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Perspective

Nature provides valuable sanitation services

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SUMMARY

Much previous research shows that safe disposal of human waste has a positive impact on human wellbeing, while preventing the degradation of ecosystems. However, to date, the role that ecosystems themselves play in treating human waste has been largely neglected. We conceptualize the role nature plays in treating human waste—acting as a pipeline and/or treatment plant. We estimate that nature is treating ~41.7 million tons of human waste per year worldwide, a service worth at least 4.4 ± 3.0 billion USD year^{-1}. We demonstrate the opportunities and challenges of quantifying these "sanitation ecosystem services," using 48 cities across the globe as a worked example. In highlighting this, we are not marginalizing the vital role of engineered infrastructure, but instead are promoting better understanding of how engineered and natural infrastructure interact within a circular economy. This is a promising route for further research and may allow adaptive design and management, reducing costs, and improving effectiveness and sustainability.

INTRODUCTION

While researchers and practitioners have discussed the many and varied benefits natural environments provide to humans (termed ecosystem services),[1] the formal ecosystem service concept evolved between the 1970s and 1990s.[2] Before this, nature was often little more than an afterthought in many landscape and development decisions, which were instead driven by human need and/or economics resulting in most ecosystem services being degraded through unsustainable use.[3] The ecosystem service concept views nature from an anthropocentric viewpoint, providing a framework to acknowledge, categorize, and, in some cases, quantify and monetize them.[2] Many other related terms are also prevalent in this research field (including ecosystem goods, environmental services, natural capital, nature's contributions to people, public goods, and payment for services), but the fundamental basis is similar. Some have argued against the anthropocentric approach of the concept, resenting a utilitarian view of nature—that nature only exists to "service" humans.[4] Others argue against using the ecosystem service concept to value nature, instead stating that we should preserve and protect nature strictly "for its own sake," for its "intrinsic value."[4] However, the consensus is that a better understanding of ecosystem services will help sustainability decision making (e.g., through improved governance and provision of these services).[1]

Goal 6 of the 2030 Agenda for Sustainable Development recognizes the importance of ensuring the availability and sustainable management of sanitation.[5] Traditionally, engineered systems have been seen as the best way to manage human waste, using physical, chemical, and biological processes to treat it and turn it into harmless products—[6]the process of sanitation. However, it has recently been recognized that nature-based solutions are essential if Sustainable Development Goal (SDG) 6 is to be achieved.[6] Such "sanitation ecosystem services" were identified in the Millennium Ecosystem Assessment (as "waste treatment"),[3] but have received little attention since[7] and so how nature contributes to sanitation is understudied.[8]

To the best of our knowledge, no paper has quantified how much human waste is safely managed by nature nor the value of these sanitation ecosystem services at continental/global scales. We reviewed the numerous disciplines covering the role of nature in sanitation literatures together to provide a foundation for future research (see Box 1 for an example of the terminology used). For example, a Web of Science search for either "waste treatment" or "sanitation" and "ecosystem service*" yielded 85 results on December 17, 2018. Of these papers: 48% were not relevant to sanitation, focusing on other ecosystem services (e.g., recreation, crop production, etc.). Thirty-six papers (42%) valued the sanitation/waste treatment ecosystem services (henceforth referred to as sanitation ecosystem services) mostly using benefit transfer methods[9] (97%) within China (67%). Benefit transfer methods rely on global values, typically obtained from a limited number of studies, which are then applied to different land covers across the world (e.g., extrapolating a few localized studies on the value of mangrove forests for sanitation to all mangrove forests globally). As such, benefit transfer methods are known to be error prone because, for example, not all forests are functionally equal

Box 1. Key definitions from environmental, water, sanitation, and hygiene sectors

- Ecosystem: a biological community of interacting organisms and their physical environment
- Ecosystem service: the benefits humans derive from nature[1]
- Human waste: human waste is the waste products of the human digestive system[12]
- Treatment: treatment is the process which is used to convert wastewater into a useful effluent (with negligible health and environmental issues), which is then returned back to the water cycle[13]
- Safely managed [sanitation]: informed by the excreta flow diagram (Figure 2)[14]
- Fecal sludge: fecal sludge comprises all liquid and semi-liquid contents of pits and vaults accumulating in on-site sanitation installations, namely latrines or septic tanks[15]
- Excreta flow diagram: expert-based diagrams that capture how excreta physically flows through a city or town, and categorizes it into ten possible service outcomes[16,17]

and their value differs according to local economies.[10,11] Finally, 4% reported the impacts of sewage on nature; and 6% documented the natural processes included in sanitation infrastructure, with almost all (five out of six papers) documenting the role constructed wetlands can play in sanitation provision (detailed below; Figure 1).

