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RESEARCH ARTICLE

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Revegetation of degraded ecosystems into grasslands using biosolids as an organic amendment: A meta-analysis

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Abstract

Questions: Biosolids are a source of nutrient-rich organic material that can be used to improve degraded or disturbed soils. Research on vegetation responses to the land application of biosolids has increased in the past 20 years, but there is no consensus on how plant communities respond to biosolids applications. What factors influence productivity and vegetative cover following biosolids application for grassland reclamation? How does the addition of biosolids impact plant community responses?

Location: Global, but predominantly North America and Europe.

Methods: To explore vegetative responses following biosolids application, we used a global systematic review and meta-analysis of 59 articles. Our meta-analysis used the log response ratio (LRR) as an effect size for productivity, total cover, species richness, diversity and exotic species abundance and explored covariates addressing various site characteristics and reclamation strategies.

Results: We found that across sites, the land application of biosolids significantly increased productivity and cover but had no significant overall effect on species richness, Shannon diversity or exotic species abundance on degraded lands. These increases in the LRR for productivity and vegetative cover were lower on sites that experienced a fire prior to biosolids application. Climatic variables like mean annual temperature were shown to alter the response of vegetative cover, where warmer sites tended to have more positive responses to biosolids. Seeding was found to increase plant cover but decrease species richness early in the reclamation process.

Conclusions: This area of research is growing; most of the publications we used come from the last 20 years and were mostly conducted in North America and Europe. While we can build on the present literature, there is clearly room for more research to ensure the process of reclaiming degraded ecosystems using biosolids results in desired plant communities, e.g. high native species diversity. Future research should consistently report biosolids chemical characteristics as well as application and processing methodologies.

KEYWORDS

biodiversity, disturbance, municipal biosolids, organic amendment, reclamation, sewage sludge

1 | INTRODUCTION

Biosolids are treated municipal wastewater solids (sewage sludge) that meet regulatory requirements controlling the levels of pathogen and pollutants within biosolids before land application in agricultural and reclamation settings (Cogger et al., 2006; Iranpour et al., 2015; Wallace et al., 2016). Over the past several decades, the land application of biosolids has increased following laws, such as the United States' Federal Water Pollution Control Act Amendments of 1972 (PL 92-500, 1972) and the Ocean Dumping Ban Act 1988, which place restrictions on the disposal of wastewater into waterways and encourages alternative disposal strategies (Lu et al., 2012). These restrictions along with the costs associated with alternative disposal strategies, such as incineration and landfill disposal, and increases in population and urbanization, have increased interest in understanding the effects of biosolids applied on land as an alternative strategy for waste disposal and to recover nutrients and organic matter (Lu et al., 2012). Recently, the World Water Environment Federation (WEF) adopted the Nutrient–Energy–Water (NEW) model for wastewater treatment plants to produce recovered resources from sludge (Grobelak et al., 2019). NEW was established to implement sustainable development and to address the growing issues of climate change, demographic changes and water pollution with biogenic substances, notably new biocides and pharmaceutical products (e.g. Triclosan, nano-silver, microplastics, ibuprofen, anti-depressants), that accelerate water eutrophication and could impact human health (Pritchard, Penney, McLaughlin et al., 2010; Grobelak et al., 2019).

While there are many aspects of biosolids that should be explored, such as those outlined in NEW, the use of biosolids in ways that meet regulatory requirements is generally considered safe for land application (Pritchard et al., 2010; Grobelak et al., 2019). Methods have been developed to reduce organic volatile compounds, odours and pathogens found in sewage sludge, including anaerobic or aerobic digestion, alkaline stabilization, heat drying, dewatering and composting (U.S. EPA, 2005; Wang et al., 2009). While some countries in Europe and Asia have a long history of recycling human organic wastes, cultural differences in attitudes to applying biosolids to potential food crops has led to undesirable scenarios in others, where biosolids are stockpiled at sewage treatment plants indefinitely, incinerated or dumped in the ocean, resulting in increased greenhouse gas emissions and water pollution (Field and Sullivan, 2003; Paschke et al., 2005; Wijesekara et al., 2016). Responsible biosolids application has been underpinned by countries and organisations by establishing application rate guidelines, best-management practices and restricted-site regulations according to biosolids pathogens levels to ensure beneficial impacts (Field and Sullivan, 2003; Wijesekara et al., 2016; Hudcová et al., 2019). Even with these restrictions, some undesirable disposal scenarios have occurred, where biosolids are stockpiled at sewage treatment plants indefinitely, incinerated or dumped in the ocean, resulting in increased greenhouse gas emissions and water pollution (Paschke et al., 2005; Wijesekara et al., 2016). However, sustainable disposal strategies exist, including their reuse as an organic amendment for ecosystem reclamation of degraded lands. The reuse of biosolids as an organic amendment for reclamation of degraded lands can be a key sustainable strategy. Thus, responsible biosolids application has been underpinned by most countries and organisations (Field and Sullivan, 2003; Wijesekara et al., 2016).

Lands can become degraded as a result of human and environmental processes, such as agricultural tillage, erosion by violent precipitation events, desertification, overgrazing by livestock and land-use change through industrial activities. For instance, mine tailings facilities are lands where the original topsoil has been removed to stockpile large quantities of tailings (fine waste materials from ore processing), resulting in heavily disturbed soil (Sheoran et al., 2010; Antonelli et al., 2018). These disturbances can have profound impacts on vegetative cover, species composition, the physiological function of biological soil crusts and soil chemical and physical characteristics, including the removal of organic matter or organic carbon (Belnap and Eldridge, 2001; Ryals et al., 2014). Thus, revegetation of these systems is often a substrate/soil-driven process that is governed by soil health and the seeds that can arrive and survive in these conditions and establish a protective plant cover to control soil erosion (Wali, 1999). One method commonly used to restore degraded soils is the application of organic amendments to increase soil carbon and fertility (Gravuer et al., 2019). In this era of urbanisation and human population rise, it has become increasingly important to dispose of sewage waste in ways that minimize environmental impacts. Land application of biosolids could be a useful means for disposal of these wastes, restoring or reclaiming degraded ecosystems, and an effective means for recycling the organic matter and nutrients contained within this waste (Diacono and Montemurro, 2010; Gravuer et al., 2019). Historically, biosolids have been the predominant type of amendment applied to reclaim mining sites although animal manure, papermill sludges, and wood chips have been used as well (Haering and Daniels, 2000).

