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Aligning Product Chemistry and Soil Context for Agronomic Reuse of Human-Derived Resources

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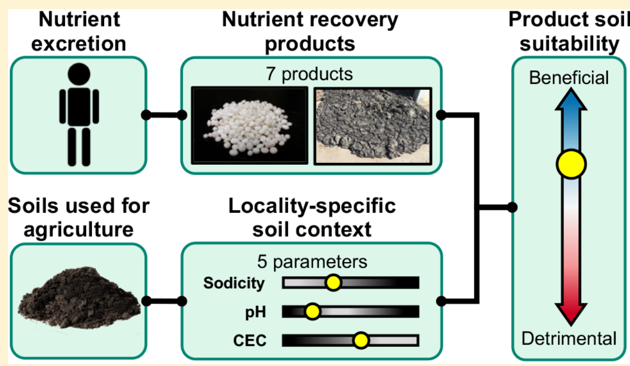
Supporting Information

ABSTRACT: Recovering human-derived nutrients from sanitation systems can offset inorganic fertilizer use and improve access to agricultural nutrients in resource-limited settings, but the agronomic value of recovered products depends upon product chemistry and soil context. Products may exacerbate already-compromised soil conditions, offer benefits beyond nutrients, or have reduced efficacy depending on soil characteristics. Using global spatial modeling, we evaluate the soil suitability of seven products (wastewater, sludge, compost, urine, ammonium sulfate, ammonium struvite, potassium struvite) and integrate this information with local recovery potential of each product from sanitation systems that will need to be installed to achieve universal coverage (referred to here as "newly-installed sanitation"). If product recovery and reuse are colocated, the quantity and suitability of nutrient reuse was variable across countries. For example, alkaline products (e.g., struvite) may be particularly beneficial when applied to acidic soils in Uganda but potentially detrimental in the southwestern United States. Further, we illustrate discrepancies across soil data sets and highlight the need for locally accurate data, knowledge, and interpretation. Overall, this study demonstrates soil context is critical to comprehensively characterize the value proposition of nutrient recovery, and it provides a foundation for incorporating soil suitability into local and global sanitation decision-making.



INTRODUCTION

Nutrient inputs are needed to meet the agricultural productivity requirements of a growing global population and replenish nutrient export associated with harvested crops or environmental transport. The past century's use of inorganic inputs (e.g., Haber-Bosch nitrogen, mined phosphate rock) has enabled dramatic increases in food production[1−3] but has caused substantial environmental degradation (e.g., eutrophication). Discharges of anthropogenically mobilized phosphorus and anthropogenically fixed reactive nitrogen already exceed estimated planetary boundaries, beyond which abrupt global system shifts may occur.[4,5] Additionally, converting atmospheric nitrogen gas into ammonia fertilizer through the Haber-Bosch process is energy-intensive,[6] while phosphorus and potassium fertilizers are produced from finite, geographically concentrated supplies of phosphate rock and potassium ores.[1,7]

Global nutrient flows through agricultural systems and human populations are characterized by substantial losses, including urban and agricultural runoff and leaching (leading to eutrophication), gaseous nitrogen emissions (e.g., nitrous oxide, a potent greenhouse gas), and food supply chain losses.[8−10] Concurrently, many farmers in resource-limited settings face low fertilizer access, constraining regional food production and food security.[11,12] For example, much of Uganda's cropland is nutrient-limited,[13] but national surveys suggest only 3.2% of Ugandan farming households use fertilizers[14] (reflecting factors such as the prohibitive cost of imported nutrients, limited supplies, credit constraints, and poor transportation networks[15]).

Nutrient waste streams (e.g., human or animal waste collected in sanitation or manure management systems) represent recoverable flows that could alleviate regional limitations on nutrient access and offset sizable fractions of global fertilizer consumption[16] (Figure S1, Tables S1−S3). On the basis of existing literature estimates (used to develop Figure S1), over half of the nitrogen in livestock manure is already recycled, while recirculation of human-derived nitrogen remains relatively limited (<15% of nitrogen in human excreta is recycled).[8,17,18] If all unrecovered human-derived nitrogen could be recovered and recirculated, it could offset 16−21% of inorganic nitrogen inputs to agriculture. A greater portion of

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human-derived phosphorus (<55%) is estimated to be recycled,[18,19] likely because sewage sludge (with high phosphorus but low nitrogen levels due to gaseous nitrogen removal during processing[20]) is a common source of recycled nutrients. Unrecovered human-derived phosphorus could offset 9−12% of inorganic phosphorus inputs to agriculture. Moreover, as these waste flows are often collected and aggregated, they may be easier to capture than more diffuse flows (e.g., agricultural runoff). Other alternative nutrient sources (e.g., phosphorus from animal bone products) may offer further recycling opportunities.[21]

However, this global mass balance assumes an idealized, homogeneous world, where wastes can easily be reused. In reality, regions are heterogeneous, characterized by variations in population density, sanitation access, crop/livestock systems, climate, topography, soils, and other factors. Previous research has, for example, estimated distances human-derived nutrients produced in urban settings would need to travel for cropland application, finding wide variations (spanning 2 orders of magnitude) across 56 of the world's largest cities.[22] Moreover, local soil conditions may play a particularly important role in determining whether resource recovery is worth pursuing or even possible. In a given soil context, different types of nutrient products (e.g., reclaimed wastewater, digested sludge, compost, source-separated urine, crystalline products) will behave differently from one another once applied to the field and may have divergent impacts on crop production, nutrient use efficiency, and soil quality.[23−29] However, little work has been done on a global level to assess and compare the suitability of potential recovery products relative to soil conditions. Thus, soil context could play an important role in driving decisions around whether nutrient recovery should be pursued and what recovery products should be generated and/or reused in a given locality.

