Global Change Biology

Global Change Biology (2014) **20**, 666–679, doi: 10.1111/gcb.12438

Animal manure application and soil organic carbon stocks: a meta-analysis

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Abstract

The impact of animal manure application on soil organic carbon (SOC) stock changes is of interest for both agronomic and environmental purposes. There is a specific need to quantify SOC change for use in national greenhouse gas (GHG) emission inventories. We quantified the response of SOC stocks to manure application from a large world-wide pool of individual studies and determined the impact of explanatory factors such as climate, soil properties, land use and manure characteristics. Our study is based on a meta-analysis of 42 research articles totaling 49 sites and 130 observations in the world. A dominant effect of cumulative manure-C input on SOC response was observed as this factor explained at least 53% of the variability in SOC stock differences compared to mineral fertilized or unfertilized reference treatments. However, the effects of other determining factors were not evident from our data set. From the linear regression relating cumulative C inputs and SOC stock difference, a global manure-C retention coefficient of 12% ± 4 (95% Confidence Interval, CI) could be estimated for an average study duration of 18 years. Following an approach comparable to the Intergovernmental Panel on Climate Change, we estimated a relative SOC change factor of 1.26 ± 0.14 (95% CI) which was also related to cumulative manure-C input. Our results offer some scope for the refinement of manure retention coefficients used in crop management guidelines and for the improvement of SOC change factors for national GHG inventories by taking into account manure-C input. Finally, this study emphasizes the need to further document the long-term impact of manure characteristics such as animal species, especially pig and poultry, and manure management systems, in particular liquid vs. solid storage.

Keywords: animal manure, manure carbon input, manure retention coefficient, meta-analysis, soil carbon change factor, soil organic carbon

Received 17 May 2013 and accepted 22 September 2013

Introduction

As animal manure contains organic matter, an increase in soil organic carbon (SOC) content is generally expected following its land application, as reported in many individual studies. For example, in the southeastern United States, Sainju *et al.* (2008a) observed an increase of soil surface (0–20 cm) SOC stock of about 3.2 Mg C ha^{-1} after 10 years of poultry litter application in comparison to mineral fertilizer plots. In Nepal, after 25 annual cattle manure applications, surface (0–30 cm) SOC stocks were higher by about 19.1 Mg C ha^{-1} than control (unfertilized) plots (Gami *et al.*, 2009). In China, after 22 years of pig manure application, the surface soil layer (0–15 cm) accumulated 3.8 Mg C ha^{-1} more than mineral fertilizer alone (Huang *et al.*, 2010a). However, some studies report no significant or even negative change of SOC stocks following manure application (Franzluebbers *et al.*, 2001; Angers *et al.*, 2010). Obviously, there is great variability in the magnitude of SOC stocks change after manure application.

Individual studies and a few review articles have attempted to relate the variability in the magnitude of SOC change to various explanatory factors such as climate (Triberti *et al.*, 2008), manure application rate (Franzluebbers *et al.*, 2001), manure management system (farmyard manure/slurry) (Grignani *et al.*, 2007), soil texture (Gami *et al.*, 2009), initial SOC concentration (Dersch & Bohm, 2001), land use, and time of application. Few global studies have attempted to quantify the effects of these explanatory factors from all the available literature. Ogle *et al.* (2005) and Franzluebbers & Doraiswamy (2007) focused solely on the impact of climatic zone on SOC change after manure application. The former study used probably <5 experimental sites, and the latter probably <15. Moreover, the data presented suggest that the effect of climatic zone on SOC change after manure application was not statistically significant.

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Due to the close relationship between SOC and soil quality (Gregorich *et al.*, 1994), there is strong interest in developing tools to advise farmers on the effect of manure on SOC. For that purpose, some fertilizer and crop management guidelines report retention coefficients for manures of different animal species or decomposition degree (e.g., Soltner, 2000; Clément *et al.*, 2010). The retention or isohumic coefficient is defined as the fraction of applied organic matter which is 'transformed' into soil organic matter (Hénin & Dupuis, 1945). The determination of manure C retention coefficient is also of interest for C modeling as C retention coefficient for crop residues is a substrate quality parameter used in most SOC models (Kätterer *et al.*, 2011).

The global quantification of SOC change after manure application is also relevant for national greenhouse gas (GHG) emission inventories. The Intergovernmental Panel on Climate Change (IPCC) provides default SOC stock change factors for manure application for C accounting for national GHG inventories (IPCC, 2006). These factors represent the effect on SOC stocks after regular addition of animal manure for a period of at least 20 years (IPCC, 2006). We understand that these estimates were generated from probably five individual studies, and the amount of manure-C input and management activity categories such as animal species or manure management system were not taken into account. Such considerations would represent a major improvement in estimate accuracy. Emission factors for CH_4 and N_2O are already proposed for specific animal species and manure management systems (IPCC, 2006).

There is therefore a need to refine global quantification of SOC changes following manure application from both agronomic and environmental perspectives. The objective of our work was to quantify the response of SOC stocks to manure application from a large worldwide pool of individual studies, and to assess the impact of explanatory factors such as climate, soil properties (texture, initial SOC concentration), land use and manure characteristics (C input, animal species, manure management system).

