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Integrating regional transportation and ecological factors into anaerobic digestion siting decisions

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Landfilling wasted food (WF) is a significant source of greenhouse gas emissions. Anaerobic digestion (AD) is emerging as a promising alternative to jointly manage WF and generate bio-based energy, yet its widespread adoption is limited by transportation and operating costs. To reduce costs, AD facilities must be sited reasonably close to WF sources, energy transmission infrastructure, and available cropland for managing digestate, the liquid by-product from AD. Nutrient-rich digestate can displace synthetic fertilizer use on farms but can also runoff and create ecological risks, depending on location and application rate. Here, we introduce a multi-criteria geospatial model to assess the placement of future AD systems relative to (1) the distance over which AD feedstocks and products must be transported and (2) ecological risks created by land-application of digestate. Using Western New York State as a case study, we show that only 12% of land within the study area is suitable for siting AD systems. Further, the distance that digestate can be transported for land application is constrained to between 6 and 15 km to avoid exceeding crop nutrient demand. However, runoff modeling using the long-term hydrological impact analysis (L-THIA) tool showed that even sites with sufficient capacity to accept digestate could be sources of downstream water quality risk. This type of integrated analysis of ecological and economic constraints to AD siting is critical for sustainable food waste management strategies.

More than one-third of the food produced in the United States is not eaten[1]. This waste contributes to more than 24% of municipal solid waste entering landfills and leads to the release of 55 million MT of CO_2-equivalents—more than half of total landfill methane emissions—each year[2,3]. In order to mitigate these impacts and turn waste into resources, a growing number of states in the US have enacted legislation to limit landfilling of organic waste[4,5]. For example, New York State (NYS) enacted the Food Donation and Food Scrap Recycling law to reduce environmental impacts associated with wasted food (WF) disposal. This law requires the separation and recycling of organic waste by generators producing more than 1.81 tonnes per week and having an alternative recycling option within 40 km that has adequate capacity and is not cost-prohibitive[5]. Like other landfill diversion policies emerging across the US, compliance thresholds start low and then gradually become more stringent, allowing time for construction of new regional infrastructure with the capacity to accept an increased influx of material[6]. Of the treatment options available, anaerobic digestion (AD) technology has gained much attention because of its potential to convert organic waste to bio-energy and other value-added resources[7–11]. AD is preferable to landfilling or incineration, especially when the residual liquid material is managed to recover nutrients[1,12].

Despite the promise of AD technology for WF management, its broad adoption is still limited by technical, economic, and logistical barriers. For example, siting new digester facilities requires consideration of multiple regional factors[13], including proximity to WF feedstocks, energy markets, electricity transmission infrastructure, and locations where by-products can be disposed[13–15]. Previous efforts to develop spatially explicit siting models using geographic information systems (GIS) often sought to minimize transportation distance between organic waste sources and the AD location. Early geospatial approaches generated a decision space of feasible sites outside of exclusionary zones, such as residential or ecologically sensitive areas, but reasonably close to energy infrastructure[16,17]. Others used location-allocation analysis tools to jointly identify feasible locations while

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simultaneously minimizing economic burden by optimizing feedstock transportation distance[18–21]. Custom linear programs function similarly to location-allocation, but consider additional economic criteria for facility placement[22–24]. These previous efforts highlight the importance of proximity to source materials and exclusionary zones, but AD siting decisions must also consider regional factors that might govern downstream management of other AD by-products[25].

One byproduct of particular interest is digestate, the residual, nutrient-rich liquid remaining after the degradation of organic materials to produce biogas. Because digestate contains nitrogen and phosphorus, carried over from the organic materials processed, it can be viewed as a key input for circular biofertilizer systems[26] and a potential replacement for synthetic agrochemicals[10,11,27–30]. However, the nutrient profile of digestate may vary widely, depending on the AD feedstocks, which may reflect WF treatment only or co-digestion of WF along with dairy manure or other organic wastes[31]. In addition, the high water content of digestate makes transport economically and environmentally costly[32,33]. Existing estimates indicate that transporting digestate more than 16–32 km from the AD site is cost-prohibitive for operators[34,35].

Further, digestate management introduces new ecological risks that are not yet fully understood. Because digestate has a high water content and requires heavy machinery to spread on farm fields, its application can cause greater soil compaction than the use of traditional chemical fertilizers[36]. Following application, volatilization of ammonia may lead to atmospheric deposition of nitrogen downwind of fields, microbial activity may release greenhouse gases, and runoff of excess phosphorus and nitrogen during storms may exacerbate eutrophication of sensitive waterbodies[11,37–39]. As a result, regulations regarding timing and volume of digestate application to agricultural fields are not unlike those for conventional fertilizers[40]. Digestate management is also confounded by the co-management of organic wastes such as dairy manure. For example, if AD operators increasingly accept WF, both the on-site storage capacity and cropland digestate acceptance capacity within a viable transportation distance may be reached. Overflow of storage lagoons associated with large storms may have negative implications for water quality[41]. Likewise, over-application to cropland poses risks of nitrogen, phosphorus, and organic carbon runoff (e.g., refs. 42–44). Nutrients in runoff, especially phosphorus, are linked with water quality in freshwater ecosystems, including the Great Lakes[45,46], and are therefore a critical component of management targets[47]. Ultimately, storage and distribution of digestate may be the bottleneck that limits large-scale implementation of AD as a mechanism to mitigate landfilling of WF[11,48–50].

