops was estimated via systematic literature review and meta-analysis. A literature search was conducted using the Scopus search engine (Elsevier), with search terms including "organic fertilizer," "manure," "compost," or "meal," and "yield" in the article title. The search was limited from 1980 through 16 July 2015 and returned 960 matches. Articles were then reviewed to identify suitability for inclusion in the meta-analysis.

For the purposes of this study, organic amendments were defined as any organic material applied to the soil during a fallow period or immediately prior to planting a cash crop. Cover crops and green manures were excluded, unless the green manure was grown outside of the study field (e.g., maize [*Zea mays* L.] stover from field A composted and applied to field B). The most common organic amendment types included animal manure (e.g., poultry, cattle, and swine) and plant-based composts. Because the aim of this study was limited to determining immediate yield impacts of organic amendments, only annual cropping systems were included in the meta-analysis and only the first season of yield data after application was extracted from the study (even when, as was most often the case, the study was conducted for two or more years). This excluded all tree, pasture, and most bioenergy cropping systems, though these studies were far less common than those in annual cropping systems. In some studies, yield was only reported for an average of two or more years and these articles were culled from analysis due to the cumulative and potentially confounding effects of long-term soil amendment within the same field. However, if yield data was reported for each year of a study, the first year of data was extracted for analysis even if manure was applied to the study area on an annual basis thereafter. Similarly, annual yield data could be extracted from multiple-year studies if the study area rotated within a field to a new location that was not previously amended with organic materials.

Specific study factors necessary for inclusion in the meta-analysis included: (i) a non-fertilized control (e.g., no synthetic fertilizer or organic amendment; this was the most common factor excluding studies from meta-analysis because most studies compared organic amendments to N–P–K fertilized plots at rates typical for a specific crop and region, without including a non-fertilized control); and (ii) at least one sole organic amendment treatment (e.g., no integration of synthetic fertilizer and organic amendment) to compare with the non-fertilized control. Studies were also excluded if they were not published in the English language, if they contained confounding experimental treatments (e.g., effect of compost on diseased crops), or did not include field-based results (e.g., greenhouse or pot studies). From the initial search result of 960 articles, a total of 53 studies fulfilled necessary criteria for meta-analysis of first-season yield response of annual crops to organic amendment, including 215 unique observations from six different continents (Fig. 1).

Data Extraction and Analysis

From each study, information was extracted regarding amendment type, amendment application rate on a dry weight and total N basis, crop species, soil organic matter content (SOM) or soil organic C (the latter multiplied by 1.72 to estimate SOM; Nelson and Sommers, 1996), soil texture, irrigation, geographic coordinates, and yield. Coordinates were used to determine aridity index for each study location using the WorldClim database (Hijmans et al., 2005). In cases where yield data were presented graphically, data were extracted using the Web Plot Digitizer v. 3.8 (http://arohatgi.info/WebPlotDigitizer). Additional data was extracted from articles for amendment properties (e.g., pH, P, and K), management (e.g., number of applications and incorporation), and initial soil properties (e.g., pH, N, P, and K), but data for these potentially predictive factors was too infrequently reported for inclusion in this meta-analysis.

A yield response ratio was determined for each treatment within a study as *organic amendment yield/non-fertilized control yield*. Multiple response ratios were calculated for the same study when more than one amendment type or rate was tested and these were treated as independent observations when included in the same analysis. However, it has been shown that this approach can lead to issues of non-independence and underestimated CI (Nakagawa and Santos, 2012). To assess potential effects of non-independence, a hierarchical random-effects model was fit to the data using the "metafor" package (R v. 3.1.3) with study considered as a grouping factor to account for studies containing several observations. In general, slight changes to mean effect sizes but not confidence intervals were observed using this approach compared to the non-parametric bootstrapping method, which did not influence the conclusions of the study.