Materials and methods

Literature search and study selection

We searched literature published up to the end of 2011 using two bibliographic databases: CAB Abstracts and Scopus. Specific keywords describing animal category (*animal, pig, cattle, hog, poultry, sheep, horse, livestock*), manure (*compost, mud, sludge, ooze, effluent, waste, manure, dung, slurry, muck slurry, farmyard manure*), and soil carbon (*soil carbon sequestration, soil carbon accumulation, soil carbon content, soil carbon quantity, soil carbon concentration, soil carbon density, soil carbon stocks*) were combined. From >1000 articles containing these keywords, we selected those which met the following criteria:

- Agronomic field experiments on cropland or grassland were included, but greenhouse, forest and mine soil reclamation experiments were excluded;
- The experimental design should be replicated;
- The soil C stocks (Mg C ha^{-1}) should be available or computable from soil C concentrations (g C kg^{-1} or %) and bulk density values. In studies which reported soil organic matter concentration instead of C, we estimated C as 58% of the organic matter;
- Experiments should include at least one treatment with animal manure and a reference treatment which could be a control (without any fertilization) and/or a mineral fertilization treatment. Based on this criterion, two data sets (REF-zero; REF-min) were computed to evaluate SOC response to manure application in comparison to an unfertilized control and a mineral fertilization treatment, respectively. Studies could be part of one or both data set(s). Mineral fertilization had to include nitrogen (N). For the REF-min data set, manure could be applied alone or combined with mineral fertilization to carry additional N, P, and K to approach mineral supply of the mineral fertilization treatment.
- Study duration should be at least 3 years. When there were more than one article on the same experiment, the latest was considered if soil C stocks (Mg ha^{-1}) were reported in both articles. If only one reported soil C stocks, this article was selected even if it was not the latest.

Soil C stocks were recorded or computed to 30 cm depth when possible. Stocks for soil depths of <15 cm were not retained. For one site, soil C stocks were given for a whole profile of 100 cm (Srinivasarao *et al.*, 2011). Only two sites reported soil C stocks on an equivalent mass basis (Kätterer *et al.*, 2011; Viaud *et al.*, 2011). Standard deviations for each treatment were collected or evaluated from standard errors or critical value of comparison test (e.g., LSD). The sample size was also collected. The DataThief software (Tummers & Van Der Laan, 2006) was used to estimate data from graphs. In addition, for each experimental site, we compiled metadata that would be used as explanatory factors of the effect of manure application, that is, climatic data, soil properties (texture, initial SOC concentration), land use, manure properties (application rate, C concentration, C input, animal species, management system: liquid or solid storage), and study duration. If the data were not available in the article, the authors were requested to provide missing information. IPCC climate zone was determined for each experimental site from geographic coordinates and the world map of IPCC climate zones (European Commission, 2012). We also considered precipitation and temperature data in the articles to confirm the climate zone given by the world map. For two sites, cumulative manure-C input was known for a shorter study duration and was extended for the whole period of application (Singh *et al.*, 1998; Holeplass *et al.*, 2004; Bandyopadhyay *et al.*, 2011; Nayak *et al.*, 2012). For two sites, manure-C input was evaluated with manure-C concentration which was available only for 1 year (Grandy *et al*., 2002; Gami *et al*., 2009).

Choice of effect size index

An effect size is a value reflecting the magnitude of the treatment effect in comparison to a reference treatment (Borenstein *et al*., 2009). For each observation (comparison between manure and reference treatment), we calculated two effect size indices to evaluate SOC response to manure application. A first index corresponded to the difference between the SOC stock in the plot receiving manure and the SOC stock in the reference plot (Mg C ha^{-1}) thereafter referred to as *SOC stock difference*. As mentioned earlier, two data sets were created according to the reference plot, that is, a REF-zero data set when the reference plot was a control and a REF-min data set when the reference plot was a plot receiving mineral fertilization. Finally, a second index corresponded to the ratio of the SOC stock in the plot receiving manure to the SOC stock of the plot receiving mineral fertilization thereafter referred to as *relative SOC change*. This index would be comparable to the default relative SOC change factors provided by IPCC (2006) and to factors determined by Ogle *et al.* (2005) from experiments which lasted at least 20 years. This index was estimated on a reduced REF-min data set including only studies with duration of 20 years or more to be consistent and comparable with the IPCC approach.

Statistical analysis

Three categorical factors (climate, animal species, and land use) and three continuous factors [cumulative manure-C input, clay and silt content, and initial SOC concentration (g kg^{-1})] were retained for the analysis. Three climate classes were constituted from the IPCC climate classification: cool temperate, warm temperate, and tropical. Three land use classes were tested: annual crops, perennial crops, and rice paddies. For animal species, cattle and poultry manure had sufficient observations for statistical analysis of both data sets. The effect of pig manure could only be determined for the REF-zero data set and the effect of goat manure could not be tested due to lack of observations. The effect of manure management system (solid vs. liquid) could not be tested due to too few observations for liquid manure.

A mixed model was used by including a random variable for the site, to take into account the dependency of several effect sizes at a same site. Since standard deviations were rarely available to weight by the inverse of variance, the analysis was weighted by sample size. Statistical significance of each explanatory factor (cumulative manure-C input, animal species, clay and silt content, initial SOC concentration, climate, and land use) was tested independently from the others for the two indices as data sets were not complete for all explanatory factors. The assumptions of homogeneity of variance and normality of the residuals were verified graphically. For normality, Shapiro–Wilk and Kolmogorov–Smirnov tests were also verified. Heterogeneity was corrected either by modeling a different variance for each level of a categorical factor or by modeling the variance as a power of the mean. Log transformations were carried out for some cases. The statistical significance between means of the different levels of categorical factors was given by least square differences. For continuous factors, R-Squared was calculated using a method recommended for mixed models (Edwards *et al*., 2008). As data sets were not complete for all categorical and continuous factors, the number of observations was specified on the figures. A Student's *t*-test was used to test the statistical significance of global means for both indices. All statistical analyses were performed using the SAS software, version 9.2 (SAS Institute, Cary, NC, USA). Statistical results were considered to be significant at the 0.05 α level.