While concerns about economic and environmental implications of digestate management have been raised (e.g., refs. 50–52), to the authors' knowledge, no existing models have considered both the transportation and potential water-quality implications of digestate management among the regional siting criteria for new AD facilities. Therefore, our goal was to demonstrate how AD siting and operational decisions may be influenced by incorporating economic and ecological facets of digestate management alongside traditional considerations of WF hauling and energy product utilization. To this end, our objective was to create a novel multicriteria spatial model that incorporates the availability and transportation of AD feedstocks (WF and dairy manure); ecologically relevant landscape characteristics, including land cover and use, agricultural crops, and sensitive ecosystems; and potential downstream ecological risk due to nutrient release. Using a case study region in Western New York State (WNY), the model was applied to evaluate WF sourcing, digestate disposal capacity, and ecological risk under alternative digester siting scenarios. These methods use relevant and authoritative data sets in the study region to assess regional infrastructure build-out to meet policy goals and minimize ecological risk in order to contribute to a broader decision-making process for sustainable WF management.

Results and discussion

Results described herein first characterize the availability of sites across NYS where digesters could theoretically be built to receive the anticipated increase in WF being diverted from landfill as a result of policy implementation. We then focus on WNY and combine these results with estimates of the amount and locations of WF and manure anticipated to be sent to an anaerobic co-digestion facility and the area and locations of farm fields where the resulting liquid digestate could feasibly be land-applied. Because manure provides stability and enhances biogas yield[53–55], co-digestion was considered as the baseline scenario, with comparison to a second scenario of WF-only digesters. The resulting set of locations that could meet all feedstock and digestate management criteria is then evaluated from the standpoint of ecological risk, specifically the potential for downstream runoff of phosphorus from field-spread digestate into local waterways. Phosphorus was the key nutrient tracked for our modeling because it is conserved during digestion and storage (unlike carbon and nitrogen)[39,56], is required for crop growth, and contributes to eutrophication[57].

Land exclusion assessment

Approximately 11.1% of the land in NYS meets minimum siting criteria, and is therefore considered theoretically feasible for building potential AD facilities (Fig. 1). This result accounts for proximity to road access, minimum size needed to construct a digester, setback distance to protected waterbodies and land, and exclusion of residential and commercial areas, highways, and schools. Feasible locations were most prevalent near the center of the state, away from major cities and populated areas. Exclusion of the Adirondack Park, protected by the NYSDEC, eliminated a large area in the northeast. The New York City region and Long Island have few suitable locations, due to highly developed landscapes. Focusing on the WNY study region, the proportion of suitable land area (12.1%) was similar to the statewide estimate (Fig. 1b), with greater availability in rural locations outside of the cities of Buffalo (northwest) and Rochester (north-central). However, three issues were noted with closer inspection: the cluster of feasibility on the western edge is Tribal land, and on the eastern edge, clusters are a military base and the Finger Lakes National Forest (south). These regions would be manually excluded in practice, suggesting that spatially-explicit models require greater tailoring to account for specific regional factors. Nonetheless, our results show that NYS has a similar land suitability profile as that seen in a similar study in Vermont (12%)[17,18], but lower than an analysis for rural areas in Canada (~32%)[19].

Quantity and availability of manure and wasted food

We estimated the amount of WF and manure generated within a sourcing radius for each feasible site (e.g., how much material is produced within a set radius of each location), which illustrated that potential digester feedstock is primarily associated with urban centers and concentrated animal feeding operations (CAFOs) (Fig. 2a). Manure production dominates material availability (1.3 million t yr^{-1}) with a maximum in the agricultural center of the study region (Fig. 2; Max WF and Manure Supply) where WF constitutes only 0.4% of the total feedstock. For reference, the largest current AD facility globally processes 304,000 t (335,000 US tons) of material annually[58]. Closer to city centers, the contribution of WF to total organic feedstocks peaks at 19.8% because manure availability is substantially lower in these regions (Fig. 2a; Max WF supply; see also SI Fig. S4 for WF-only availability). This analysis provides a useful first step in digester siting by identifying where material supplies - WF and/or manure—are greatest, and thus transportation costs can be minimized at the sourcing stage. These feedstock flows were converted to phosphorus equivalents to track the nutrients entering AD systems that will ultimately require management in the form of digestate. The resulting maps show similar patterns to the former analysis of total organic waste (Fig. 2b), but because WF has a higher phosphorus content than manure, the WF contribution to the phosphorus flow entering ADs increases to 36% contribution at the location with maximum WF and 0.8% at the location with maximum overall organic waste availability.

Phosphorus acceptance capacity of farmland

About 98% of total cropland in the study region is theoretically able to accept digestate as a soil amendment, including corn, grass, hay,

