Environmental Evidence

SYSTEMATIC REVIEW PROTOCOL

Open Access

What is the impact of human wastewater biosolids (sewage sludge) application on long-term soil carbon sequestration rates? A systematic review protocol

Mike J. Badzmierowski*, Gregory K. Evanylo, W. Lee Daniels and Kathryn C. Haering

Abstract

Background: Human wastewater biosolids, hereafter referred to as biosolids, are produced in significant quantities around the world and often applied to an extensive land mass including agricultural fields, forests, mine lands, and urban areas. Land-application of biosolids has been reported in peer-reviewed and non-peer-reviewed work to change soil organic carbon stocks in varying amounts. Determining the potential of soil organic carbon (SOC) stock change and sequestration from biosolids land application is critical for biosolids producers and users to gain access to carbon credit markets. Our review question is, "what is the impact of biosolids application on long-term soil carbon sequestration rates?" We look to explore this main question with the follow-up, "does biosolids processing methods and characteristics, application method, soil properties, land management and other modifiers affect rates of carbon accumulation from land-applied biosolids?"

Methods: Searches will be conducted using online databases (i.e., *Web of Science Core Collection*, *CAB Abstracts*, *Scopus*, *ProQuest Dissertations & Theses Global*), search engines (*Google Scholar* and *Microsoft Academic*), and specialist websites to find primary field studies and grey literature of biosolids land-application effects on soil organic carbon stocks. We will use English search terms and predefined inclusion criteria of: (1) a field study of at least 24 months that reports soil organic carbon/matter (SOC/SOM) concentrations/stocks; (2) has two types of treatments: (i) a control (non-intervention AND/OR synthetic fertilizer) AND (ii) a biosolids-based amendment; and (3) information of amendment properties and application dates and rates to estimate the relative contribution of the applied materials to SOC changes. We will screen results in two stages: (1) title and abstract and (2) full text. A 10% subset will be screened by two reviewers for inclusion at the title and abstract level and use a kappa analysis to ensure agreement of at least 0.61. All results in the full text stage will be dual screened. Data will be extracted by one person and reviewed by a second person. Critical appraisal will be used to assess studies' potential bias and done by two reviewers. A meta-analysis using random effects models will be conducted if sufficient data of high enough quality are extracted.

Keywords: Land application, Meta-analysis, Sewage sludge, Soil organic carbon, Soil organic matter

Introduction

Human wastewater biosolids, hereafter referred to as biosolids, are nutrient-rich organic materials resulting from the treatment of human digestive residuals often in wastewater treatment facilities. Biosolids are produced in significant quantities on a global scale

*Correspondence: mikejb7@vt.edu
School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

(10×10^7 Mg year^{-1}) [1]. They are often applied to an extensive land mass including agricultural fields, forests, mine lands, and urban areas [2–6]. Applications of biosolids can increase soil organic C (SOC), improve soil physical and chemical characteristics, and reduce fertilizer needs and water usage [7–9]. Many of the soils on which biosolids are applied are low in organic matter (OM) and thereby SOC. Applications of biosolids are generally expected to increase OM content and thereby reduce atmospheric greenhouse gas emissions. However, SOC stock changes after land application vary from study to study. Several long-term studies indicate C sequestration potential of land applied biosolids [10, 11]. Antonelli and Fraser [12] found long-term C storage efficiency was higher for lower biosolids application rates. In contrast, Badzmierowski and Evanylo [13] found that SOC stocks decreased during years with no amendment application. This indicated that the applied carbon from the organic amendments was still undergoing decomposition and not being "stored." Variability of SOC stock changes from land-applied biosolids is most likely a result of various factors such as climatic conditions, soil properties, land use management, biosolids characteristics, application strategies (i.e., rate, surface-applied or incorporation, one-time or repeated applications), and timing between last application and sample measurement.