Results and discussion

General results

By applying our selection criteria, 42 articles were retained for 49 sites in the world (Table 1). Among these 49 replicated sites, 40 were randomized, eight were presumed to be randomized based on the description of the experimental design, and one was not randomized. The soil depth considered varied from 15 to 100 cm, with an average of 26 cm. Duration of the studies ranged from 3 to 82 years, with an average of 18 years (18 years also for studies with known cumulative manure-C input).

The 130 observations from the 49 sites were separated into REF-zero and REF-min data sets to evaluate the SOC response to manure application in comparison to an unfertilized control and to mineral fertilization, respectively. The *SOC stock difference* (1st index) was calculated for every observation of both data sets. In total for this effect size, 36 sites (57 observations) were available for the REF-zero data set and 43 (73 observations) for the REF-min data set. Among the 43 sites included in the REF-min data set, 22 (28 observations) had duration of ≥20 years and were used to analyze the *relative SOC change* (2nd index).

Overall effect of manure application on SOC stocks compared to a reference

Overall, as expected, the positive response in the *SOC stock difference* (first index) indicated a significantly larger SOC stock in plots receiving animal manure than in both reference treatments (Table 2). The higher SOC stock in manured treatments could be due to direct C input by the manure itself and indirect C input through increased net primary production (including roots and crop residues) (Aoyama *et al*., 1999; Whalen & Chang, 2002; Bhattacharyya *et al*., 2010). The average SOC response to manure application was larger when using control plots as the reference (9.4 Mg C ha^{-1}) than

Table 1 Summary of data for the sites included in the analysis

Location	Data set	n*	Sampling depth (cm)	Duration (years)	Cumulative manure-C input (Mg C ha^{-1})	Animal species	IPCC climatic zone	Soil clay (%)	Soil silt (%)	Initial SOC (g kg^{-1})	Land use	Reference†
Saint-Lambert de Lévis, Qc, Canada	REF-zero	2	30	20	NA	pig	cool temperate	34	56	NA	perennial	(Angers *et al.*, 2010)
Ludhiana, Punjab, India	REF-zero, REF-min	4	15	7	28	NA	tropical	17	24	5	paddy	(Benbi & Senapati, 2010)
Almora, Uttarakhand, India	REF-zero, REF-min	2	30	8	13	cattle	warm temperate	34	56	7	annual	(Bhattacharyya *et al.*, 2007, 2009); pers. comm.
Meden Vale, Nottinghamshire, UK	REF-zero	5	30	4	6;13;19;25;32	poultry	cool temperate	6	8	11	annual	(Bhogal *et al.*, 2009); (Bhogal & Shepherd, 1997)
Foulum, Denmark	REF-zero	1	30	11	2	pig	cool temperate	9	13	23	annual	(Chirinda *et al.*, 2010)
Koraput, Orissa, India	REF-min	4	15	3	NA	cattle	tropical	19	24	6	annual	(Dass *et al.*, 2008)
Waldviertel, Austria	REF-zero, REF-min	2	25	21	NA	NA	cool temperate	8	13	NA	annual	(Dersch & Bohm, 2001)
Alpenvorland, Austria	REF-zero, REF-min	2	25	21	NA	NA	cool temperate	50	40	NA	annual	(Dersch & Bohm, 2001)
Pingliang, Gansu, China	REF-zero, REF-min	2	20	26	20	cattle	warm temperate	34	43	5	annual	(Fan *et al.*, 2008); pers. comm.
Farmington, Georgia, USA	REF-min	4	20	12	29	poultry	warm temperate	13	18	NA	perennial	(Franzluebbers & Stuedemann, 2010); (Franzluebbers & Stuedemann, 2009); pers. comm.
Bhairahawa, Nepal	REF-zero, REF-min	2	30	25	NA	cattle	tropical	18	71	NA	paddy	(Gami *et al.*, 2009); pers. comm.
Tarahara, Nepal	REF-zero, REF-min	2	30	25	NA	cattle	tropical	11	58	NA	paddy	(Gami *et al.*, 2009); pers. comm.
Parwanipur, Nepal	REF-zero, REF-min	3	30	23	22	cattle	tropical	14	58	NA	paddy	(Gami *et al.*, 2009); pers. comm.
Presque Isle, Maine, USA	REF-min	1	15	6	26	cattle	cool temperate	NA	NA	NA	annual	(Grandy *et al.*, 2002)
Isfahan, Isfahan, Iran	REF-zero, REF-min	6	20	7	44;87;175	cattle	warm temperate	34	56	5	annual	(Hemmat *et al.*, 2010)

Table 1 (Continued)