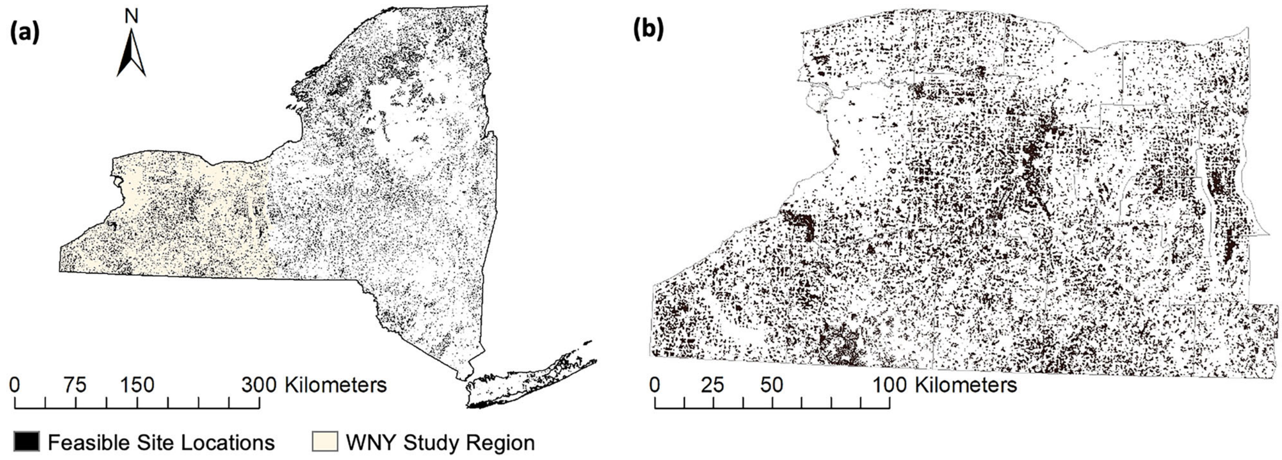

Fig. 1 | Potential anaerobic digester locations in New York State. Locations in **a** New York State as a whole and **b** the Western New York (WNY) case study region that have adequate size and meet minimum land inclusion criteria for building an anaerobic digester to accept wasted food. New York City is excluded from the analysis because it is governed by a local organic waste management law that predates state-wide regulations.

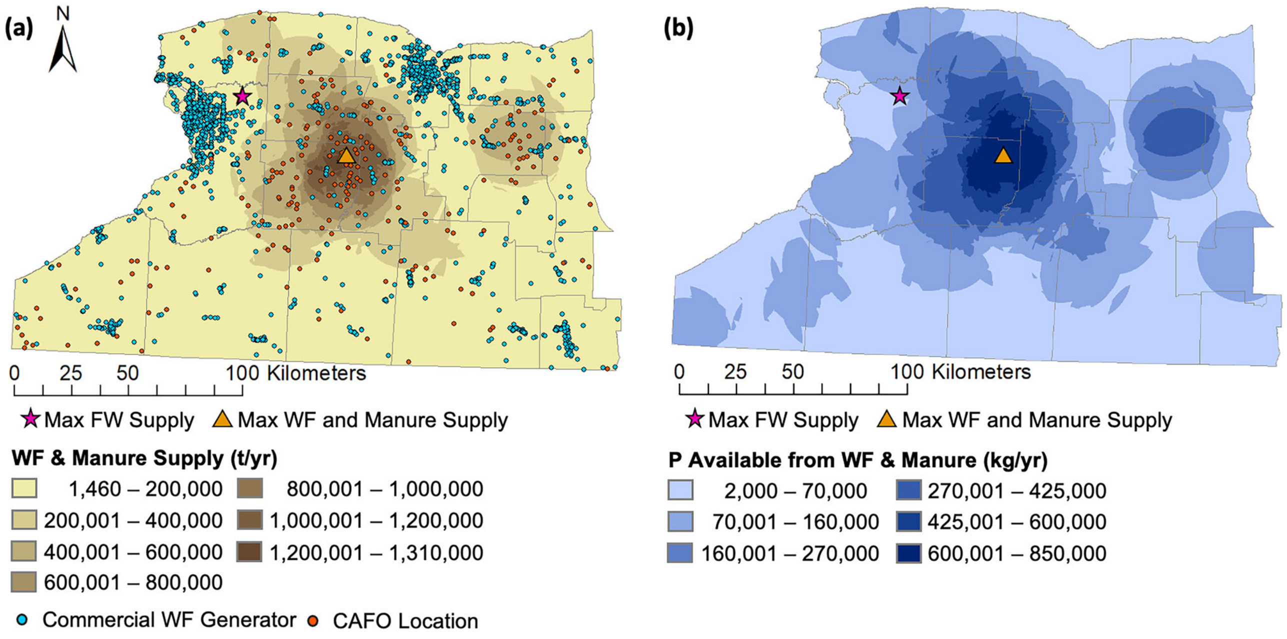

Fig. 2 | Manure and wasted food feedstocks are available for anaerobic digestion. Annual generation of **a** manure and wasted food (WF) and **b** the corresponding phosphorus (P) content contained within these feedstocks. Estimates are based on the annual manure production from concentrated animal feeding operations (CAFOs; indicated with red dots) and wasted food (WF) production at commercial generators (indicated with blue dots) within a transportation range of 20 and 40 km, respectively, from potential anaerobic digester locations. The red star and orange triangle indicate the locations where the largest quantity of WF (Max WF) or WF plus manure (Max WF and Manure Supply) can be sourced, respectively, when the two sources are evaluated separately.

soybeans, winter wheat, and dry beans grown on more than 10,000 ha. The quantity of phosphorus that could potentially be spread on fields was assumed to be equivalent to the amount of phosphorus in the crop yield. Corn and hay, which combined to 60% of total crops, have the highest phosphorus yield of all crops considered (>30 kg P ha^{-1} per harvest) and thus the greatest potential capacity for digestate acceptance. These estimates reflect a conservative level of potential digestate land application, since agronomic fertilization recommendations are complex in practice[59]. Nonetheless, to validate potential field capacity, we estimated the typical P spread on fields using recommended digestate application rates (20 m^3 ha^{-1} at a mean material density of 985 kg m^{-3})[60] and P concentration in WF or manure derived digestate (SI Tables S2 and S3) and derived a potential P application rates to fields of 28.2 and 12.6 kg P ha^{-1} for WF and manure derived digestate, respectively. For comparison, the recommended fertilization rate for modest grain corn yield and field fertility is 41.6 kg ha^{-1} (based on a rate of 95.3 kg P_2O_5 ha^{-1} from Table 7.4 in ref. 61). A comparison of these values to the potential P capacity of the fields (~11–40 kg ha^{-1} yr^{-1}; Fig. 3a) suggests that our estimated P capacity of fields is in line with both the rates at which both digestate and traditional inorganic fertilizers are typically spread on crops. The high phosphorus capacity of these crops coupled with their dominance in the central and eastern regions of the study area (SI Fig. S3), led to the highest field application capacity in this region (Fig. 3a). Not surprisingly, these livestock feed crops are co-located with the highest density of CAFOs, suggesting an opportunity to minimize transportation distances between manure generation and digestate utilization locations.