The natural log of response ratios were calculated to linearize the ratio and improve normality (Hedges et al., 1999). Due to infrequent reporting of within-study error, response ratios were weighted according to the number (n) of reps × sites contributing to a reported mean observation as (Adams et al., 1997):

$$\text{weight} = (n_{\text{amended}} \times n_{\text{control}})/(n_{\text{amended}} + n_{\text{control}})$$

Non-parametric bootstrap CI (95%) were calculated for mean response ratios of interest (i.e., crop type, amendment type and rate, soil organic matter content and texture, irrigation, and aridity index) using a first-order normal approximation and 4999 iterations ("boot" package; R v. 3.1.3) (Adams et al., 1997). Response ratios were considered significant if the bootstrap CI did not overlap with zero and if CI from different groups did not overlap. Response ratios and CI were backtransformed and reported as a percent yield increase relative to the non-fertilized control for ease of interpretation. Continuous predictive data were divided into agronomically meaningful categorical groups (e.g., low, medium, and high soil organic matter content) with a secondary goal of creating categories of similar size for analysis. While the relationship between this continuous data and the yield response ratios could have been analyzed using meta-regression (e.g., metafor package in R), this approach is not well suited to small sample sizes with random effects (e.g., variability among study methods; Borenstein et al., 2009). In these cases, categorical meta-analysis is a common and useful approach for exploring possible trends in the literature.

The potential for publication bias was investigated and sensitivity analyses were conducted to examine how individual observations influenced weighted mean effect sizes (Philibert et al., 2012). Sampling variances were not available for individual observations, thus standard errors were approximated to estimate the precision of the effect size by randomly

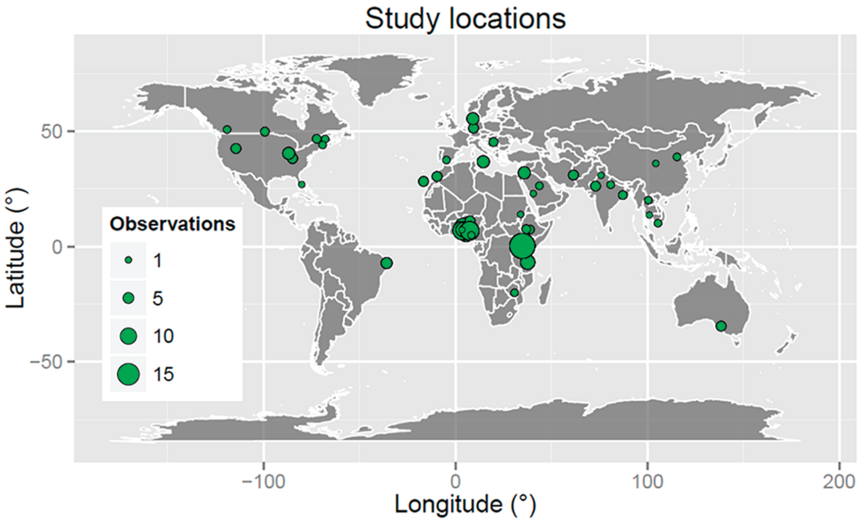

Fig. 1. Map of 53 study locations including the number of observations included in the meta-analysis.

assigning standard deviation values between 10 and 20% of the sample mean to individual observations. Sampling variances were calculated following Hedges et al. (1999) and a random effects model was fit to data using the metafor package in R (Viechtbauer, 2010). Funnel plots were evaluated using regression tests for data asymmetries which revealed no significant evidence of publication bias (Supplemental Fig. S3–S6). Sensitivity analyses were conducted using the "influence" function in metafor which produces leave-one-out diagnostics to identify values considered as influential. Results for DFFITS indicate how many standard deviations the average effect changes when individual observation are omitted from model fitting, with red values being classified as influential (Viechtbauer, 2010). In general, there was little to no influence of individual observations on predicted averages (i.e., never more than one influential observation per effect group; Supplemental Fig. S3–S6).

RESULTS AND DISCUSSION

Global Yield Response to Organic Amendments

Averaged across all studies, locations, crops, and amendment types and rates, crop yield increased by an average of 43±7% in the first season following organic amendment (Fig. 2). Although the magnitude of yield benefit varied, it is impressive that organic amendments increased crop yield the first season after application in 96% of cases (data not shown). Application of organic amendments is often considered a long-term investment in soil quality and improved crop yield, but this result demonstrates a substantial short-term yield benefit as well. An important reality is that organic amendments, because of the mass and cost of transport, are only feasible to use if they are locally available (Araji et al., 2001).Nonetheless, these results suggest that farmers should consider application of any locally available organic waste because any amendment appears to be better than no amendment.