Comparable literature searches within related disciplines (e.g., using terminology from water, sanitation, and hygiene research fields [Box 1]) show similar data paucity. For example, recently, Trimmer et al.[18] acknowledge that efficiently delivering sanitation services likely uses ecosystem services, but concentrate on how sanitation can increase ecosystem service delivery by developing a conceptual framework of pathways through which resources recovered from human waste can enhance ecosystems. There is an extensive body of literature on the natural attenuation in aquifers, but this is mostly about industrial pollutants, although there is some focus on nitrates that can derive from human waste.[19] How poor management of human waste can damage ecosystems is also frequently researched,[20] as is finding technical solutions to managing human waste. Expanding sewer networks is challenging, especially when cities are dense or unplanned and there is little financial resource available.[21] Thus finding a way to safely empty pit latrines[22,23] and treat this concentrated waste stream[24,25] (known as fecal sludge) has been a focus. Others have focused on alternative on-site sanitation, such as composting toilets[26] and container-based toilets.[27] However, the role nature plays in treating human waste in each of these sanitation solutions has been understudied.

Due to gaps in engineered infrastructure, some human waste ends up being processed by nature. For example, in 2017, 1 billion people (14% of the global population) used toilets where latrines where disposed *in situ* and a further 2 billion people (>25% of the global population) did not have access to basic sanitation facilities—with 673 million of these defecating in the open (i.e., behind bushes or into open bodies of water).[28] While some of this waste may present a danger to local populations, it is likely that natural processes contribute to reducing this risk either partially or entirely. However, nature's role in sanitation is poorly understood and difficult to quantify—predominantly due to data deficiency—and, as such, nature's role in sanitation is likely underappreciated.

At present the contributions that ecosystem services make to global sanitation provision are unquantified. We recognize the role of nature in sanitation—introducing the concept that nature is likely acting as a pipeline and/or treatment plant in some places (Figure 1). In addition, we discuss the current challenges in quantifying and valuing sanitation ecosystem services. Our overall aim is to develop a pathway for future research to ensure the sanitation services provided by nature are neither taken for granted nor overwhelmed—the latter likely resulting in both environmental degradation and the release of unsafe human waste.

CONCEPTUALIZING THE ROLE OF NATURE IN SANITATION

Here, we conceptualize two main mechanisms by which sanitation ecosystem services may be delivered, with nature taking a lead or supporting role (alongside engineered infrastructure) by acting as a pipeline (diluting human waste and taking it away from people), and a treatment plant (adsorbing and filtering human waste via competition, die-off, predation, and taking up nitrates; Figure 1).[29] Where human waste is predominantly made safe by natural processes with minimal input from infrastructure, we propose that nature acts as a *safe disposal facilitator*. In other locations not all human waste will be made safe, but a proportion of it may still be treated by ecosystems (i.e., nature acting as a *risk reducer*). However, in many locations human waste is treated predominantly via an engineered sanitation infrastructure. An engineered infrastructure often harnesses natural processes (e.g., biological oxidation of wastewater and fecal sludge or anaerobic digestion)[30] and so in these cases nature plays the role of *infrastructure supporter* (Figure 1).

Nature as a pipeline

Globally, approximately 711 million people (~9% of the global population) have sewer connections that do not connect to wastewater treatment plants; the vast majority of these people (>90%; >640 million people) live in urban areas.[14] Many more are connected to wastewater treatment plants that do not provide effective treatment or comply with effluent requirements, so at least some wastewater ends up in water courses.[14] In these instances, nature may fill a gap by transporting the high-risk sewage away from human populations, acting as a conduit for untreated sewage into wetlands or the sea, which then further dilutes and treats the waste (discussed below). Evidence of rivers acting as a pipeline is readily available—between one-fifth and one-third of all river stretches in Asia, Africa, and Latin America contain severe fecal coliform pollution.[31] Of course, the river may not be transporting all the human waste safely away from the source, or may be transporting water (and waste) to other communities downstream and so the reduced level of risk may remain unacceptably high for some populations[32] (Figure 1). To