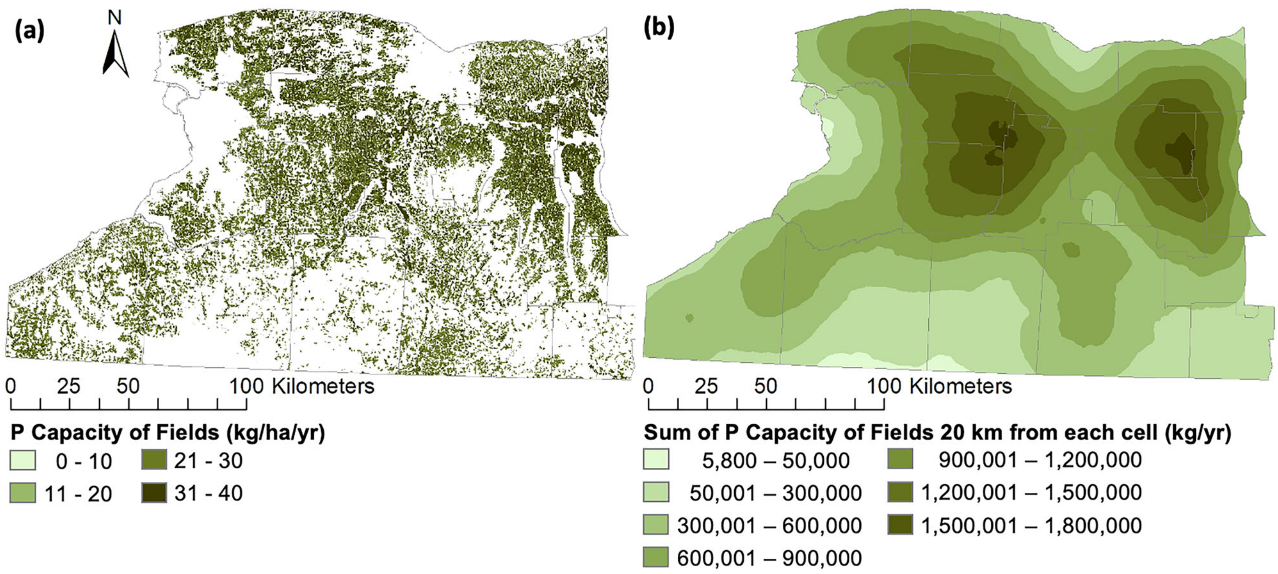

Fig. 3 | Phosphorus acceptance capacity in fields surrounding potential anaerobic digestion locations. a The maximum amount of phosphorus (P) that can theoretically be accepted by individual crops surrounding potential anaerobic digestion locations. This estimate reflects an assumption that any manure generated from nearby concentrated animal feeding operations (CAFOs) would be co-digested with wasted food, increasing the number of fields available for digestate application. **b** The sum of phosphorus application capacity of fields within a 20 km transportation radius surrounding each potential digester location. This radius represents the practical distance over which digestate can be feasibly transported from the anaerobic digester to a nearby field for land application. Phosphorus application capacities of fields decline if transportation is limited to within 10 km of each digester location (SI Fig. S5).

However, the ability to apply digestate on fields is limited by the practical distance over which it can be transported. With a maximum transportation radius of 20 km from each potential digester location, many central and eastern sites have a capacity of more than 1,000,000 kg yr^{-1} (Fig. 3b). However, if the maximum distance to transport digestate is constrained to within 10 km of the AD facility (thereby decreasing the total land area surrounding each potential digester site from 125,664 to 31,416 ha), the phosphorus acceptance capacity drops substantially, with much of the regional capacity <300,000 kg yr^{-1} and the maximum (~625,000 kg yr^{-1}) isolated to a small eastern region (SI Fig. S5). Thus, digestate transportation distance presents a critical constraint on the size of new AD facilities. We also modeled a scenario for WF ADs only, with the constraint that CAFO-derived manure takes precedence in field application, and WF-derived digestate may only be applied if capacity is not already saturated by existing manure production. In this case, field acceptance capacity for new WF-only digestate is substantially reduced throughout most of the study area for both a 20 km (SI Fig. S6a and b) and 10 km digestate transportation distance because manure distribution to fields takes precedence (SI Fig. S6c).

Comparison of potential digestate phosphorus generation and farmland capacity

Introducing siting preferences to include WF transport and digestate disposal creates a multi-criteria problem for identifying benefits and challenges of alternate AD locations. To evaluate these tradeoffs, we conducted a gap analysis and compared the potential digestate phosphorus generated at each feasible location with the capacity of surrounding cropland to accept this material. This analysis revealed regions of capacity exceedance and remaining capacity. Approximately 27% of feasible siting locations have more phosphorus available than can be accommodated by fields within a 10 km transportation radius (Fig. 4a). Doubling the transportation radius eliminates most of the oversupply across the region, with the exception of a small area west of the City of Buffalo (Fig. 4b) where urbanization prevents feasibility at either transportation distance (Fig. 1).

