Received: 30 January 2024 | Accepted: 6 June 2024
DOI: 10.1002/2688-8319.70009

BRITISH ECOLOGICAL SOCIETY Ecological Solutions and Evidence

REGISTERED REPORT STAGE 1

The impacts of multiple anthropogenic environmental drivers on plant–soil feedbacks: A systematic review protocol

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Funding information
University of Manchester University of Toronto Joint Research Fund; Natural Sciences and Engineering Research Council of Canada, Grant/Award Number: 386151

Handling Editor: Florent Noulekoun

Abstract

1. Plant–soil feedbacks (PSFs) regulate plant growth, plant community dynamics and ecosystem functioning and are important for global biogeochemical cycles. However, human activities and their associated impacts on the environment can alter the strength and direction of PSFs, but these effects, and especially the interactions among human impacts, are poorly understood.
2. In urbanised and other human-modified landscapes, anthropogenic sources of change are more varied and pronounced, resulting in a myriad of biotic and abiotic human-caused drivers simultaneously affecting ecological processes across multiple scales. These anthropogenic environmental drivers can have severe consequences for the delivery of ecosystem services in urbanised areas and beyond.
3. Here, we systematically review the literature on the impacts of environmental drivers on PSFs to address the question: how do multiple anthropogenic drivers impact PSFs? Further, we will determine the dominant and interactive drivers of changes to PSFs across 21 potential anthropogenically influenced environmental drivers and assess the relative importance of biotic and abiotic drivers.
4. We will assess how these drivers shape the plant and soil microbial communities involved in PSFs to determine their scale and directionality. We will also outline research gaps to guide future studies on PSFs in anthropogenically impacted ecosystems and especially urban environments. Besides extracting key variables, such as the range of values of the driver and impacts on plant growth or microbial diversity from reviewed articles, we will also determine how attributes of the studies themselves, such as location or duration of studies, influence the strength of findings.
5. *Practical implication*: This work will be crucial to understand not only human impacts on ecosystems, but also developing mitigation and management solutions

Menilek S. Beyene and Adriano N. Roberto contributed equally; order decided by coin toss.

to reduce the negative consequences of altered PSF, and so can be instrumental for managing ecosystem services in human-dominated landscapes.

KEYWORDS
anthropogenic habitats, environmental change drivers, habitat degradation, plant–soil feedback, pollution, soil microbial communities, species invasion, urban ecosystems, urbanisation

1 | INTRODUCTION

Plant–soil feedbacks (PSFs) are the interactions between plants and their soil environments whereby plants condition the biotic and abiotic conditions of the soil they grow in, which then alters the growth and reproduction of subsequent plant generations (Bever, 1994; Bever et al., 1997; Van der Putten et al., 2013). These PSFs are ubiquitous in nature and play an important role in regulating plant population and community dynamics, and influence ecosystem functioning (Bardgett, 2005; Van der Putten et al., 2013). However, how the myriad of environmental consequences of anthropogenic activities and their impacts on ecosystems influence PSFs are not well understood (Bardgett, 2005; Hassan et al., 2022). In this review, we will assess how anthropogenic drivers can alter PSFs and apply the findings to predict how PSFs will be impacted by urbanisation.

Feedbacks that occur through direct and indirect pathways can be negative or positive (Bennett & Klironomos, 2018). Direct negative pathways include allelopathy, which induces direct toxic effects on neighbouring plants (i.e. negative feedback) (Qu et al., 2021). Direct positive pathways include, for example, rhizospheric enzymes that enhance the hydrolysis of phosphorus-containing compounds, thus supplying additional bioavailable resources to the resident plant (positive; Hinsinger et al., 2011). Indirect pathways are mediated through effects on other organisms, most frequently beneficial and antagonistic root-associated, mycorrhizal fungi, nitrogen-fixing bacteria and pathogens, and free-living soil organisms, influenced by rhizodeposits. Conversely, plants can alter soil conditions in ways that negatively impact the biomass, diversity and composition of microbial communities with impacts on other plants. For example, invasive plant species that either enrich soil with nutrients (Broadbent et al., 2017) or exude allelopathic chemicals can disrupt native plant–fungal mutualisms that then reduce their uptake of nutrients (Grove et al., 2017).

Meta-analyses and reviews of literature have confirmed the importance and ubiquity of PSFs across ecosystems, life history strategies of plants, and plant growth forms and functional groups (Beals et al., 2020; Crawford et al., 2019; Kulmatiski et al., 2008; Meisner et al., 2014). In general, intraspecific PSFs tend to be negative for herbaceous plants (Crawford et al., 2019; Kulmatiski et al., 2008), which plays an important role in promoting species coexistence (Bonanomi et al., 2005; Liu et al., 2012), but could be positive in some systems such as temperate ectomycorrhizal trees (Bennett et al., 2017). Negative PSFs can reinforce density dependence and reduce competitive asymmetries, especially in ecosystems with high species diversity (Chen et al., 2019; Liu et al., 2012). However, a recent meta-analysis argued the opposite, that PSFs frequently drive competitive exclusion and that other equalising mechanisms or niche differences are required to adequately explain coexistence (Yan et al., 2022). Regardless of the variation among different studies, regions, taxa and methodologies, the consensus is that PSFs are a major factor that influences plant species abundance and diversity.