Location	Data set	n*	Sampling depth (cm)	Duration (years)	Cumulative manure-C input (Mg C ha^{-1})	Animal species	IPCC climatic zone	Soil clay (%)	Soil silt (%)	Initial SOC (g kg^{-1})	Land use	Reference†
Akershus, Norway	REF-min	3	25	48	29	cattle	cool temperate	20	40	40	annual; perennial	(Holeplass *et al.*, 2004); (Singh *et al.*, 1998)
Nanchang, Jiangxi, China	REF-zero, REF-min	2	15	22	67	pig	warm temperate	26	NA	9	annual	(Huang *et al.*, 2010a); (Huang *et al.*, 2010b); pers. comm.
Prairie du Sac, Wisconsin, USA	REF-min	1	30	4	NA	cattle	cool temperate	15	60	NA	annual	(Jokela *et al.*, 2009)
Nairobi, Kenya	REF-zero, REF-min	4	20	19	20;39	cattle	warm temperate	67	22	20	annual	(Kamoni *et al.*, 2007); (Kapkiyai *et al.*, 1999); (Kibunja *et al.*, 2010)
Embu, Kenya	REF-zero	2	20	13	20;41	goat	tropical	31	13	NA	annual	(Kamoni *et al.*, 2007); (Kihanda *et al.*, 2005)
Uppsala, Sweden	REF-zero, REF-min	2	20‡	53	101	cattle	cool temperate	37	41	15	annual	(Kätterer *et al.*, 2011); (Kirchmann *et al.*, 2004)
Taipei, Taiwan	REF-zero	2	20	3	NA	pig	tropical	14	66	14	annual	(Lee *et al.*, 2006)
Brookings, South Dakota, USA	REF-zero, REF-min	4	30	4	12;23	cattle	cool temperate	32	62	NA	perennial	(Lee *et al.*, 2007)
Therwil, Switzerland	REF-zero, REF-min	2	20	27	24;32	cattle	cool temperate	16	72	15	annual	(Leifeld *et al.*, 2009);(Fliessbach *et al.*, 2007)
Yangling, Shaanxi, China	REF-min	1	20	17	NA	cattle	warm temperate	17	52	6	annual	(Liang *et al.*, 2011); (Zhao *et al.*, 2010)
Shenyang, Liaoning, China	REF-zero, REF-min	3	20	22	44;22	pig	cool temperate	25	58	9	annual	(Lou *et al.*, 2011)
Padova, Italy	REF-zero, REF-min	4	30	36	155;129	cattle	warm temperate	15	38	12	annual	(Morari *et al.*, 2006); pers. comm.
Parbhani, Maharashtra, India	REF-min	2	15	7	NA	NA	tropical	53	16	5	annual	(More & Hangarge, 2003)

Table 1 (Continued)

Location	Data set	*n**	Sampling depth (cm)	Duration (years)	Cumulative manure-C input (Mg C ha^{-1})	Animal species	IPCC climatic zone	Soil clay (%)	Soil silt (%)	Initial SOC (g kg^{-1})	Land use	Reference†
Chinon, France	REF-zero	2	30	28	23;46	cattle	warm temperate	9	5	8	perennial	(Morlat & Chaussod, 2008); pers. comm.
Cuttack, Orissa, India	REF-zero, REF-min	2	15	35	32	cattle	tropical	20	14	7	paddy	(Nayak *et al.*, 2009)
Kanpur, Uttar Pradesh, India	REF-min	1	30	25	NA	NA	tropical	18	35	3	paddy	(Nayak *et al.*, 2012)
Sabour, Bihar, India	REF-min	1	30	25	NA	NA	tropical	28	22	5	paddy	(Nayak *et al.*, 2012)
Kalyani, West Bengal, India	REF-min	1	30	23	12	cattle	tropical	50	30	9	paddy	(Nayak *et al.*, 2012); (Bandyopadhyay *et al.*, 2011); pers. comm.
Ludhiana, Punjab, India	REF-min	1	30	26	NA	cattle	tropical	18	28	3	paddy	(Nayak *et al.*, 2012); (Walia *et al.*, 2010)
Pendleton, Oregon, USA	REF-zero, REF-min	2	30	56	37	cattle	warm temperate	18	70	NA	annual	(Rasmussen & Parton, 1994)
Ludhiana, Punjab, India	REF-zero, REF-min	2	30	32	NA	NA	tropical	7	33	3	paddy	(Rasool *et al.*, 2007); (Kukal *et al.*, 2009)
Ludhiana, Punjab, India	REF-zero, REF-min	2	30	32	NA	NA	tropical	16	24	3	annual	(Rasool *et al.*, 2008); (Kukal *et al.*, 2009)
Almora, Uttarakhand, India	REF-zero, REF-min	8	15	3	34;27;20;14;22	cattle	warm temperate	34	56	11	annual	(Saha *et al.*, 2008)
Bhubaneswar, Orissa, India	REF-zero, REF-min	6	30	3	NA	cattle	tropical	10	25	NA	perennial	(Saha *et al.*, 2010b)
Umiam, Meghalaya, India	REF-min	1	30	5	NA	NA	tropical	34	34	NA	annual	(Saha *et al.*, 2010a)
Belle Mina, Alabama, USA	REF-zero, REF-min	4	20	10	11	poultry	warm temperate	27	58	12	annual	(Sainju *et al.*, 2008a); (Sainju *et al.*, 2010); (Sainju *et al.*, 2008b)
Varanasi, Uttar Pradesh, India	REF-zero, REF-min	3	15	9	22;11	NA	tropical	62	22	1	annual	(Sarkar *et al.*, 2003)
Akola, Maharashtra, India	REF-zero, REF-min	3	15	19	NA	NA	tropical	NA	NA	NA	annual	(Sharma *et al.*, 2011)

Table 1 (Continued)

Location	Data set	n*	Sampling depth (cm)	Duration (years)	Cumulative manure-C input (Mg C ha^{-1})	Animal species	IPCC climatic zone	Soil clay (%)	Soil silt (%)	Initial SOC (g kg^{-1})	Land use	Reference†
Patna, Bihar, India	REF-zero, REF-min	3	15	4	NA	NA	tropical	74	9	5	paddy	(Singh *et al.*, 2001)
Sardar Krushinagar, Gujarat, India	REF-zero, REF-min	5	100	18	27;10	cattle	tropical	11	4	2	annual	(Srinivasarao *et al.*, 2011); pers. comm.
Zhangye, Gansu, China	REF-zero, REF-min	2	20	23	52	pig–cattle–sheep	cool temperate	20	52	12	annual	(Su *et al.*, 2006); (Hai *et al.*, 2010)
Lucknow, Uttar Pradesh, India	REF-zero, REF-min	2	30	5	23	NA	tropical	13	25	3	perennial	(Suman *et al.*, 2009); (Singh *et al.*, 2007)
Bignan, France	REF-min	1	30‡	8	18	poultry	warm temperate	17	42	25	annual	(Viaud *et al.*, 2011); pers. comm.
Moystad, Norway	REF-zero, REF-min	4	20	82	NA	cattle	cool temperate	14	34	24	annual	(Yang *et al.*, 2007)

*n = number of observations.