Jiang et al. (2006) reported a nearly 200% increase in wheat (*Triticum aestivum* L.) yield in China after 20 yr of continuous manure application (compared to a zero fertilizer control); however, the first-season yield benefit was approximately 40%, which is consistent with the results of this meta-analysis. Similarly, Buyanovsky et al. (1997) reported a 900% increase in wheat yield after a century of continuous manure application, whereas the first-season yield benefit was approximately 60%. Bedada et al. (2014) reported a 42% maize yield increase in the first season following compost amendment, and after 5 yr of continuous compost application the yield benefit had increased to more than 150%. Yields tend to increase over time with repeated organic amendment, but it is important to note that long-term yield differences between amended and non-fertilized soils are driven in part by yield declines in soils receiving no amendment or fertilizer.

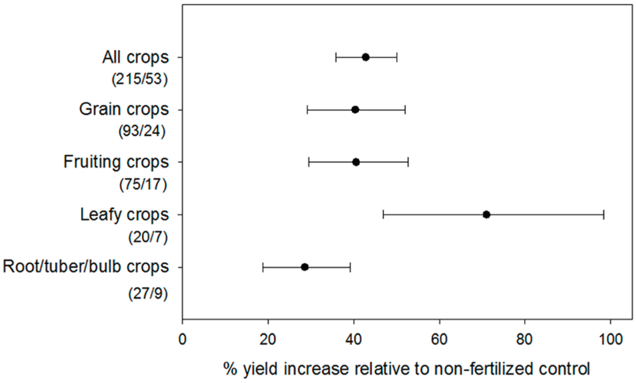

Fig. 2. Mean yield response to organic amendments relative to a non-fertilized control among crop types. Numbers below *y* axis labels indicate the number of (left) observations and (right) studies contributing to each mean. Error bars represent 95% bootstrapped confidence intervals.

Crop Specific Yield Response

Yield response to organic amendment varied by the type of crop (Fig. 2; Supplemental Fig. S1). Leafy vegetable crops (e.g., *Brassica oleracea* L.) demonstrated the greatest yield benefit, whereas yield gains were more modest for root, tuber, and bulb crops (e.g., *Manihot esculenta* Crantz). Leafy vegetable crops and herbs are often more responsive to increasing fertility (organic amendments or synthetic fertilizer) than fruiting, grain, or root crops (e.g., Wortman, 2015). Moreover, elevated soil N can result in greater shoot growth and reduced root vs. shoot biomass partitioning (Davidson, 1969; Wortman and Dawson, 2015). Assuming sufficient mineralization of nutrients from organic amendments within the first growing season, the resulting nutrient-rich soil environment may favor leafy crop growth over root crop growth. Oliveira et al. (2010) reported a yield increase of 23% in sweet potato (*Ipomoea batatas* L.) following a one-time application of 10 Mg/ha cattle manure, and increasing the amendment rate to 30 Mg/ha improved yield by 63% compared to the non-fertilized control. However, the yield benefit decreased to 30% when the amendment rate was further increased to 50 Mg/ha, which suggests excessive soil fertility may have reduced root to shoot biomass partitioning. In another study, compost and manure application rates between 23 and 64 Mg/ha did not significantly alter yield of sugarbeet (*Beta vulgaris* L.; a root crop) compared to a non-fertilized control (Lehrsch et al., 2015). In contrast, Pavlou et al. (2007) observed increases in lettuce (*Lactuca sativa* L.) yield that were proportional to the increases in organic and inorganic fertilizer rates until an upper asymptote or yield limit for that environment was reached.