The objective of this work was to assess the soil suitability of various human-derived nutrient recovery products on a global scale. We evaluated recovery products based on their suitability to soil context and used global soil data[30] to generate soil suitability maps for each product. These maps can help frame and guide conversations that consider local soil conditions when making decisions around nutrient recovery, identifying locations where certain products may be detrimental or where they may improve existing conditions. Further, we consider relationships between the potential magnitude of recovered nutrients if products are reused locally (acknowledging products may also be exported or transported in-country to appropriate reuse locations) and the soil suitability of specific recovery products. We discuss how this information might inform decision-making and investment to simultaneously advance sustainable development goals for sanitation and food security.[31] Overall, this global study offers a foundation for incorporating soil suitability into analyses and discussions surrounding locally appropriate sanitation, nutrient recovery, and agricultural reuse.

METHODS

Recovery Products and Pathways. Sanitation systems can employ various pathways to generate numerous products for nutrient recovery. In our analysis, we evaluated seven products, including reclaimed wastewater, digested sludge, compost, source-separated urine, ammonium sulfate, ammonium struvite, and potassium struvite (Tables S4−S5 show relationships between product characteristics and various soil parameters). For wastewater, we considered two global treatment and recovery cases: aerobic (conventional activated sludge) or anaerobic (upflow anaerobic sludge blanket) treatment without biological nutrient removal,[32] allowing most of the nutrients to remain in the reclaimed effluent. Urine, containing most of the nutrients humans excrete,[33,34] was assumed to be source-separated and stored in closed containers for treatment (minimizing ammonia volatilization).[35] Solid products rich in organic carbon include anaerobically digested sludge and aerobically treated compost (we assumed both were generated from source-separated feces).[32,36−39] Crystalline products, including ammonium sulfate ($(NH_4)_2SO_4$), ammonium struvite ($MgNH_4PO_4 \cdot 6H_2O$), and potassium struvite ($KMgPO_4 \cdot 6H_2O$), are nutrient-dense materials recovered through processes such as precipitation (struvite) or ammonia stripping and absorption (ammonium sulfate),[40−42] each of which may require substantial quantities of chemical additives and energy-intensive separation techniques.[43,44] We assumed crystalline products were recovered from source-separated urine (a more nutrient-dense stream than domestic wastewater).

Soil Suitability Parameters. We evaluated these recovery products relative to spatially explicit soil parameters. In this global analysis, we considered five parameters that may impact whether application of nutrient recovery products is locally suitable (pH, sodicity, clay content, soil cation exchange capacity [CEC], and clay fraction CEC; Tables S6−S7), acknowledging that numerous additional factors will also play a role in many specific cases. Our selection of parameters and threshold levels was based on a literature review focused on soil classifications and fertility in agricultural settings (Section S1). Given that suitable soil conditions will vary depending on local factors such as climate and crop selection, we define uncertainty ranges for each parameter rather than specifying a single threshold (Table S6; see the global soil suitability mapping section and Table S8 for more information on how our suitability classifications incorporated these uncertainty ranges).

Recovery Product Characteristics Relevant to Soil Suitability. Each recovery product has distinctive characteristics that may affect its suitability relative to one or more soil parameters. For wastewater, we assumed that soil suitability characteristics are similar for both aerobically and anaerobically treated waters. The nutrients in treated wastewater tend to be present as soluble ions, making them highly mobile and potentially prone to retention issues (i.e., losses). Nutrients may leach from coarse-textured soils, while phosphorus fixation may occur in weathered soils. In either case, limited crop nutrient utilization may reduce the product's efficacy and achievement of desired crop yields may require greater inputs than in soils without these retention and availability issues.

During storage of source-separated urine, spontaneous urea hydrolysis results in an alkaline product that may compromise soils with high pH or help to increase pH in acidic soils. Nutrients are more concentrated in urine than in wastewater, but these products are similar in that nutrients are highly mobile, creating potential retention issues in certain soils. Additionally, both urine and wastewater can contain high concentrations of sodium ions,[32] which may exacerbate conditions in sodic soils and further limit nutrient retention, especially in arid climates with limited water for sodium leaching.

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In compost and digested sludge, at least some nutrients are bound in organic compounds that require mineralization to become available to crops. Accordingly, nutrients are less mobile and potentially less prone to issues of low retention, but they are also less immediately available for crop uptake. Nutrient benefits from these products may not become apparent until future growing seasons. However, beyond increased nutrient supplies, the organic matter contained in compost and sludge represents a valuable noncrop nutrient contribution to soils, potentially improving structure, erosion resistance, and nutrient and water absorption and retention.[14,45]

Among crystalline products, ammonium sulfate is an acidic compound that is unlikely to be detrimental to or may even benefit alkaline soils, but it may be detrimental for soils with low pH. It is highly soluble, making its nutrients highly mobile. In contrast, struvite is less soluble in water particularly under high soil pH conditions, suggesting it could act as a slow-release fertilizer. However, acidic soil conditions may cause struvite to dissolve more rapidly, increasing nutrient mobility.[24] Struvite may also benefit sodic soils, as its magnesium could displace sodium ions from the soil exchange complex.

Global Soil Suitability Mapping. The relationships between soil parameters and product characteristics suggest conditions in which each recovery product may be detrimental or beneficial to agricultural soils or where a given product's efficacy (i.e., ability to deliver nutrients to crops) may be diminished. Using global maps of soil parameters from the Harmonized World Soil Database,[30] we applied the criteria defined for each parameter (Tables S6−S7) to assess the suitability of each recovery product based on its characteristics (Tables S4−S5). Given the available resolution of the global soil database, we generated global suitability maps having a resolution of 0.5 × 0.5 arcmin (approximately 1 km^2 at the equator). In all locations, we focused on values reported for the soil surface layer(s) (0−30 cm depth).[30] Criteria that would classify a product as detrimental in a given location took the highest precedence (for example, a product that is detrimental relative to one soil parameter and beneficial relative to another was classified as detrimental). Beneficial characteristics were next, followed by characteristics related to limited efficacy. Within this final category, characteristics affecting general nutrient utilization took precedence over those specific to phosphorus fixation. If no product characteristics were classified as being detrimental, beneficial, or related to reduced efficacy in a given location, the product was classified as "acceptable" there.

