A Systematic Review of Management Practices for Biosolids Land Application

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ABSTRACT

Land application is generally considered a cost-effective and sustainable method to manage biosolids by recycling and reusing them as soil amendments to improve soil quality. However, biosolids are not a panacea. Health concerns, malodors, and environmental precautions are some of the controversial topics that drive public opposition towards biosolids land-application. The purpose of this review is to gather existing knowledge and related information regarding biosolids and the current management practices and regulations that dictate land application limits. This paper also suggests changes to current management practices and regulations that might be outdated and inconsiderate towards public health risks. Additional research and amendments to existing regulation are needed to reduce potential short-term and long-term detrimental effects of biosolids land application to humans and the environment.

KEYWORDS

40 CFR Part 503, wetland restoration, human health effects of biosolids, environmental risks of biosolids, policy recommendations for biosolids

INTRODUCTION

Increasing global population and the adverse effects of climate change have prompted researchers to explore ways to re-use resources and sustainably dispose of waste generated (Garcia-Cuerva et al. 2016). As the world's population size grows, waste generation also increases, including the production of biosolids, or treated sewage sludge. Processing and management of biosolids is an ongoing issue for most wastewater treatment plants (WWTP). Many, if not all, wastewater treatment facilities generate solid waste either as a result of the physical or biological treatment process (Jin et al. 2018). These solid sludge wastes undergo further disinfection processes. The outputs after the treatment process are called biosolids. The U.S. Environmental Protection Agency (EPA) defines biosolids as "nutrient-rich organic materials resulting from the treatment of domestic sewage in a treatment facility" (EPA 2018). Currently, biosolids are being managed in a variety of ways: landfilling, incineration, composting, land applications, and fertilizers (Figure 1). In 2013, the California Association of Sanitation Agencies (CASA) reported an annual generation of 723,000 dry metric tons of biosolids in California, more than 30% of which are being disposed of in landfills (CalRecycle n.d.).

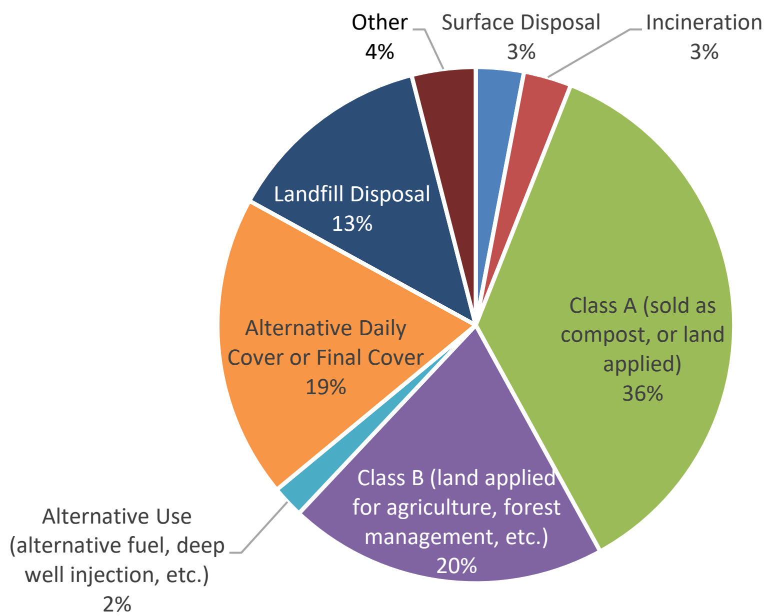

Figure 1. Management of biosolids produced in California for 2013, Total: 723,000 dry metric tons (CalRecycle n.d.).

With current waste management practices for biosolids and the recent passage of California Senate Bill 1383 (2016), which constrains landfill disposal of organic waste to 25% maximum by 2025 (Kauffman and Gunther 2018), alternative disposal methods are needed to address the issue of biosolids management. Federal agencies, along with local municipalities and industries are actively seeking alternative ways to dispose of biosolids as current landfill regulations tighten and disposal costs escalate (Nikolaidis 2012).

In 1999, the United States Environmental Protection Agency (EPA) projected a 1.1 metric ton increase of biosolid waste generated in the U.S (Figure 2) by 2010. The latest report from the North East Biosolids and Residuals Association (NEBRA) was published in 2007 and states that 7,180,000 dry tons of biosolids were generated for the year 2004 (EPA 2018). As current trends follow this projected increase, major WWTPs are looking at increasing the amount of biosolids applied to lands to help in disposal and management.