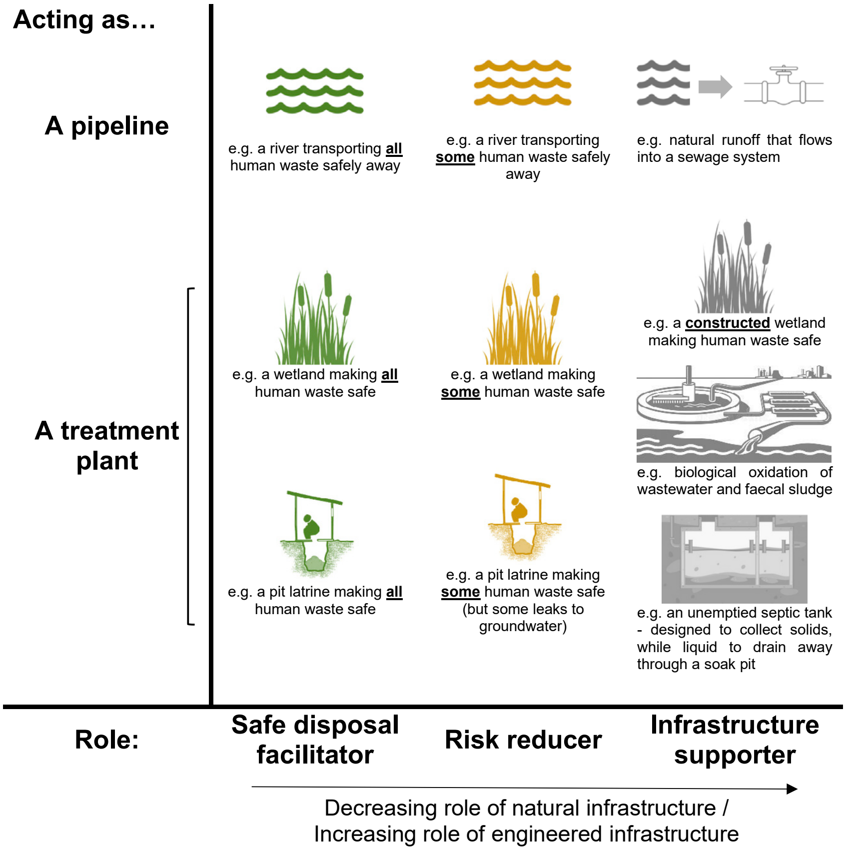

Figure 1. The roles nature can play in treating human waste

Safe disposal facilitator—human waste made safe by natural processes with minimal input from engineered infrastructure; *risk reducer*—while it is unlikely that all human waste has been treated, a proportion of the human waste may be made safe by ecosystems; and *infrastructure supporter*—human waste is treated via engineered sanitation infrastructure, which harnesses natural processes.

quantify the sanitation ecosystem service from rivers it is necessary to quantify how much human waste is being removed and relocated by rivers and also account for the health impacts suffered by downstream river users—this could be possible for specific sites but is challenging to do on a global scale.

Nature as a treatment plant

Over 892 million people (~12% of the global population) use safely managed on-site facilities where human waste is disposed *in situ*.[14] Although, it is likely that this value is an underestimate as shared facilities and areas where data on excreta management are not available are excluded. Assuming wet fecal mass of 128 g per person per day,[12] we estimate that nature is safely treating ~41.7 million tons of human waste per year *in situ* (i.e., before liquid entering groundwater).

Accordingly, the soil can act as a filter, with microbiota cleaning human waste before it can enter groundwater supplies, and this sanitation ecosystem service is globally important. Lawrence et al.[29] describe how pathogens are attenuated in unsaturated soil. They can be adsorbed onto soil particles, particularly viruses that carry an electrical charge. Larger pathogens, such as protozoan cysts and helminths, can be physically filtered. Pathogens take a tortuous route through the soil particles, which enhances dilution and dispersion, increasing the time taken to reach groundwater. In the meantime they might die through lack nutrients or be predated by other soil organisms. Nitrate is taken up biologically by plants[29] and microorganisms.[19] It is these mechanisms and processes that we propose underpin sanitation ecosystem services.[3]

Research has focused on developing and testing simple guidelines for minimum separation distances between latrines and water sources[29,33–37] and defining the maximum safe hydraulic loading rate for a pit latrine (i.e., the sustainable rate at which soil can filter fecal sludge) can only be done for a particular hydrogeological setting. Thus, understanding the precise temporal dynamics of this ecosystem service can only be done at local scale. However, if a full pit is covered (for example, with soil or concrete) then the pathogens will eventually be inactivated. The current World Health Organization (WHO) recommendations are that this waste is made safe within 1 year (assuming ambient temperatures above 20°C)[38] and this has been confirmed to be suitably conservative by recent work on the deactivation of various pathogens, including *Ascaris* eggs.[39]

Where wastewater ends up in aquatic environments, there is potential for both dilution to safe levels and natural processes leading to pathogen attenuation. For example, pathogens can be both diluted and killed in the saline environment[40] by mechanisms, including inactivation by biofilms,[41] predation by protozoa,[42] sunlight deactivation, reduced nutrients, temperature-induced stress,[43] filtration by filter feeders,[44] and flocculation onto particles (although the latter is reversible).[45] The ability of nature to act alone as a treatment plant in place of engineered systems has been studied in natural wetlands in New Zealand[46] and the US.[47] A small body of evidence has linked natural wetlands to sanitation ecosystem services by reducing the nutrient load flowing into downstream water bodies.[48,49] In fact, it has been suggested that natural wetlands and mangroves provide effective and economical wastewater treatment services[50] and can fill the gap between the level of basic services that a government is able to provide and that which rapidly increasing urban populations require.[51] For example, near Kampala, Uganda, the Navikubo Wetland processes untreated wastewater from ~100,000 households (a process valued at 1.0–1.8 million USD year^{-1}) and in doing so protects Murchison Bay and Lake Victoria.[51] The Mississippi River is diverted through coastal wetlands in the Gulf of Mexico in order to remove nitrogen.[52] The Muthurajawela integrated coastal wetland system in Sri Lanka receives a high load of domestic wastewater, trapping nutrients while