Biosolids provide a nutrient-rich organic material with an organic matter content of up to 50%, making them an important option to consider as a soil conditioner to improve physical, biological and chemical properties of soils, particularly on degraded or disturbed soils (Gardner et al., 2010; Lu et al., 2012; Ryals et al., 2014). Soil organic matter plays an important role in ecosystem processes by retaining and supplying plant nutrients, enhancing water-holding capacity, reducing soil erosion and improving soil aggregation (Ryals et al., 2014). Grassland soils are generally considered to be rich in organic matter, but intensive or uniformed management, shifts in vegetation and changes in climate have decreased soil organic matter in many of the world's grasslands (Bai et al., 2008; Ryals et al., 2014). Grasslands are vulnerable to degradation (e.g. overgrazing, overcultivation), but are also typically established on degraded sites (e.g. mine sites, industrial sites) because they are cost-effective and fast at establishing a dense vegetative cover to protect erodible surfaces (Iverson and Wali, 1982). Grasses are often used because their fine root systems help build-up organic matter and provide soil nutrients (particularly N) to plant communities (van Eekeren et al., 2010). Reclamation of grassland ecosystems using organic matter-rich biosolids could enhance soil water-holding capacity (Blumenthal et al., 2017; Ott et al., 2018), enhance root penetration (Cuevas et al., 2000; Meyer et al., 2004; Walter et al., 2006), provide a gradual source of plant-available nutrients (Cogger et al., 2006; Ryals et al., 2014) and remediate sites contaminated with trace metals through immobilization processes (Basta, 2001; Brown et al., 2003). Other benefits of using biosolids on degraded soils include increases in above-ground productivity (e.g. Gardner et al., 2012a), restored vegetative cover (e.g. Madejón et al., 2006), carbon sequestration (e.g. Antonelli et al., 2018), and re-establishment of ecosystem viability with active microbial communities (Barbarick et al., 2004; Brown et al., 2005). However, biosolids may also produce undesirable outcomes, such as plant invasions (Newman et al., 2014; Blumenthal et al., 2017) or negative impacts on the soil microbial community (Sullivan et al., 2006) and other soil fauna (Waterhouse et al., 2014). Biosolids mixtures that incorporate other materials (e.g. limestone, ash, wood wastes, cattle manure, papermill sludges, sugar beet lime, etc.) can also be used to achieve specific reclamation goals in terms of soil chemical objectives, bioavailability, pH, erosion and nitrate leaching (Brown et al., 2003; Mosquera-Losada et al., 2019).

While biosolids and biosolids mixtures appear to be beneficial for many aspects of ecosystem function and properties, less is known about plant community responses to biosolids application in grassland reclamation. For instance, many authors have addressed concerns about the application rates of biosolids, as nutrient addition can reduce native diversity (DiTommaso and Aarssen, 1989; Cleland and Harpole, 2010; Schuster, 2015; Seabloom et al., 2015; Yin, Qi, and Du, 2017) and increase the success and dominance of fast-growing, often exotic, species (Seabloom et al., 2015; Blumenthal et al., 2017). Mixtures of amendments are often used to achieve specific soil chemical objectives (e.g. biosolids can be combined with high-carbon materials, such as wood wastes, to reduce the potential for nitrate leaching; Brown et al., 2003). A recent meta-analysis exploring ecosystem responses to the use of organic amendments, such as biosolids, composts and manures, on rangeland ecosystems found benefits for the use of organic amendments including increases in soil carbon, soil water-holding capacity, above-ground net primary productivity and plant tissue nitrogen along with potential negative impacts, including increased concentrations of soil lead, losses of nitrate and phosphorus and increased soil CO_2 emissions (Gravuer et al., 2019). Our research expands upon this meta-analysis by exploring one organic amendment, biosolids, focusing on plant responses in grassland restoration or reclamation and including degraded and severely degraded lands, lands that have been surface-mined or experienced a contamination through a mine spill, in our analyses.

We conducted a global systematic review and a meta-analysis to explore how the application of biosolids impacts ecosystem processes, including above-ground productivity, total vegetative cover, and plant community responses (species richness, Shannon diversity and exotic species success) on reclaimed land. We were interested in understanding how the land application of biosolids impacts vegetative responses and if there were appropriate application rates depending on site specific variables, such as climate or disturbance level, and reclamation strategies like seeding. Specifically, this study explores how application rates of biosolids or biosolids mixtures (e.g., biosolids mixed with ash, wood chips, lime, etc.) may affect productivity and plant community responses and if these factors impact how long the effect of biosolids persists following its application.

2 | METHODS

2.1 | Systematic review

We conducted a systematic search for experimental field studies that reported the effects of biosolids application on productivity, vegetation cover, species richness, species diversity and exotic species success within plant communities in reclaimed grasslands and other systems comprised primarily of non-woody species. Only field studies were included in this analysis, as several studies strongly suggest that field experiments are needed to properly quantify the effects on plant communities in natural settings (Limpens et al., 2012; Forero et al., 2019). We used a combination of terms in Web of Science (Table 1) and examined the title, keywords and abstract to assess the potential eligibility of the study (Appendix S1). If the paper appeared to fit our criteria, it was examined in more detail. References from these studies were also used to locate relevant articles.

2.2 | Data extraction

Several papers reported different response variables or measurements at different times following the initial reclamation following biosolids application and were from the same field plots (or experiment). Thus, we assigned each observation a unique code for experiment to account for this non-independence in our analyses. An observation within our dataset was defined by a unique combination of response variable + experiment +publication (author, year) + case (observation number) + years since reclamation + level of biosolids applied (Mg/ha).