The range provided for each soil criterion represents an uncertainty range (Table S6). If a location's parameter value relevant to a given product was within the uncertainty range, we characterized the product's suitability as being "potentially" affected. Parameter values beyond the uncertainty range suggested suitability was "likely" affected. For example, if soil pH is 8.0 (within the alkaline criterion's range of 7.2−8.5), an alkaline recovery product such as urine would be classified as "potentially detrimental" in that location. Alternatively, urine would be classified as "likely beneficial" if soil pH is 4.2 (beyond the acidic criterion's range of 4.5−5.5). This system resulted in nine product suitability classifications (listed from highest to lowest precedence): likely detrimental, potentially detrimental, likely beneficial, potentially beneficial, likely limited nutrient effectiveness, potentially limited nutrient effectiveness, likely limited phosphorus availability, potentially limited phosphorus availability, acceptable (see Table S8 for further details). While this categorical classification system cannot adequately capture all local factors associated with each recovery product, we feel it provides a reasonable first estimate of potential suitability from a global viewpoint. The incorporation of even the coarsest information regarding soil context could markedly improve global assessments concerning the contextual appropriateness of nutrient recovery strategies.

Nutrient Recovery Potential from Newly Installed Sanitation Systems. To estimate the quantities of nutrients that could be recovered from sanitation systems in different forms, we began by using procedures from previous work[16,22] to generate spatially resolved estimates of nutrient excretion, based on population density and country-level per capita protein and calorie intake (Section S2, Table S9). These procedures incorporated a Monte Carlo analysis with Latin Hypercube Sampling[46] (10000 runs) to produce distributions of likely excretion rates. In each country, we extracted median, 5th percentile, and 95th percentile values from these distributions to represent expected, low, and high nutrient excretion scenarios, respectively.

To estimate nutrient recovery from excreted urine and feces entering sanitation systems that will need to be installed to achieve universal basic coverage (subsequently referred to as newly installed sanitation), we assumed that each recovery product was generated under either combined stream processing or source-separated treatment (Section S3). Each option represents potential recovery from the given waste stream and assumes the process is engineered to optimize production of the given product (Table S10). Combined processes included aerobic (activated sludge) and anaerobic (upflow anaerobic sludge blanket) wastewater treatment, while source-separated urine was treated via closed storage. Crystalline products were generated from separated urine (as it contains 74−93% of total excreted nitrogen, 33−75% of phosphorus, and 53−93% of potassium[33,34]). Compost and sludge were produced from separated feces. Although nutrient recovery from separated feces is relatively low, high total recovery can still be achieved by capturing nutrients from both source-separated urine and fecal streams in parallel.

For all products, three recovery scenarios reflected expected, low, and high recovery efficiencies (based on the uncertainty bounds in Table S10). From a combination of these recovery efficiencies with estimated excretion rates, three overall scenarios for nutrient excretion and recovery were defined as follows: expected (median excretion rate in each country, expected recovery efficiency for each product), low (5th percentile excretion, minimum recovery), and high (95th percentile excretion, maximum recovery). Together, these scenarios produced a broad range (including worst and best cases) of potential nutrient recovery from newly installed sanitation systems.

Co-Location and Soil Suitability of Nutrients Recovered from Newly Installed Sanitation. In our analysis, colocation refers to the degree to which recoverable nutrients spatially align with agricultural nutrient requirements. We used procedures from previous work to estimate spatial distributions of agricultural nutrient demands based on harvested areas and fertilizer recommendations for 52 crops.[22] We then compared nutrient demand with potential recovery to estimate colocation, using procedures similar to those developed in previous work.[16] The nutrient quantities present in a given recovery product were compared with agricultural requirements in the same cell, and we calculated colocation as the fraction of the product that could be applied without exceeding nitrogen, phosphorus, or potassium demands.

We then evaluated the soil suitability of each colocated product. The colocated quantity in a given grid cell was assigned the suitability classification specified for that cell in the product's suitability map. It should be noted that results from this simplified spatial assessment should be taken as first-order estimates of product colocation and suitability. Recovery products could be transported beyond the grid cell in which they are generated, relocating nutrients to areas with better suitability characteristics and greater crop demands.[22] The scope of this global exercise excluded transport beyond the initial grid cell.

Finally, results were aggregated, globally and by country, to estimate the percentages of each recovery product colocated with crop demands and falling within each suitability category. To provide quantitative estimates comparable across countries, we report the nutrient mass from each product in each suitability category, normalized to each country's total cropland area (Tables S11−S14).

RESULTS AND DISCUSSION

Understanding local soil conditions is critical in fully characterizing the value proposition associated with different forms of nutrient recovery. To examine the soil suitability of seven recovery products (reclaimed wastewater, source-separated urine, digested sludge, compost, ammonium sulfate, ammonium struvite, and potassium struvite), we identified several soil parameters that may be affected by a given product or impact the product's ability to meet crop nutrient demands. We focused on parameters relevant to crop production, as agricultural application is a straightforward and commonly promoted use of recovered nutrients.[12,16] The key parameters we considered were pH, sodicity, soil cation exchange capacity (CEC), clay content, and clay fraction CEC (see Section S1 for descriptions of why specific parameters were included and Tables S6−S7 for a summary of suitability criteria). Soil organic carbon (SOC) was not directly included, due to a lack of general guidelines defining desirable levels.[47−49] However, especially where SOC has been depleted,[50] organic-rich recovery products (e.g., compost, sludge) are likely to benefit agricultural use of soils by reducing erosion, elevating soil organic matter content, and increasing nutrient and water retention[14,45] (see Section S1 for additional details on SOC). To accommodate a global scope, employ existing data, and enable transparent, communicable findings, we focused on a relatively limited set of parameters critical to agricultural soil conditions around the world, acknowledging the selected parameters are not always mutually independent or fully representative of relevant contextual factors.