Human-caused environmental change, pollution and disturbance can affect different components of PSFs, thus altering the strength and direction of PSFs. For example, warming is expected to stimulate plant growth and the duration of the growing season in temperate regions, which could result in a greater accumulation of soil pathogens and result in more negative PSFs (Pugnaire et al., 2019). While there is ample research on how various environmental change drivers impact the individual plant and soil components of PSFs, there is surprisingly little research on how these drivers impact PSFs directly (Veresoglou et al., 2022). For example, numerous studies have investigated the effects of nutrient deposition on plant community diversity and composition (Cleland & Harpole, 2010; Harpole et al., 2016) and nutrient effects on microbial diversity and abundance (Campbell et al., 2010; Leff et al., 2015), but relatively few have examined these impacts on PSFs (but see: Valliere & Allen, 2016; Xu et al., 2021). Exceptions include work on plant invasions and drought effects on PSFs. For example, several studies have examined the effects of PSFs on the success of invasive nonindigenous plants, and their impacts on native plant species due to the release of novel chemicals that can have significant impacts on native communities (Inderjit & Cahill, 2015; Suding et al., 2013). Additionally, there is also a rich literature examining how drought influences the strength and direction of PSFs (Kaisermann et al., 2017; Lozano et al., 2022) with plant roots or arbuscular mycorrhizae positively modulating surface water through night time hydraulic lift of deeper soil layers' water (Ehrenfeld et al., 2005).

Human-modified landscapes, such as urban and agroecosystems, provide a multitude of ecosystem services for large human populations worldwide, such as pollination, water filtration and flood control. Yet, urbanised ecosystems are often subject to multiple, and more extreme, environmental changes than non-urbanised ecosystems (Figure 1), including higher and more variable temperatures, altered soil moisture and pH, increased salinity, excess nutrient loads, changes in trophic interactions, plant biomass removal, and the release and build-up of organic and inorganic chemical pollutants (Bowler et al., 2020; Lu et al., 2020; Sala et al., 2000). The extent of these environmental changes can vary depending on a combination of the history and patterns of human activity, the types of industries present, the distribution of human populations, green space and transportation networks.