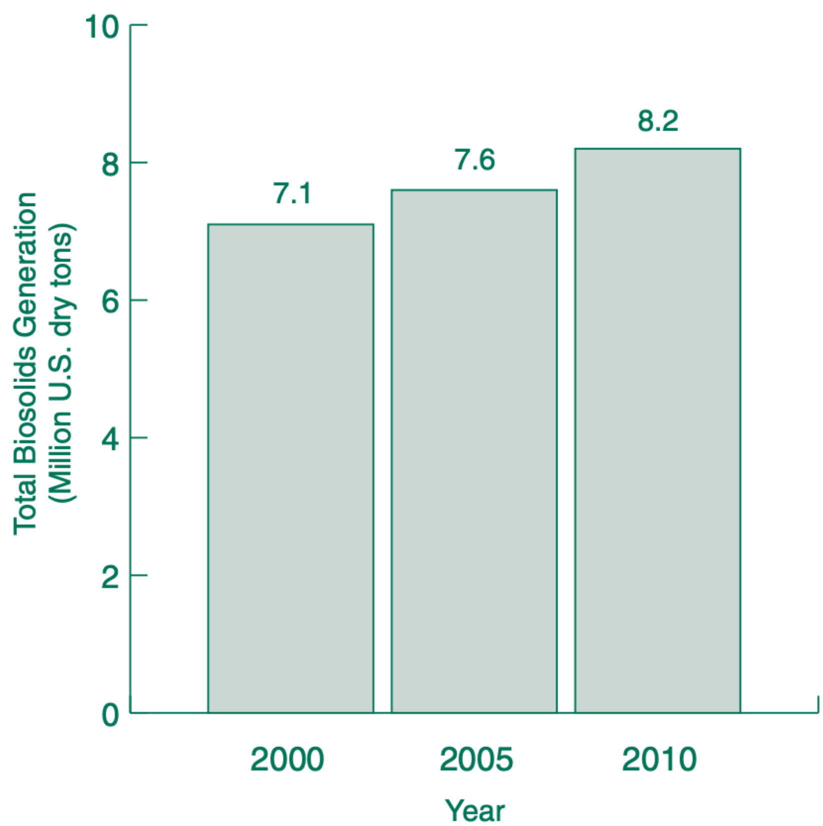

Figure 2. Projections of biosolids generation for use or disposal from 1999 data (EPA 1999).

One proposed new management solution for biosolids is as an alternative sediment supply in wetland restoration projects. Wetlands are an essential part of the environment, providing various ecosystem services such as carbon sequestration, flood management, and habitats for wildlife (Foster-Martinez and Variano 2018). However, rising sea levels threaten the health of wetlands. Like all coastal places, the Bay Area is vulnerable to sea level rise (SLR) brought about by climate change. The California Ocean Protection Council estimates that there is a 67 percent probability, assuming successful mitigation efforts, that sea levels will rise between 1.0 foot and 2.4 feet from current mean levels by 2100 (2017). However, that range could increase to 1.6 to 3.4 feet if no mitigation efforts are taken (California Ocean Protection Council 2018). In this century, much of the existing wetland cover in the Bay Area will be inundated by rising seas. Hence, recent efforts are being made to restore wetlands, including the massive South Bay Salt Pond Restoration Project. Public support for marsh restoration projects has also gained traction with the passing of Measure AA in the nine-county Bay Area (2016), which will raise approximately $500 million for wetland restoration projects throughout San Francisco Bay. Residents of the Bay Area showed great support for Measure AA, also known as the “Clean and Healthy Bay Ballot Measure,” which passed by a 70 percent margin (San Francisco Bay Restoration Authority 2016). Due to river sediments and dredged material being expensive sediment sources for wetland restoration, biosolids can be a valuable potential sediment source as they are readily available, nutrient-rich, and more cost-effective.

Studies have shown that biosolids induce a positive effect on vegetation growth, making them an invaluable resource in early marsh restoration projects. A recent study from 2018 have used biosolids as a marsh restoration amendment and observed a considerable increase in plant biomass, root depth, and root to shoot ratio increases in plants grown in a biosolid and soil mix substrate (Foster-Martinez and Variano 2018). However, biosolids are not a panacea; land applications of biosolids have always been a controversial topic primarily due to public opposition. Some of the issues that hinder public acceptance include concerns regarding pollutants, health risks, and foul odors (EPA 1999). Despite the problems with public opposition, however, land application remains one of the most economical and sustainable ways for managing and disposing of biosolids and is the prime solution for reducing landfill disposal methods (EPA 1999).

This literature review explores the costs and benefits of biosolids land application, from an environmental, health, and community perspective. This paper also assesses current management practices and evaluates regulations regarding pathogens, trace elements, heavy metals, and nutrients. Because the application of biosolids to wetlands is a relatively new area of study, a combination of different land applications including on rangelands, pastures, grasslands, reclaimed lands, and agriculture were also studied as these findings also have relevance for wetland application. With this literature review, I compile important information that can guide future policies and guidelines for biosolid management that minimize risks to the public and the environment.

METHODS

I searched the peer-reviewed literature using Elsevier, Google Scholar, and the UC Berkeley Library EBSCOhost database. Keywords and phrases used to search for literature in the databases are listed in the table below (Table 1).

Table 1. List of keywords used to search for literature.

General Category Keyword	Keywords/Phrases
Biosolids	Biosolids, biosolids characteristics, biosolids metal uptake, biosolids nutrient values, sludge, wastewater treatment
Land Application	Biosolids land application, biosolids application in rangeland, biosolids application in agriculture, compost biosolids, metal uptake in biosolids, plant reaction to biosolids, biosolids soil effect, soil amendments
Policies and Regulations	EPA, biosolids regulation, biosolids policy
Wetlands	Wetland restoration using biosolids, biosolids marsh restoration, sea level rise in wetlands, wetland restoration project
Management Practices	Biosolids in landfill, biosolids in landfill waste, biosolids generation, wastewater, sludge management, biosolids recycling, biosolids use in the US
Risks	Biosolids health risks, biosolids land application health risks, risk assessment of biosolids land application, public health report for biosolids land application, metal contamination from biosolids, pharmaceuticals in biosolids, heavy metals in biosolids, organic compounds in biosolids, human health effects in land-applied biosolids.

I limited the search to English publications and Environmental Science subjects. About 29,000 citations pertained to the keywords, and from these, I disregarded search results for literature relating to antibiotics, microbiological studies, engineering methods, and pyrolysis. Further results were filtered to peer-reviewed articles, journals, reviews, and reports from 1966 to 2019. From the resulting citations, I used 40 papers, published reports and surveys, excluding website and book resources, for the systematic literature review as a representation of existing studies.