At the time of this writing, there has been no peer-reviewed, quantitative synthesis of SOC stock changes after biosolids land-application. Due to the incomplete scientific basis and uncertainty regarding the permanence of SOC with time and management strategy following biosolids application, organizations such as the Intergovernmental Panel on Climate Change and the American Carbon Registry have been unable to include biosolids as a specific carbon dioxide removal mechanism. Biosolids stakeholders (e.g., wastewater treatment plants and biosolids users) seek a quantitative synthesis on the potential of C sequestration from land-applied biosolids to gain access to C credit markets.

We plan to conduct a systematic review and meta-analysis in response to biosolids stakeholders needs. The systematic review and meta-analysis will identify potential C sequestration rates of land-applied biosolids and assess explanatory factors that may affect rates. Research questions and systematic review protocol were developed by the authors (Badzmierowski, Evanylo, Daniels). Funders only had input on desired goals of the systematic review- to determine the carbon sequestration potential of land applied biosolids. Funders will have no other input regarding systematic review design, search strategy, analysis, or interpretation of results.

Objective of the review

Our objective is to perform a systematic review of peer-reviewed and grey literature to develop sequestration rates of land-applied biosolids and associated explanatory factors. Our study will address the primary review question (Population, Intervention/Exposure, Comparator, Outcome, and Study design—"PICOS" elements are defined in Table 2) and secondary review questions:

What is the impact of human wastewater biosolids (sewage sludge) application on long-term soil carbon sequestration rates?

How do geographical location and climate (i.e., moisture and temperature) affect long-term C sequestration rates?

Do biosolids processing methods (e.g., aerobic, anaerobic, lime-stabilized, etc.) and final characteristics (e.g., total solids, iron and aluminum content, etc.) affect long-term C sequestration rates?

Does application method of land-applied biosolids (i.e., surface, incorporated, or injected) affect long-term C sequestration rates?

How do land use (e.g., cropland, forests, reclamation, etc.) management (e.g., crop rotation and cover crop), and vegetation affect long-term C sequestration rates from land-applied biosolids?

What is the relationship between SOC changes from land-applied biosolids and soil properties (e.g., depth, soil textural class, clay content, iron content, aluminum content, carbon to nitrogen (CN) ratio, etc.)?

Methods

Our study will follow the methodologies established by the Collaboration for Environmental Evidence (CEE) Guidelines and Standards for Evidence Synthesis in Environmental Management, version 5.0 and use the "RepOrting standards for Systematic Evidence Syntheses" (ROSES) to document our systematic review [14, 15]. See Additional file 1 for our completed Roses form for systematic review protocols.

Searching for articles

Our search strategy has employed the assistance of three Virginia Tech librarians (Cozette Comer, Evidence Synthesis Librarian; Inga Haugen, Life Science, Agriculture, and Scholarly Communication Librarian; and Rachel Miles, Research Impact Librarian) to optimize search terms, search strategies, and databases to be used.

Search languages

The search will be conducted using English search terms and use Boolean operators and wildcards to improve search results relevancy. For studies that are not published in English we will attempt to get a translation for these results. We will exclude a result if we cannot obtain a translation. This is a shortcoming of our review, but we do not have the resources to work in other languages.

Search strings

Our search string is made of three components population, intervention/exposure, and outcome terms. See the list of components and terms within each component listed below.

Population term: soil.

Intervention terms: biosolid* OR sewage OR sludge OR "sewage sludge" OR biosludge OR milorganite OR "human solid waste" OR "waste amend*".

Outcome terms: carbon OR "soil OC" OR SOC OR "soil organic C" OR "soil organic carbon" OR "organic matter" OR "soil OM" OR SOM OR "soil organic matter".

The three components will be linked using the Boolean operator "AND." The Boolean operator "OR" will be used to separate terms/phrases within a given component. The asterisk (*) represents a 'wildcard' meaning it represents any group of characters including no character. Quotation marks are used to search exact phrases (e.g., "sewage sludge" will search the exact phrase sewage sludge and the hyphenated sewage-sludge).