Global Soil Suitability Mapping of Recovery Products. Interactions between soil parameters and recovery product characteristics can determine where a product may be most suitable relative to local soil quality or where it may have limited efficacy (Figure 1). Soil pH tends to play the largest role in determining suitable locations for several products. Alkaline products (urine and struvite) are classified as "detrimental" in regions with high soil pH since application (and dissolution in the case of struvite) would exacerbate growth inhibition due to alkaline soil conditions ("potentially detrimental" indicates local pH is within the uncertainty range defined in Tables S6, while "likely detrimental" denotes local pH beyond the uncertainty range; see Methods and Table S8 for further description of this nomenclature). These areas cover large swaths of several continents, often corresponding with arid environments (e.g., the Sahara, the Gobi). Formation of carbonate salts tends to contribute to desert regions' alkaline conditions. Conversely, alkaline products may benefit acidic soils in large areas of North and South America, central Africa, northern Eurasia, and southeast Asia. However, some of these locations represent large, unmanaged forests (e.g., the Amazon, the Congo), suggesting agricultural application may be less likely. Locations of potential benefit and detriment associated with acidic ammonium sulfate are essentially the reverse of those for alkaline products. As each crystalline product tends to focus on the recovery of one or two nutrients and is either acidic or alkaline, the recovery and application of multiple products may buffer against pH changes while supplying multiple nutrients.

High sodicity affects relatively small areas mostly in South America and central Asia (Figure S2). Products with high sodium levels (urine, wastewater) may exacerbate sodium toxicity in these soils. Struvite could prove beneficial in these areas, as its magnesium may displace sodium from the soil exchange complex for potential leaching out of the crop root zone. However, many sodic soils are also alkaline. In our analysis, detrimental characteristics of a product take precedence over its benefits if both are locally relevant. Therefore, struvite is classified as detrimental in these areas (Figure 1). For other products, sodic soils may limit nutrient retention and crop utilization, due to sodium saturation of the exchange complex.

Much larger areas of the world are susceptible to nutrient retention issues associated with low clay content or soil CEC. In particular, these conditions tend to drive the soil suitability of wastewater in many locations (Figure 1). For wastewater and other products with highly mobile nutrients (urine, ammonium sulfate), low clay content or soil CEC may lead to greater leaching losses of nutrients, limiting possible yield improvements. We did not classify struvite as having highly mobile nutrients. However, under acidic conditions, struvite may dissolve rapidly, increasing its nutrients' mobility.[24] Often, in locations where nutrient retention may be a concern, clay content and soil CEC are both low (e.g., parts of Australia, southern Africa, and Russia; Figure S2). Similar geographic distributions of these parameters reflect the fact that the clay-sized fraction drives total soil CEC, due to the high specific surface area and reactivity of clay-sized minerals.[51,52]

Finally, phosphorus fixation (i.e., immobilization of phosphorus by irreversible adsorption and/or precipitation to metal cations, making the nutrient less accessible to crops) most often impacts highly weathered soils in tropical areas rich in aluminum and iron oxides (e.g., ferralsols, covering 7−8% of global ice-free land area).[51] Low clay CEC can serve as a proxy for high weathering,[51] with particularly low values in Brazil and central Africa (Figure S2). However, many of these locations were already prone to general nutrient retention issues, which took precedence (Figure 1). Given that total soil CEC is predominantly derived from the clay-sized fraction, a low clay CEC often aligns with low soil CEC. On our maps, areas with phosphorus fixation issues are especially uncommon for urine, as highly weathered soils—generally situated in the tropics—also tend to be acidic. Urine was already classified as beneficial in these locations.