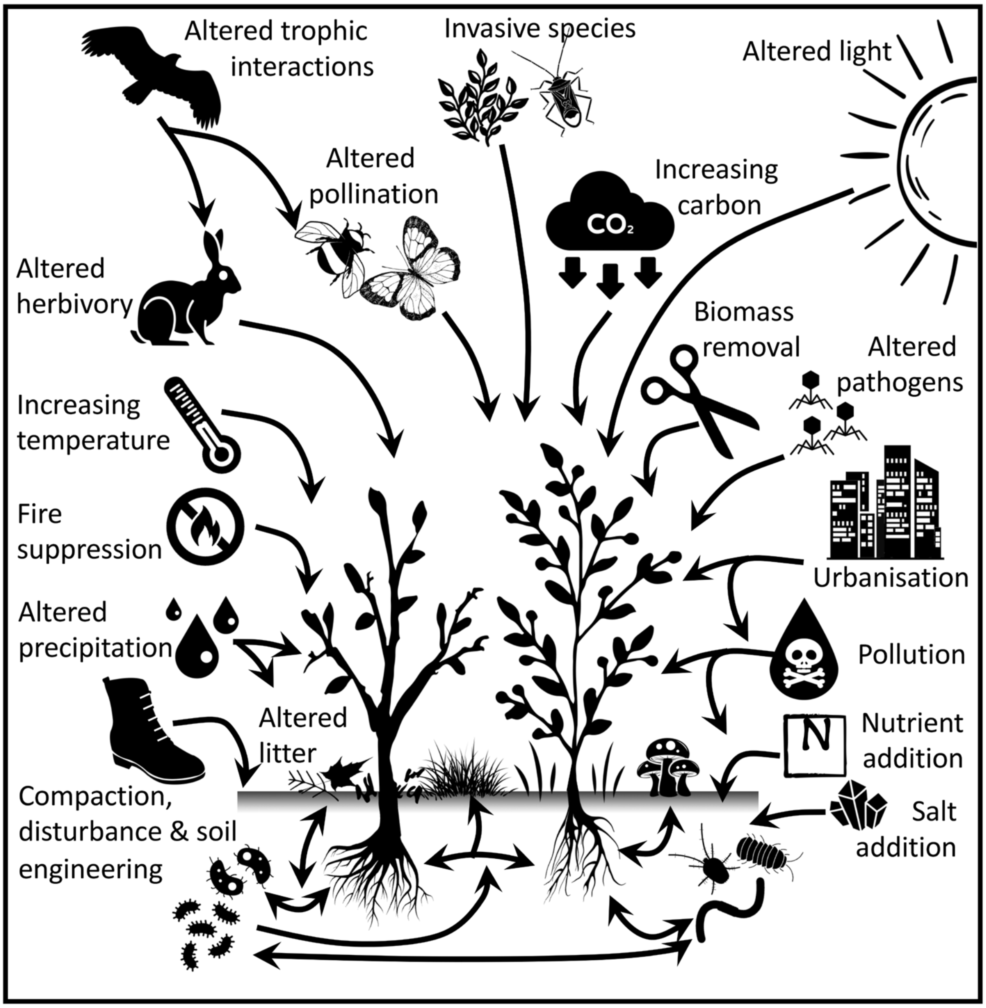


FIGURE 1 A cartoon showing the diverse set of anthropogenic and environmental change factors that could influence the magnitude and direction of plant–soil feedbacks. Arrows describe the direct effects on the local plant and soil communities, as well as interactions between plant and soil components within the communities.

With severe soil degradation in urban areas, the use of highly managed technosoils is seen as a valuable option to restore these areas (Barredo et al., 2020; Ugolini et al., 2020). These anthropogenic soils consist of imported soils, urban waste and artificial materials that undergo decontamination (WRB, 2014). Such management activities could make it difficult to predict PSFs in urban areas because of the vast potential conditions of the modified soil.

Little is known about how these anthropogenic factors impact PSFs, both individually and interactively, and especially in the soils of urbanised landscapes. In this systematic review, we will assess how 21 anthropogenic environmental change factors associated with urban ecosystems affect PSFs (Table 1). Here, we present a registered report of our review process to control for research bias (i.e. hypothesis changes, selective reporting) or publication bias (Chambers & Tzavella, 2022; Nakagawa et al., 2023; O'Dea et al., 2021). We outline the hypothesised effect of anthropogenic drivers and whether they are likely to increase, decrease or become more variable. We will draw on literature investigating these drivers from across ecosystems, then suggest how these drivers alter PSFs directly, or how they influence the two main components of PSFs (i.e. plant and soil biota), and infer the plausible net effect on PSFs. We will determine the likely interactions and directionality of these effects.

Questions:

Primary: How do multiple anthropogenic drivers impact PSFs in human-dominated ecosystems?

Secondary:

1. What are the dominant and interactive anthropogenic drivers of changes to PSFs?
2. What is the relative importance of biotic and abiotic drivers on PSFs?
3. What is the magnitude of direct and indirect effects on the components (i.e. plant and soil communities) of PSFs?
4. What are the research gaps that limit understanding of the impact of environmental change drivers on PSFs?

We will then apply the generated answers to the above questions to make predictions about how PSFs will be modified by

TABLE 1 The main abiotic and biotic effects of anthropogenic factors and the potential impacts on PSFs.

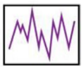
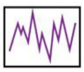
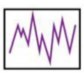
	Factor	Effect of anthropogenic activity	Explanation of driver	Expectation for PSFs
Abiotic	Temperature	↑ 	Climate change; impervious surfaces in urban areas create heat-island effect	Temperature increases could strengthen positive or negative PSFs because of higher plant growth and longer growing season. Should also speed up soil processes (like mineralisation rates)
	Nutrient loading	↑ ↓	Excess fertilisations, atmospheric deposition from industrial activities	Variable effects but could disrupt PSFs by reducing reliance on mutualist but potentially increasing pathogen loads
	Soil compaction	↑	Machinery, trampling	Weakens PSFs by reducing soil organism abundance and root growth
	Soil physical disturbance	↑	Tilling, invasive pigs, over-grazing, excavation	Weakens PSFs by impacting mycorrhizal fungi and promoting microbes that might rely less on plants. Plant removal and mortality removes plant inputs to soil
	Soil salinity	↑	Irrigation practices and use of road salt in some regions	Weakens PSFs by creating water stress on plants and supplying selective regime on soil microbes
	Moisture	↑ ↓ 	Climate change effect and depends both on regional climate/precipitation predictions and management regimes. Further influenced by extreme events	Lower water availability leads to disrupted PSFs because decreased microbial growth and plant stress. Higher plant stress could enhance effects of root pathogens, strengthening negative PSFs
	Biomass removal	↑	Management regimes such as forestry, mowing and grazing	Might be variable, but root growth should be reduced with frequent mowing, but infrequent mowing could stimulate PSFs
	Fire	↑ ↓ 	Increases due to droughts, management regimes reduce frequency. Changes in frequency and intensity likely to vary by region	Fire removes plant biomass, negative impacts on soil biota, release of nutrients into soil, all of which should weaken PSFs
	Light (visible and ultraviolet)	↑	Both night (through artificial lighting) and day (through reflectance, reduced canopy cover) increase in anthropogenic landscapes	Increasing light availability should strengthen PSFs because of higher plant growth and longer growing season
	CO_2	↑	Automobile traffic and industry release of CO_2, along with habitat destruction and disturbance	Increasing CO_2 should stimulate PSFs because of increased plant growth and carbon allocation to roots
	Organic pollutants	↑	Persistent organic pollutants include pharmaceuticals, pesticides, solvents and other compounds, which increase with human activity	Increasing contamination should negatively impact PSFs by reducing microbial and plant growth. Increased plant stress could enhance effects of root pathogens, strengthening negative PSFs
	Heavy metal contamination	↑	Industrial, automotive and waste disposal increase release of several heavy metals	Increasing contamination should negatively impact PSFs by reducing microbial and plant growth
	Particulate matter	↑	Industrial processes and combustion result in release of particulate matter of different sizes (PM_{10} and $PM_{2.5}$)	Increasing $PM_{2.5}$ might reduce plant growth, thus reducing PSFs
	Atmospheric pollution	↑	O_3, NO_2 and VOCs increase with industry and automobile traffic	Should disrupt PSFs by both direct effect on plants and indirect on microbes through acidification
	Soil acidification	↑	Sulphur, nutrient addition and some planted trees decrease pH in anthropogenic landscapes	Disrupts PSFs by reducing microbial diversity and perhaps plant growth