Yield Response by Amendment Type

Amendment rate (typically between 5 and 30 Mg ha^{-1}), calculated on a dry weight or N basis was not an effective predictor of yield response in this meta-analysis (Supplemental Fig. S2) due in part to a high degree of variability in response ratios and potentially confounding effects (e.g., amendment type and crop). Unfortunately, too few studies included multiple amendment rates to test this effect on a study by study basis. However, yield was influenced by the type or source of the amendment (Fig. 3; Supplemental Fig. S1). Poultry manure and compost was the most commonly used amendment (16 of 53 studies) and provided a yield increase of 76±21%. In contrast, plant-based amendments (e.g., municipal yard waste compost) increased yield by 27±9% relative to the non-fertilized controls. Compared to cattle or swine manure, poultry manure tends to be more N-rich (Bernal et al., 2009). Because N is a primary essential plant nutrient, poultry manure may have greater fertilizer value than other animal manures. Chae and Tabatabai (1986) compared the chemical properties of animal manure and plant-based soil amendments and reported nitrate levels in poultry manure (1450 mg kg^{-1}) nearly 10 times greater than in swine, horse, and cattle manure, or crop residues. Similarly, ammonium in the poultry manure (785 mg kg^{-1}) was greater than in all other animal and plant-based amendments, except swine manure (Chae and Tabatabai, 1986).

Leguminous plant residues may have greater potential to increase crop yield in the first season following application due to greater organic and mineral N contributions (Chae and Tabatabai, 1986). In contrast, woody, straw-based, and municipal yard waste amendments are typically characterized by a relatively high C/N ratio and lower organic and mineral N compared to animal manures and compost (Chae and Tabatabai, 1986; Hartz and Giannini, 1998; Thangarajan et al., 2015). Indeed, the majority of studies in this meta-analysis that included a plant-based soil amendment reported using straw residue or municipal yard waste compost, which may explain the modest first-season yield benefits compared to animal-manure amendments. While the N composition of the different organic amendments is the simplest explanation for the observed differences in yield response, it is worth repeating that N application rate was not an effective predictor of yield response in this analysis. It is possible that pooling across crop species and amendment types with variable yield responses (Fig. 2 and 3) may have confounded a possible N rate effect. Unfortunately, a larger database or targeted field studies would be necessary to critically analyze possible interactions among these effects.

Influence of Soil Properties on Yield Response

Crop yield response did not vary between coarse and finely textured soils (Supplemental Fig. S2), but SOM did influence yield response (Fig. 4; Supplemental Fig. S1). The potential for yield benefits from soil amendment were greatest (56±13%) when SOM was between 1 and 3%. However, in studies where SOM was greater than 3%, the yield increase dropped to 27±10%. Soils with high levels of organic matter content, like many croplands in the Midwest, can have a greater potential for N mineralization, and crop yield is often less responsive to fertilization (Mulvaney et al., 2001; Wortman et al., 2011). Indeed, SOM is positively correlated with pre-plant soil nitrate levels and subsequent crop yield (Quiroga et al., 2006). If the primary short-term yield-promoting characteristic of organic amendments is mineral and mineralizable N (as the positive response to poultry amendments would suggest; Fig. 3), then it will be less likely to observe substantial first-season yield benefits following organic amendment of inherently fertile soils (e.g., high SOM).

However, the relationship between yield and SOM was not linear; yield response was relatively low in studies with both high (>3%) and low (<1%) SOM (Fig. 4). Soils with low SOM should theoretically be more responsive to the fertility provided by organic amendments, but several factors may limit this potential yield benefit. First, SOM is typically lower in coarse-textured sandy soils compared to clay soils (Burke et al., 1989). Sandy soils also have lower microbial biomass and activity (Kaiser et al., 1992), which could limit the capacity for nutrient mineralization in the first season following organic amendment. Moreover, SOM tends to be lower in arid environments (Burke et al., 1989), where soil moisture may be more limiting to crop growth than nutrient availability. Although organic amendments can improve soil structure and water holding capacity, these benefits become more apparent over the long-term (Haynes and Naidu, 1998). Because soil microbial activity and nutrient mineralization are driven in large part by soil texture and moisture (Skopp et al., 1990), it will probably be more difficult to achieve above-average yield gains (>43%) with organic amendments in locations with low SOM in the first season after application.

