Biosolids and ecosystem services: Making the connection explicit
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Abstract
Ecosystem services are services provided by natural systems that enable our existence. The nutrients and carbon in municipal biosolids and human excreta can enhance these services. Explicit recognition of this connection can amplify the benefits associated with appropriate use of these residuals. The connection between the carbon and nutrients in biosolids and soils including soil health and ecosystem services related to soils are described. The tie between use of phosphorus in recycled materials, the global phosphorus cycle, and water quality is discussed. As the globe moves toward safe sanitation, understanding and taking advantage of this connection will have multiple and far ranging benefits.

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Introduction
A seminal article outlined the various services we receive from nature and attempted to quantify the value of these services using ecosystem accounting [1]. A total of 17 ecosystem services (ESs) were described with a global value estimated to range between US $ 16–54 trillion per year (1997 $s). Many of the services described in the article depend directly on soil health and functions. These include erosion control and sediment retention, soil formation, and nutrient cycling. Others describe critical functions of soil that are also shared with aquatic systems. Examples include disturbance regulation, water regulation and water supply, and waste treatment. Others are indirectly related to soils as they derive from biota supported by soils. Examples include gas regulation, refugia, food production, raw materials, and genetic resources. When biosolids are used as a soil amendment, they have the potential to impact soil health and function. As such, land application of biosolids can be viewed through the lens of ES.

Biosolids and ESs
Typically land application of biosolids is studied outside of the context of ES. For example, extensive work has been carried out to characterize the phytoavailability and potential environmental risks associated with biosolids phosphorus. However, these studies do not make the connection between the observed impact and ES. When biosolids or sanitation is considered within the context of ES, it is often carried out in from the perspective that providing adequate waste treatment is an ES. A proactive context can also be considered: that wastewater treatment and its by-products are able to enhance a range of ES [2]. As the concept of a circular economy, the importance of nutrient recycling and soils as a living entity are increasingly considered, the connection between biosolids and ES is likely to become more explicit [3].

A recent article directly addressed the connection between resource recovery from wastewater and ESs [2]. The authors examined the literature from 2000 to 2019 for studies focused on sanitation and resource recovery (65,495) and ESs (36,918) and found that only 155 of those studies explicitly recognized the intersection of the two fields. The authors continue to discuss how a deliberate recognition of the linkage between the two fields can work to strengthen both. They go on to illustrate overlaps between sanitation and ESs across types of services. ESs here are separated into supporting services, regulating services, and provisioning services. Biodiversity is also considered. An example of how land application of biosolids can enhance ESs, based on this work illustrates the authors’ points (Figure 1). The authors include the connections between organic matter, water and nutrients from wastewater treatment, and the range of ES in their work. Depending on diet, each human excretes between 1.6 and 7.4 kg of nitrogen and...
0.4–1.0 kg of phosphorus per year \([4,5]\). These nutrients are also associated with fixed carbon (5–20 kg yr\(^{-1}\)). The nutrients have value as a fertilizer replacement. The carbon has value as a soil conditioner, as an energy source. For this review, the focus will be on how organic matter and nutrients contained in the biosolids can positively impact ESs\([5]\). For this review, municipal biosolids is the term used for solids after stabilization and pathogen reduction for municipal water-based systems. In many cases, these systems can accept influent from industrial sources. We use human excreta which refers to untreated human waste. There are also a range of systems that at least partially stabilize the excreta on a home, community, or municipal basis.

**Global perspective**

Much of the research on land application of municipal biosolids has focused on the parts of the planet, where centralized wastewater treatment is readily available. When writing about the connection between municipal biosolids and wastewater treatment and ES, it is critical to also address where centralized wastewater treatment is not available. In these areas, open defecation and use of unlined pit latrines typically results in eutrophication of freshwater and in high levels of pathogens in drinking water supplies, resulting in significant environmental and human health impacts. Access to sanitation and potable water is closely linked and is the focus of the United Nations Sustainable Development Goal 6 \([6]\). A recent evaluation of the progress toward reaching that goal noted that across the globe, 892 million people practice open defecation with an additional 4.5 billion lacking access to improved sanitation. As a consequence, water quality has suffered. Water pollution is increasingly associated with the degradation of ESs. In addition, over 2 billion people do not have access to safe drinking water. In areas with centralized sanitation systems, use of chemical fertilizers also has a detrimental impact on water quality, a critical component of ESs \([7]\). In developed areas, access to potable water is an increasing concern owing to depletion of aquifers, climate change, and population pressures \([8,9]\). Provision of adequate sanitation and appropriate use of treated residuals (resource recovery) from sanitation is important for its potential to address a number of SDG and bolster ESs \([10]\).

**Biosolids and soil carbon**

On the most basic level, use of the fixed carbon and associated nutrients from sanitation has repeatedly been shown to improve soil quality. Increasing organic matter is the critical component for healthy and highly functional soils \([11,12]\). Addition of organic amendments including biosolids and biosolids-based composts have been shown to increase the organic matter concentrations of soils across a range of soil types.
climates, and cropping systems [13,14]. The link between increased soil organic matter and the ability of soils to support a range of ESs is also recognized [15,16]. These services include water infiltration, retention and filtration, erosion control, nutrient cycling, biodiversity (soil fauna), and higher productivity. In addition, the soil can function as sink for CO2. Increasing soil organic matter effectively provides a carbon sink. A recent study found that nature-based climate solutions (including soil stewardship) could provide up to 37% of the CO2 mitigations required by 2030 [17], and the authors also noted the associated ESs that would be provided. A recent study of organic residuals management in California (including municipal biosolids) concluded that anaerobic digestion followed by land application of digestate or composted digestate was a net carbon negative proposition [18]. A carbon accounting of different biosolids stabilization and end use options found that anaerobic digestion followed by land application resulted in net carbon storage. In contrast, combustion or landfilling of the biosolids emitted large quantities of CO2 equivalent [19]. Finally, carbon emissions associated with improperly managed excreta are likely significantly higher than those associated with collection and treatment. A recent study of ecological sanitation in Haiti found that collection and composting of feces had lower net carbon emissions than waste stabilization ponds [20].