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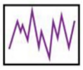
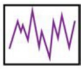
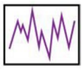
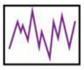
TABLE 1 (Continued)

	Factor	Effect of anthropogenic activity	Explanation of driver	Expectation for PSFs
	Species invasion	↑	Human activity, movement and trade increase the movement of species to other regions	Potentially positive PSFs on themselves and other exotic plants, but negative on native communities
	Herbivory	↑↓ 	Declines of large-bodied mammal herbivores, but also large increases in some because of lack of predators (e.g. rabbits)	Depends on the life history and the nature of herbivory (e.g. grazer vs. sap-sucker), effect on PSFs depends on whether effect results in plants releasing exudates or less litter produced
	Pollination	↑↓ 	Can be variable depending on floral diversity and pesticide use prevalence	Unknown, but successful pollination should result in altered resource allocation in plants, influencing PSFs
Biotic	Pathogens/pests	↑↓ 	Can be variable depending on density of hosts, lack of top-down control and use of pesticides	Increasing pathogen loads should disrupt PSFs by reducing plant growth
	Higher trophic levels	↓ 	Overall reduction, especially of large-bodied predators. Some mesopredators increase in anthropogenic landscapes	Depends if there is a trophic cascade that results in decreased plant biomass because of higher herbivore populations. Predator loss might weaken PSFs
	Litter	↓	Overall reduction because of mowing and removal of leaves/branches	Less litter weakens PSFs because of reduced microbial growth and mineralisation

Note: ↑ Factor expected to increase with human activity. ↓ Factor expected to decrease with human activity. Factor expected to become more variable with human activity. These factors include those that are believed to be impacted by anthropogenic activities by creating increased or decreased temporal trends, or else causing increased spatial or temporal variation. We then include simple expectations for the effect of altered factors on PSFs to anchor our inferences.

urbanisation, and specifically link how the environmental drivers associated with urbanisation should impact PSFs.

2 | MATERIALS AND METHODS

The registration of the article questions, hypotheses and methods in a publicly accessible archive was completed to control for the likelihood of false-positive findings, issues with reproducibility in narrative literature reviews and positive result publication bias (Allen & Mehler, 2019; Chambers & Tzavella, 2022). We adhered to the methods described throughout the systematic review process to clearly describe the coverage, decision-making, concepts of interest and limitations of the study.

2.1 | Article search

We followed the methods for systematic reviews and mappings as described in the Collaboration for Environmental Evidence (Collaboration for Environmental Evidence, 2018; Haddaway et al., 2018) and a general format of article searches, screening and synthesis. This search primarily aims to retrieve an extensive list of studies that quantitatively investigate the effects of several shifts in urban-associated environmental factors on PSFs. Our search string captures PSFs and iteratively investigates the effects of multiple anthropogenic drivers on these processes (see Table 1). We limit our search to articles written in English, Spanish and Chinese that investigate PSFs and recognise that language limitations will mean that some research articles could be missed.

2.1.1 | Databases

We selected two search engines for the sources of our literature search: (i) Web of Science (WoS) Core Collection: SCI-E, SSCI, ESCI; and (ii) Scopus. The choice of a suitable literature database is dependent on the review objectives. Both WoS and Scopus have been shown to bias toward natural and medical sciences and have been determined to be comprehensive in their coverage of a wide and inclusive list articles in these subject categories (Pranckute, 2021). We therefore opted for both literature databases in our systematic review to overcome mismatches in coverage and since neither database has been currently determined to be entirely better suited to systematic reviews.