Climatic Influence on Yield Response

Organic amendment increased yield by 52±12% in humid climates, compared to 32±7% in arid climates (Supplemental Fig. S1). Yield gain in rainfed production systems was 49±11%, compared to 34±9% in irrigated systems, though this difference was not statistically different (Supplemental Fig. S2). The majority of rainfed studies, though not all, were located in humid climates (and the majority of irrigated studies were located in

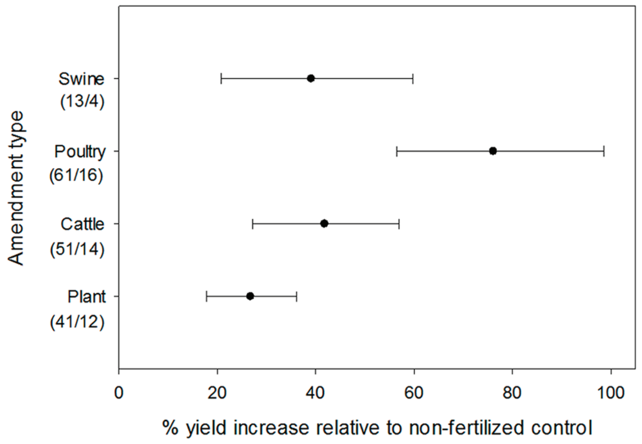

Fig. 3. Mean yield response to different types of organic amendments relative to a non-fertilized control. Numbers below y axis labels indicate the number of (left) observations and (right) studies contributing to each mean. Error bars represent 95% bootstrap confidence intervals.

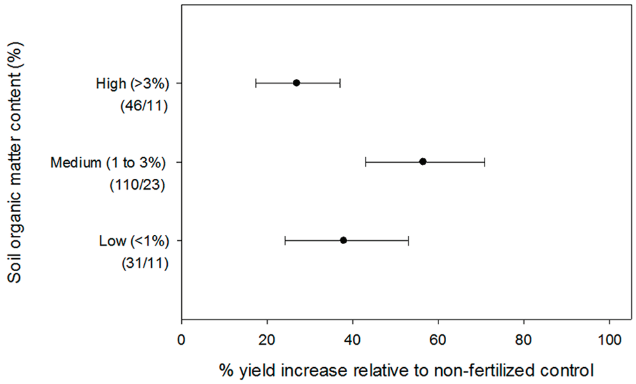

Fig. 4. Mean yield response to organic amendments relative to a non-fertilized control among different levels of soil organic matter content. Numbers below y axis labels indicate the number of (left) observations and (right) studies contributing to each mean. Error bars represent 95% bootstrap confidence intervals.

arid climates), which explains the observed relationship between climate and irrigation treatment groups. As previously discussed, soil moisture can be a limiting factor to microbial respiration and mineralization of nutrients from organic amendments (until soil reaches saturation and anaerobic conditions; Skopp et al., 1990). Although irrigation should increase soil mineralization of nutrients in arid climates, mineralization rates and crop yield potential may still be limited depending on irrigation method, frequency, timing, and placement. For example, flood or furrow irrigation may temporarily increase mineralization rates and soil nutrient availability, but many of these nutrients could be leached below the effective rooting zone in subsequent irrigation events (Schepers et al., 1995). Moreover, deficit irrigation is a globally common practice (Fereres and Soriano, 2007) and could limit nutrient mineralization from organic amendments in arid climates. Unfortunately, detailed information about irrigation management was rarely reported and these effects could not be explored in this meta-analysis. It is also important to note that climate and geographical clines are not always effective predictors of plant response and yield in short-term studies due to the potential for irregular weather events at a given site-year (Wortman et al., 2012b). However, observed annual precipitation and soil temperature (potentially useful and predictive weather variables in this meta-analysis) were not reported in most studies.

Other Potentially Important Factors Not Assessed

There are a number of potentially important agronomic factors known to influence nutrient mineralization from organic amendments that could not be tested in this meta-analysis due to insufficient reporting across studies in the database. Baseline soil fertility, including soil nitrate and ammonium, is positively correlated with crop yield (Quiroga et al., 2006) and may influence site-specific response to organic amendments (Mulvaney et al., 2001). While SOM and nitrate are positively correlated, and SOM seems to be a relatively effective predictor of yield response (Fig. 4), we did not have enough data to directly test the hypothesis that baseline soil nitrate and ammonium are negatively correlated with relative yield response to organic amendments. The timing and method of amendment application are also known to influence nutrient availability and crop yield, but these details were rarely reported and could not be analyzed. In temperate climates, yield benefits from organic amendments are typically greater when applied in the spring compared to fall or winter (Zebarth et al., 1996; Jackson and Smith, 1997); moreover, soil incorporation or tillage method following organic amendment can influence N mineralization potential and crop yield (El-Haris et al., 1983). Lastly, the physical and decomposition state of the organic amendment (e.g., fresh liquid, fresh solid, or composted solid) will likely influence the timing of nutrient availability and subsequent crop yield (Gale et al., 2006), but these effects could not be tested here.