For each observation, we extracted the means, standard deviations and sample size for treatment vs. control comparisons. In cases where this information was not readily available in the article, the corresponding author was contacted to obtain this information. When data could not be obtained from the authors, data were extracted from figures using WebPlotDigitizer (Rohatgi, 2014). In several cases, standard deviations were not available and were estimated from the interquartile range (IQR) or using available means ($\bar{x}$) and standard deviation (*SD*) from control or treatment groups from all studies using equation (1) with the former being the preferred method (Koricheva et al., 2013).

$$S\tilde{D}_J = \overline{x_j}\left(\frac{\sum_i^K SD_i}{\sum_i^K \overline{X_i}}\right) \tag{1}$$

TABLE 1 Search terms used in Web of Science

Category	Search terms
Ecosystem	TS = (grassland* OR steppe* OR shrubland* OR mine* OR rangeland* OR prairie* OR tailings OR pasture* OR oldfield* OR "degraded land*" OR restor* OR "disturbed land*" OR reclamation OR reclaim* OR savanna* OR meadow*) AND
Amendment	TS = ("organic amendment*" OR biosolid* OR sewage* OR sludge* OR "municipal waste*" OR "urban solid refuse" OR "solid refuse") AND
Plant community	TS = (vegetati* OR reveget* OR herb* OR legume* OR forb* OR grass* OR "exotic plant*" OR "exotic species" OR "alien plant*" OR "alien species" OR "invas*" OR "invasive plant*" OR weed*) AND
Variable measured	TS = (biodiversity OR diversity OR communit* OR biomass OR "percent cover" OR "total* cover" OR productivity OR production OR "above-ground net primary productivity" OR ANPP OR yield OR evenness OR richness OR composition OR dominance) NOT
Include only terrestrial ecosystems	TI = ("wetland*" OR river*)

TABLE 2 Descriptions of covariates used in model selection

Covariate	Description
Categorical variables	
Site characteristics	
Severe disturbance (Y/N)	Yes indicates a site that had a history of a severe disturbance from mining activity, including surface mining and mine spills
Burn (Y/N)	Yes indicates a site that was burned
Reclamation strategies	
Multiple applications (Y/N)	Yes indicates that biosolids were applied multiple times from the time of the response variable measurement to the time of the additional application
Mixture (Y/N)	Yes indicates that biosolids were mixed with another material, such a wood chips, ash, or lime
Seeded (Y/N)	Yes indicates that a seed mixture was used in the restoration process
Continuous variables	
Site characteristics	
Years since reclamation	The total time in years from the initial biosolids application to the time that the measurement was taken. In the event of multiple applications, the years since reclamation, the start of the reclamation was considered to be from the first application. To account for measurements taken less than one year after initial application of biosolids, a one was added to each value and rounded to the nearest whole number. Values range from 1, measurements taken less than six months after restoration, to 25, measurements taken between 23.5 and 24.5 years after initial application
Mean annual temperature	Mean annual temperature of a site according to longitude and latitude using data from Worldclim (Fick & Hijmans, 2017)
Mean annual precipitation	Mean annual precipitation of a site according to longitude and latitude, using data from Worldclim (Fick & Hijmans, 2017)
Global Aridity Index	Aridity index of the site according to longitude and latitude, using data from https://cgiarcsi.community/data/global-aridity-and-pet-database/ (Zomer et al. 2008)
Reclamation strategies	
Level of biosolids applied	The total amount of biosolids applied in Mg/ha. When biosolids were applied multiple times, the amount used was reflective of the total amount applied before the response variable measurement was taken

In Equation 1, the missing *SD* of a given study (denoted with *j*) was estimated, where $\overline{x_j}$ is the mean for the study with missing information and *K* is the number of *i*th studies with complete information (Koricheva et al., 2013).

We also extracted data from each paper that could potentially explain variation in the summary effect sizes across studies (Table 2). Many of the articles did not include mean annual temperature and/or precipitation, so these were extracted from

WorldClim using longitudes and latitudes (Fick and Hijmans, 2017). We also extracted the global aridity index, an estimate of the degree of dryness of the climate at each location from the global aridity index database using longitudes and latitudes, where higher values represent more humid conditions and lower values represent higher aridity (Trabucco and Zomer, 2018). Only a portion of the papers reported nutrient levels in the biosolids, and when nutrient levels were reported, it was often difficult to decipher if the nutrient measurements were the same (e.g. Total Nitrogen [TN] vs. Total Kjeldahl Nitrogen [TKN]). Thus, we did not conduct further analyses based on nutrient information to avoid misinterpretation of the available data.

2.3 | Meta-analysis

Meta-analyses were conducted in R (R Core Team, 2018) using the *metaphor* package (Viechtbauer, 2015). We explored the effect sizes of the following variables in response to biosolids application: above-ground net primary productivity (ANPP), total vegetative cover, species richness, Shannon diversity, and exotic species abundance (%). In each case, we calculated the log response ratio (LRR) with the "escalc" function in the *metaphor* package, using the equation $\mathrm{LRR} = \ln [(\bar{x}_{\mathrm{treatment}} / \bar{x}_{\mathrm{control}})]$ (Hedges et al., 1999; Viechtbauer, 2015). A few observations contained a zero in the denominator and in these few cases, a constant of ½ was added to the experimental and control means in order to calculate LRR (Bennett et al., 2018). While adding a constant to calculate LRR can greatly overestimate the effect size and is generally not recommended (Koricheva et al., 2013), we found similar findings for our data set as Bennett et al. (2018), namely that adding a constant likely underestimated the true LRR in these observations and that the alternative recommended effect size, Hedges' (*d*), showed poor statistical properties (Appendix S2).

TABLE 3 Sample size for calculation of effect sizes representing the impact of biosolids application in grassland restoration

Response variables	Number of publications	Number of observations	Sufficient data to perform metaregressions?
Productivity	33	269	Yes
Total vegetative cover	32	214	Yes
Richness	18	159	Yes
Shannon diversity	4	24	No
Exotic species			
Number of plants per m^2	1	6	No
Abundance (%)[a]	6	42	No
Richness	1	1	No

[a]Includes cover of exotic species per total vegetative cover and relative biomass of exotic species per total biomass.

LRRs and their variances were used to estimate the overall effect size for each observation and supporting variable using random effects models generated with the "rma.mv" function in the *metaphor* package (Viechtbauer, 2015). A response variable was considered to have sufficient data for estimating overall effect size if there were at least ten observations from three experiments (Table 3). Metaregressions were run on all response variables except Shannon diversity and exotic species abundance (%), because these variables lacked enough observations (>50). To account for non-independence of observations made on the same experimental plots, all models included observation number and publication as random variables.