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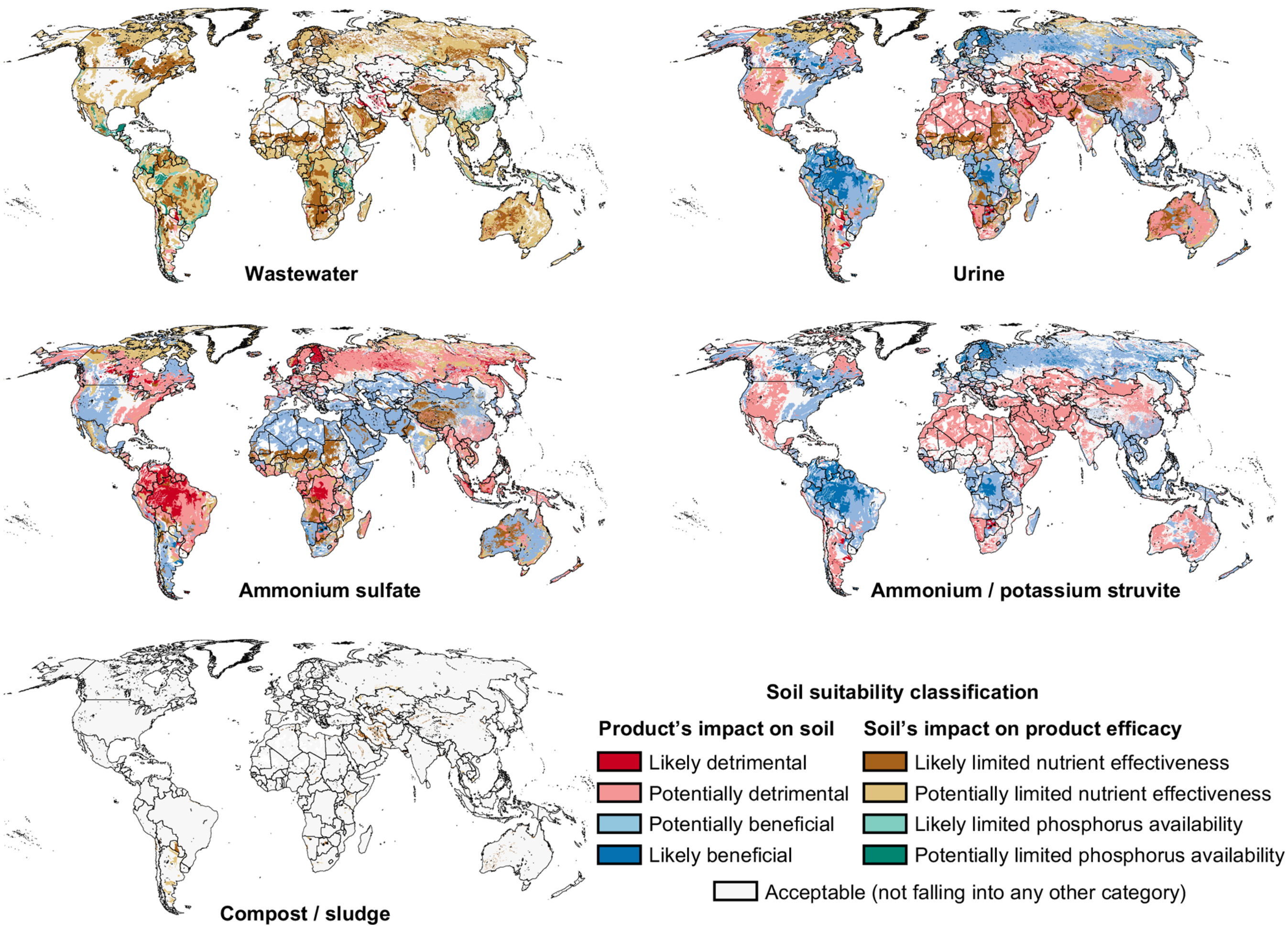

Figure 1. Global soil suitability maps for all recovery products. The coloring of each map shows where that product may impact soil conditions detrimentally (exacerbating one or more poor soil conditions for crop production, red) or beneficially (improving poor soil conditions, blue), and/or where soil conditions may limit a product's fertilizer efficacy (due to the soil's low nutrient retention, brown; or high phosphorus fixation capacity, teal). Locations not falling into any of these categories are classified as being acceptable (light gray). Shading also differentiates between "likely" impacts (where the relevant soil parameters fall beyond the uncertainty range in Table S6) and "potential" impacts (relevant parameters fall within the uncertainty range; see Methods and Table S8 for a more detailed description of this nomenclature). Ammonium struvite and potassium struvite are shown in one map, because these two products have similar characteristics. Compost and sludge also appear in one map. National administrative boundaries that provide the base of each map were taken from the Gridded Population of the World (versions 3 and 4).[63,64]

Potential Nutrient Recovery from Newly Installed Sanitation Systems. Global soil suitability mapping of recovery products represents an important category of information that has been lacking. However, these findings must be combined with several other factors (e.g., nutrient recovery potential, agricultural demands, social acceptability, economic viability) to more fully evaluate the locality-specific implications and appropriateness of nutrient recovery processes. Below, we illustrate such a combined analysis, although we do not consider all potentially important factors. We keep our scope focused on global nutrient cycles and local agricultural reuse of recovery products, acknowledging that other considerations will play into local sanitation decisions.

Achieving universal sanitation access is a sustainable development goal (SDG),[31,53] and we focus this analysis on populations currently lacking basic sanitation to explore the opportunities associated with recovering nutrients from systems that will need to be newly installed to meet this target (referred to as "newly-installed sanitation"). Many populations without sanitation access face simultaneous challenges of resource access and economic security, suggesting resource recovery may generate multidimensional benefits.[16] For each recovery product, we leverage existing literature and previously developed methods[16,22] to generate quantitative, spatially resolved estimates of nutrient recovery potential from newly installed sanitation (i.e., the nutrient quantity recoverable in a given product at a given location, based on population density, basic sanitation coverage, per capita nutrient consumption and excretion, and the product's potential recovery efficiency). We account for uncertainty around nutrient excretion and recovery by employing three scenarios (expected, low, and high; see Methods for full scenario description). We then estimate the degree to which nutrients present in recovery products are colocated (i.e., in the same grid cell) with local crop nutrient demands. Combining these results with our soil suitability maps, we generate quantitative estimates of nutrient recovery, colocation, and soil suitability for 158 countries with sufficient data (Figure 2, Tables S11–S14; see Sections S2–S3 for further details).

Across countries, the relative nutrient quantities recoverable in various products follow similar patterns (Figure 2).