2.1.2 | Search terms

Search string structure follows the format of selecting an environment factor search string and using the 'AND' Boolean to combine this with the PSFs search string, which is the primary search topic. This produces an individual search for the effect of the selected factor on PSFs (see Table 2 for the full list of search strings). Factors include the primary factor, urbanisation and a list of 22 environmental factors deemed relevant to urban systems and human-caused global change (i.e. temperature, nutrient loading and soil compaction). This approach was due to an identified gap in the peer-reviewed scientific literature on the cumulative effects of urbanisation on PSFs, which can be driven by multiple environmental factors. If insufficient literature articles were included for the effect of the selected factor on PSFs, then the second topic search was expanded to include relevant review papers on plant and soil biota responses. If insufficient literature articles are identified following topic 2, then a third topic search is completed, broadening the included responses to plant and soil biota responses to the selected factor (see Figure 2 for topic—factor search decision flow chart).

TABLE 2 List of investigation main topics plant–soil feedbacks and the effect on anthropogenic urban-associated environmental factors.

A. Topics	Search string
1. Plant–soil feedbacks	"Plant–soil feedback*" OR "plant - soil feedback*" OR "plant soil feedback*"
2. Plants & Soil Biota Reviews	Plant* OR "Soil microb*" OR "Soil biot*" OR "Soil communit*" OR rhizosphere* OR fung* OR bacteria* AND review OR synthesis OR "meta analysis" OR "meta-analysis"
3. Plants & Soil Biota	Plant* OR "Soil microb*" OR "Soil biot*" OR "Soil communit*" OR rhizosphere* OR fung* OR bacteria*

B. Factor	Search string
Urban	urban* OR city OR cities OR metropoli* OR town* OR built*
Temperature	temperatur* OR heat* OR cold OR warm* NOT burn* OR fire* OR pyro* OR flam*
Nutrient loading	nutrient* OR nitrogen OR nitrate* OR phosph* OR potassium OR micronutrient* OR fertiliz* OR fertilis* OR ammoni* OR organic* OR compost* OR humic* OR humus* OR eutroph*
Soil compaction	compact* OR compress* OR densit* OR trampl*
Soil disturbance	"Soil disturb*" OR plow* OR till* OR furrow OR erosion OR erod* OR dig* OR excavat* OR burrow* OR break*
Soil Salinity	Salin* OR Salt* OR chloride OR MgCl* OR KCl OR NaCl OR CaCl
Moisture	water* OR moist* OR drought OR rain* OR precipitation OR flood* OR rewet* OR hydrol* OR dry* OR wet*
Fire	burn* OR fire* OR pyro* OR flam*
Biomass removal	prun* OR mow* OR harvest* OR loss* OR remov* OR deforest* OR deveget* OR manage* OR reduc* OR deduct* OR copp* OR clip*
Light (visible and ultraviolet)	*light* OR radiation OR shad* OR "Photo pollution" OR photopollution OR photo-pollution OR "photo - pollution" OR dark* OR night*
CO_2	"Carbon dioxide" OR CO2
Organic pollutants	*plastic* OR "Organic pollutant*" OR pharmaceutical* OR solvent* OR "Organic contamin*" OR pesticid* OR hydrocarbon OR phenol* OR oil OR waste NOT phenology
Antimicrobial agents / antibiotics	Anti-microb* OR "Anti microb*" OR Antibio* OR Anti-bio*
Heavy metal contamination	metal* OR "trace element*" OR radioactiv* OR lead OR cadmium OR mercury OR aluminum OR aluminium OR iron OR copper OR zinc OR metal toxic*
Particulate matter	"PM 2.5" OR "PM 10" OR "Air pollution*" OR Aerosol* OR Soot OR "black carbon" OR particulate
Atmospheric pollution	gas* OR greenhouse OR "green house" OR green-house OR "green - house" OR methan* OR CH4 OR O_3 OR ozon* OR NO_2 OR nitrous OR VOC OR volatile* OR CFC OR aerosol*
Soil acidification	pH OR acid* OR alkalin* OR bas* OR cation OR anion
Species invasion	invas* OR "non native" OR non-native OR "non - native" OR nonnative OR alien OR introduced OR "non indigenous" OR non-indigenous OR "non - indigenous" OR nonindigenous OR exotic
Herbivory	Herbivor* OR graz* OR consumption OR brows* OR fenc* OR exclu*
Pollination	Pollinat* OR Bee* OR insect* OR ant* OR butterfl* OR moth* OR reproduct*
Pathogens	Pathogen* OR Virus OR Viral OR Phage OR Parasit* OR diseas* OR infect*
Trophic complexity	"food web" OR trophic OR insect* OR collembola OR fauna OR "soil fauna"
Litter	litter OR debris OR "plant mat*" OR "plant residu*" OR necromass OR "dead organic matter" OR dead* OR humus OR humic

Note: Search strings are iteratively merged between 'Topics' and 'Factors', using the AND Boolean operator, and follows the combination description between steps outlined in Figure 2.