We evaluated the impact of transportation distance on the proportion of land area that meets exclusion criteria and does not exceed the potential digestate application capacity using a 2 km distance-step (Fig. 5). When considering co-digested manure and WF, there is a gradual increase in the favorable land area as the transportation radius expands, reaching a plateau at ~15 km. Thus, longer distances increase digestate disposal capacity, allowing for larger digesters and WF diversion, but also increase labor and fuel costs. We acknowledge here that our use of the straight-line distance between potential digester sites and fields may be an underestimate of the actual travel distance because of the inherent tortuosity of road networks; given the lower road density, this underestimate may be greater in rural than urban areas[62].

In contrast, for WF-only, the availability of land roughly doubles between transportation distances of two and four km, and then plateaus at 12% land area with a 10 km transportation distance (Fig. 5). Eliminating manure from the sourced material considerably decreases the digestate that must be managed, suggesting that siting WF digesters in regions not already saturated by CAFO-derived material may lead to lower storage needs, less oversaturation of fields, and fewer downstream water quality concerns. These results suggest a need for enhanced research and development of technology for WF-only digestion, potentially at smaller, more distributed scales. Ancillary benefits from WF-only digesters stem from the higher biomethane production potential of WF relative to manure[63,64] and the potential to produce digestate with higher nutrient content[29].

However, full-scale development of WF-only digesters currently faces significant challenges, stemming primarily from the nature of the feedstock. These include highly variable feedstocks, especially with respect to lipid and ammonium content, which lead to instability, microbial community dysfunction, and foaming events[65,66]. In addition, because of food packaging and persistence of other non-food materials associated with the wasted food stream, pre-treatment to depackage organic material and awareness of contaminants such as microplastics is required[67,68]. While co-digestion with manure provides stabilization, additional technological innovations are needed for the full buildout of WF-only digesters that will enable more distributed digester siting in non-CAFO areas. The excess digestate application capacity we observed in our study region could also be viewed as an opportunity to divert additional organic waste streams, including those from industrial, residential, and agricultural sources. However, the highly agricultural nature of our study region and the steep gradient from urban to rural systems allow for a minimization of transport distances while

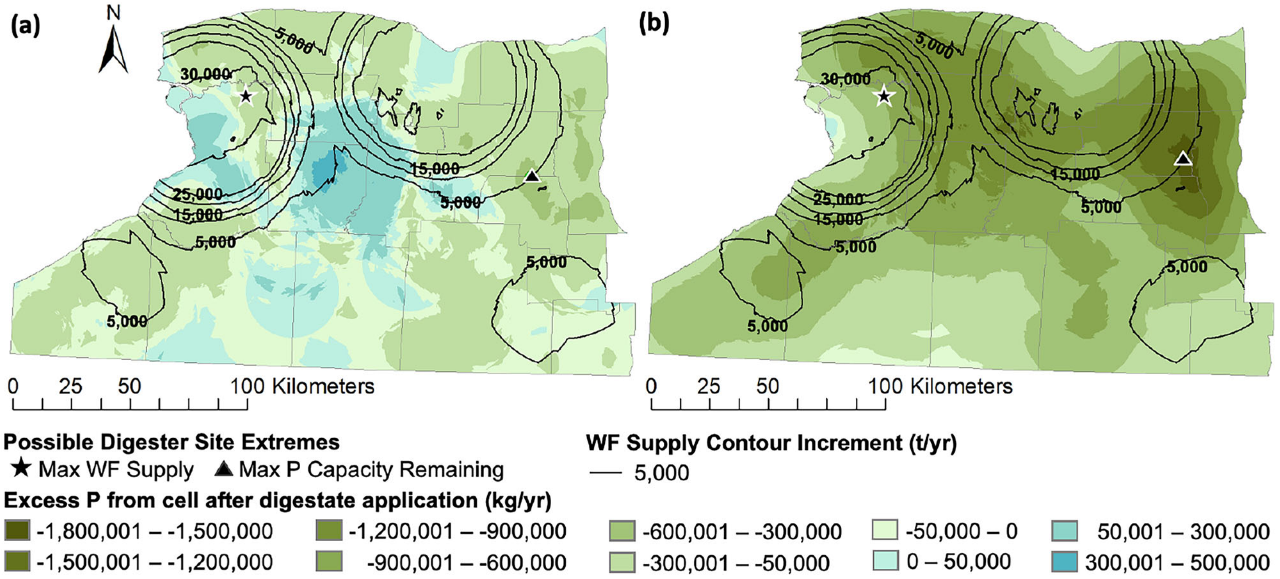

Fig. 4 | Excess phosphorus availability remaining after digestate land application. Values in this figure represent the net phosphorus (P) availability, accounting for phosphorus contained in wasted food (WF) and manure feedstocks within the sourcing radius around potential anaerobic digester locations, less the phosphorus acceptance capacities on fields within a transportation radius of **a** 10 km and **b** 20 km of each potential digester location. Positive values (blue colors) indicate excess phosphorus, while negative values (green colors) indicate remaining capacity. Two siting extremes are shown: the black star represents the potential anaerobic digester location where the largest amount of wasted food feedstock could be sourced (Max WF Supply), and the black triangle represents the potential digester location that would result in maximum remaining field capacity for accepting phosphorus (Max P Capacity Remaining).