Estimating the comprehensiveness of the search

To estimate the comprehensiveness of the search, a brief list of 12 benchmark studies that fit the inclusion criteria was established based on previous related reviews and knowledge of the review team (see Additional file 2). The final search strings were tested for each of the three databases that have been selected to use in our review (see below for publication databases). All databases had a 100% comprehensiveness using the final search string. See Additional file 2 for search string results, benchmark list used for testing search comprehensiveness, and previously published related reviews on our topic.

Publication databases to be searched

We will be using our Virginia Polytechnic Institute and State University subscription to search the following databases, *CAB Abstracts* (1910s-present), *ProQuest Dissertations & Theses Global* (1637-present, full-text dissertations 1997-present), *Scopus* (1800s-present), and *Web of Science Core Collection* (1900–present). Our subscription for the *Core Collection* includes: Science Citation Index Expanded (1900–present), Social Sciences Citation Index (1900–present), Arts & Humanities Citation Index (1975–present), Conference Proceedings Citation Index- Science (1990–present), Conference Proceedings Citation Index-Social Sciences & Humanities (1990–present), Book Citation Index-Science (2005–present), Book Citation Index-Social Sciences & Humanities (2005–present), Emerging Sources Citation Index (2005–present), Current Chemical Reactions (1985–present), and Index Chemicus (1993–present).

Internet searches to be conducted

We will use the Publish or Perish 7 software tool [16] to query the top 1000 "relevant" search results for both Google Scholar and Microsoft Academic. The use of these search engines will be used to target "grey" literature including theses and dissertations, institutional reports, and conference proceedings. We will use the "keywords" search field in the Publish or Perish 7 software. See Table 1 for search specifications.

Specialist searches–Searches for grey literature

We will search specialist websites with two simplified search strings using English terms:

- (carbon AND biosolids)
- (carbon AND sewage sludge)

Specialist websites will include:

- United States Department of Agriculture–Agricultural Research Service (https://www.ars.usda.gov/)
- United States Environmental Protection Agency (https://www.epa.gov/)
- European Environment Agency (https://www.eea.europa.eu/)
- Swedish Environmental Protection Agency (http://www.swedishepa.se/)
- German Environment Agency (https://www.umweltbundesamt.de/en)
- Rothamsted Research (https://www.rothamsted.ac.uk/)

Supplementary searches

Backward and forward snowballing (i.e., backward = identifying articles from reference lists and forward = identifying articles that have cited the articles) will be done on all accepted articles and relevant reviews (see Additional file 2). Our "grey literature" search will be expanded by reaching out to our known biosolids research contacts and stakeholders requesting relevant datasets via email and to alert the community of

Table 1 Search specifications and string for each database or search engine

Database or search engine name (Abbrev.)	Search field specification	Search string	Search dates
Bibliographic databases			
CAB Abstracts from CAB Direct	All fields (does not have a "Topic" field)	(soil) AND (carbon OR "soil OC" OR SOC OR "soil organic C" OR "soil organic carbon" OR "organic matter" OR "soil OM" OR SOM OR "soil organic matter") AND (biosolid* OR sewage OR sludge OR "sewage sludge" OR biosludge OR milorganite OR "human solid waste" OR "waste amend*")	All years (1915–present)
ProQuest Dissertations & Theses Global	Abstract	ab(soil) AND ab(carbon OR "soil OC" OR SOC OR "soil organic C" OR "soil organic carbon" OR "organic matter" OR "soil OM" OR SOM OR "soil organic matter") AND ab(biosolid* OR sewage OR sludge OR "sewage sludge" OR biosludge OR milorganite OR "human solid waste" OR "waste amend*")	1637–present, full-text dissertations 1997–present
Scopus	Article title, Abstract, and Keywords	(TITLE-ABS-KEY (soil) AND TITLE-ABS-KEY (carbon OR "soil OC" OR SOC OR "soil organic C" OR "soil organic carbon" OR "organic matter" OR "soil OM" OR SOM OR "soil organic matter") AND TITLE-ABS-KEY (biosolid* OR sewage OR sludge OR "sewage sludge" OR biosludge OR milorganite OR "human solid waste" OR "waste amend*"))	All years (1800s–present)
Web of Science from Clarivate Analytics, Core Collection	Topic (titles, authors, abstracts, keywords)	TOPIC: (soil) *AND* TOPIC: (carbon OR "soil OC" OR SOC OR "soil organic C" OR "soil organic carbon" OR "organic matter" OR "soil OM" OR SOM OR "soil organic matter") *AND* TOPIC: (biosolid* OR sewage OR sludge OR "sewage sludge" OR biosludge OR milorganite OR "human solid waste" OR "waste amend*")	All years (1900–present)
Search Engines			
Google Scholar search query in Harzing's Publish or Perish	256-character limit (No field category)	soil (carbon|"soil OC"|SOC|"soil organic C"|"soil organic carbon"|"organic matter"|"soil OM"|SOM|"soil organic matter")(biosolids|sewage|sludge|"sewage sludge"|biosludge|milorganite|"human solid waste"|"waste amendment")	First 1000 results sorted by relevance according to Google Scholar's algorithm
Microsoft Academic search query in Harzing's Publish or Perish	Keywords	soil AND (carbon OR "soil OC" OR SOC OR "soil organic C" OR "soil organic carbon" OR "organic matter" OR "soil OM" OR SOM OR "soil organic matter") AND (biosolids OR sewage OR sludge OR "sewage sludge" OR biosludge OR milorganite OR "human solid waste" OR "waste amendment")	First 1000 results sorted by relevance according to Microsoft Academic's algorithm