CONCLUSIONS

This meta-analysis of 53 studies helps to establish a global, quantitative benchmark for the short-term agronomic benefit of organic amendments compared to a non-fertilized control in annual cropping systems. Across all observations, application of an organic amendment (typically between 5 and 30 Mg ha^{-1}) increased crop yield by 43±7% (95% CI), but the magnitude of this yield benefit varied by crop type, amendment source, and local SOM and climate. Results may help to inform practical strategies for maximizing the agronomic efficiency of recycled organic agricultural wastes and byproducts. For example, a diversified vegetable grower with local access to composted poultry manure may consider planting lettuce (a leafy vegetable crop), instead of sweet potato [*Ipomoea batatas* (L.) Lam.] (a tuberous root crop), in the first season after organic amendment. This meta-analysis may also serve to guide directions for future research exploration and investment. The relative yield benefit from organic amendments was limited in arid climates and soils with low SOM, and these conditions are characteristic of many farms in developing nations where organic amendments are more likely to be used as a substitute for synthetic fertilizer. Given the potential agronomic and socioeconomic benefits of crop fertilization in these regions, it is important for researchers to continue seeking ways to improve the efficiency of organic amendments in arid regions with relatively poor soil quality (Braimoh and Vlek, 2006; Hamilton et al., 2014). The long-term soil quality and yield benefits of continuous organic amendment of soils has been well documented (Edmeades, 2003; Diacono and Montemurro, 2010), but this meta-analysis confirms and quantifies the short-term value of organic soil amendments for increasing first-season yields across a diverse range of crops, amendments, and local conditions.

SUPPLEMENTAL MATERIAL

Supplemental Fig. S1. Box plots demonstrating the distribution of yield responses (median, 25% quartiles, and outliers) to organic amendments relative to a non-fertilized control as influenced by significant effects of (top left) crop type, (top right) amendment type, (bottom left) soil organic matter content, and (bottom right) climate.

Supplemental Fig. S2. Box plots demonstrating the distribution of yield responses (median, 25% quartiles, and outliers) to organic amendments relative to a non-fertilized control as influenced by nonsignificant effects of (top left) amendment rate on a dry weight basis, (top right) amendment rate on a total N basis, (bottom left) soil texture, and (bottom right) irrigation.

Supplemental Fig. S3. (top) Funnel plots and (bottom) DFFITS values for each observation contributing to the mean response ratio for (left) arid and (right) humid climates. Significant asymmetry in the funnel plot suggests possible publication bias and a dot above a short dash line in the DFFITS plot identifies potentially influential observations.

Supplemental Fig. S4. (left) Funnel plots and (right) DFFITS values for each observation contributing to the mean response ratio for (top) high, (middle) medium, and (bottom) low organic matter content soils. Significant asymmetry in the funnel plot suggests possible publication bias and a dot above a short dash line in the DFFITS plot identifies potentially influential observations.

Supplemental Fig. S5. (left) Funnel plots and (right) DFFITS values for each observation contributing to the mean response ratio for (top) swine, (middle-top) poultry, (middle-bottom) cattle, and (bottom) plant compost and manure amendments. Significant asymmetry in the funnel plot suggests possible publication bias and a dot above a short dash line in the DFFITS plot identifies potentially influential observations.

Supplemental Fig. S6. (left) Funnel plots and (right) DFFITS values for each observation contributing to the mean response ratio for (top) fruiting, (middle-top) grain, (middle-bottom) leafy, and (bottom) root crops. Significant asymmetry in the funnel plot suggests possible publication bias and a dot above a short dash line in the DFFITS plot identifies potentially influential observations.

Supplemental References: Those included in the meta-analysis.

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