RESULTS & DISCUSSION

Benefits of land application of biosolids

Biosolids production has been on the rise due to increasing population and urbanization. Considering energy efficiency, technological limits, and costs, land application has proven to be the most economical way to manage biosolids (Haynes et al. 2009). Biosolids are known to be nutrient-rich, containing up to 50% organic matter (Lu et al. 2012). Because of this rich nutrient concentration, they can be utilized effectively as soil conditioners to improve physical, biological, and chemical characteristics of soils, provide better drainage and aeration, and a food source for microorganisms. A four-year trial of anaerobically digested biosolids application to silt loam soil was found to increase aggregate size and stability of the soil with increased soil organic matter after the biosolids were incorporated (Lindsay and Logan 1998). Similarly, García-Orenes et al. (2005) found that bulk density significantly decreased, while porosity, moisture retention, percentage of water-stable aggregates, mean weight diameter aggregates, and liquid and plastic limits increased in the surface soils (0-15cm) with biosolids application. García-Orenes et al. attributed this increase in aggregate stability to increased organic C in the soil (García-Orenes et al. 2005).

Biosolids have also been proven to increase aboveground biomass in plants, as well as belowground biomass and rooting depth (Foster-Martinez and Variano 2018). In an experiment where biosolids were applied as a subsurface layer to marsh plants mesocosms, the mean value for alive aboveground was significantly greater in treatment pipes with biosolids incorporated into the substrate (AG: Alive $p = 0.0149$) (Figure 3) (Foster-Martinez and Variano 2018).

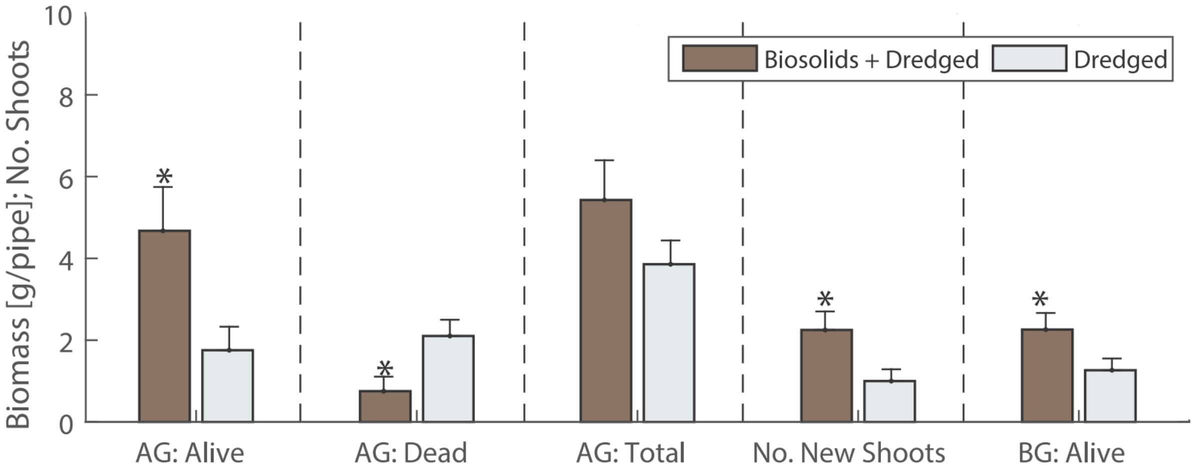

Figure 3. Metrics of biomass for the treatment and control pipes (AG=Aboveground, BG =Belowground). Mass is given as mass per pipe (cross-sectional area=1.7×10−2 m2). Error bars show standard error. Metrics with statistically significant difference ($p < 0.05$) are marked with an asterisk (Foster-Martinez and Variano 2018).

Foster-Martinez and Variano (2018) also found that the biosolid-inundated pipes had significantly more belowground biomass (Belowground Biomass, 6-8cm $p = 0.0228$) (Figure 4a). While not statistically significant, the average rooting depth was found to be greater in control pipes, however ($p = 0.3874$) (Figure 4b) (Foster-Martinez and Variano 2018).