Nutrients
Trimmer et al. noted that if the number of people without access to sanitation is reduced by half by 2030 and the nutrients contained in the wastewater are recovered, the quantities recovered would be 15 (11–20) MMT (10^6 Mt) of nitrogen and 2.2 (1.1–3.4) MMT of phosphorus. These amounts represent 11% (9–16%) and 9% (5–15%) of the projected demand for these fertilizers. The authors also note that, if the carbon matrix that contains the fertilizers were to be used to produce energy, a much smaller impact on global energy demands would be met 1% (0–2%). When energy recovery is accomplished through anaerobic digestion, both energy and nutrient recovery along with recovery of a portion of the fixed carbon is possible.

Recovery and reuse of nutrients contained in human excreta beneficially impact a range of ESs. Carbon emissions associated with production of synthetic N and mined P are significantly reduced. Estimates of energy required to fix N and P vary but have been estimated at four Mt CO2 per Mt N and 2 Mt CO2 per Mt P [19]. Yields for crops grown using nutrients in a carbon matrix have generally been shown to be equivalent to or greater than yields for crops grown using commercial fertilizers [21–24]. The nutrient density of the crops grown using biosolids can be higher than those grown with synthetic fertilizers [25,26]. Excreta provides a source of nutrients for agriculture for farmers who in many cases are not able to afford synthetic fertilizers with associated yield responses [10,27–29]. By capturing nutrients and applying them to soil, direct release into water bodies is eliminated [30]. This last point is especially significant for phosphorus.

Phosphorus
A recent study noted that release of P to water bodies in the Midwest U.S. would be reduced if recovered P were used in place of synthetic fertilizers [7]. This region is known as the corn belt, with 70% of the total maize production in the U.S. and one-third of the total world production. Total P required to grow the corn in this area was 405 10^3 Mt P or 56% of the P used for corn cultivation in the U.S. Phosphorus fertilization in this region is also responsible (along with excess N) for the hypoxic conditions in the Gulf of Mexico. The authors note that in 2012, phosphate rock–derived fertilizer accounted for the majority of P applied to fields (1.71 10^3 Mt) and that about 0.54 10^3 Mt of P applied ended up in receiving waters as a result of erosion [7]. They also note that more than 40% of the rock P used in 2012 could have been replaced by recovered P from wastewater, food waste, and animal manures. Another study used a similar approach to determine the impact of recovered P from sources, including animal manure, food waste, and human waste, on P demand on a world scale. The authors found that recovered P could meet the demands of 2.5 billion people and that, if all proposed recovery and interventions were to be enacted, that number could increase to 14.7 billion in a sustainable fashion [31]. A study looked at the distance that would need to be traveled from urban areas around the globe to use the nutrients contained in wastewater to meet the agricultural needs of crops [27]. The authors noted that travel distance varied by region, with the shortest distances generally for European, African, and Asian cities. They conclude that efficiency of recovered nutrients could be increased by cultivating high nutrient-intensive crops near urban areas. These studies have focused on use of recovered P for agronomic crops. A wide range of benefits is possible for use of biosolids-derived nutrients in urban and peri-urban areas. Recent studies have looked at use of wastewater solids for urban uses and found good growth response with minimal environmental impact as a result of nutrient leaching. Additional value for nutrients in an organic matrix has been shown for turf and green stormwater infrastructure [32–35].

Conclusions
The relationship between biosolids and human excreta and ESs is rarely explicitly recognized. Explicitly recognizing this connection has the potential to amplify benefits associated with collection, treatment, and land application of these materials, both in areas with centralized wastewater systems and from areas where
waste treatment has yet to be developed. For the range of materials that originate as human excrement, the value in these materials needs to be captured in a manner that is protective of both human and environmental health. Optimizing end uses for these materials is critical to connecting urban and rural sectors and to creating a circular economy. It can also reduce dependence on synthetic and mined fertilizers and build healthy soils. Pretreatment of industrial discharges has proven to be critical to product quality in areas where these regulations have been developed and enforced. This suggests that this approach can be replicated as new contaminants to these systems are identified or in areas where centralized wastewater systems are being constructed.

Conflict of interest statement
Nothing declared.

References
Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest


Direct linkage of ES to sanitation looking at both fuel and nutrient value of solids from a global context


Understanding phosphorus in agriculture intensive region and the potential for recycled materials to meet demand. Discusses ties between soil P losses and water quality impacts and notes the potential for recycled P to limit impacts.


Paper showing linkage between resource recovery from sanitation and beneficial impacts to environment and sustainable development goals.


Paper showing deep soil sampling has an impact on soil carbon sequestration accounting with compost amendment only showing net sequestration


Revised estimate of benefits associated with focusing on natural systems to limit climate change. Emphasis on reforestation


Paper focuses on potential for waste – including materials from WWTP from both an energy perspective and a soils perspective. Heavy focus on biochar and compost rather than direct application of biosolids or digestate


Looked at proximity of agricultural soils with a focus on large-scale or agronomic crops to absorb nutrients generated by wastewater treatment. Distances varied greatly depending on region.


Paper on global phosphorus demand and availability. Notable as authors consider recycled P. Characteristic of new understanding in the literature that recycled materials are critical to sustainable or circular systems.