2.1.3 | Grey literature

Only peer-reviewed articles will be selected for our analysis.

2.2 | Article screening

2.2.1 | Screening process and article eligibility criteria

Article duplicates stemming from searches conducted using both WoS and Scopus will be removed automatically using Zotero (REF), a free and open-source reference management software with built-in duplicate removal function, for each search. Of the resulting articles, screening will be performed manually by a minimum of two reviewers to reduce bias. All retrieved articles will be initially screened for title and abstract to remove irrelevant documents. Eligible articles will be determined based on them meeting the following criteria:

(i) *Study type*: Field and laboratory primary studies and/or experiments (but see Figure 2 for instances of insufficient literature).
(ii) *Population*: Plant(s) and associated soil biota.
(iii) *Exposure*: Relevant environmental factor or intervention (see Table 2b).
(iv) *Response*: Explicitly measure feedback(s) between plants and soil biota.
(v) *Article types*: Peer-reviewed journal articles.

2.2.2 | Study validity—Critical appraisal strategy

To evaluate the validity and/or generalisability of the article in different contexts, an evaluation of the quality of the study will be conducted by extracting references, metadata and information to account for selection, performance, measurement/detection and attrition biases. This will be quantified based on measures such as the sample size of the article, the study design and/or methodology, the impact factor of the journal and the number of authors, which can have an impact on the scope, scale and / or validity of the articles (Cadotte et al., 2012).

2.2.3 | Consistency checking

Participants will independently review a shared subset of randomly selected articles from the total, then consult to resolve discrepancies between inclusions and ensure consistency across screening and research questions. At the initial title-abstract screening, the pool of papers for each search string will be divided by one less than