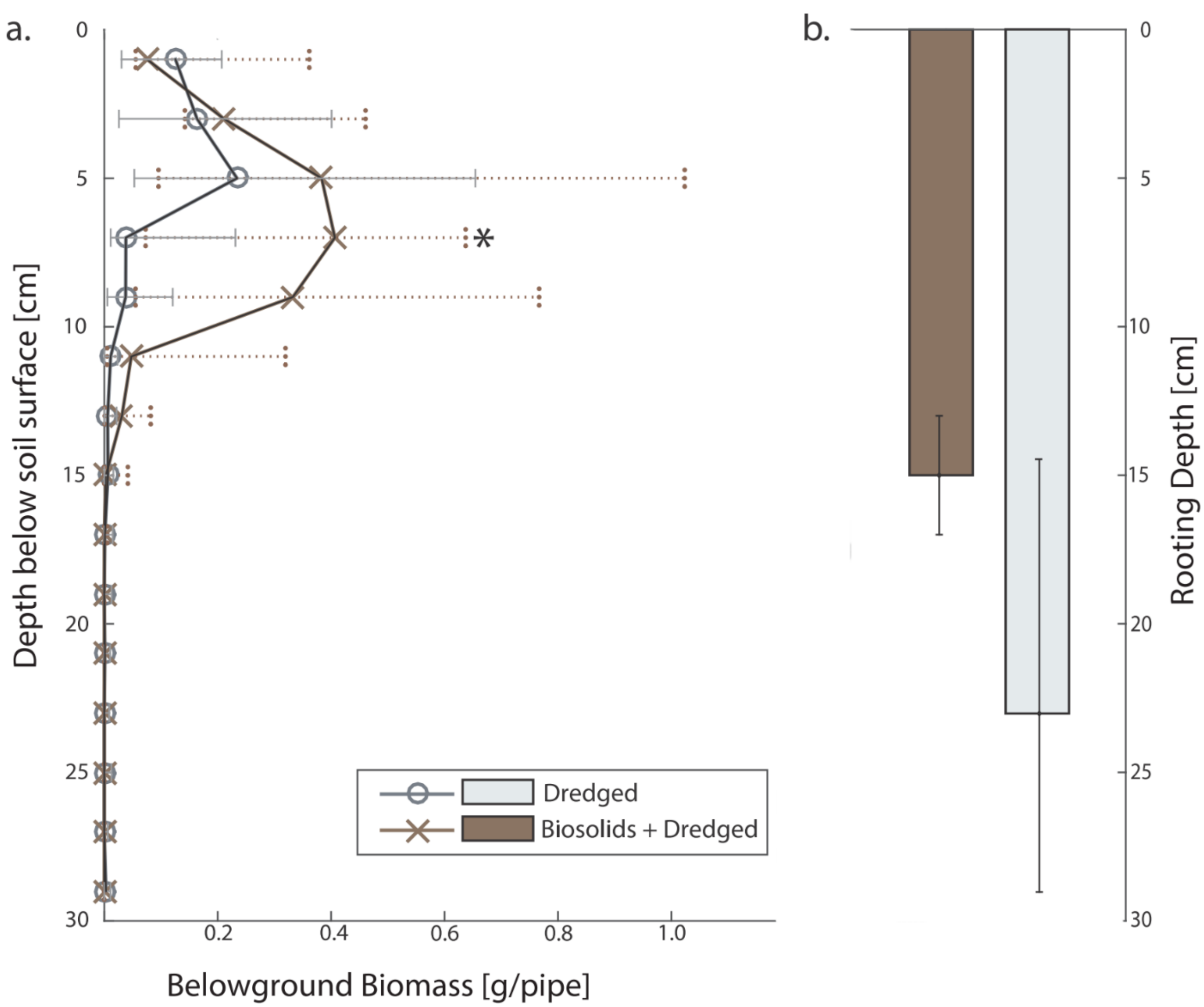

Figure 4. a) Belowground biomass vertically resolved by 2 cm increments for the treatment (brown) and control (gray) pipes. Symbols mark the median values and are shown at the center of the increment (e.g., biomass from 0 to 2 cm is marked at 1 cm). Mass is given as mass per pipe per 2 cm (total volume=3.5×10−4 m3). **b) The median values of the total rooting depth**. Error bars for both show the interquartile range. All levels, except 6–8 cm (marked with an asterisk), and the rooting depths were not significantly different (p>0.05) (Foster-Martinez and Variano 2018).

Biosolids application can also supplement or replace commercial fertilizers if managed correctly. The addition of biosolids to soils increases total soil N and P concentrations compared to commercial fertilizers (Brown et al. 2011). Biosolids as supplements also have the ability to slow-release the nutrients over several growing seasons (Binder et al. 2002). The slow release of nutrients is more beneficial to plants as they can extract the nutrients when they need to, while most nutrients in commercial fertilizers are subjected to leaching losses due to being water soluble

(Obreza and Ozores-Hampton 2000). Furthermore, this puts biosolids at an advantage because they will not largely affect runoff from farms as most commercial fertilizers do.

Current policies and regulations regarding biosolids management and disposal

Management and disposal of biosolids is regulated by the U.S. EPA. The Clean Water Act and Ocean Dumping Ban Act of 1988 prohibits disposal of sludge in the ocean and requires WWTPs to follow controls on sludge disposal. Under the Clean Water Act, WWTPs are required to have National Pollutant Discharge Elimination System (NPDES) permits—an EPA program that sets limits on biosolids constituents and routinely monitors WWTPs in their management practices. In 1993, the EPA developed a set of regulations called 40 CFR (Title 40, Code of Federal Regulations) Part 503 Biosolids Rule (also called 503 Rule) which further restricts biosolids to meet EPA standard pathogen and chemical limits prior to disposal (Lu et al. 2012). Despite the 503 Regulation, however, local communities have concerns regarding other toxicants such as steroids, pharmaceuticals, and chemicals from personal care products not monitored by the EPA (Lowman et al. 2013).

Pathogens

Pathogens such as bacteria, protozoa, and viruses are major causes of diseases. As such, the 503 Rule requires wastewater treatment plants to reduce the number of pathogens in biosolids before using them for land applications to minimize the risks for potential spread of diseases. The reduction of pathogens creates two different types of biosolids: Class A and Class B.

Class A biosolids require stricter pathogen reduction limits by the EPA since they are often applied to home gardens, sold to the general public, or used for other land applications that have higher chances for human contact (Table 2) (US EPA 2002). To meet these requirements, WWTPs can make use of several disinfection methods such as specific time-temperature regimes, and high pH- temperature processes, among others (Lu et al. 2012).

Table 2. Maximum concentration limits for pathogens in Class A biosolids (EPA 2003).