our systematic review. The Review Team will attempt to contact authors of any articles that are unobtainable through our library subscription or interlibrary loans to gain access to their full articles. There will be no search updates for this review.

Screening process

Results from all searches will be imported to EndNote [17] and exported as Extensible Markup Language (.xml) to the online systematic review management tool, *Covidence* (access via Virginia Tech license) [18]. All results will be added to Covidence. Covidence will be used to identify and remove duplicates from search results.

The results will be screened in two stages: (1) title and abstract, and (2) full-text. We will select a random 10% subset of results at the title and abstract level and two reviewers (Badzmierowski and Haering) will screen the articles independently based on the eligibility criteria defined in Table 2. Cohen's kappa will be used to determine the inter-rater reliability as a consistency measure between the two reviewers. If the Kappa score is 0.61 or higher, the consistency will be considered acceptable. A score below 0.61 will require a review of eligibility criteria and the screening process among the systematic review team. The screening process will be repeated until an acceptable Kappa score is achieved. After a 10% subset with acceptable agreement has been obtained, the remaining articles will be reviewed by one reviewer at the title and abstract level by the lead principal investigator (Badzmierowski). Reviewing articles by one reviewer at the title and abstract stage is not best practice in a systematic review and we will highlight this in our final synthesis.

All results at the full-text stage will be screened by two reviewers. No reviewer will screen their own studies for inclusion or exclusion at this stage. Disagreements for inclusion will first go to discussion between the two reviewers to reach a consensus. If a consensus is not