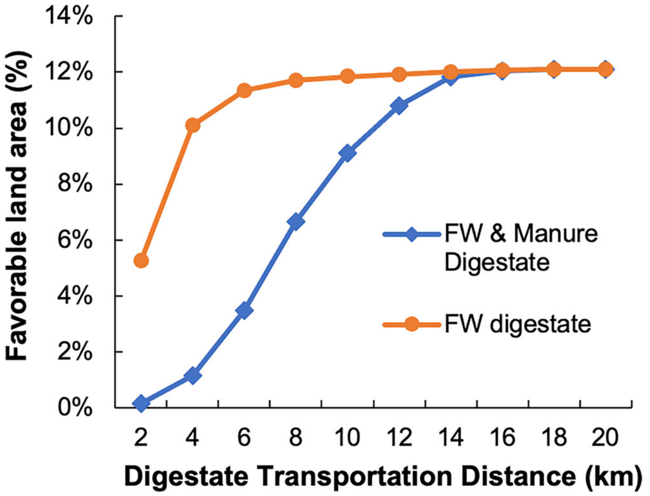

Fig. 5 | The influence of digestate transportation distance on the amount of favorable land for siting anaerobic digesters. The percent of available land with favorable conditions for siting an anaerobic digester in Western New York as a function of the distance over which digestate must be transported to nearby fields for land application. Here, favorable land reflects places where an anaerobic digester could be sited and not lead to more phosphorus application than fields within this transportation radius could accept. This graph reflects two scenarios: one in which digestate is generated from wasted food (WF) and manure co-digestion (blue line) and one in which lower volumes of digestate are generated from the digestion of wasted food alone (orange line).

maximizing the sourcing of feedstock availability. This may not be the case in all areas where WF availability is high, again underscoring the need for technological advances in WF processing.

Phosphorus runoff risk

The above analysis identified theoretically feasible sites for new AD facilities based on site suitability, WF availability, and access to potential fields for digestate application. However, because agricultural fields vary in crop type, soil quality, slope, and management practices, the ultimate environmental risk of AD to surface runoff of nutrients is also spatially heterogeneous[69]. We extracted two end-point scenarios: a site with the greatest supply of WF within the sourcing radius (Max WF Supply) and a site with the greatest availability of cropland to accept digestate (Max P Capacity Remaining) (Fig. 4; noted with a star or triangle, respectively). The Max WF Supply site has residual digestate application capacity at both 10 and 20 km for the manure and WF scenario and the WF-only scenario because there are few CAFOs in this region (Figs. 4 and 5, respectively). Cropland within 20 km of the potential digester sites for the Max WF Supply and Max Phosphorus Capacity scenarios comprised 20% and 53% of the total land area, respectively (Fig. 6). However, land availability alone does not indicate an avoidance of ecological risk.

The long-term hydrological impact analysis (L-THIA) model is a watershed model used to estimate runoff, with specific applicability to agricultural regions in the Great Lakes Basin[70,71]. L-THIA incorporates the Curve Number (CN), an average runoff parameter that includes surface runoff plus infiltration/initial abstraction and provides a relative rating of the runoff volume from a given location[72]. We used the CN as a spatially-explicit estimate of ecological risk at the watershed scale, as done previously to estimate flood risk[73], with higher CN indicating greater potential for runoff. Of the cropland at the Max WF site, 74% of the area had CN > 80, indicating higher runoff risk on these fields relative to only 28% with CN > 80 of the larger crop area in the Max P Capacity scenario. Thus, at one extreme (Max P Capacity), there is excess farmland available for disposal such that marginal land subject to high runoff risk can be avoided. At the other extreme (Max WF), limited farmland with a greater proportion of land with high phosphorus runoff potential may force digestate application under undesirable circumstances, increasing risk to sensitive aquatic ecosystems.

Using the CN, the crop distribution in the study region, and a representative P concentration from agricultural runoff[74], the L-THIA model estimated that the potential phosphorus runoff from farmland within the Max WF scenario was roughly double that of the Max P Capacity scenario under existing conditions (1.26 versus 0.69 kg ha^{-1} yr^{-1}). Thus, areal