Pathogen Type	Maximum Concentration Limit (dry weight basis)
Salmonella sp.	Less than 3 MPN (Most Probable Number) per 4 grams total solids biosolids
Enteric viruses	Less than 1 PFU (Plaque-forming unit) per 4 grams total solids biosolids
Viable helminth ova	less than 1 viable helminth ova per 4 grams total solids biosolids

Class B biosolids are regulated more loosely and are used for any other applications. Unlike Class A biosolids, Class B biosolids still contain some pathogens and are most commonly applied to agricultural lands, forests, or reclamation sites. Class B Biosolids are required to have less than 2 million CFU (Colony Forming Units) per gram of biosolids (EPA 2003). There are a number of different processes that the EPA recommends per the 503 Rule to meet pathogen reduction limits for Class B biosolids (Table 3). These methods include aerobic digestion, air drying, anaerobic digestion, composting, and lime stabilization. Most WWTPs use a combination of anaerobic digestion and one of the other methods for sludge treatment. The anaerobic digestion method requires close monitoring of mean cell retention time (MCRT) of bacteria, along with pH and DO levels to be effective.

Table 3. Processes to significantly reduce pathogens (EPA 2003)

Disinfection Process	Description
Aerobic Digestion	Sewage sludge is agitated with air or oxygen to maintain aerobic conditions for a specific mean cell residence time (i.e., solids retention time) at a specific temperature. Values for the mean cell residence time and temperature shall be between 40 days at 20°C and 60 days at 15°C.
Air Drying	Sewage sludge is dried on sand beds or on paved or unpaved basins. The sewage sludge dries for a minimum of 3 months. During 2 of the 3 months, the ambient average daily temperature is above 0°C.
Anaerobic Digestion	Sewage sludge is treated in the absence of air for a specific mean cell residence time (i.e., solids retention time) at a specific temperature. Values for the mean cell residence time and temperature shall be between 15 days at 35°C to 55°C and 60 days at 20°C.
Composting	Using either the within-vessel, static aerated pile, or windrow composting methods, the temperature of the sewage sludge is raised to 40°C or higher and remains at 40°C or higher for 5 days. For 4 hours during the 5 day period, the temperature in the compost pile exceeds 55°C.
Lime Stabilization	Sufficient lime is added to the sewage sludge to raise the pH of the sewage sludge to 12 for ≥2 hours of contact.

Trace elements

In addition to pathogens, biosolids are also monitored for trace elements as they pose a significant concern for human and animal health. The EPA regulates 14 different trace elements that are commonly detected in biosolids (Table 4). The EPA requires land application of biosolids to meet these ceiling concentrations. In addition, if estimated cumulative loading limits are being approached, land application must be ceased.

Table 4. Pollutant concentrations and cumulative loading amounts for biosolids (Lu et al. 2012).

Trace metal	Ceiling concentration limit (ppm)[a]	Cumulative pollutant limit loading (kg ha^{-1})	Mean (ppm)
Arsenic (As)	75	42	10
Cadmium (Cd)	85	39	7
Copper (Cu)	4300	1503	741
Lead (Pb)	840	301	134
Mercury (Hg)	57	17	5
Molybdenum (Mo)	75	---[b]	9
Nickel (Ni)	420	421	43
Selenium (Se)	100	100	5
Zinc (Zn)	7500	2805	1202

[a]Dry weight basis.
[b]The February 25, 1994 Part 503 Rule amendment deleted the molybdenum cumulative limit loading for sewage sludge applied to agricultural land but retained the molybdenum ceiling concentration.

Nutrients

The 503 Rule also regulates nutrients from biosolids, particularly nitrogen,, to protect groundwater, surface water, and runoff quality. This regulation, however, is not very well defined by the 503 Rule due to a lack of viable data. Of the nutrients in biosolids, only nitrogen (N) is regulated by the EPA, while phosphorus (P) is not (EPA 2003). However, many states, including California and Pennsylvania, have state laws that require monitoring of phosphorus in biosolids.

The N to P ratio of biosolids is quite low which could pose problems for land applications (Table 5). This issue is discussed further in the next section.

Table 5. Nutrient concentrations of biosolids in Pennsylvania. Data from 1993 to 1997. Concentrations are on a dried biosolids basis (Lu et al. 2012).

Nutrient	Total Kjeldahl N (%)	NH_4-N (%)	Organic N (%)	Total P (%)	Total K (%)
Mean	4.74	0.57	4.13	2.27	0.31
Standard deviation	1.08	0.30	1.03	0.89	0.27

Risks of biosolids land application

Environmental health risks

Concerns regarding contamination and pollution have long plagued land application for biosolids disposal. Many local organizations oppose land applications due to concern about potential contamination to groundwater sources from trace elements and heavy metals. In addition, overloading of N and P in the soil poses considerable risk of eutrophication in nearby water bodies.

Biosolids have a higher Phosphorus to Nitrogen ratio (approximately 0.5 – 1.1) (Lu et al. 2012) than is optimal for plant growth (0.07 – 0.14) (Torri et al. 2017). Due to this, continued application of biosolids in agricultural land poses a risk in excessive P buildup since regulations are based on N rates. Furthermore, nutrients in biosolids, in combination with chemical fertilizers, remain in the soil even after the desired plant growth is attained (Torri et al. 2017). If left unchecked, this could cause excess loading of nutrients in the soil which could lead to eutrophication. High nitrate (Nitrogen in the form of Nitrate) concentrations have also been detected in land-applied biosolids on coarse-textured soils, and mine reclamations. The detected concentrations are often higher than the maximum contaminant limit for drinking water established by EPA (10 mg NO_3-N L^{-1}) (Lu et al. 2012).