Table 2 Systematic review eligibility criteria using the PICOS framework

Question: "What is the impact of human wastewater biosolids (sewage sludge) application on long-term soil carbon sequestration rates?"	
Question key elements	Eligibility criteria
Populations (P): Soil carbon stocks in various ecosystems and land uses	Included: All ecosystem types and land uses are acceptable if there is documentation of the study site and description of method used to determine carbon concentration and/or stock. Experiments that report results of multiple systems that can be deemed independent of another (e.g., different climatic region, soil type, cropping system) will be designated as a separate study. Excluded: Laboratory and greenhouse experiments will not be included. Container/pot setups in field conditions will not be included.
Interventions (I): Land application of biosolids	Included: Field studies of at least 24 months in duration that investigates biosolids/sewage sludge or domestic sewage/human waste that has undergone a recognized treatment practice to clean the waste [19]. Biosolids treatments can be mixed with other materials (e.g., compost, sand, sawdust, etc.), however biosolids must be at least 50% (on a dry weight basis) of the mixture. Liquid sewage sludge will be included. The purpose of the application of sewage sludge/biosolids should be for soil value and not irrigation value. Digestate and biochar derived from human fecal matter/domestic sewage will be included. Must include amount of biosolids carbon/organic matter added or provide enough details to calculate biosolids carbon/organic matter added to experiment (e.g., dry weight of biosolids added and total carbon content of biosolids). Excluded: Municipal waste is defined as waste collected and treated by or for municipalities (e.g., food waste, glass, metals, paper, plastics, yard trimmings, etc.) [20]. Industrial wastes (e.g., papermill sludge, tannery sludge, etc.) will not be included in this study. Wastewater (i.e., effluent) will be excluded. Biosolids that are spiked by researchers (e.g., additional metals or other contaminants) will not be included as this represents a manipulated media outside of standard wastewater treatment processes for biosolids/sewage sludge/domestic waste. Studies less than 24 months.
Comparators (C): Non-amended control Synthetic fertilizer control	Included: Must include at least one or both control types (i.e., non-amended or synthetic fertilizer). Must include "before-and-after" soil organic carbon/matter measurements for both a control and biosolids populations (i.e., soil organic carbon/matter measurement prior to experiment and after intervention) OR a final control and biosolids soil organic carbon/matter measurement. Excluded: Studies that do not have a control "final" measurement comparator.
Outcomes (O): Changes in soil organic carbon/matter Changes in biomass Changes in soil biological, chemical, physical parameters	Included: Must include primary research that documents the change in soil organic carbon/matter concentration/stock. Other measurements will be documented if reported (i.e., change in plant biomass, soil bulk density, etc.). Excluded: If there is more than one primary research article on the same experiment, the latest reported measurement values will be used.
Study type (S):	Included: Before-After-Control-Impact (monitors control and impact groups from before and after impact occurred), Control-Impact (lacks pre-impact data), and Randomized Controlled Trials (though these are not typical study designs and do not expect them). Excluded: Before-After (lacks control) and After (lack pre-impact and a control). Personal views and perspectives, and model predictions.

reached, then a third person will be used. We will provide a list of articles excluded at the full-text level and include basic meta data for rationale for exclusion.

Eligibility criteria

We have adopted the "PICOS" framework to determine eligibility criteria. The inclusion and exclusion criteria are detailed below in Table 2 for each component of the PICOS framework.

Study validity assessment

Critical appraisal will be performed for all studies that pass the full-text screening process following the elements outlined in the CEE guidelines [14]. The critical appraisal will be done on a study-by-study basis. This means that if one article reported more than one experiment (e.g., different experimental setup/multiple sites) these will be regarded as multiple studies and receive independent validity rating. Where multiple articles have been published for a given experimental system, the data across the collection of articles will be aggregated and appraised as a whole. In cases with multiple articles, we will use the latest appropriate values. If the latest reported value across articles of the same system is not used, we will provide a written rationale for excluding the latest reported value. We will email authors of studies that are missing data and provide this meta data of authors contacted and their responses (or non-responses).

The appraisal (see Table 3) includes standard criteria listed in the CEE guidelines such as statistical design, similar starting point for control and treatment group, randomization of sampling, presence of confounding variables, and time between intervention and sampling. Our appraisal is also formulated to our specific review question. We establish three additional criteria, soil organic carbon/matter measurement method, soil sampling depth, and soil bulk density. Ideally, studies use a high quality method such as dry combustion or the Walkley–Black procedure for soil organic carbon/matter determination as it is viewed as the best methods to determine these outcomes and treat for inorganic carbonates, if necessary [21]. Studies examining soil organic carbon using different land management strategies also need adequate soil sampling protocol as sampling to different depths can result in different interpretations [22]. Therefore, it is necessary that a study should sample to at least the lowest depth of treatment incorporation. Additionally, changes in soil organic carbon results in changes in soil bulk density [23]. Soil bulk density is necessary to estimate soil organic carbon stocks and improved by comparing changes on an equivalent soil mass basis [23].