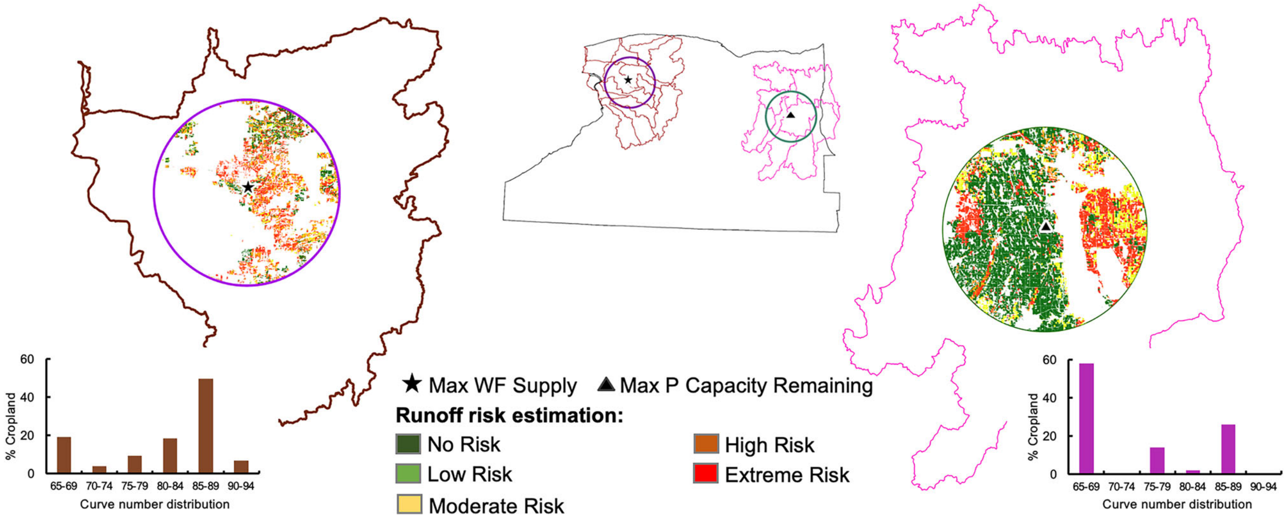

Fig. 6 | Phosphorus runoff risks from land application of digestate. Estimated risk of phosphorus runoff from cropland within a 20 km transportation radius of two distinct digester siting scenarios. The scenario shown on the left, marked with a black star on the center map, reflects a potential digester site within the Niagara River watershed where the largest amount of wasted food (WF) feedstocks can be sourced (Max WF Supply). The scenario shown on the right, marked with a black triangle on the center map, reflects a potential digester site within the Seneca Lake watershed that has the maximum remaining field capacity for accepting phosphorus (Max P Capacity Remaining). Within each region of interest, the croplands are shaded by curve number, which was calculated based on soil type, slope, and crop type. The inset bar charts indicate the distribution of cropland across the range of curve numbers, where lower curve numbers have a reduced potential for nutrient runoff following land application of digestate.

phosphorus release from the region within the Max WF scenario is already elevated, and the additional burden of digestate disposal may exacerbate eutrophication risk. While these estimates are based on typical agricultural practices and not meant to convey the actual release of phosphorus to waterways following digestate application, the big differences in the potential for downstream water quality impacts demonstrate how variable potential siting options are with respect to ecological risk. Deviation from typical field fertilization—for example, over-application of digestate on specific fields—will likely result in higher phosphorus runoff than estimated here. Combining this assessment of farmland quality with the potential digestate acceptance quantity yields a more complete assessment that takes into account both the availability of land within a cost-effective transportation distance and the character of the fields vis-à-vis downstream water quality. Both perspectives are critical for the sustainable build-out of regional AD infrastructure that enables cost-effective and ecologically mindful WF valorization systems. Thus, future site selection tools that combine capacity and quality are needed to maximize valorization potential without sacrificing environmental quality.

Limitations and future research needs

The digestate component of WF management has not yet been part of decision-making for AD deployment, but results presented here underscore its importance for policy formulation, process improvements, and market development[11,26,75,76]. This case study yielded three important implications: digestate transportation distance may limit AD siting potential; co-AD may lead to over-application of digestate because of the need to manage both WF and manure in areas with a high density of CAFOs; and both cropland availability and suitability must be assessed to reduce the ecological risk of digestate application.

When AD operators face constraints on digestate transportation distance, the result is a considerable decrease in capacity for digestate application on nearby farmland. If digestate management is not considered proactively, it may lead to the need to build additional storage lagoons, risk over-application to fields and downstream water quality impacts, or require costly wastewater treatment of residual digestate[33]. Thus, the management of WF valorization byproducts, such as digestate, should be considered when formulating policies and incentives. For example, state policies that mandate WF landfill diversion might include economic mechanisms to subsidize digestate management costs or incentivize siting in locations with maximal land availability and lowest ecological risks. In the case of Western New York, optimal siting would balance the greatest WF availability, maximum P acceptance capacity, and the lowest runoff risk, as seen in the Max P Capacity example.

Findings also illustrate the tension between managing two complex and growing organic waste streams—WF and manure. Although co-locating WF AD systems with CAFOs is a common practice, this significantly increases the local production of digestate. Use of digestate as a fertilizer is limited by lower nitrogen to phosphorus ratios[25] and, when compared to land-applying raw manure, higher moisture content[77] and lower overall nutrient content[39]. WF-only AD may promote decentralization, decrease WF transportation costs, and reduce ecological risks, but faces technological hurdles to stable, consistent performance. There is a clear need for future research and technology development aimed at improving WF-only digestion and other new valorization methods with lower byproduct risks. In parallel, technology development is also critical for improving digestate treatment and valorization, such as biochar adsorption[78] and struvite precipitation[79] to reduce digestate volume, increase nutrient concentration, and lower transportation and application costs[75,76,80,81]. Other options include integration of lactic acid production, to optimize economic benefits and take advantage of the unique nature of WF-only anaerobic digestion[82]. The increased flexibility in digestate management afforded by these improvements could provide an opportunity to not only increase WF diversion from multiple sources but also increase the circularity of nutrient use and reuse in agriculture[83].

Additionally, we demonstrate that cropland availability must be supplemented with an analysis of spatially explicit pollution risk because of heterogeneity in runoff potential associated with underlying landscape characteristics. Runoff modeling tools can be used to supplement a spatial analysis of material availability and digestate acceptance capacity of fields to proactively determine if land application of digestate may result in a nutrient surplus and lead to unintended ecological consequences on a regional scale[84]. These tools are not commonly incorporated into traditional siting and optimization models, but could be more widely used to promote both economically and ecologically sustainable build-out of WF management infrastructure.

Assumptions in this study are based on data and conditions that are specific to the study region and should be further explored and supported as knowledge about AD systems grows. For example, we used several assumptions to simplify the modeling of the sourcing and transportation of WF. We assumed a constant WF supply, rather than a variation based on seasonal trends in production[85]. In addition, we constrained WF sourcing to only facilities within the radial sourcing distance from each potential digester site using focal statistics. This method may overestimate availability because it doesn't account for the existing road network[86]. Future iterations may achieve a more robust analysis using road network analysis and broader consideration of regional fertilizer use and crops suitable for fertilization with digestate.

The distance-based exclusions set forth by NYS legislation are intended to identify generators that will be required to manage their WF, not to define collection distances. However, systems for WF collection within broader waste logistics are still emerging and evolving, and will likely face challenges of economic feasibility. Thus, further work that takes into account a more detailed analysis of the transportation system, coupled with the spatial and seasonal variability in WF generation, will provide insight into the systemic feasibility of collecting WF from generators and hauling it to treatment facilities as part of an ecosystem of WF solutions.