Heavy metals in biosolids are also a major concern in land application. The accumulation of heavy metals in the soil is also an issue as they can bioaccumulate to hazardous levels with repeated land applications of biosolids on the same site. This poses risks of contamination to runoff water especially those from agricultural lands. Researchers modeled repeated biosolids land applications and created what is known as a “time bomb model.” The time bomb model shows that repeated applications of biosolids in a site creates bioaccumulation of heavy metals in plant tissues, and as organic matter dies and biodegrades, toxic concentrations of heavy metals from the plant tissues could be released to the environment posing environmental and health risks to the public (Lu et al. 2012).

One other risk in land application that environmental and public health activists are concerned about is organic pollutants. With current wastewater treatment methods, synthetic organic compounds from pharmaceuticals, personal care products, and industrial processes may end up in biosolids. Current technology does not support the removal of these compounds because they are water soluble, persistent throughout the treatment process, and difficult to degrade. In addition, many of these organic compounds bioaccumulate and may be carcinogenic to animals and humans exposed to high concentrations over long periods.

Sludge treatment wetlands (STW) on the other hand, have been proven to be beneficial in promoting biological stability (odor generation, leaching, pathogen regrowth, dry matter content) of resulting sludge (Müller et al. 1998, Magri et al. 2016). STWs consist of manmade wetland systems specifically developed for sludge treatment. They consist of sealed basins with a filter consisting of successive layers of stone and gravel, in which wetland plants like the common reed *Phragmites australis* are planted (Uggetti et al. 2012a). In addition to reduction of pathogens and nutrient concentrations, heavy metal uptake by wetland plants is a major biological removal system that could address accumulation of toxic metals in soils by long-term biosolids application (Sheoran and Sheoran 2006, Uggetti et al. 2012b). Sludge treatment wetlands, however, have not been well-studied, and currently lacks proper research on surface loading rates and patterns for sludge application. Literature search results for STW research included STWs as sites for wastewater treatment studies or sometimes, effects of STWs on another variable being observed. STWs are rarely the subject of a research. It lacks the focus that agricultural land application research often get, and even then, information on biosolids is still lacking, partly due to the biosolids project being a lower priority in the EPA (Office of Inspector General 2000). With further research and scientific data, STWs could prove to be a sustainable and cost-effective way to do promote biological stability in land application projects.

Public health risks

In addition to environmental risks, land application of biosolids also poses health risks to local communities. Public health is the primary concern for environmental injustice activists that fight against unmonitored land application of biosolids. Odor is one of the most common hindrances to public acceptance and is the main issue for WWTP managers when biosolids are land applied. The EPA does not regulate odors from biosolids in its 503 Rule, and local communities are fighting for the inclusion of this issue when sites are considered for land application.

Although previous studies have found that no associated risks have been linked to biosolids, several surveys by locals who live near the application sites have reported illnesses such as mucous membrane irritation and other respiratory distress (Lewis et al. 2002, Harrison and Oakes 2003, Shields 2003). There has been relatively little research done on human health effects of land application due to a lack of systems for surveillance and low population densities in these rural areas where most Class B biosolids are applied (Lowman et al. 2011). A health survey by Lowman et al. indicates that more than half of interview respondents (n = 18/34) correlated gastrointestinal and respiratory distress-related symptoms to living within 2 miles from an application site (Table 6) (2013).

Table 6. Physical symptoms (short duration) respondents attributed to sludge exposure (*n* = 18/34) (Lowman et al. 2013).

Acute symptom	No. of respondents reporting symptom
Eye, nose, throat irritation	8
Nausea, vomiting, diarrhea	8
Cough	5
Difficulty breathing	4
Sinus congestion, drainage	4
Skin infection, irritation, sore	2

Another study (Khuder et al. 2007) also suggest an increased risk for certain respiratory and gastrointestinal diseases among residents in a biosolids land application site. Furthermore, elevated frequencies of occurrences of upper respiratory irritations were also found to be statistically significant (Table 7).

Table 7. Reported symptoms for residents living within 1 mi of application sites (exposed) and residents living >1 mi from the site (unexposed) (Khuder et al. 2007).

Symptom	Exposed (n = 437)		Unexposed (n = 176)		p
	n	%	n	%	
Headache	342	80.9	133	76.9	0.274
Fever	214	50.4	90	50.6	0.615
Excessive secretion of tears[a]	106	25.2	28	16.5	0.023*
Cough	346	81.6	133	76.9	0.189
Sneezing	351	82.4	139	79.4	0.395
Sore throat	310	72.4	118	67.8	0.258
Chest pain or discomfort	130	30.3	48	27.8	0.534
Abdominal pain	180	42.5	64	37.2	0.239
Abdominal bloating[a]	150	35.9	44	25.9	0.020*
Nausea	193	45.8	79	45.9	0.985
Vomiting	153	36.3	64	37.4	0.789
Diarrhea	273	64.5	111	63.8	0.863
Constipation	189	45.1	68	39.8	0.236
Jaundice	33	7.9	4	2.3	0.012*
Skin rash	110	26.1	34	19.8	0.105
Ulcer on the skin	36	8.5	6	3.6	0.035*
Muscle spasm	128	30.3	44	25.9	0.281
Chills	129	30.6	56	32.9	0.573
Dehydration[a]	72	17.1	15	8.8	0.009*
Loss of appetite	92	21.8	41	21.0	0.565
Weight loss	93	22.1	18	10.6	0.001*
Insomnia	197	46.6	83	48.5	0.664
Fatigue	224	53.2	96	55.5	0.612
Weakness	143	34.1	44	25.6	0.043*
General ill feeling	187	44.8	74	43.0	0.686

*p values are significant at 0.05
[a]Significant dose-response from the Cochran-Armitage test

Khuder et al. (2007) found an elevation of excessive secretion of tears among exposed residents (p = .023), which could be attributed to ammonia being released from the biosolids. Abdominal bloating and dehydration were also common complaints (35.9% and 17.1%, respectively), and found to be of statistical significance (p = 0.020, 0.009, respectively).