To select models that best explain the heterogeneity in effect sizes, we used the *glmulti* package in R (Calcagno and de Mazancourt, 2010). We used a candidate set of models with only first-level variable combinations (no interactions) for model averaging. We narrowed relevant variables using automated model selection with the package and selected variables for further analyses when the variable importance was 0.8 and above. Using the selected variables from this model, we fit metaregression models with interactions with the *metaphor* package using all possible combinations of a single continuous and a single categorical variable (Viechtbauer, 2015). We used variance inflation factors using the function "vif" in the *metaphor* package to determine multicollinearity and fit only combinations of variables that were determined to be non-collinear (VIF < 10; Viechtbauer, 2015). From these interaction models, model fit was compared to the no-interaction model using Akaike's Information criterion corrected for small sample size (AICc; Schielzeth and Nakagawa, 2013). Models were considered to have similar fit if the difference in AICc was less than 3. Marginal and conditional coefficients of determination (R^2) and pseudo-R^2 were also calculated as metrics of model explanatory power (Schielzeth and Nakagawa, 2013).

3 | RESULTS

3.1 | Systematic review

From our search completed in February 2020, we found 59 references that fit our search criteria (Appendix S1). Our search contained papers from 1988 to 2019 with the majority of publications after the year 2000 and included one unpublished dataset (Appendix S3). Most of our studies were from North America and Europe with a dearth of studies from Africa and Asia. These studies extended across 12 countries (Figure 1). The majority of studies did not report using a mixture of biosolids and other amendments (n = 38) (Appendix S4). There were 23 studies in which seeds were sown in addition to biosolid application (Appendix S5) and 25 studies in severely disturbed sites

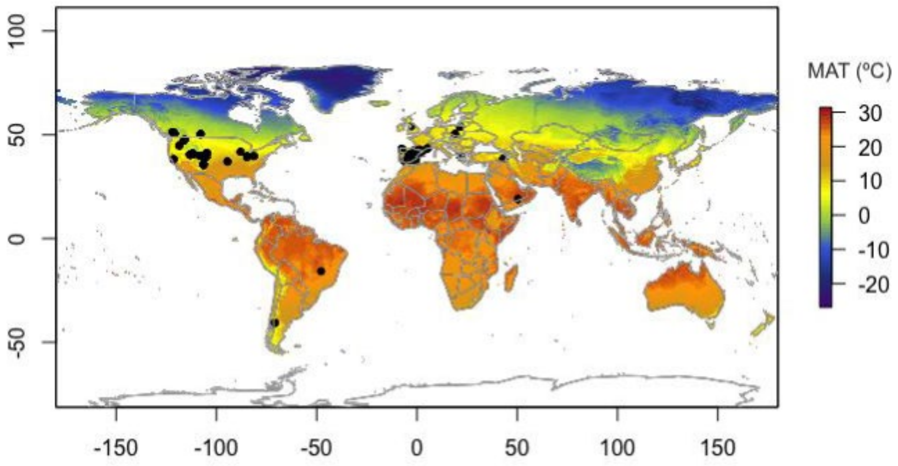

FIGURE 1 Location of selected study sites. Colors indicate the mean annual temperature (MAT; °C) for each site using high-resolution (30 arc-seconds) global raster climate data from 1970 to 2000 (Fick & Hijmans, 2017)

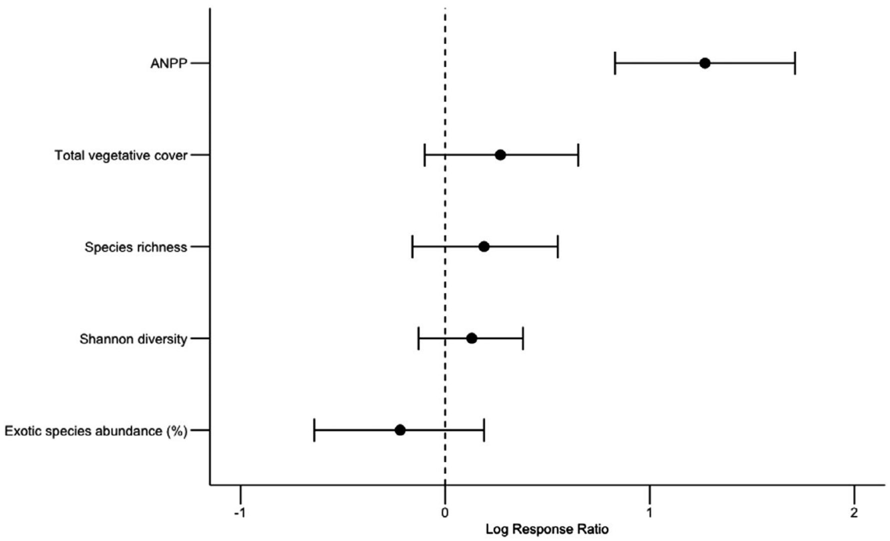

FIGURE 2 Overall effects sizes of the five response variables represented as the log response ratio (LRR)

(Appendix S6). Only six studies were conducted in areas that had previously experienced a burn or experienced multiple applications of biosolids (Appendices S7 and S8). Studies tended to take measurements within the first five years of reclamation with the longest observation taking place approximately 24 years post-biosolids application (Appendix S9). Most researchers applied biosolids at a level below 100 Mg/ha with the highest level applied at 404 Mg/ha (Appendix S10).

3.2 | Overall effect sizes

The use of biosolids on degraded lands led to a significant overall increase in productivity ($p < 0.0001$, log response ratio [LRR] = 1.27 [95% confidence interval {CI}: 0.83, 1.71], number of observations [k] = 269) and total vegetative cover ($p < 0.0001$, LRR = 1.17 [0.81, 1.53], $k = 214$; Figure 2). Biosolids were not found to have an overall effect on species richness ($p = 0.15$, LRR = 0.27 [−0.10, 0.65], $k = 159$), Shannon diversity (H; $p = 0.34$, LRR = 0.13 [−0.13, 0.38], $k = 24$), or exotic species abundance (%; $p = 0.30$, LRR = −0.22 [−0.64, 0.19], $k = 42$).