Studies will be excluded from quantitative synthesis and given specific written reasoning if any of the following factors apply:

- No true replication in experimental design or sampling protocol (Pseudoreplication will not be considered as a treatment replication).
- Intervention and comparator sites with substantial differences prior to intervention.
- Unaccounted for severe confounding factors (e.g., irrigation at intervention sites but not at the comparator sites).
- Insufficient methodological description to determine how the study was conducted (e.g., unable to determine/calculate biosolids carbon loading rate) or if data cannot be interpreted or is missing (e.g., study is missing comparator soil organic carbon data).

Studies that pass study validity assessment will be classified as "low" or "high" susceptibility to bias based on variables assessed (see Table 3). "Unclear" will be designated to variables with insufficient details and "Not applicable" will be designated to variables that were not measured in each study. All included studies will be appraised by two reviewers independently. Disagreements in appraisal will first go to discussion between the two reviewers to reach a consensus. If a consensus is not reached, then a third person will be used. We will perform a sensitivity analysis to determine the potential differences between studies of higher and lower validity. Reviewers will not assess studies for validity for which they are an author.

Data coding and extraction strategy

Data from included studies will be extracted using a predefined form (Additional file 3). The extracted data will be made available as additional files in the final review. The data coding and extraction form was developed to be fully encompassing including, study meta-data, experimental design and location, initial conditions, amendment characteristics, and outcomes post-intervention. Data that is only shown in graphical format will be estimated by using the data extracting software, DataThief [25]. We will contact authors if data is missing or not clear and provide documentation of our contact. Data will be extracted by one person and reviewed by a second person for accuracy.

We will extract the mean values of the control (no amendment or suitable fertilizer) and treatment groups (suitable biosolids interventions). These means will be

Table 3 Critical appraisal criteria used to assess included studies

Group	Criterion[a]	Low susceptibility to bias[b]	High Susceptibility to Bias
Study design	Study type	Before-After Control-Impact and Randomized Controlled Trials (though we do not expect to find RCTs as they are uncommon in this field)	Control-Impact study designs (no pre-impact data)
	Experimental randomization[c]	Suitable experimental designs for randomization (e.g., completely randomized, randomized complete block, Latin square, factorial, split-plot, strip-plot)	Purposive (selective)
	Experimental replication (spatial)	Replication at level of intervention (i.e., spatial replication) and of large sample size (3 +)	Replication at level of intervention but of low sample size (< 3)
	Similar starting point	Experimental treatment and control groups are similar at the start of the trial	Experimental treatment and control groups are not similar at the start of the trial
	Randomization	Some degree of randomization in sample selection	No randomization (i.e., purposive sampling)
	Replication of sampling	Replication of samples (3+)	Low replication (< 3)
Study measurement and data analysis methods	Time between intervention (i.e., last amendment/biosolids application and soil measurement sampling)	At least 1 year since last application	< 1 year since last application
	Soil organic carbon/matter measurement method and details	Uses dry combustion/elemental analysis or Walkley–Black titration method to measure soil organic carbon/matter. Uses and details acid treatment to remove inorganic carbonates, if necessary	Uses loss-on-ignition or other method to measure soil organic carbon/matter or missing methodological detail to determine soil organic carbon/matter
	Soil measurement depth (if incorporated or injected in soil subsurface)	Soil measured to at least depth of biosolids incorporation/injection	Soil not measured to depth of biosolids incorporation/injection or does not include details to determine depth measured
	Soil bulk density measured	Soil bulk density measured	Soil bulk density not measured
	Incomplete/Missing outcome data	No missing data; reasons for missing data not related to outcome; missing data balanced across control and intervention groups (and reasons similar); or proportion missing/plausible effect size not enough to have a relevant effect	Reasons related to outcome, and imbalance in numbers or reasons; or proportion missing/plausible effect size enough to have a relevant effect
Account for confounding variables	Presence of confounders	No obvious confounders or adequately accounted for as a result of blocking/pairing	Confounders present and/or unaccounted for (e.g., different irrigation strategies with no blocking of added treatment effect)

[a] Criterion to assess internal validity (risk of bias)

[b] Unclear classification given to any study where substantial details within the methods are either unclear or missing. Not applicable (N/A) is given to any study where the variable is not applicable to the study

[c] See Singh and Masuku [24] for appropriate experimental designs and statistical techniques

standardized (e.g., soil organic carbon stocks standardized to Mg organic carbon ha^{-1}). Measures of variability (i.e., standard deviation, variance, standard error, or confidence intervals) and sample sizes will also be recorded.