Results from a survey of 48 residents living with 2 km of an application site also confirms the aforementioned findings for elevated upper respiratory irritation and gastrointestinal symptoms. From the survey (Novak et al. 2002) found that within 1 hour of exposure, residents reported symptoms of coughing (63%), burning throat (56%), burning eyes (56%), and headaches (46%). Coughing and burning throats were found to be statistically significant with *p* values of 0.02 and 0.03, respectively. Furthermore, half of their survey respondents reported bacterial, viral, and fungal infections, which medical records attributed to exposure to endotoxins and *S. aureus* (Novak et al. 2002, Brooks et al. 2006).

Czajkowski et al. (2010) did a spatial analysis of diseases experienced by residents living in close proximities from land application sites and WWTPs in Wood County, Ohio, using GIS. Acute diseases such as bronchitis, upper respiratory infection, and Giardasis were significantly higher in their respondents closer to application sites. Their findings, however, showed that although there is some correlation between illness and proximity to biosolids-permitted fields, is not proof that the biosolids were the cause of illnesses, and suggests that further research is necessary, along with bigger sampling sizes (Czajkowski et al. 2010)

In addition to the health risks, local residents also complained about quality of life due to incapability to perform certain outdoor activities because of malodors from biosolid sites. Such activities include letting children play outdoors, opening house/car windows, hosting outdoor social gatherings, line-drying laundry, gardening or walking outside, and even staying at home (Lowman et al. 2011, 2013). Residents also reported noticeable changes in the environment allegedly attributed to biosolids land applications such as spillage on roadways and private property, and even deaths and illness among livestock and water life (Table 8) (Lowman et al. 2013).

Table 8. Reports of concerns regarding land application operations. (*n* = 18/34 respondents) (Lowman et al. 2013)

Reported Observation	No. of respondents reporting observation
Sludge spillage on road, path, or property	9
Cattle grazing <30 days after an application event	7
No signage marking application sites during and after application events	6
Sludge runoff into surface waters	5
Sludge in buffer zones (e.g., across property lines, ditches, gardens, and private wells)	4
Failure of sludge to assimilate into soil	3
Unmarked application boundaries	2
Application during rain event	2
Application in critical water shed	1

Biosolid application sites are not routinely monitored by the EPA for human health risks, and certain parts of the 503 Regulation are weak (EPA 2000). Community members suggest that further application of biosolids should be more just and done in a more democratic way (Lowman et al. 2011, 2013). Stricter policy guidelines should be enforced, and community health risk assessments should be done on a regular basis especially for prolonged and repeated applications.

CONCLUSION & IMPLICATIONS

Land application is a beneficial method to dispose of biosolids waste, and to reduce management costs for WWTPs. Biosolids can improve physical, chemical, and biological properties of soils, as well as improve vegetation and biomass and help restore degraded ecosystems. However, biosolids also contain heavy metals, organic pollutants, and pathogens. Although existing in low concentrations, these contaminants may pose a threat to the environment and human and animal health at heavy application rates or prolonged repeated applications (Apedaile 2001). Therefore, extreme caution and consistent long-term monitoring need to be exercised in future land application projects.

The use of biosolids as soil amendments should be safety-oriented, and therefore, requires control for various contaminants such as organic waste, odor emissions, trace elemental concentrations, pathogens, and runoff of contaminants. Guo (2012) found that air transport is the major path for sludge contaminants, and suggests that sludge quality, application methods, distance from the site, exposure duration, and wind speed must be controlled for when applying biosolids close to residential sites.

Because wetlands are mostly secluded from neighborhoods due to the nature of its soil structure, it makes them perfect sites for biosolids land application and disposal. However, even wetland applications must be restricted to Class A biosolids, and even those types must be deodorized, and controlled for nutrients and other contaminants to minimize risks for runoff-related problems to marine bodies and marine life. Son and Striebig (2003) and He et al. (2009) found that pre-treatment of biosolids with hypochlorite or ferrate (VI) had significant effects on reducing sludge odors, although further research is needed to analyze its effects on soil upon application of biosolids.

Currently, practical and innovative approaches are needed to effectively treat biosolids in WWTPs, and to manage their land applications with little risk to human and environmental health. The EPA should complete a cumulative risk assessment tool (Sexton and Linder 2010) and screening tools for biosolids land application, and until such risk assessments are complete, the EPA should conduct studies determining long-term impacts of land-applied biosolids.