3.3 | Metaregression models

3.3.1 | Above-ground net primary productivity (ANPP)

Model averaging revealed the best model for explaining the LRR for the impacts of biosolids on ANPP included the variables: years since reclamation, burn, mean annual temperature (MAT), severe disturbance and biosolids mixture (Table 4; $Q_{M(5,263)} = 19.46$, $p = 0.002$, $k = 269$). The LRR for ANPP decreased as the time since restoration (years) increased ($p = 0.0003$, LRR = −0.06 [−0.09, −0.03]; Figure 3a). The best-fit interaction model included interactions between the variables years since reclamation and burn ($Q_{M(3,265)} = 18.41$, $p = 0.0004$). To better understand how each interaction affected the LRR for productivity, the data were subset by whether the site experienced a fire or not before the reclamation, and models were run with years since reclamation as the independent variable. When a site experienced a fire before biosolids were applied, the LRR for productivity decreased earlier after the initial biosolids application ($p = <0.0001$, LRR = −0.22 [−0.30, −0.13], $k = 25$) compared to sites that did not experience

TABLE 4 First-level explanatory variable combinations (no interactions) used for metaregression models

	ANPP	Total vegetative cover	Species richness	Shannon diversity	Exotic species (%)
Years since restoration	X	-	X	-	-
Burn	X	X	-	-	-
Mean annual temperature (°C)	X	X	X	-	-
Severe disturbance	X	X	X	-	-
Biosolids mixture	X	-	-	-	-
Mean annual precipitation (cm)	X	X	-	-	-
Aridity index	-	-	-	-	-
Multiple applications	-	X	X	-	-
Seeded	-	X	-	-	-
Biosolid level applied (Mg/ha)	-	-	-	-	-

Abbreviation: ANPP, above-ground net primary productivity.

Shaded areas indicate that there were not enough observations (>50) to conduct a metaregression and an X indicates that the variable was used in the model.

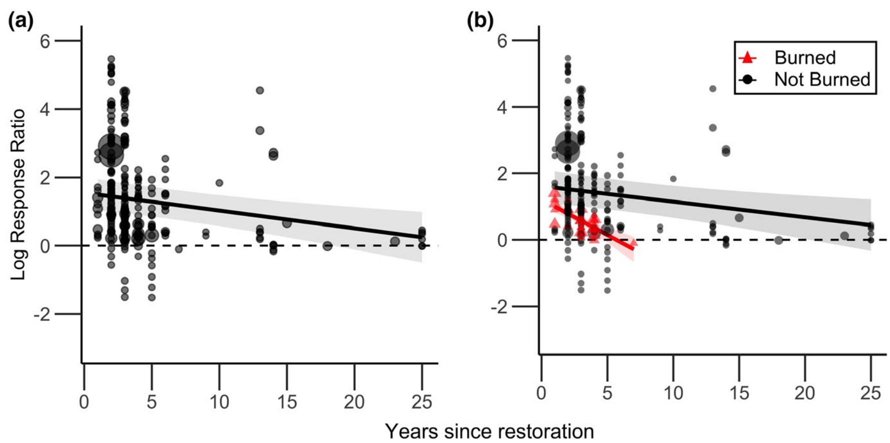

FIGURE 3 Metaregression results for the log response ratio of productivity in response to: (a) years since initial biosolid application; and (b) the interactive effects of years since reclamation and whether or not a site was burned. The size of the points represents the weight that each data point contributed to the metaregression. The shaded area around the lines represents the 95% confidence intervals for the regression lines

a burn before biosolids were applied (p = 0.004, LRR = −0.05 [−0.08 −0.02], k = 244; Figure 3b).

3.3.2 | Total vegetative cover

The model that best predicted the LRR of cover following biosolids application included the variables: MAT, seeded, severe disturbance, burn, multiple application, seeded and mean annual precipitation (MAP) (Table 4; $Q_{M(6,207)}$ = 15.33, p = 0.02, k = 214). The effect size for cover increased as a result of biosolids applications but varied depending on whether or not the site experienced a fire prior to applying biosolids (p = 0.04). To better understand the impacts of a fire prior to biosolids application on the LRR for total vegetative cover, the data were subset by whether or not the site experienced a fire before the reclamation, using the intercept-only model. When a site experienced a burn before biosolids were applied, the LRR for cover was lower after the initial biosolids application (p < 0.0001, LRR = 0.39 [0.17, 0.60], k = 50) compared to sites that did not experience a fire before biosolids were applied (p < 0.0001, LRR = 1.35 [0.94, 1.77], k = 166; Figure 4a). The best interaction model included the variables MAT and whether a site was seeded or not ($Q_{M(4,209)}$ = 10.19, p = 0.017, k = 214). The effect size for cover increased with MAT (p = 0.006, LRR = 0.09 [0.02, 0.16]; Figure 4b), suggesting that the effect of biosolids application on cover decreased with lower temperatures. Seeding prior to reclamation impacted the LRR of cover; according to the intercept-only models subset by seeded (yes or not), sites that were seeded during the reclamation process had a higher effect size on cover (p < 0.0001, LRR = 1.52 [1.04, 2.00]) compared to sites that were not seeded (p = 0.0002, LRR = 0.89 [0.42, 1.37]: Figure 4c).

3.3.3 | Species richness

The model-averaging approach revealed that the model that best predicted the LRR of species richness included the variables: disturbance,

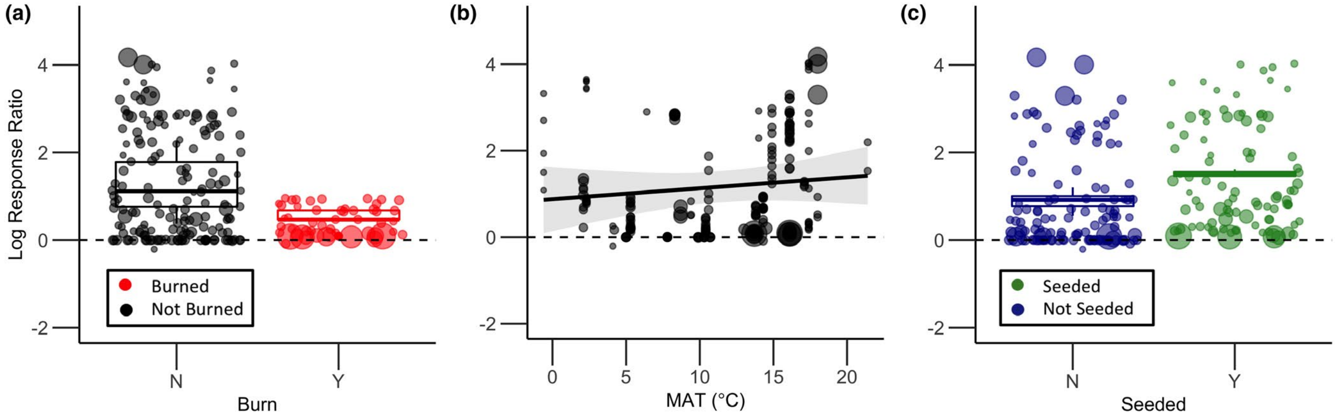

FIGURE 4 Metaregression results for the log response ratio of cover to: (a) whether a site experienced a burn prior to restoration; (b) mean annual temperature (MAT); and (c) whether a site was seeded following biosolids application. The size of the points represents the weight that each data point contributed to the metaregression. The shaded area around the lines represents the 95% confidence intervals for the regression lines