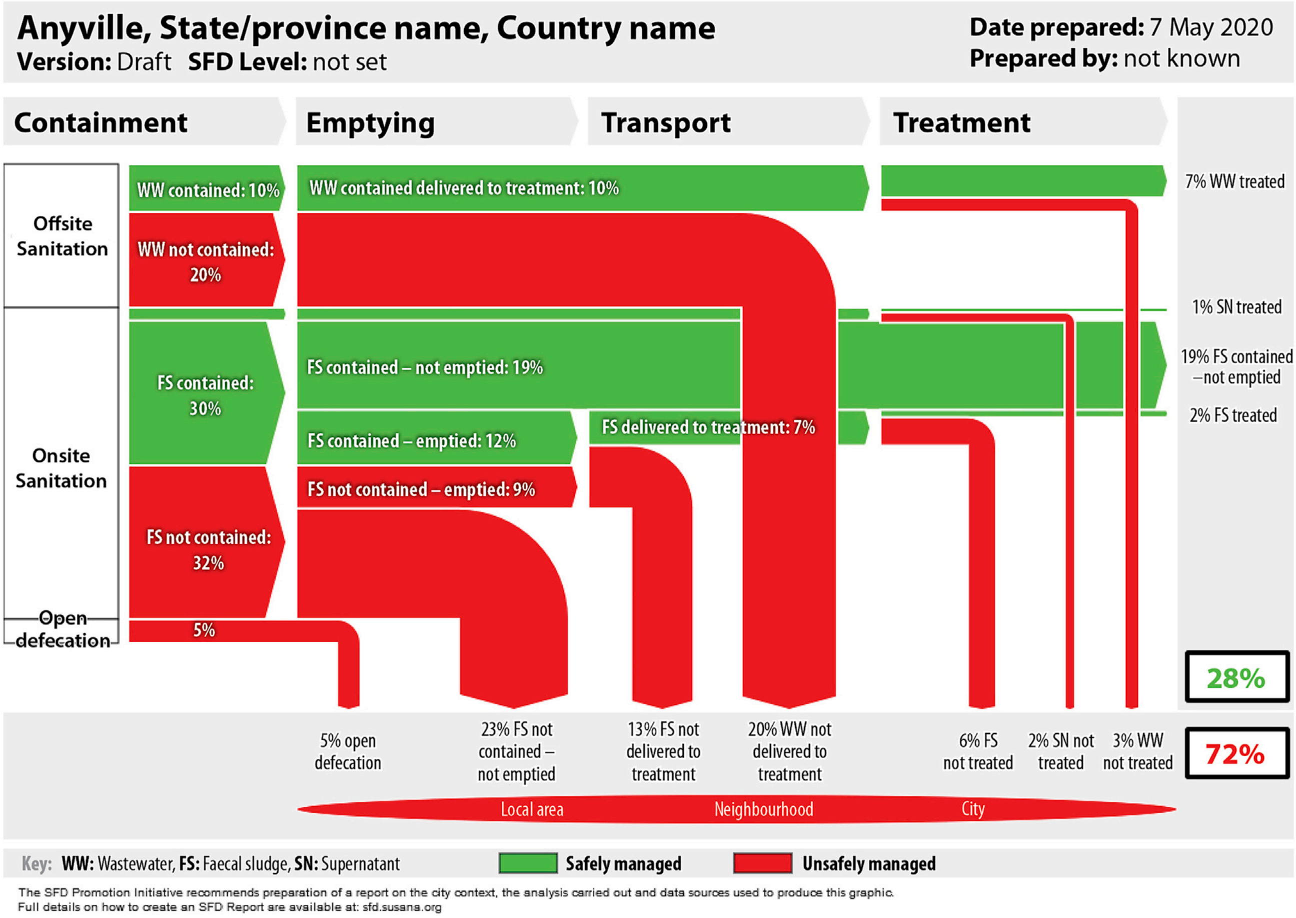

Figure 2. An example excreta flow diagram
This is similar to the ones found in the Sustainable Sanitation Alliance (SuSanA) collection.[16]

pathogenic organisms accumulate and decompose in the wetland's bottom sediments. It is estimated that the marsh and lagoon area receive raw or partially treated sewage from a population equivalent to 200,000 people.[53] The high water table and recurrent waterlogging in these residential areas, and their close proximity to the wetland, would require the construction of elevated pit latrines to prevent sewage from entering directly into the wetland. The costs avoided in constructing improved latrines for households who currently discharge sewage into the wetland work out at more than USD 57,000 per year.[54] Similarly, the processes used in treatment plants are also replicated in some marine environments.[55] For example, in coastal settings, shellfish can remove nutrients and particulates from seawater and sometimes are deliberately farmed for this process.[44] Overall, the treatment potential of natural ecosystems was highlighted 20 years ago but this idea has not received attention more recently.[54]

In areas with complete connection to treatment plants via sewage networks, people still benefit from sanitation ecosystem services as all wastewater treatment plants use biological processes as a key part of the sanitation process (Figure 1).[30] Thus, nature clearly plays a supporting role even where a conventional, engineered sanitation infrastructure is present. Biological treatment processes can range from anaerobic digestion to constructed wetlands, which rely on plants to filter, detoxify, and decompose human waste. As constructed wetlands mimic natural processes, they are increasingly being labeled as "nature-based solutions."[6]

QUANTIFYING SANITATION ECOSYSTEM SERVICES

To quantify these sanitation ecosystem services, we need to understand the proportions of different types of sanitation infrastructure that are in use. Doing this at large (e.g., global) scales requires standardized monitoring and reporting. As such, data deficiency can prevent such analyses. Here we discuss current opportunities and challenges in quantification of sanitation ecosystem services, using excreta flow diagrams (often described as "shit flow diagrams"; Figure 2) as collated by the Sustainable Sanitation Alliance (SuSanA) as a worked example.