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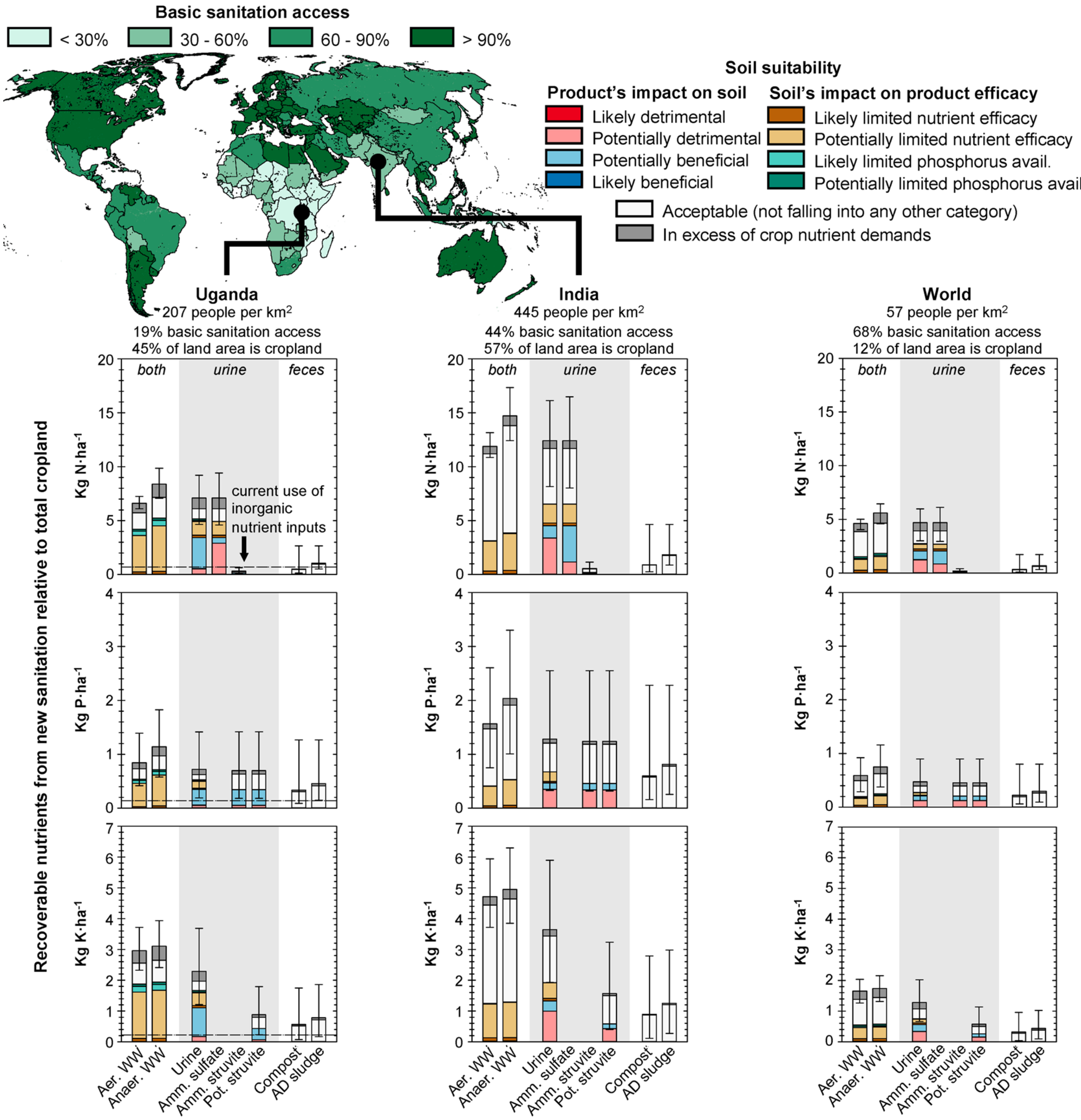

Figure 2. Nutrient recovery quantities and suitability from newly installed sanitation systems. The world map shows each country's level of basic sanitation access in 2015. Bar graphs show estimated quantities of nutrients (nitrogen, phosphorus, potassium) that could be recovered if systems installed to achieve universal sanitation coverage are optimized to generate a given recovery product from a given waste stream, globally and in two illustrative countries (values from all countries and scenarios are in Tables S11−S14). Recovery products are grouped based on assumed source: combined waste streams (aerobically or anaerobically treated wastewater), source-separated urine (all crystalline products), or feces (compost, sludge). Each bar shows total recovery potential of that product from the assumed waste stream (normalized relative to total cropland area) in the expected excretion and recovery scenario, with error bars showing recovery potential in low and high scenarios. Missing bars indicate the given nutrient is not present within that product (e.g., ammonium struvite does not contain potassium). Dark gray shading within each bar shows the fraction of the total recovered product in excess of crop nutrient demands within the same grid cell. For the remaining colocated fraction (not in excess), coloring indicates the suitability of that product relative to soil conditions in the same cell (using the same color scheme as Figure 1). The graphs for Uganda also show current levels of inorganic nutrient application (all from imported fertilizers),[11] because potential nutrient recovery exceeds this level. Average inorganic nutrient use levels in India (99 kg N·ha^{-1}, 17 kg P·ha^{-1}, 12 kg K·ha^{-1}) and the world (69 kg N·ha^{-1}, 13 kg P·ha^{-1}, 20 kg K·ha^{-1})[11] are higher than recoverable nutrient quantities. Population density,[11] basic sanitation coverage,[53] and cropland area[11] are also noted for each illustrative country and the world. National administrative boundaries that provide the base of the map were taken from the Gridded Population of the World (versions 3 and 4).[63,64]

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Anaerobically treated wastewater could provide the largest nutrient quantities of any single product (in part because a combined waste stream contains nutrients from urine and feces). Under anaerobic conditions, microbial growth and nutrient uptake are lower than in aerobic conditions,[32] allowing more nutrients to remain in the effluent. Anaerobic treatment may be particularly applicable in contexts with high organic loading[32] (e.g., fecal sludge from latrines). Regardless of treatment approach, adequate pathogen reduction is needed for safe wastewater reuse. Irrigation with partially treated or untreated wastewater can increase risks for diarrheal disease and helminth infections, especially among agricultural workers.[54]

Products derived from source-separated urine can also capture substantial nutrient quantities. Urine itself can act as a liquid fertilizer after storage (especially when undiluted, urine's high pH and intrinsic ammonia content can reduce pathogen levels[35,55]), while crystalline products (ammonium sulfate, ammonium struvite, potassium struvite) recover nutrients in concentrated forms that may be easier to transport to more distant cropland.[22] Conditions under which crystalline products are generated determine bacterial inactivation and product safety.[56] Although no single crystalline product contains all three nutrients, a sequential configuration can generate multiple products (e.g., potassium struvite precipitation from fresh urine, followed by ammonium struvite precipitation and finally stripping, absorption, and evaporation to recover remaining nitrogen as ammonium sulfate). Products derived from feces (compost, sludge) offer lower recovery levels, because urine contains most excreted nutrients (74−93% of nitrogen, 33−75% of phosphorus, 53−93% of potassium).[33,34] However, if nutrients are captured in multiple products derived from both urine and feces, total recovery rates in these systems may be similar to those in anaerobic wastewater treatment.