Suggested management practices for land application of biosolids

Despite reported health risks, land application is still a beneficial and sustainable way to recycle biosolids. Not only does it improve physical and chemical properties of the soil (Brisolara and Qi 2013), it is also proven to help increase vegetation and aboveground biomass of plants (Clarke et al. 2016, Foster-Martinez and Variano 2018). In response to health risks, I suggest that only Class A biosolids should be permitted for land application to sites within at least 5 to 10 miles of residential communities. Class B biosolids should be restricted to areas that have low chances for human contact such as treatment wetlands, marsh restoration projects, forest reclamation sites, among others. Furthermore, the EPA should include guidelines to Phosphorus limitations in addition to N-based regulations to avoid overloading of nutrients in soils. Physical characteristics of application sites, including slope, soil condition and proximity to water bodies should be assessed prior to application. Biosolids must be tested for pathogens at the time of treatment, and again right before disposal, use, or land application. Lu et al. (2012) mentions that bacteria such as *Salmonella sp.,* fecal coliforms, or enteric viruses may no longer be detected after treatment, but some may still be viable and grow by the time the biosolids are land-applied or disposed of.

Addressing public concerns is also important to garner acceptance for further applications. As such, wind direction, timing, and weather should be considered during periods of application. In addition, residents must be informed about whether they will be affected before a project occurs. As of 2000, the EPA cannot assure the public that current land application practices are protective of human health and the environment (Office of Inspector General 2000). This has to change immediately. Community inputs must be taken seriously and adapted to and management practices must ensure that people are protected from harmful pollutants and their quality of life remains unaffected. Surveillance and monitoring should be done routinely and data should be publicly accessible and open for evaluation by the scientific community. In a 2018 report, the Office of Inspector General discovered that the EPA was unable to assess the impact of unregulated pollutants in land-applied biosolids on human health and the environment due to lack of control in the implementation of the agency's own laws and regulations (Lovingood et al. 2018). The report also indicated that EPA has not been very good at sharing information even about the pollutants that are in biosolids in its website or to the public. Lovingood et al. (2018) summarizes the areas in which the EPA are lacking in terms of its implementation of regulations and management of biosolids including testing and researching pollutant risks to the environment and human health, sharing public information, training its workers and WWTP managers with regards to the risks of land applying biosolids, and compliance monitoring (Table 9).

Table 9. Control weaknesses and implementation status for land-applied biosolids (Lovingood et al. 2018).

Control	Description	EPA Implementing?
Testing	• Biosolids Rule 40 CFR § 503.13[a]	Yes
Research	• Clean Water Act § 405(d)(2)(C)[b]	Yes, but with control weaknesses
Pathogen and vector attraction reduction methods	• Biosolids Rule 40 CFR § 503.13[a]	Yes, but with control weaknesses
Sharing information with the public – EPA website	• EPA mission statement • EPA open government plan • EPA enterprise information management policy • Office of Management and Budget circular A-130[c] and Memos-M-10-06, M-13-13 and M-16-16 on open government	Limited
Sharing information with the public – Labeling	• Biosolids Rule 40 CFR § 503.14[d] • EPA mission statement • EPA open government plan • EPA enterprise information management policy • Office of Management and Budget circular A-130[c] and Memos M-10-06, M-13-13 and M-16-16 on open government	Yes, but with control weaknesses
Training	• Clean Water Act §§ 104(a)(1)[e], 104(g)(1)[f] and 104(g)(3)(C)[g]	Limited
Compliance monitoring	• Clean Water Act NPDES and goals set by EPA	Yes, but with control weaknesses

[a]Pollutant limits for use or disposal of sewage sludge
[b]Review of regulations every 2 years to identify additional toxic pollutants
[c]Managing Federal Information as a Strategic Resource
[d]Management practices for use or disposal of sewage sludge
[e, f, g]Promote coordination and acceleration of research relating to causes, effects, and reduction of pollution, and maintaining adequate supply of trained personnel.

The EPA was not fully implementing policies set by the Clean Water Act to review biosolids regulations until 2018. The required 2013 and 2015 biennials reviews were not done by the time of the report and in over 20 years, no new pollutants have been regulated (Lovingood et al. 2018). The EPA has reduced staff and resources in its biosolids program. In 2012, the Biosolids Center of Excellence has two full-time-equivalent employees. The Office of Water's Office of Science and Technology, who conducts risk assessments for biosolids, stated that biosolids have lower priority for EPA management, resulting in funding and data shortages in addition to a departure of biosolids expertise (Lovingood et al. 2018). To address this concern, I recommend that the EPA prioritize biosolids management, allocate proper funding, and conduct regular biosolids training and proper resources to state officials and wastewater treatment plant operators to improve the consistency in reporting and aid in reliable knowledge transfer.

Future regulations and policies should be based not only on environmental factors, but also on community input. Affected communities should be given proper warning and appropriate information when concerns arise. The EPA should include such information in its website regarding unregulated pollutants in biosolids, disclose gaps in data and current information, and descriptions of areas where potential risks for human health are high. These resources should be given and distributed to the public with a proper address and contact information. Residents' inputs and ideas for improvements to this relatively new endeavor in sustainable biosolids management are a valuable and distinct perspective on practices that the EPA or WWTPs might oversee. As such, increased involvement of the local communities in decision-making is needed to strengthen environmental and public health protections. Issues of environmental justice should also be taken in consideration. Currently, biosolids are being spread disproportionately in low income, minority, and mostly African-American neighborhoods (Snyder 2008, Levine 2013). This is a major environmental justice issue and the voice of those who are "voiceless" in politics must be properly represented and considered as well, either through public forums, protests, or formal complaints. As of now, a lot of groundwork is still needed before the biosolids land application program can be considered as a running process. The EPA should take proper actions and invest in researches and studies, as well as community inputs, to further achieve the goals of the biosolids land application program.

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