Excreta flow diagrams document how excreta physically flows through a city or town, and categorize it into 10 possible service outcomes[16,17] (Figure 2; Table 1). They are based on in-person interviews, informal and formal observations, and direct measurements in the field. They are reviewed by staff from the five research institutions who sit on the steering committee of the

Table 1. Identifying the potential role of nature within safely and unsafely managed excreta flow diagram categories

Excreta flow diagram service outcome	Risk	Role of nature
Offsite		
Wastewater not delivered to treatment	Unsafe	Risk reducer
Wastewater delivered to treatment		
Wastewater treated	*Safe*	*Infrastructure supporter*
Wastewater not treated	*Unsafe*	*Risk reducer*
Onsite		
Fecal sludge contained		
Fecal sludge contained not emptied	***Safe***	***Safe disposal facilitator***
Fecal sludge emptied		
Fecal sludge delivered to treatment	Safe	Infrastructure supporter
Fecal sludge not delivered to treatment	Unsafe	Risk reducer
Fecal sludge not contained		
Fecal sludge emptied		
Fecal sludge delivered to treatment	Safe	Infrastructure supporter
Fecal sludge not delivered to treatment	Unsafe	Risk reducer
Fecal sludge not contained not emptied	*Unsafe*	*Risk reducer*
Open defecation	Unsafe	Risk reducer

The category of focus for our work example is highlighted in bold. Safe disposal facilitator—human waste made safe by natural processes with minimal input from engineered infrastructure; risk reducer—while it is unlikely that all human waste has been treated, a proportion of the human waste may be made safe by ecosystems; and infrastructure supporter—human waste is treated via engineered sanitation infrastructure, which harnesses natural processes (Figure 1).

excreta flow diagrams initiative.[16] While they are arguably rough estimates, intended only to highlight issues to policymakers, they are, to the best of our knowledge, the only standardized estimates of the whole sanitation value chain (i.e., proportions of different types of sanitation infrastructure for all management pathways) available for a subset of cities across the globe. Thus, in the absence of empirical quantitative data, excreta flow diagrams are the best available data.

Of the excreta flow diagrams service outcomes, we predominantly focus on "fecal sludge contained not emptied" (FSCNE) where the fecal sludge is safely contained beneath the ground, typically in a pit latrine or septic tank[16,17] (Table 1). FSCNE excludes scenarios where the pit or tank fills quickly, such that the human waste needs emptying and treatment or disposal elsewhere. Thus, to be classified as FSCNE, a pit should be covered and safely abandoned, or the volume of its contents should be reduced in the pit or tank through leakage into the soil,[56] either through the walls of the pit or through a soakpit, which is designed to receive the effluent from a septic tank.[57] It is important that this leakage does not contaminate the groundwater, and guidelines exist to ensure this.[29] These guidelines are used in the excreta flow diagrams, such that human waste can only be classified as FSCNE if it is safely managed according to the criteria in Box 2. Thus, we are confident that the FSCNE is a useful indicator of where nature plays a significant role in treating human waste by driving many of mechanisms that transform it into harmless products.[6]

However, the overall sanitation process associated with FSCNE typically combines an engineered infrastructure to safely contain the human waste (e.g., in a pit latrine) with natural processes (i.e., adsorption, filtration, dilution, dispersion, die-off, and predation),[29] making fecal sludge safe over time. The relative importance of nature versus infrastructure for FSCNE will vary on a case-by-case basis (Figure 1). For example, an unemptied pit or tank that loses volume via leakage into the soil[56] consists of little engineered structure beyond the pit itself (and of course the slab on the top of it and the superstructure), with the soil undertaking the processes necessary to make the leaked fecal sludge safe. By contrast, an unemptied septic tank is designed to collect solids, while liquid drains away through a soakpit,[57] incorporating an additional component of engineered infrastructure into the sanitation process.

Here, we use excreta flow diagrams to provide a first-order estimate of sanitation ecosystem services volume and value at a globally relevant scale. We use all the published, reviewed excreta flow diagrams reports and their associated appendices that were available on December 17, 2018, to quantify the sanitation ecosystem services in 48 cities (containing approximately 82.0 million people) across the globe (Figure 3). Note, the authors had no control over the city selection as these are chosen by researcher collaborations within the SuSanA team (i.e., according to where they are working and where they have good relationships with local organizations). Although there are geographical clusters, these cities include a range in terms of size (minimum, 27,386; maximum, 16.787 million) and level of economic development (including low GNI, such as Bolivia, and high, such as the US) (Table 2).