multiple application, years since reclamation and MAP (Table 4; $Q_{M(4,154)} = 11.03$, $p = 0.03$, $k = 159$). The interaction between seeding and years since reclamation did not significantly explain heterogeneity in effect size between studies ($Q_{M(3,155)} = 6.03$, $p = 0.10$, $k = 159$), however there was a significant interaction between the two variables ($p = 0.023$). We subset the data by whether the site was seeded or not and found that, when plots were seeded, the effect size increased with years since reclamation (LRR = 0.083 [0.036, 0.13], $p = 0.0005$, $k = 64$), while the effect size decreased with years since reclamation in plots that were not seeded (LRR = −0.039 [−0.066, −0.012], $p = 0.004$, $k = 95$; Figure 5a). Severe disturbance also explained a significant portion of the variation in species richness ($Q_M[df = 1] = 4.25$, $p = 0.04$). Plots that were disturbed showed significant positive response to biosolids (LRR = 0.62 [0.18, 1.06]) compared to undisturbed plots (LRR = −0.16 [−0.65, 0.33]; Figure 5b).

4 | DISCUSSION

4.1 | Overall effects

Applying biosolids for grassland reclamation generates large increases in above-ground productivity and vegetative cover, which help reduce erosion rates and increase C sequestration rates. While there was no overall effect on richness, diversity (*H*), or exotic species after biosolids application, the literature available did not allow us to more thoroughly investigate plant community dynamics and revealed the need for experimental data using similar measures for diversity and exotic species abundance and/or dominance.

4.2 | Productivity

Increases in above-ground productivity could persist for up to 15–20 years following the initial application of biosolids and may be attributed to improvements in soil physiological parameters associated with biosolids (Ryals et al., 2015; Antonelli et al., 2018; Ott et al., 2018). Biosolids tend to decompose slowly, retain organic matter over long periods of time, improving soil parameters like enhanced water-holding capacity, greater cation exchange capacity and higher concentrations of plant nutrients, which, together, have a positive effect on plant growth (Ryals et al., 2014; Blumenthal et al., 2017; Antonelli et al., 2018; Ott et al., 2018). The persistent effect of an increase in productivity on biosolids-amended sites suggests a gradual release of nutrients through mineralization, fewer nutrient losses through leaching and volatilization and/or less overall plant uptake of nutrients (Wang et al., 2003; Cogger et al., 2006; Lu et al., 2012). As a result of data constraints, we were not able to assess the importance of nutrient levels in the biosolids. However, it is generally accepted that biosolids can provide an ecosystem with a substantial amount of nutrients over time (Cogger et al., 2006), and this demonstrates the need for nutrient analysis of biosolids to be disseminated in a common manner both before the biosolids are applied and monitoring of nutrient cycling as time progresses. Further, the studies used in this analysis did not consistently describe the application methods (e.g. surface-applied vs ploughed into existing soil substrate or wet vs dry application) or the processing methods (e.g. anaerobic vs aerobic digestion, composting) of the biosolids used in the study; thus, we recommend future studies include this methodological information.

Current literature suggests that soil texture plays an important role in how a system responds to biosolids applications (e.g. Gardner et al., 2012a; González Polo et al., 2015). For example, a long-term increase in productivity following a single, high-dose application was found when biosolids are applied to fine-textured soils compared to coarse-textured soils (Gardner et al., 2012b; González Polo et al., 2015; Antonelli et al., 2018). It is suggested that high levels of clay within the soil slows soil organic matter decomposition, allowing for a gradual release of soil nutrients over a longer period of time (Pascual et al., 1999; Bastida et al., 2008; Gardner et al., 2012a; González Polo et al., 2015). Conversely, in sandy soils, the protection of organic matter

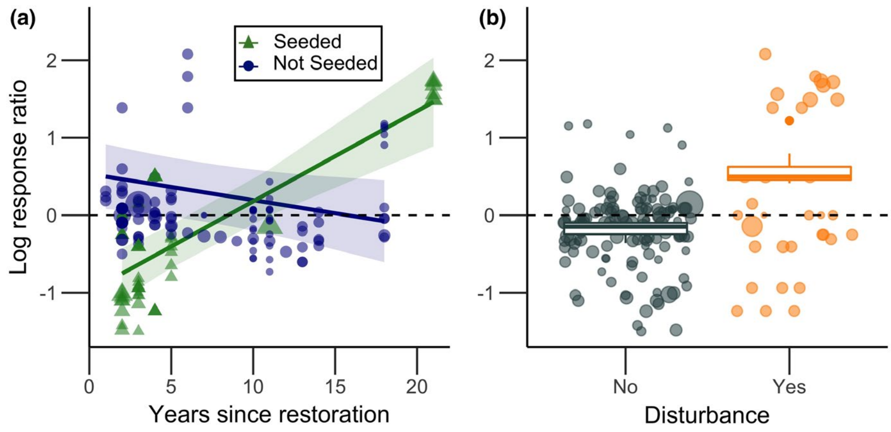

FIGURE 5 Metaregression results for the log response ratio of richness to: (a) the interaction between years since reclamation and seeding; and (b) whether a site was disturbed prior to biosolid application, where "yes" indicates a site that had a history of a severe disturbance from mining activity, including surface mining and mine spills. The size of the points represents the weight that each data point contributed to the metaregression. The shaded area around the lines represents the 95% confidence intervals for the regression lines

by the mineral matrix is low compared to fine soils and could result in the positive responses to a single dose of biosolids to persist for shorter periods of time (De León-González et al., 2000; Hargreaves et al., 2008; Gardner et al., 2012a; González Polo et al., 2015). Thus, an understanding of basic soil properties, such as soil texture, could aid in our understanding of the effectiveness of biosolids for increasing vegetative growth.