†for each site, the first cited reference included soil C stocks. The other references contained unavailable information in the first one.

‡Equivalent topsoil depth of the study reference treatment.

Table 2 Global means of the two effect size indices with the 95% Confidence Interval (CI) and probability level corresponding to the Student's t-test

Index	REF-zero data set	REF-min data set
First: SOC stock difference (Mg C ha^{-1})	9.4 ± 4.1 (95% CI); $P < 0.0001$	5.6 ± 2.8 (95% CI); $P < 0.0001$
Second: relative SOC change		1.26 ± 0.14 (95% CI); $P < 0.0001$

mineral fertilizer (5.6 Mg C ha^{-1}). If we assume that in most studies of the REF-min data set the amount of C added as roots and crop residues was similar in the manure treatment and in the mineral fertilizer reference treatment, thus the positive SOC response following manure application can probably be mainly attributed to direct C input by manure.

Factors influencing the SOC stock difference

Our meta-analysis showed a significant linear relationship between the *SOC stock difference* (first index; Mg C ha^{-1}) and cumulative manure-C input (Mg C ha^{-1}) for the REF-zero ($P < 0.0001$; $R^2 = 0.53$) and the REF-min ($P < 0.0001$; $R^2 = 0.59$) data sets (Fig. 1a, b). In this analysis, cumulative manure-C input is a combination of annual manure-C application rate and study duration. Positive linear relationships between cumulative amount of added organic matter and SOC stocks or stock changes associated with treatments involving various amounts of manure or other organic C sources have often been observed in individual studies (e.g., Thomsen & Christensen, 2004; Kong *et al.*, 2005; Majumder *et al.*, 2008). As far as we know, our study is the first one reporting such a relationship between *SOC stock difference* compared to a reference treatment and cumulative animal manure-C input from a worldwide set of studies. It is noteworthy that despite widely variable sources of data (soil, climate, study duration, animal species, land use, etc.), we can explain at least 53% of the variability in *SOC stock difference* by cumulative manure-C input. For comparison purposes, we added eight individual observations (not included in our meta-analysis due to lack of replications) from seven long-term sites in the United Kingdom (Jenkinson & Johnston, 1977; Jenkinson *et al.*, 1990), Germany (Ludwig *et al.*, 2011), Canada (Grant *et al.*, 2001), and China (Guo *et al.*, 2007) (Fig. 1a, b). These points clearly fit in the same general linear relationship as the data retained in our meta-analysis. Our results corroborate linear increases in SOC stocks with increasing organic C inputs shown by most current models of SOC dynamics

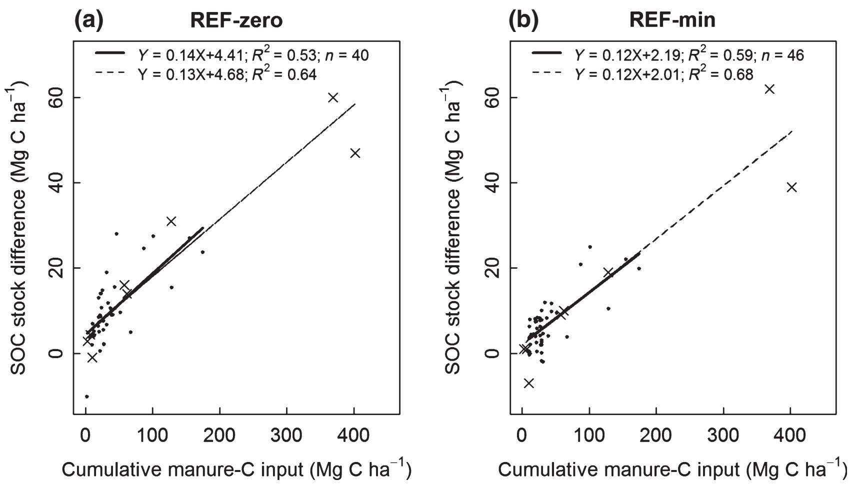

Fig. 1 Relationship between *SOC stock difference* and cumulative manure-C input for the REF-zero (a) and REF-min (b) data sets (•), and with additional observations from non-replicated sites (×).

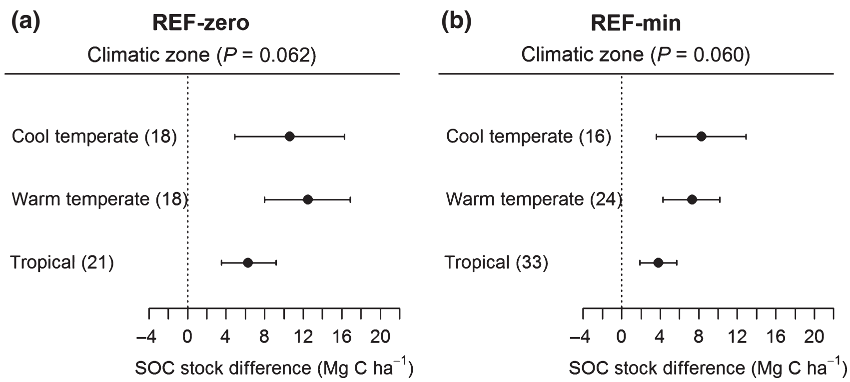

Fig. 2 Effect of climatic zone on the *SOC stock difference* due to manure application for the REF-zero (a) and REF-min (b) data sets [number of observations in each climate class in brackets, means and 95% Confidence Interval (CI)].