Box 2. Requirements for safely managed *in situ* sanitation

Human waste is not categorized as safely managed where groundwater sources are used for drinking *and*:

- the depth to the water table is less than 5 m
- *or* the depth to water table is less than 10 m in areas of weathered basement or medium sand
- *or* the aquifer is fractured limestone or sandstone or coarse gravels
- *or* more than 25% of sanitation facilities are located more than 10 m from groundwater sources
- *or* more than 25% of sanitation facilities are located uphill from groundwater sources[56]

A small number of studies have detected that pathogens can travel further than 10 m away from a pit latrine, for example, protozoa traveled up to 500 m from a pour-flush latrine in India,[33] and adenovirus and rotavirus traveled 50 m away from pit latrines in Benin.[34] Some studies that detect fecal coliforms in wells do not detect increased nitrate concentrations, while other studies report nitrate concentrations more than double the WHO recommended guideline (50 mg L^{-1}).[58,59] However, nitrate pollution has numerous possible sources, including fertilizer and livestock slurry and it is difficult to pinpoint the actual sources of nitrate in groundwater.[60] Models suggest that pit latrines 5 m above the water table could lead to nitrate pollution groundwater over WHO levels only if a moderate to long nitrate half-life was assumed.[37] WaterAid advise a larger separation of 50 m between latrines and water sources,[61] and the Sphere project advise 30 m in a humanitarian context.[62] However, most studies that have set out to test this guidance have concluded that increasing the distance between latrines and groundwater sources has a minimal impact on microbial risk[35] and that local pathways associated with poor borehole construction are much more important.[36]

From the 48 excreta flow diagrams, we recorded the population of the city and the percentage of fecal sludge within the FSCNE category. Where available, we also collated data on the volume of FSCNE and/or cost required if conventional infrastructure were used to treat the FSCNE instead of nature (hereafter termed the sanitation ecosystem service value) from the excreta flow diagram reports. If the volume/value was not documented, but these data were available for another service outcome, we estimated it using the ratio between the outcomes (Table 2). If volumes/values for multiple service outcomes were available, then we used the data relating to the largest percentage category. For example, for an excreta flow diagram that categorized 10% of human waste as FSCNE, 60% as contained fecal sludge that was emptied and treated (valued at USD 6,000 $year^{-1}$), and 30% as not contained fecal sludge that was emptied and treated (valued at USD 3,300 $year^{-1}$), we estimate ecosystem service value using the data for the larger category (i.e., contained fecal sludge that was emptied and treated) as follows: $Ecosystem\ service\ value = \$6,000\ yr^{-1} \times \left(\frac{10\%}{60\%}\right)$.

We find that 18.1% ± 4.9% (unweighted mean ± the 95% confidence interval) of the sanitation within the 48 case studies (82.0 million people; Figure 3) is classified as FSCNE (Table 2). This is substantial evidence for the importance of sanitation ecosystem services, and indicates a reliance on these services for 7.0 million people within these cities. For a subsample of our cities, volume (n = 15; 35.3 million people) and value (n = 8; 29.1 million people) data are available and we conservatively estimate that sanitation ecosystem services process 2.2 million m^3 of fecal sludge per year within these cities, worth approximately 0.57 ± 0.39 USD $year^{-1}$ per person.

Assuming a global population of 7.7 billion,[63] we estimate sanitation ecosystem services to be worth at least 4.4 ± 3.0 billion USD $year^{-1}$, a previously unaccounted proportion of the total value of global ecosystem services (estimated at 125–145 trillion USD $year^{-1}$).[64] Thus, sanitation ecosystem services provide substantial value to people, comparable with that invested in an engineered infrastructure; for example, 27–30 billion USD is spent annually on the water and sanitation sector in developing countries.[65] Our worked example is conservative and underestimates the value of sanitation ecosystem services. This is for two main reasons: (1) we only focus on 48 city sites and (2) within these sites, we only quantify the role of nature for a single excreta flow diagram service outcome (FSCNE), as this is the only service outcome where we are confident attributing the role of nature in a robust way (i.e., where an engineered infrastructure may help to contain the human waste but natural processes are responsible for most of the sanitation process;[29] Figure 1). We recognize that nature is a contributory factor across nearly every sanitation pathway, particularly in rural areas (Figure 1; Table 1), and so the role of nature in sanitation is unlikely to be limited to the excreta flow diagram service outcome we focused on here (FSCNE).

CONCLUSION

We have presented evidence that nature is currently providing sanitation ecosystem services, and provided a first-order quantification of these services and their value for a sample of cites across the globe. There needs to be a holistic understanding of the fully coupled links between sanitation and nature (and so between SDG 6 and other SDGs).[66,67] Nature can (and does) take the role of sanitation infrastructure. Moving forward, investing in supporting and strengthening sanitation ecosystem services may be more cost effective than some equivalent investments in engineered sanitation infrastructures.[68,69] While we are not marginalizing the vital role of engineered infrastructures, we believe a better understanding of how engineered (i.e., gray) and natural (i.e., green/blue) infrastructures interact is a promising topic for further research and may allow adaptive design and management, reducing costs, and improving effectiveness and sustainability.[8] Similarly, while our examples predominantly detail linear wastewater treatment trains, we believe these should be viewed within the context of a wider circular economy.[18] As with engineered infrastructure, taking a circular economy perspective is a conceptual advance on sanitation services globally.[18] Thus, for example, it is important to understand both the roles nature plays in sanitation, but also the impacts of human waste on ecosystems.[20]