Further, we found that the effect size for productivity in response to the time since initial restoration was impacted by whether or not the site experienced a fire prior to the land application of biosolids. We found that sites that experienced a fire had an initial positive response in ANPP that was similar to that in sites that did not experience a fire, but the duration of production gain from biosolids application was shorter for burnt sites (within five years) compared to non-burnt sites (within 20 years). Landscapes that have been disturbed by wildfires are associated with losses of plant nutrients and destabilization of the soil structure that can inhibit vegetative growth, resulting in increased soil erosion and deterioration of surface water quality (Debano et al., 1998; Meyer et al., 2004; McFarland et al., 2010). Studies monitoring fire-affected areas have demonstrated that the greater the extent of soil heating, the higher the rate of nutrient and soil organic matter loss, which can affect the water-holding capacity, soil porosity and moisture infiltration rate of these terrestrial ecosystems. In addition to high-temperature wildfires accelerating nutrient removal, vapourized soil organic matter can move deeper into the soil profile and condense in the cooler underlying soil layers, creating a water-repellent layer that further reduces moisture infiltration (Debano et al., 1998; Meyer et al., 2004; McFarland et al., 2010). Rehabilitation of fire-affected ecosystems using biosolids may aid in improving soil structure, increasing soil water retention and nutrient levels and enhancing root penetration (Meyer et al., 2004) and short-term increases in soil C and N and soil microbial activity (Meyer et al., 2004; Kowaljow et al., 2010; McFarland et al., 2010). Our results suggest that the positive effects on ANPP may be short-lived. Thus, more frequent applications of biosolids may be needed to maintain plant growth.

4.3 | Total vegetative cover

Application of biosolids increased vegetative cover, which is critical for land reclamation as vegetative cover stabilizes soil structure, minimizes erosion and improves soil organic matter (Washburn et al., 1994; Guerrero et al., 2001; Elseroad et al., 2003). While there was still an overall positive effect on plant cover when biosolids were applied post-fire, increases in cover were generally lower on burnt sites compared to sites that did not experience a fire. As previously mentioned, fire can have a destabilizing effect on soil structure and nutrients (Debano et al., 1998; Meyer et al., 2004; McFarland et al., 2010), and while the addition of biosolids likely aided in improving soil physiological parameters on these sites, the effects of fire on the existing soil layer appear to result in diminished effects of biosolids on establishing vegetative cover compared to sites that did not experience a burn.

The impact of biosolids on plant cover increased with temperature, which may be the result of faster plant growth in warmer environments, resulting in greater uptake of nutrients from biosolids (and less leaching). Wang et al. (2003) showed that N mineralization proceeds faster under warmer temperatures indicating that plant-available nutrients found in biosolids may become available quicker to plants in warmer ecosystems, thereby increasing plant cover. Higher temperatures can also increase the microbial activity necessary for the breakdown of organic matter in biosolids, because at high temperatures, the density and diversity of microbes are dramatically increased (Strom, 1985; Miller, 1992; Liang et al., 2003).

Finally, we found that seeding during the reclamation process increases the effect size for total vegetative cover compared to sites that were not seeded following biosolids application. Studies that used seed mixes found that biosolid amendments on nutrient-poor soils promoted grasses over other life forms (Pierce et al., 1998; Rigueiro-Rodríguez et al., 2000; Meyer et al., 2004; Paschke et al., 2005). As previously mentioned, biosolids are associated with an increase in soil fertility, which is associated with a reduction in plant species diversity and dominance by perennial grasses (Paschke et al., 2005). Reclamation methods for revegetation of degraded land should find a balance between the short-term needs like soil stabilization and erosion control and long-term objectives, such as increasing native biodiversity or establishing woody vegetation. Site preparation and seeding may assist in reducing the negative environmental conditions that often constrain establishment, like poor soil quality, limitations in the number of microclimates suitable for growth and establishment of different species, and propagule pressure by exotic species (Zobel et al., 2000; Martin and Wilsey, 2006; Baethke et al., 2020). Unfortunately, we were unable to assess plant-functional groups or exotic species, but the relatively rapid cover provided by seeding may aid in reducing the probability of establishment of invasive plants (Jessop and Anderson, 2007). However, several authors have cautioned that seeding may have long-term and less desirable impacts that may overshadow the short-term benefits of establishing rapid vegetative cover (Walker and Powell, 1999; Farrell and Fehmi, 2018).

Specifically, the community trajectory of seeded communities may resemble that of the seed mix over the long term and the community may not experience the same successional patterns of nearby undegraded land (Walker and Powell, 1999; Farrell and Fehmi, 2018). The increased cover on seeded sites to which biosolids have been applied may be a result of increased nitrogen and phosphorus availability (Meyer et al., 2002; You et al., 2017). Agronomic species are often used to revegetate severely disturbed sites, which are able to take rapid advantage of increases in nutrient availability and provide rapid cover (Carrick and Krüger, 2007; Bochet et al., 2010; Baethke et al., 2020). Research remains limited on the use of native seed mixes when reclaiming severely degraded lands (Alday et al., 2011; Baethke et al., 2020), but it will be important to select plant species that are able to compete in this nutrient-rich environment.

4.4 | Plant community responses

Species richness and diversity were not significantly affected by biosolid application, but a more thorough analysis that incorporates measures of diversity or evenness could not be completed. While studies that presented a diversity index were lacking, our study did reveal significant influences of seeding and disturbance on the effect of biosolids application on species richness. Previous studies have suggested that the overall lower species richness in unseeded plots could be explained by decreased spatial heterogeneity in light availability resulting from the high vegetative cover, increased nutrient availability and/or seeding (see previous section) providing fewer growing habitats compared to the unseeded plots (Willems et al., 1993; Halofsky and Mccormick, 2005a). We found a significant interaction between seeding and year since restoration, such that seeded plots maintained a consistent increase in species richness over a 20-year time period. Fischer et al. (2013) showed that different methods of seeding resulted in higher species richness in reclaimed wastelands compared to the control. Our study indicates that the application of biosolids in combination with seeding may have a long-term positive effect on the species richness compared to areas that were not seeded. It is, however, possible that undesirable plants can contribute to this increased richness, but there were not enough data to determine the effects of biosolids on undesirable exotic plants in this study; thus, further studies on the plant composition of restored communities are important, particularly regarding the impacts on exotic-plant invasion.