Comparisons across countries reveal how total recoverable nutrient quantities from newly installed sanitation depend upon factors including existing sanitation coverage, population density, and dietary intake (Figure 2; quantities are normalized relative to total cropland area for comparison). As illustrations, we discuss two countries with relatively high recovery potentials. India's recovery potentials are associated with the country's relatively low sanitation coverage and high population density (more people need newly installed systems, and more nutrients are excreted per unit area). In Uganda, basic sanitation access is particularly low, while a rapidly rising population will increase population density in the future. However, Uganda's normalized recovery potentials are lower than India's. Potential explanations include Uganda's population density (currently lower than India's) and low nutrient excretion (due to disparities in protein intake,[11] we estimate median nitrogen excretion in Uganda at 7.9 g $N \cdot cap^{-1} \cdot d^{-1}$, compared with 9.1 g $N \cdot cap^{-1} \cdot d^{-1}$ in India). Nevertheless, nutrient recovery in Uganda could greatly increase access to agricultural inputs, as the country's current use of inorganic inputs per hectare of cropland is <2% of the global average.[11]

Recovery Product Suitability and Decision-Making. Overall, our results provide several layers of information potentially useful for local, regional, or global decision-makers. They offer estimates of nutrient recovery and colocation with local crop demands, and they suggest how these data can interact with information on the soil suitability of various recovery products to provide guidance for local or national sanitation strategies. For example, while Uganda could capture considerable quantities of human-derived nitrogen by recovering ammonium sulfate, application of this product to acidic soils common in Uganda may adversely affect crop production (Figure 2; although, application in relatively small quantities may provide much-needed nitrogen without impacting soil pH too severely). In contrast, focusing on recovery of ammonium struvite may provide valuable opportunities to alleviate acidic soil conditions with an alkaline product while providing nitrogen and phosphorus. In other places (India, for example), decision-makers who take these considerations into account may reach different conclusions (Figure 2), underscoring the importance of accounting for local soil context when assessing nutrient recovery alternatives.

However, global soil databases may not provide the best information to guide local, national, or regional decisions. The accuracy of global soil maps is likely to be less than that of continental or regional maps, and coarse-resolution maps may have limited usefulness for localized spatial planning.[57] For our analysis, we used global data (the Harmonized World Soil Database[30]) because the study's main proposition—that considering soil context can help inform sanitation and nutrient recovery strategies—is of global consequence. Nevertheless, to illustrate the importance of using contextually appropriate data, we repeated our analysis for Africa using a finer-resolution continental data set (Africa Soil Information Service[57]). While the soil suitability of recovery products appeared similar across some parts of sub-Saharan Africa (Figure S3), other locations (e.g., Uganda) revealed considerable disparities between global and continental results (Figure 3).

For example, the global analysis suggested that up to 42% of the struvite recoverable from newly installed sanitation systems in Uganda may have beneficial agricultural impacts given local soil conditions (e.g., moderation of acidic pH), whereas the repeated analysis based on the continental data set estimated that only up to 12% of recoverable struvite may beneficially impact local recipient soils (Figure 3; while we focused on local recycling as a logical first step in improving nutrient access, these percentages could be increased with transportation beyond the grid cell). In most locations throughout the country, product suitability classifications changed to "acceptable" (i.e., not meeting the criteria for any other category), likely because soil parameter values (e.g., pH, soil CEC) in the continental data set vary to a lesser degree than in the global data set. Beyond the "acceptable" category, the remaining quantity of each product tends to follow trends similar to those seen in the global analysis (e.g., in both analyses, most struvite not classified as "acceptable" falls into the "potentially beneficial" category). Despite considerable disparities between the analyses at these two scales, this comparison suggests that the global analysis may still provide useful information regarding general country-level soil suitability trends. It could serve as a mechanism to identify locations for more focused study with localized information.

Regarding the general issue of appropriate map scale and resolution, we would typically expect finer-resolution soil maps to be more accurate. More localized maps, therefore, might provide better information for local decision-makers, and the continental data may be more appropriate than the global database for countries in sub-Saharan Africa. Reliability may also depend on how maps are constructed (e.g., using soil profiles or remote sensing) and mapping focus (e.g., soil