To support this transformational shift, provision of sanitation ecosystem services needs further study to quantify the pollution-carrying capacity of various ecosystems and ensure they

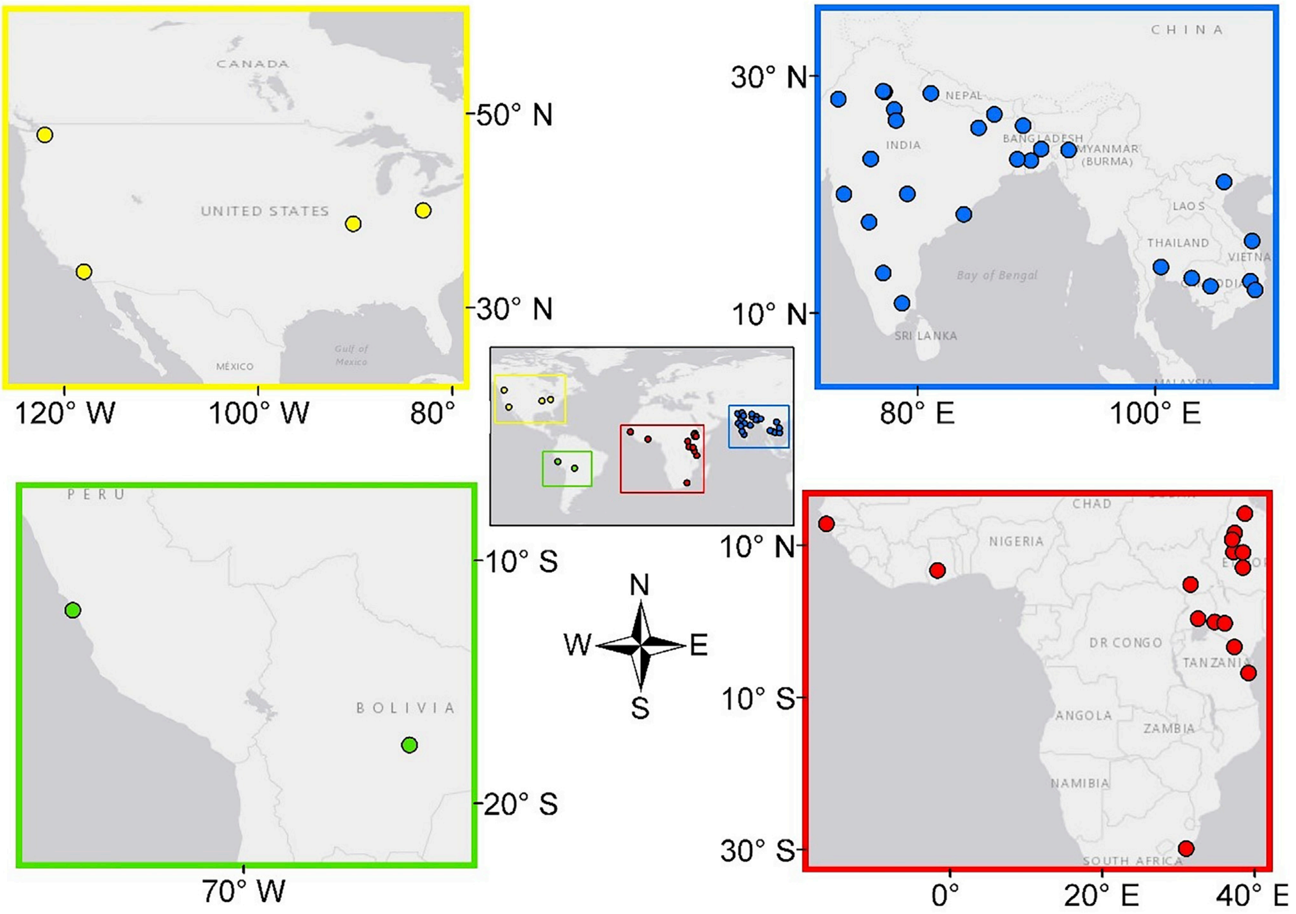

Figure 3. The geographic spread of our 48 city case studies based on the excreta flow diagrams
These are derived from the collection maintained by SuSanA.[16]

are not overloaded.[50] We urgently need to understand the rates that human waste can be treated by ecosystems sustainably—i.e., without having a detrimental impact on the ecosystem and its future ability to provide these sanitation ecosystem services. For example, defining the maximum safe hydraulic loading rate for a pit latrine (i.e., the sustainable rate at which soil can filter fecal sludge) can only be done for a particular hydrogeological setting (see, e.g., Foppen [2002][70]). Thus, understanding the sustainable rate at which soil can act as a filter can only be done accurately at local scale. That said, a first-order estimate using human population density may be possible. Pit latrines safely manage human waste in many rural areas but may be less safe in urban areas where they cannot be moved and need emptying—at what population density can nature no longer be relied upon to safely treat all the human waste produced? Similarly, questions remain for other ecosystems: e.g., What ratio of human waste production, river volume, and transport distance is required to make this waste safe? How far downstream of the human waste production must the next human population be in order to remain safe? What quantities of human waste per unit area can mangrove, natural wetland, and marine environments safely treat? And, at what levels does the human waste risk damaging the natural environment?