[e.g., RothC (Coleman & Jenkinson, 1995), Century (Parton *et al.*, 1987)]. Indeed, the relationship between C input and *SOC stock difference* is linear up to very high levels of cumulative C input.

The group analysis indicated a strong trend toward an effect of climatic zone on the *SOC stock difference* for both the REF-zero ($P = 0.062$) and the REF-min ($P = 0.060$) data sets (Fig. 2a,b). The *SOC stock difference* was lower in tropical climate than in warm temperate climate for the REF-zero ($P = 0.027$) and REF-min ($P = 0.052$) data sets. In addition, for the REF-min data set, the *SOC stock difference* tended to be lower in tropical climate than in cool temperate climate ($P = 0.078$) (Fig. 2b). This observation is consistent with the general understanding that soils in warmer climates, where decomposition is faster, may accumulate C slower than soils in colder climates (Freibauer *et al.*, 2004). However, it should be noted that for tropical climate, a significant number of observations (10 of 21 for the REF-zero data set and 12 of the 33 for the REF-min data set) actually had a cumulative manure-C input <45 Mg C ha^{-1} and that cumulative manure-C input was unknown for the other observations. Therefore, from our meta-analysis, we cannot rule out that the lower SOC stocks under tropical climate may simply be due to relatively lower cumulative manure-C inputs. This clearly emphasizes the importance of documenting C inputs in agronomic studies reporting SOC change.

The effect of animal species on the *SOC stock difference* was not statistically significant (Fig. 3a,b). However, in both REF-zero and REF-min data sets, cattle manure showed a slight trend to higher values than the others, and confidence intervals suggested a significant positive *SOC stock difference* after cattle manure application but not after pig and poultry manure application. This significant response of SOC after cattle manure application would be consistent with the idea that its organic

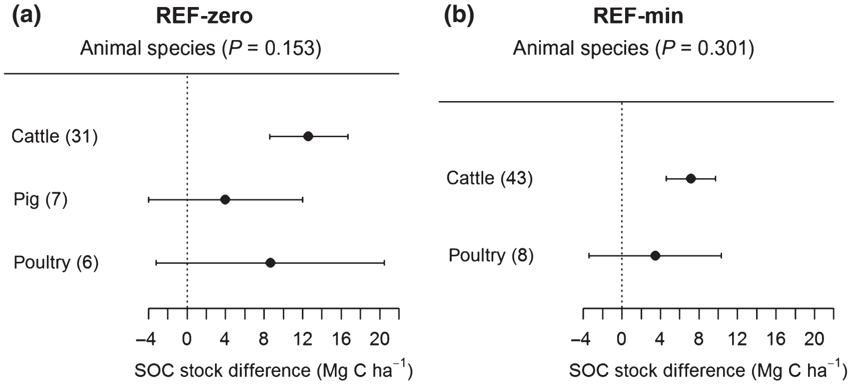

Fig. 3 Effect of animal species on the *SOC stock difference* due to manure application for the REF-zero (a) and REF-min (b) data sets [number of observations in each species class in brackets, means and 95% Confidence Interval (CI)].

matter is more stable than that from poultry and pig manure (Velthof *et al.*, 2000). However, it should be underlined that compared to cattle, the number of observations was very low and the variability very high for pig and poultry manures, which limits the interpretation. In addition, similar to climate, we cannot rule out that the low values for pig and poultry manure may also be related to a relatively low cumulative manure-C input associated with these studies (<45 Mg C ha^{-1}, for all relevant studies except one). Clearly, more studies on the impact of pig and poultry manure are required, and these should include C input data.

We found no effects of land use, clay and silt content, or initial SOC concentration on the *SOC stock difference*. This is partly due to missing observations in the case of initial SOC concentration (Table 1) or to the limited number of studies involving 'perennial' and 'paddy' cropping systems in the case of land use. In addition, these explanatory factors may be of minor significance compared to the overwhelming effect of cumulative manure-C input.

Estimation of manure-C retention coefficient

Overall, our global analysis showed that cumulative manure-C input was the main factor explaining SOC response to manure application. Many studies have estimated C retention coefficients from the slope of linear relationships between cumulative C input and SOC stocks or stock changes associated with experimental treatments including various amounts of manure or crop residues (Campbell *et al.*, 1991; Bhogal & Shepherd, 1997; Buyanovsky & Wagner, 1998; Thomsen & Christensen, 2004; Kong *et al.*, 2005; Mandal *et al.*, 2007; Benbi & Senapati, 2010). We outlined previously that in the case of the REF-min data set, the positive SOC response to manure application can probably be mainly attributed to C input by manure. Thus, the slope of the linear relationship between the cumulative manure-C input (Mg C ha^{-1}) and the *SOC stock difference* (1st index; Mg C ha^{-1}) for the REF-min data set (Fig. 1b) can be considered an approximation of the manure-C retention coefficient, which represents the average proportion of manure-C remaining in soil. Our estimated global manure-C retention coefficient is 12% ± 4 (95% Confidence Interval, CI) for an average study duration of 18 years. As described earlier, by adding eight individual observations from seven long-term sites (without replicates) in the United Kingdom (Jenkinson & Johnston, 1977; Jenkinson *et al.*, 1990), Germany (Ludwig *et al.*, 2011), Canada (Grant *et al.*, 2001), and China (Guo *et al.*, 2007), the slope remains at 12% ± 2 (95% CI).