Potential effect modifiers/reasons for heterogeneity

We will look at the following potential effect modifiers and method of testing:

- Sampling methodology (sub-group analysis)
- Time since last intervention (meta-regression)
- Frequency of management intervention (sub-group analysis/meta-regression)
- Geographical location/climate (i.e., moisture and temperature) (sub-group analysis)
- Biosolids processing methods and iron + aluminum content (sub-group analysis)
- Application method (i.e., surface, incorporated, or injected) (sub-group analysis)
- Differing land use (e.g., cropland, forests, reclamation, etc.) (sub-group analysis)
- Disturbance vs. no disturbance post-intervention (i.e., tilling) (sub-group analysis)
- Soil properties (e.g., soil textural class and clay content) (sub-group analysis)

The potential effect modifier list was compiled by the review team after consultation with stakeholders. This list was compiled to contain known potential effects on carbon dynamics in terrestrial ecosystems. Additional effect modifiers and reasons for heterogeneity may be identified from the studies as the review proceeds.

Data synthesis and presentation

We will conduct a narrative and quantitative synthesis of the results extracted from included studies. The narrative synthesis will detail the validity of the results and findings. Tables and figures will be prepared to summarize results. A meta-analysis using random effects models will be conducted if sufficient data of high enough quality are extracted. Sensitivity analyses will be done by including/excluding studies of high risk of bias and when applicable, selected effect modifiers. Meta-regressions and sub-group analysis of potential effect modifiers will be performed where sufficient studies report common heterogeneity sources. We will also use the Egger test to produce funnel plots of the effect size plotted against the standard error of the effect size to assess publication bias [26, 27]. We expect that this review will help identify major research and knowledge gaps related to carbon sequestration potential of land-applied biosolids.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13750-021-00221-3.

Additional file 1. Filled in ROSES checklist and meta-data form for this systematic review protocol manuscript.

Additional file 2. Search string results exercise, benchmark study list, and related reviews.

Additional file 3. Data coding and extraction form to be used for the systematic review and meta-analysis

Acknowledgements

We would like to thank the Virginia Tech librarians who helped develop our search strategy: Cozette Comer, Inga Haugen, and Rachel Miles.

Authors' contributions

This manuscript was drafted by MJB. GKE, WLD, and KCH provided comments. All authors read and approved the final manuscript.

Funding

This work was funded by the Virginia Biosolids Council and the Metropolitan Washington Council of Governments.

Availability of data and materials

All data generated or analyzed during this study will be included in the final published review and an online data repository.

Declarations

Ethics approval and consent to participate

This systematic review does not include human participants, data, or tissue. Likewise, it does not include any research on animals.

Consent for publication

This systematic review does not include data from any individual person.

Competing interests

The authors declare that they have competing interests. Authors will not make decisions regarding the inclusion or critical appraisal of articles written by themselves.

Received: 17 October 2020 Accepted: 10 March 2021
Published online: 19 March 2021