Our worked example also highlights data deficiency. While 48 cities is a reasonable sample for a first-order estimation, it is not enough to accurately understand the global picture—particularly as the excreta flow diagrams in rural and peri-urban areas might differ substantially. Even for cities with a published excreta flow diagram, many are still data deficient, with 15 having data describing excreta volume and only 8 with data on the cost of the sanitation process (which can be used to indicate the value of sanitation ecosystem services).

In summary, nature is undoubtedly providing valuable sanitation ecosystem services in many countries across the globe and, in some areas, these services may make up most of the available sanitation infrastructure. However, this paper demonstrates that, to sustainably manage this service, more research quantifying it is needed and we hope that this manuscript serves as a "calls to arms" for improved collaboration between ecologists and water, sanitation, and hygiene researchers to achieve this.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead contact, Alison Parker (a.parker@cranfield.ac.uk).

Table 2. Quantified sanitation ecosystem services within the 48 city case studies

Continent	Country	City	Estimated population	Human waste categorized as FSCNE (%)	Volume of FSCNE (m^3 $year^{-1}$)	Ecosystem service value (USD $year^{-1}$)	Ecosystem service value per capita (USD $person^{-1}$ $year^{-1}$)	Data quality
Africa	Ethiopia	Axum	46,887	22				medium
		Bahir Dar	318,429	17	70,179			high
		Bishoftu	128,272	14	6,465			high
		Bure	27,386	33	3,299	11,816	0.43	high
		Hawassa	351,469	71				medium
		Holleta	57,828	26	5,504	72,618	1.26	medium
	Ghana	Kumasi	2,700,000	18	24,163	224,233	0.08	high
	Kenya	Kisumu	419,072	11	–[a]			high
	Senegal	Bignona	44,783	34				medium
	South Africa	Durban	3,550,000	18				high
	South Sudan	Yei	230,000	46				medium
	Tanzania	Dar es Salaam	5,167,707	36	1,005,517	6,796,552	1.32	high
		Moshi	185,000	17	214,370			medium
	Uganda	Kampala	2,250,000	24	350,400	2,890,800	1.28	high
	Kenya	Nakuru	268,411	10				medium
Asia	Bangladesh	Dhaka	16,000,000	0				low
		Khulna	*1,500,000*	0				high
		Saidpur	127,104	13				low
	Cambodia	Battambang	197,000	61				medium
		Kampong Chhnang	42,082	42				medium
	India	Agra	1,574,542	1				medium
		Aizawl	293,416	50				medium
		Bansberia	103,799	0				high
		Bikaner	644,406	17		5,854	0.01	medium
		Cuttack	606,007	0				medium
		Delhi	16,787,941	3	143,539	672,286	0.04	high
		Dewas	289,438	7				high
		Gwalior	*1,053,505*	1				medium
		Kochi	600,000	0				low
		Nashik	1,500,000	20		263,577	0.18	low
		Patna	1,680,000	2				medium
		Solapur	951,118	2				medium
		Srikakulam	133,911	0				medium
		Tiruchirapalli	916,857	1	330			medium
		Tumkur	305,821	10				medium
	Nepal	Lahan	93,000	23				medium
		Tikapur	60,000	30				low
	Thailand	Nonthaburi	256,457	34	6,691			low
	Vietnam	Buon Ma Thuot	457,000	10				medium
		Da Lat	226,978	18	2,713			low
		Da Nang	1,007,400	23	35,768			medium
		Hanoi	3,146,939	1	22,172			high

(*Continued on next page*)

Table 2. *Continued*

Continent	Country	City	Estimated population	Human waste categorized as FSCNE (%)	Volume of FSCNE (m^3 year^{-1})	Ecosystem service value (USD year^{-1})	Ecosystem service value per capita (USD person^{-1} year^{-1})	Data quality
North America	USA	Cape Cod[b]	215,888	40				high
		King County	2,100,000	10	350,917			high
		Madison	252,551	0				medium
		St Louis City	1,300,000	0				unknown
South America	Bolivia	Santa Cruz	1,900,000	34				medium
	Peru	Lima	9,904,727	1				medium

Based on estimates of "fecal sludge contained not emptied" (FSCNE) from the excreta flow diagrams from the Sustainable Sanitation Alliance (SuSanA).[16] Authors of the excreta flow diagrams also provided indications of the quality of the data supporting their city-wide sanitation assessment.

[a] A volume for Kisumu was not included in our analysis although available in the SFD report, as the value is indicated to be anomalously high within the report itself.

[b] Three scenarios for Cape Cod are available. We selected the moderate scenario (scenario 2).

Materials availability

This study did not generate new unique materials.

Data and code availability

The data used in this study was downloaded from the following link on December 17, 2018: https://sfd.susana.org/about/worldwide-projects All the data used in this paper are included in Table 2.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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