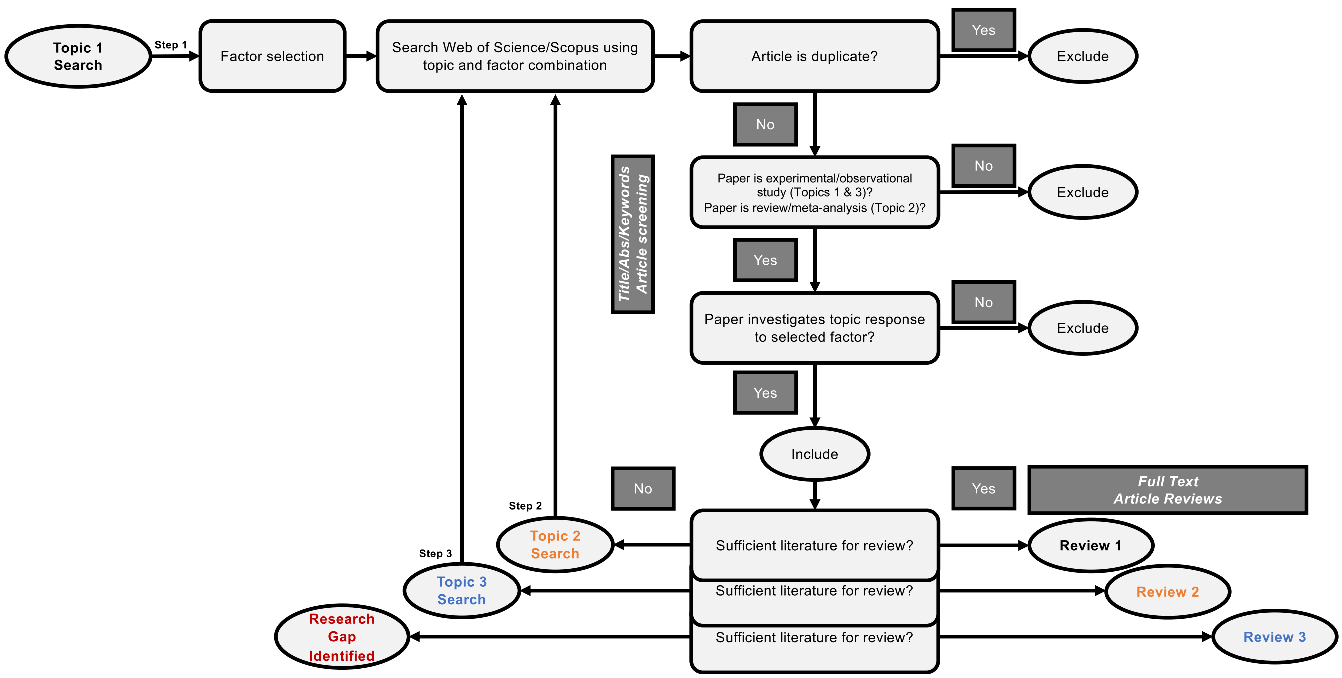


FIGURE 2 Diagram of article inclusion/exclusion criteria and search topics and factors' selection (see Table 2 for list of topics and factors). Each search commences with first topic and a selection of a factor of interest. Diagram outlines points of the systematic literature review, including database search, duplicate removal and exclusion criteria for articles identified for each topic—factor combination. If there is insufficient literature available after article exclusions, then the following step is taken which repeats search with the second broader topic search. If literature is still insufficient, a third step is taken to repeat search with the third broader topic and review is repeated with additional literature. Light grey text boxes are steps/questions for reviewers while completing literature searches, while dark grey text boxes are potential answers and sections of literature searches.

the number of participants in the screening. A threshold will arbitrarily be set to 99 articles per participant to initiate a second meeting for discrepancy resolution, after which the remaining articles will be screened.

Upon completion of initial screening, remaining papers will again be divided by one less than the number of participants and screened at the full-text level. Following completion of the initial 30 articles, the reviewers will initiate a meeting to resolve final discrepancies, after which the remaining papers will be evenly distributed and selected. If less than 30 papers are included following title–abstract screening, then all papers will be reviewed by participants and discrepancies will be addressed upon completion of the screening.

2.2.4 | Data coding and extraction strategy

The remaining full-text articles following screening will be assessed using a list of common metrics investigated in articles. A data extraction table with columns for relevant information will be produced. Data will be presented in the form reported in the article and any required conversions and/or transformations will be reported in the data analysis/review synthesis. The location of data within each article will be noted and the method of extraction if the data are presented in figures will be reported. If contact is made with the authors for additional and/or missing data, it will be reported.

2.3 | Data analysis/synthesis

2.3.1 | Data synthesis and presentation

A narrative synthesis will be conducted to characterise the breadth of research and address our research questions. Narrative syntheses provide a summary of the characteristics and outcomes of eligible scientific articles. Study characteristics, differences in data quality and descriptions of methods will be evaluated to determine the relative effect of these components on study quality. The key characteristics of each study include (i) article reference; (ii) setting/context; (iii) methodological design; (iv) subject population/feedback; (v) changes in PSFs; and (vi) stressor variables. A summary of specific variables used for study characteristics can be found in Table 3.

2.3.2 | Potential effect modifiers and reasons for heterogeneity

The potential for disparate results based on study context and environmental heterogeneity are present across any comparison of studies. These expected and potential reasons for heterogeneity could include soil physical and chemical properties, land/soil usage, land/vegetation/soil management (i.e. tillage and mowing), plant species and/or soil microbial or faunal communities, latitude and longitude, and differences in methodology, the number of stressors considered, and the number of assessed effect modifiers. These variables will be summarised and accounted for when reported in each reviewed article.

Selected articles will be reviewed for their relevance to the specific topic and factor combinations and assessed by their reported findings. The direction, magnitude, significance and frequency of the findings of the articles will be tallied. The diversity of effects will be quantified and the number of studies for each combination of topics and factors will be displayed. Articles will finally be qualitatively assessed for their relevance.

3 | PRELIMINARY RESULTS

The resulting number of articles from the preliminary searches for each driver-PSF string is shown in Table 4. These results show a higher proportion of studies on certain PSF drivers, including nutrient loading, pollination, biomass removal, acidification, biotic invasion and pathogens, while others have not yet been explored, such as particulate matter, antimicrobial agents/antibiotics and urbanisation, and require further investigation.

4 | DISCUSSION

Here we will review the literature on the impacts of anthropogenic environmental drivers and urbanisation on soil and plant processes and on PSFs to address the question: How do multiple anthropogenic drivers impact PSFs? We will further determine the dominant and interactive drivers of changes to PSFs and the relative importance of biotic and abiotic drivers. We will assess how these drivers impact the plant and microbial components of these feedbacks to determine the dominant directionality of impacts on PSFs. Finally, we will then align the dominant drivers with different land uses, for example urban versus rural, to make predictions about the impact of human drivers on plant–soil feedbacks across spatial scales.

We expect, based on our preliminary searches, that there will be too few articles investigating the specific or multiplicative effects of anthropogenic drivers on PSFs to provide adequate evidence to support robust conclusions. In these cases, we will examine how the drivers impact each of the main components of PSFs (plants and soil biota) to infer how these drivers will alter PSFs.

These findings will not only identify gaps in the current literature and develop our understanding of how these drivers might impact PSFs, but also how they will ultimately impact species diversity and ecosystem function. The understanding gained in this research can be used to predict where PSFs will be most impacted and to project how future changes in drivers could alter PSFs and the consequences

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TABLE 3 Description of variables for each key characteristic to be collected during analysis and synthesis of articles.