While biosolids have been used to successfully reclaim old mining sites (Halofsky and Mccormick, 2005a, 2005b; Brown et al., 2007) and following forest fires (Meyer et al., 2002; Varela et al., 2006), results are often variable (Halofsky and McCormick, 2005; Sullivan et al., 2006). Low to medium levels of biosolid application on degraded sites may result in increased species richness, as the plant community responds to initial nutrient addition (Brown et al., 2007). However, restored communities can display a response curve in which high levels of nutrient application can lead to increases in biomass of fast-growing species, which can suppress low-biomass species resulting in reduced richness (Sullivan et al., 2006). In addition, plant response to nutrients such as nitrogen and phosphorus can plateau, such that additional uptake may not result in a growth response (Simcock et al., 2019). Our meta-analysis found that biosolid application resulted in increased species richness under severe disturbance caused by mining-related activities and decreased richness in undisturbed sites. Most of the studies in disturbed areas in our dataset were on lands previously almost bare of species prior to biosolids application (e.g. Carson and Barrett, 1988; Siebielec et al., 2018). Thus, the restoration of these areas would invariably increase the number of species. The influence of biosolids in the presence or absence of disturbance is likely due to the presence of plant species before restoration in the areas being restored.

5 | CONCLUSIONS

This study has shown biosolids application can help reclaim degraded grassland ecosystems. Applying biosolids increased ANPP and cover but had no consistent effect on species richness, diversity or abundance of exotic species. Responses to biosolids applications were smaller, and shorter-lived on burnt sites, while warmer sites tended to display greater responses. Combining seeding with biosolid application may maximise plant cover, with positive influence on species richness over time. Any reclamation programme should therefore identify the priority of short- and long-term outcomes. For example, short-term stabilisation and soil rebuilding may conflict with establishment of species-diverse grasslands, especially where aggressive weeds are present. Thus, practitioners in different parts of the world must consider the prevailing climatic conditions and their choice of seed mixtures when using biosolids.

Brown et al. (2007) showed that biosolid C:N ratios ≥20 increased species diversity of reclaimed mine sites. However, due to inconsistent reporting of elemental components of biosolids, we could not investigate in this meta-analysis how specific elements that constitute biosolids, such as nitrogen and phosphorus, can affect plant community post reclamation. However, nutrients within biosolids can vary depending on the source of sewage sludge and the wastewater treatment processes (Lu et al., 2012). Processes like digestion or composting can result in losses of organic matter through decomposition, increases in P and trace-metal concentrations, decreases in ammonia through volatilization and decreases in losses of K through leaching (Lu et al., 2012). Further, mineralization of N from aerobically digested biosolids was reported to be significantly higher than from anaerobically digested biosolids (H. Wang et al., 2003). Composting decreases the amount of nitrates in biosolids, reducing the amount of leachate into the soil and surrounding water bodies (Stehouwer et al., 2006; Sullivan et al., 2015). In addition, combining biosolids with low-nitrogen organic amendments can reduce nitrogen leaching (Paramashivam et al., 2017). A host of such amendments have been explored, including wood biochar, sawdust and lignite (Scharenbroch et al., 2013; Paramashivam et al., 2016). While addition of these amendments has its advantages, it accentuates the differences between biosolid application in different studies and complicates the ability of researchers to synthesize and understand how nutrient levels in biosolids affect the reclamation process. Research to understand these nutrient differences within biosolids and how these impact revegetation strategies would be useful for informing proper applications rates given certain conditions.

There is also room for further research on the optimal reclamation strategy to boost all aspects of the revegetation reclamation of degraded lands, including soil fauna and mycorrhizal associations. For example, many studies do not report specific data on how different species or functional groups respond to biosolids addition or the impacts on native plant communities. This information would be useful as we seek to discern what combination of native species and plant-functional groups would be complementary within the ecosystem. This can be achieved by developing more long-term studies that go beyond stabilizing the degraded site. Similarly, while our study found that exotic species did not significantly increase with biosolids application, there was a dearth of studies on the impacts of biosolids on exotics species, and we did not find enough studies to investigate further. The impacts of biosolids on undesirable exotic plants should be explored and reported in future research, as well as strategies to improve reclamation success while limiting undesirable plants should be explored. We were also unable to investigate how biosolids can affect different aspects of species diversity. It remains unclear if, and how quickly biosolid application can change community structure and plant relationships in a community given the slow nutrients release times typical of many biosolids.

This area of research is growing; most of the publications we used come from the last 20 years and were mostly conducted in North America and Europe. While we can build on the present literature, there is clearly room for more research to ensure the process of reclaiming degraded ecosystems using biosolids as a soil amendment can be further evaluated and refined, specifically with regard to plant community dynamics and invasion by exotic species.

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AUTHOR CONTRIBUTIONS

LWP and LHF outlined the original ideas for the manuscript; LWP and AG completed the systematic review of the literature; LWP, MA and AG extracted data from relevant papers. LWP and MA analyzed the data; LWP, MA and AG wrote sections for the manuscript; LWP, MA, AG, WCG and LHF contributed to reviewing and editing drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

All data and analysis scripts used in this study are available on FigShare (https://doi.org/10.6084/m9.figshare.12413021).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

Appendix S1. Search criteria for including or excluding papers

Appendix S2. Histograms of Hedges' (*d*) vs log response ratio for: (a) productivity; (b) total vegetative cover; (c) species richness; and (d) Shannon diversity

Appendix S3. Number (per year) and cumulative number of studies included in the systematic review

Appendix S4. Number of studies in which biosolids mixtures were used or not

Appendix S5. Number of studies in which plots were seeded or not

Appendix S6. Number of studies with and without severe disturbance

Appendix S7. Number of studies with and without natural burns

Appendix S8. Number of studies in which biosolids were applied only once or more than once
Appendix S9. The distribution of study duration of studies included in this meta-analysis
Appendix S10. The distribution of biosolid levels used in the studies included in this meta-analysis

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