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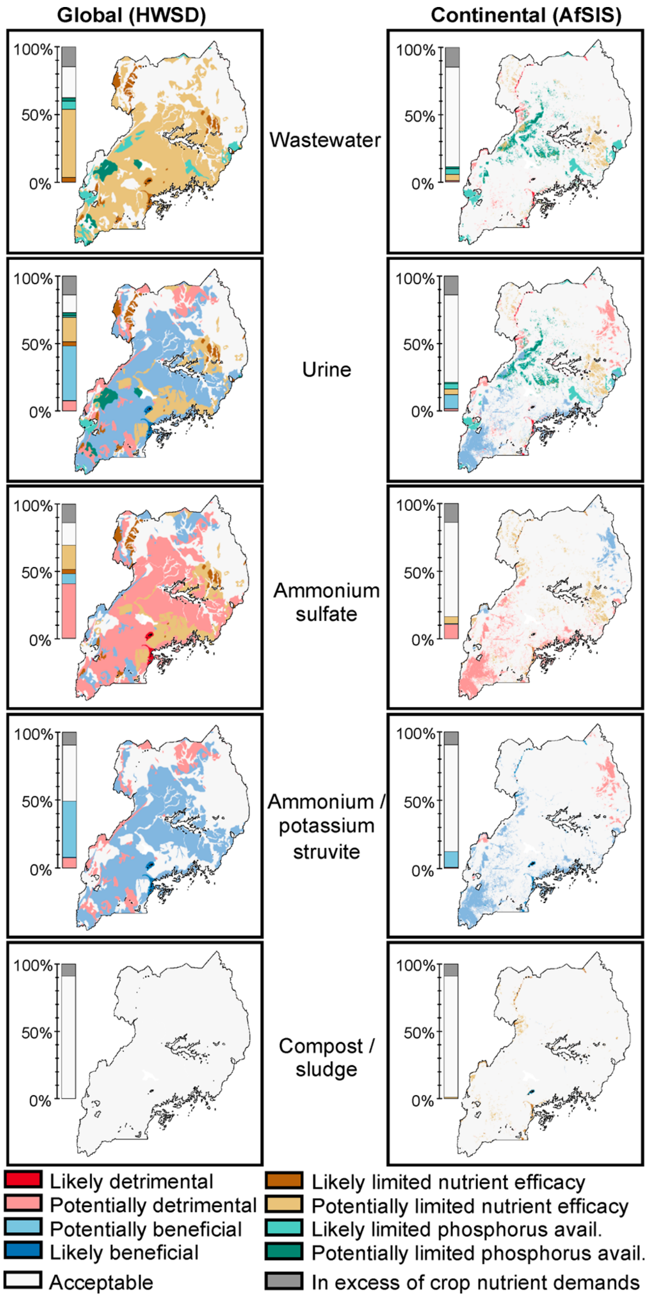

Figure 3. Comparing soil suitability findings in Uganda using two data sets. Maps on the left show soil suitability of each recovery product, using the soil data set employed in our global analysis (Harmonized World Soil Database, HWSD[30]). On the right, are results from the same procedure when using a continental soil data set (African Soil Information Service, AfSIS[57]). The bar graph inset in each map shows the fractions of that product (recoverable from newly installed sanitation systems) that fall into each suitability category. While results generated from these two data sets are similar for some locations in sub-Saharan Africa (Figure S3), Uganda represents a case with considerable discrepancies, highlighting the importance of using appropriate and accurate soil maps when making decisions about nutrient recovery from sanitation. National administrative boundaries that provide the base of each map were taken from the Gridded Population of the World (version 4).[64]

property or classification). In sub-Saharan Africa, some older country-level maps may be less accurate than newer continental data sets. Colonial-era maps used soil profiles and classification systems that are now outdated.[58,59] Deriving specific soil properties from these classifications entails some uncertainty, and conditions may have changed in the decades since the maps were developed. Overall, then, decision-makers should be aware of uncertainties associated with soil data and the benefits associated with developing soil maps. The enlistment of soil and agricultural science experts to help navigate discrepancies in data sets can increase the likelihood that appropriate information is being used when developing or assessing strategies for sanitation and resource recovery.

Implications. This study illustrates the importance of explicitly considering soil context when developing, assessing, and making decisions regarding locally appropriate sanitation, nutrient recovery, and agricultural reuse systems. Certain nutrient recovery techniques and products may appear economically or logistically feasible in a given setting, but decision-making processes should also factor in whether application of that product might help or hinder crop production through interactions with local soil conditions. Alternatively, stakeholders may explore product export to locations in which soil contexts are more favorable. The global analysis presented here has numerous limitations, primarily related to the accuracy of available global data sets and the simplifications necessary to apply a generalized analysis across a wide range of contextual conditions. We acknowledge these uncertainties through our soil suitability classifications ("likely" versus "potential" effects) and the use of multiple nutrient excretion and recovery scenarios. As such, our results represent first-order estimates of potential nutrient recovery and soil suitability, which can improve context-specific assessment at a global scale and reveal general trends and locations for further, more focused investigation.

Recycling nutrients from human sanitation may be especially valuable for smallholder farmers, many of whom live in lower-income nations where considerable gaps in sanitation access persist and agricultural yields are often constrained by nutrient and water limitations.[13,53,60] These conditions highlight the synergistic potential of resource recovery systems in addressing multiple SDGs simultaneously.[16] However, along with factors such as transport distance[22,61] and the inputs required by recovery processes (e.g., energy, chemicals),[43,44,62] local soil conditions are critical to the value proposition of nutrient recovery. Each of these considerations may have locality-specific impacts on the financial viability of nutrient recovery and agricultural reuse. In some contexts, for example, high magnesium costs may discourage struvite precipitation,[62] while long transport distances may constrain the utility of less concentrated recovery products.[22] Soil context may limit retention but also crop uptake of nutrients provided through certain recovery products, while other products may worsen conditions that hinder crop production, potentially reducing agricultural income. Alternatively, some products may provide benefits beyond their nutrient content, improving soil conditions and potentially increasing crop yields. As such, the incorporation of even the coarsest information regarding soil context could markedly improve global assessments concerning the contextual appropriateness of nutrient recovery strategies. Together, local experts, policy-makers, farmers, utilities, and other stakeholders can incorporate this information into decision-making processes that account for multiple factors to develop and implement appropriate and sustainable sanitation solutions.

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■ ASSOCIATED CONTENT

Supporting Information

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global nitrogen flows through agriculture and populations; soil suitability mapping; procedures for estimating nutrient excretion; procedures for estimating product-specific nutrient recovery from sanitation systems; comparisons of suitability results generated using different input data sets (PDF)

Table S11: country-specific estimates of nitrogen recovery potential, colocation, and soil suitability associated with each product (XLSX)

Table S12: country-specific estimates of phosphorus recovery potential, colocation, and soil suitability associated with each product (XLSX)

Table S13: country-specific estimates of potassium recovery potential, colocation, and soil suitability associated with each product (XLSX)

Table S14: country-specific estimates of carbon recovery potential, colocation, and soil suitability associated with each product (XLSX)

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