To the best of our knowledge, this is the first time that a C retention coefficient of animal manure can be deduced from a worldwide set of studies offering a wide range of cumulative C input levels (10–175 Mg C ha^{-1} for observations included in the meta-analysis; 3–402 Mg C ha^{-1} with additional observations from unreplicated designs). Indeed, all of the studies cited previously involved individual sites. Moreover, the C input estimates in these studies included either crop residues only or a mix of crop residues and manure. Using 14 long-term field experiments in Europe, Smith *et al.* (1997) established a linear relationship between yearly relative changes in SOC stock compared to a reference treatment and the amount of fresh organic manure added annually. However, the absence of manure dry matter and C contents did not allow us to calculate the cumulative manure-C input and consequently a C retention coefficient from their data.

Our estimated manure-C retention coefficient is lower than the value of 23% reported for animal manure in a study from seven different sites in the United Kingdom (Bhogal *et al.*, 2007). However, their 95% CI was 9 to 37 which overlaps with ours. In addition, Bhogal *et al.* (2007) pointed out that the average increase of SOC change representing 23% of manure-C could only be regarded as the initial rate of SOC increase, as SOC accumulation rates decline over time, and consequently their retention coefficient could be overestimated. Moreover, their value was measured by calculating the difference in SOC between manured and unmanured treatments without specifying if the unmanured treatment included mineral fertilization or not. Thus, their manure-C retention coefficient could also be overestimated if some C in soils originated from crop residues rather than manure.

Our manure-C retention coefficient can be compared to those estimated for crop residues. After 18 years of annual straw addition, Thomsen & Christensen (2004) observed a retention coefficient of 14% for straw C. Campbell *et al.* (1991) reported a C retention coefficient of 6% for crop residues on a 30-year old site. After 10 years, Kong *et al.* (2005) observed a value of 8% across ten different cropping systems. Manure was also applied in one of their cropping systems. From Buyanovsky & Wagner (1998), we calculated that 6% and 7% of C applied as crop residues, and additionally from manure in some plots, were retained in soil during a very long period of 'humification' extending to 100 years. Therefore, our value of manure-C retention coefficient (12% ± 4), estimated for an average study duration of 18 years, is comparable to those for crop residues determined in the medium to long-term (10–100 years), and supports Buyanovsky & Wagner (1998) who argued that there was no reason to consider that manure was more effective for SOM enhancement than plant residues. However, retention of C added as manure may be greater than crop residues in the short term. For instance, in an *in situ* decomposition study, Thomsen & Christensen (2010) observed a higher retention of C added in the form of sheep feces (30%) than C directly applied as crop residues (19%) after nine annual additions. Likewise, in a laboratory incubation, 14% of C applied in feed was retained in soil after 1 to 2 years, against 48% of C applied as feces (Thomsen *et al.*, 2013). Taken together, our results and the above-cited literature suggest that despite apparently faster early decomposition of crop residues compared to manure, longer term stabilization may be relatively similar for both.

Estimation of relative SOC change after manure application

The second effect size index is defined as the ratio of SOC stock in plots receiving manure to SOC stock in plots receiving mineral fertilization. It represents a *relative SOC change* factor such as used by IPCC (2006) and Ogle *et al.* (2005), and estimated from experiments that lasted at least 20 years. The average value for the *relative SOC change* (2nd index) was 1.26 ± 0.14 (95% CI) for experiments that lasted at least 20 years (Table 2). This ratio was lower than the average of IPCC relative SOC change factors (1.41) proposed for high inputs with manure (IPCC, 2006) and the average of high input factors with amendments (1.36) proposed by Ogle *et al.* (2005). Nevertheless, our estimation was based on a larger number of sites (22 sites for 28 observations) against probably five studies for IPCC (2006) and less than five for Ogle *et al.* (2005).

A significant linear relationship was also observed between the cumulative manure-C input (Mg C ha^{-1}) and the *relative SOC change* ($P = 0.026$; $R^2 = 0.31$) (Fig. 4). Climatic zone did not affect the *relative SOC change* (Fig. 5). Similar to the *SOC stock difference* (1st index), no effect of land use, clay and silt content or initial SOC concentration was observed. The reduced REF-min data set was limited by the low number of observations for cumulative manure-C input, and some climate and animal species classes. Clearly, as mentioned previously, more data are necessary to elucidate the global impact of these explanatory factors.

The IPCC Guidelines for National Greenhouse Gas Inventories provide different values of soil C stock change after animal manure application in different climatic zones: 1.37 for temperate, boreal, and tropical dry climates; 1.44 for temperate, boreal, and tropical moist/wet climates; and 1.41 for tropical montane climates (IPCC, 2006). From a statistical standpoint, these values

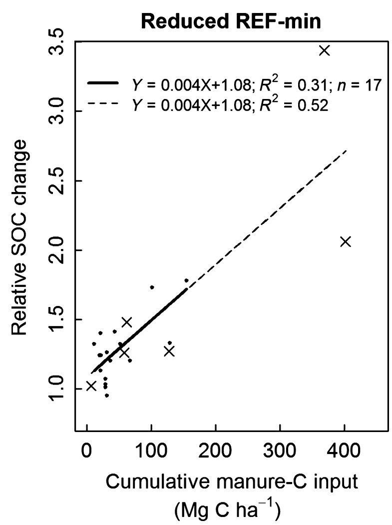

Fig. 4 Relationship between the *relative SOC change* and cumulative manure-C input for the reduced REF-min data set (•), and with additional observations from non-replicated sites (×).