Characteristic	Variable	Description
Article reference	Title	Article title
	Journal	Journal name
	Volume	Journal volume
	Year	Year published
	DOI	Article identifier
Setting/context	Country	Country where study occurred
	State	State or sub-national region of study
	Lat	Latitude
	Long	Longitude
	Habitat	Habitat type where study occurred
	Soil type	Taxonomy or classification of soil or texture
	Exp_venue	Experimental setting (e.g. field, laboratory)
	Landuse	Type of land use
Methodological design	Obs_exp	Observational or experimental study
	Unit_size	Size of sampling unit (e.g. plot size, pot volume)
	Unit_units	Units of size (e.g. m^2)
	Unit_type	Type of unit measured (e.g. pot, plot)
	Unit _rep_no	Number of replicates
	Study_duration	Study duration in days
	Biol_organization_scale	Biological scale where measurements were taken
	Level_inference	Study analysis level (e.g. individual, across species or populations)
Subject population/feedback	Plant_spp	Plant species name
	Plant_func_type	Plant functional group
	Plant_life_history	Plant life history
	Plant_status	Native status
	Plant_growth_strat	Growth Strategy (e.g. exploitative/conservative, leaf economic spectrum)
	Innoc_bulk	Soil community used (e.g. inoculated, plant leachate, bulk soil)
	PSF_method	Experimental method to assess PSF (e.g. home/away, live/sterile)
	No_plant_spp	Number of plant species
	No_plant_ind	Number of plant individuals
	PSF_lifestage	life stage of plant in PSF
Changes in PSFs	total_PSF_obs	Total number of PSF observations included
	PSF_var	Response variable measured
	PSF_calc	How is PSF quantified
	Stat_test	Statistical test used in study
	PSF_mean	Mean PSF value
	PSF_SD	Standard deviation of PSF value
	PSF_SE	Standard error of PSF value
	PSF_reg_coef	Regression coefficient (e.g. PSF vs. temperature regression)
	PSF_reg_coef_95CI	Regression coefficient 95% confidence interval
	PSF_sig	Whether or not analyses indicate a significant effect of stressor on PSFs

Note: Variables collected for specific stressors are omitted and will be determined during synthesis.

TABLE 4 Article results from preliminary searches with each driver and step 1 PSF string search.

Driver	Articles (Web of Science)	Articles (Scopus)
Nutrient loading	564	482
Biomass removal	463	402
Pollination	454	351
Soil acidification	391	273
Pathogens	374	264
Species invasion	348	289
Moisture	282	224
Light (visible and ultraviolet)	236	208
Temperature	205	179
Atmospheric pollution	220	164
Litter	219	159
Herbivory	190	153
Soil compaction	175	111
Trophic complexity	106	93
Heavy metal contamination	154	6
Soil disturbance	57	48
Organic pollutants	86	7
Fire	43	33
CO_2	46	20
Soil Salinity	24	19
Urban	13	14
Antimicrobial agents/antibiotics	3	5
Particulate matter	4	4

Note: Values reported are prior to duplicate removal and title–abstract screening. Search results received: 17-12-22 from Scopus, 19-12-22 from Web of Science.

for diversity and ecosystem function. We are particularly interested in how PSFs are shaped by the complex socio-economic and structural landscapes of urbanised areas. The drivers operating in these systems are not only proximately influenced by landscape modification and release of pollutants, but are ultimately shaped by social-economic structures and inequality (Schell et al., 2020) as well as national political and economic developments (Frenken, 2017; Li et al., 2020), and it will be important to put this work into this context.

Finally, this work will be crucial for not only understanding human impacts on ecosystems, but also developing mitigation and management solutions to reduce the negative consequences of altered PSFs.

AUTHOR CONTRIBUTIONS

All of the authors contributed to conceiving the ideas and designing methodology; Adriano N. Roberto, Menilek S. Beyene and Marc W. Cadotte led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

ACKNOWLEDGEMENTS

This work was supported by the University of Manchester-University of Toronto Joint Research Fund and the Centre for Environmental Research in the Anthropocene (CERA) at the University of Toronto-Scarborough. M.W.C. wishes to acknowledge generous funding from the Natural Sciences and Engineering Research Council of Canada (#386151).

CONFLICT OF INTEREST STATEMENT

Marc Cadotte is an Editor of Ecological Solutions and Evidence, but took no part in the peer review and decision-making processes for this paper.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70009.

DATA AVAILABILITY STATEMENT

There are no data associated with this article.

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How to cite this article: Beyene, M. S., Roberto, A. N., Broadbent, A. A. D., Cordero, I., Johnson, D., Isaac, M. E., Leizeaga, A., Lum, D., Taylor, C. R., Bardgett, R. D., & Cadotte, M. W. (2025). The impacts of multiple anthropogenic environmental drivers on plant–soil feedbacks: A systematic review protocol. *Ecological Solutions and Evidence*, *6*, e70009. https://doi.org/10.1002/2688-8319.70009