References

1. Thangarajan R, Bolan NS, Tian G, Naidu R, Kunhikrishnan A. Role of organic amendment application on greenhouse gas emission from soil. Sci Total Environ. 2013;465:72–96.
2. Chaney RL, Brown SL, Ryan JA, Hallfrisch JG, Xue Q, Stuczynski I, et al. Using Biosolids, Composts, and Tailor-Made Biosolids Mixtures in Remediating Urban and Brownfield Sites and Other Metal-Contaminated Soils. 2001. p. 156–83.
3. Brown SL, Henry CL, Compton H, Chaney RL, Voider PD. Using municipal biosolids in combination with other residuals to restore a vegetative cover on heavy metal mine tailings. J Am Soc Mining Reclam. 2000;2000(1):665–70.
4. Lu Q, He ZL, Stoffella PJ. Land application of biosolids in the USA: a review. Appl Environ Soil Sci. 2012;2012:1–11.
5. Cogger CG, Forge TA, Neilsen GH. Biosolids recycling: nitrogen management and soil ecology. Can J Soil Sci. 2006;86(4):613–20.
6. Harrison R, Xue D, Henry C, Cole DW. Long-term effects of heavy applications of biosolids on organic matter and nutrient content of a coarse-textured forest soil. For EcolManag. 1994;66:165–77.
7. Annabi M, Le Bissonnais Y, Le Villio-Poitrenaud M, Houot S. Improvement of soil aggregate stability by repeated applications of organic

amendments to a cultivated silty loam soil. Agr Ecosyst Environ. 2011;144(1):382–9.
8. Hargreaves JC, Adl MS, Warman PR. A review of the use of composted municipal solid waste in agriculture. Agr Ecosyst Environ. 2008;123(1):1–14.
9. Khaleel R, Reddy K, Overcash M. Changes in soil physical properties due to organic waste applications: a review 1. J Environ Qual. 1981;10(2):133–41.
10. Tian G, Franzluebbers AJ, Granato TC, Cox AE, O'Connor C. Stability of soil organic matter under long-term biosolids application. Appl Soil Ecol. 2013;64:223–7.
11. Tian G, Granato T, Cox A, Pietz R, Carlson C, Abedin Z. Soil carbon sequestration resulting from long-term application of biosolids for land reclamation. J Environ Qual. 2009;38(1):61–74.
12. Antonelli PM, Fraser LH, Gardner WC, Broersma K, Karakatsoulis J, Phillips ME. Long term carbon sequestration potential of biosolids-amended copper and molybdenum mine tailings following mine site reclamation. Ecol Eng. 2018;117:38–49.
13. Badzmierowski MJ, Evanylo GK, Ervin EH. Biosolids amendments improve an anthropogenically disturbed urban turfgrass system. Crop Sci. 2020;60(3):1666–81.
14. Collaboration for Environmental Evidence. Guidelines and Standards for Evidence Synthesis in Environmental Management. version 5. Pullin AS FG, Livoreil B, Petrokofsky G, editors., editor. 2018.
15. Haddaway NR, Macura B, Whaley P, Pullin AS. ROSES RepOrting standards for systematic evidence syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. Environ Evid. 2018;7(1):7.
16. Harzing AW. Publish or Perish. 7 ed. available from https://harzing.com/resources/publish-or-perish2007.
17. EndNote. Version X9. Thomson Reuters; 2019.
18. Covidence systematic review software. Melbourne, Australia, Available at www.covidence.org: Veritas Health Innovation
19. USEPA (U.S. Environmental Protection Agency). . A plain English Guide to the EPA Part 503 Biosolids Rule. Washington: United States Environmental Protection Agency; 1994.
20. Municipal waste [Internet]. 2014. Available from: https://www.oecd-ilibrary.org/content/data/89d5679a-en.
21. Schumacher B. Methods for the Determination of Total Organic Carbon (TOC) In Soils and Sediments. Ecological Risk Assessment Support Center Office of Research and Development. 2002.
22. Baker JM, Ochsner TE, Venterea RT, Griffis TJ. Tillage and soil carbon sequestration—What do we really know? Agr Ecosyst Environ. 2007;118(1):1–5.
23. Ellert BH, Bettany JR. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can J Soil Sci. 1995;75(4):529–38.
24. Singh AS, Masuku MB. An insight in statistical techniques and design in agricultural and applied research. World J Agric Sci. 2012;8(6):568–84.
25. Tummers B. Datathief iii. 2006.
26. Egger M, Smith GD, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ. 1997;315(7109):629–34.
27. Palmer AR. Detecting publication bias in meta-analyses: a case study of fluctuating asymmetry and sexual selection. Am Nat. 1999;154(2):220–33.

Publisher's Note