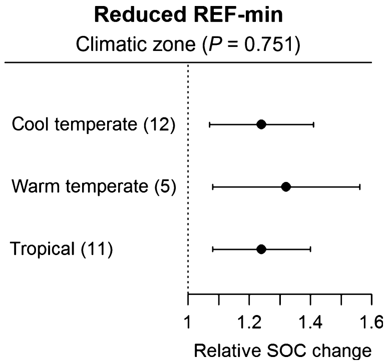

Fig. 5 Effect of climatic zone on the *relative SOC change* for the reduced REF-min data set [number of observation in each climate class in brackets, means and 95% Confidence Interval (CI)].

are not significantly different from each other. Moreover, the amount of C input by manure is not taken into account in these estimates. Our results offer some scope for refinement of these change factors by taking into account the amount of manure applied. However, the relationship between the cumulative manure-C input (Mg C ha^{-1}) and the *relative SOC change* probably needs to be confirmed with more data to propose a new operational set of IPCC factors.

Limits and outlook

To the best of our knowledge, this study is the first global analysis of factors determining SOC response to manure application which includes a significant number of studies. For this meta-analysis, we chose to work with high-quality data (replicated randomized experiments, values expressed as SOC stocks, C input from manure, etc.). Consequently, our conclusions were constrained by missing data and the meta-analysis raises many points that need to be improved in future research.

First, SOC expressed as stock or bulk density data necessary to compute SOC stock were missing in many articles that were scanned. This information is essential to examine the relationship between cumulative manure-C input and SOC change. Ideally, SOC stocks should also be expressed on an equivalent mass basis to avoid any bias in the estimation of changes in SOC stocks when the entire soil profile is not sampled (in case there would be a significant amount of SOC beneath the maximum depth of sampling) (Vandenbygaart & Angers, 2006). In the studies considered in our analysis, only two reported SOC stocks on an equivalent mass (Kätterer *et al.*, 2011; Viaud *et al.*, 2011).

Another important point that limited our analysis was detailed information allowing estimation of manure-C input (C concentration, application rate, dry matter content) which was absent from many articles reporting SOC stocks. Consequently, manure-C input could be estimated in only 29 of the 49 sites, representing a total of 86 observations in both data sets. This information is necessary to analyze the relationship between SOC change and cumulative manure-C input and refine the estimation of our manure-C retention coefficient. Indeed, there is uncertainty associated with this relationship due to the substantial lack of observations with cumulative manure-C input greater than 75 Mg C ha^{-1} (Fig. 1a,b and Fig. 4). In addition, there is significant variability in our data for cumulative manure-C input <75 Mg C ha^{-1}. However, these data represent the current state of available information for studies on SOC response to manure application.

Other relevant information for our analysis such as animal species and initial SOC concentration was often missing in the scanned articles (Table 1). In addition, some classes of explanatory factors had a low number of observations compared to others. For example, fewer studies used poultry or pig manure compared to cattle manure. Similarly, we did not find enough studies involving liquid manure compared to solid. Perennial cropping systems were less represented than annual systems. Another limitation was the lack of tropical sites outside of India. So extrapolating our results to other tropical regions should be done with caution. Most sites were located in Europe, Asia, or North America with South America, Africa and Oceania being under- or not represented.

The results of this meta-analysis show that at a global scale cumulative manure-C input has a dominant effect on SOC change following manure application. When more data become available, the effects of explanatory factors like climate, animal manure characteristics, soil clay and silt content, initial SOC concentration and land use could be studied further by determining their effect on the slope of the relationship between cumulative C input and SOC stock change using meta-regression with multiple explanatory factors.

In accordance with our selection criteria, many short-term studies (<3 years) addressing manure impact on SOC were omitted from the meta-analysis (Lynch *et al.*, 2005; Agbede, 2010; Bilalis & Karamanos, 2010; Mellek *et al.*, 2010; Islam *et al.*, 2011). Most of these studies mentioned specific information on manure characteristics including manure-C input (Lynch *et al.*, 2005; Agbede, 2010; Mellek *et al.*, 2010) which is encouraging for future meta-analyses, and we can only hope that these studies will be maintained.

In summary, our findings suggest that at a global scale, above animal species, land use or soil properties, the amount of applied manure-C was the dominant driver determining the extent of SOC increase following manure application. We also observed a strong tendency for *SOC stock difference* to be lower in tropical than other climatic zones, but this effect could not be decoupled from that of manure-C input. Our results for the relative change factors, but also for manure-C retention coefficient, offer some scope for the improvement of national GHG inventory methodologies. There were obvious gaps in the data especially with regards to animal species (especially pig and poultry manure), manure management system (e.g., liquid vs. solid storage), and under-representation of some geographic regions. We emphasize that long-term field studies covering these gaps either be initiated or continued, and that these studies document important explanatory factors such as manure application rate and C concentration which were very often absent from research articles.

Acknowledgements

We thank authors who shared additional information on studies chosen for the meta-analysis. We thank Léon-Étienne Parent for advice on meta-analysis methods, Martin Chantigny, and Philippe Rochette for helpful discussions, Julien Beguin and Anne-Sophie Julien for statistical assistance, and Anaïs Charles and Caroline Hudon for help with the literature search. We are grateful to Jérôme Laganière and Frank Larney who provided comments on a draft version of the manuscript. We acknowledge the support of Agriculture and Agri-Food Canada and the Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) for a post-graduate scholarship to one of us (É.M.).

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