Methods

Our overarching aim was to develop methods to identify potential sites for AD facilities that source WF from commercial generators and manure from dairy farms in New York State, with a focus on WNY. A flowchart of the methodology is included in the Supplemental Information (SI Fig. S1). Briefly, we identified potential sites where new facilities could theoretically be built using an exclusionary land assessment process for the state as a whole. Next, we calculated the mass of WF and manure inputs for co-digestion within a given radius around each site, estimated the resulting amount of phosphorus that would be contained within the digestate generated at that site, and assessed crop field capacity to accept the phosphorus within a range of transportation distances from the digester. Finally, the relative balance of phosphorus between material supply and field acceptance capacity was assessed to generate an environmental information layer to illustrate optimal siting.

Esri ArcMap 10.6 was used to complete the environmental assessment using the projected coordinate system UTM Zone 18N. Analyses were performed on a raster grid of 30 m × 30 m cells covering the study region; this is a spatial resolution deemed sufficient for the study and matches with underlying landuse/landcover datasets. The model evaluates the magnitude of material inputs available within a sourcing radius of each cell and the capacity to subsequently land-apply resulting digestate on fields within a disposal radius from each cell (Fig. S1).

Case study region

This analysis focuses on WNY, where AD of manure is a common practice, with some facilities also accepting WF for co-digestion in partnership with WF producers and haulers[87]. The region is home to the second and third most populous cities in the state (Buffalo and Rochester), includes NYS Department of Environmental Conservation Regions 8 and 9[88], with 46% of the harvested cropland and 38% of dairy cow inventory in the state[89]. Interest in infrastructure expansion, the steep urban–rural gradient leading to close proximity of urban areas to farmland, and the presence of numerous areas of ecological concern make this region an excellent test case.

Exclusionary site selection

The availability of suitable land for constructing new AD facilities was first determined by applying multiple exclusionary constraints previously established in literature, including setback distance to protected waterbodies and land, residential and commercial areas, highways, schools, and proximity to road access[18,19,51,52,90–92]. See Table S1 for specific values used. Wetland and open water areas were based on the National Land Cover Dataset (NLCD) for 2016[93]. Land slope was obtained from digital elevation models (DEMs) from Cornell University's Geospatial Information Repository[94]; sites were restricted to slopes <15%[19,51,90,91]. Remaining data, including political boundaries, protected land, roads, schools, and parcel types, were downloaded from the NYS GIS Clearinghouse[95]. Data were extracted, clipped to the extent of the study region, and converted to raster format compatible with the NLCD data to ensure common analysis geometry.

A binary exclusionary process was applied to these feature data layers in ArcMap, where cells suitable for development based on each criterion were assigned a value of 1; otherwise, they were assigned a value of 0 and excluded from further analysis. The minimum viable facility size was based on the land footprint of the smallest standalone AD facility in the study region (~120 m × 90 m or 10,800 m^2), corresponding to a design capacity of 23,000 tonnes of organic material processed annually[96]. Therefore, co-located 30 × 30 m cells with a combined area <10,800 m^2 were removed from consideration, leaving only potential digester sites that meet the inclusion criteria and are of suitable size.

Wasted food and manure sourcing

Location and annual estimates of WF generation from ~1200 commercial and institutional entities and manure from 250 registered CAFOs were obtained from the NYSP2I Organic Resource Locator[97]. Following the specifications of NYS food waste law[5], this dataset includes higher education, restaurants, retail, wholesale, hospitality, and corrections facilities. The annual generation ($t\,yr^{-1}$) of WF was summed within a 40 km (25 mi) sourcing radius of each 30 m × 30 m suitable cell using the Focal Statistics tool in ArcMap[86]. Because the NYS law does not specify whether the limit on transportation distance is road distance or straight distance, and to simplify the method to take into account all 1450 organic generators, we used a radial straight-line approach to identify potential organic waste mass within a defined distance from each potential site. At facilities in the study region that accept WF, dairy manure is commonly co-digested to maintain the operational stability of AD systems[98]. The annual generation of manure from CAFOs within a 20 km sourcing radius of each cell was used to evaluate the total organic material feedstock availability[99]. This calculation does not assume that the manure is all intended for AD. See Fig. S2 for an illustration of distances used.

Phosphorus availability in material sources

We assumed that the phosphorus mass in waste feedstock was equivalent to the resulting mass in digestate to be applied to cropland. The phosphorus content of mixed commercial WF ($1.43\,kg\,tonne^{-1}$) and manure ($0.64\,kg\,tonne^{-1}$) was obtained by averaging available literature values (Tables S2 and S3) and used to convert organic feedstock and digestate flows to phosphorus equivalents in $kg\,yr^{-1}$.

Nutrient capacity of farmlands

Estimating phosphorus needs for agricultural land requires an understanding of the areal extent of individual crops, which were determined for our study area from a raster dataset of crop locations and types for 2018 from the CropScape database[100]. This dataset was clipped to the study region (SI Fig. S3) and used to identify field and vegetable crop types with a total land area of more than 200 acres (81 ha). CUGIR's database of registered agricultural districts was used to retain only crops within registered agricultural districts[94] to control for erroneous cropland data (e.g., wheat growing in a public park) resulting from inaccurate processing of satellite imagery within the CropScape dataset.

Determining how much fertilizer to apply to a given crop is complex and includes factors such as anticipated erosion, existing phosphorus content in soil, and expected crop uptake[101]. To simplify our model, we assumed that the capacity of a given field to accept AD phosphorus was equivalent to the amount of phosphorus removed annually during harvest. This likely underestimates the practical fertilizer application because it ignores erosion and runoff and is therefore a conservative estimate of potential field capacity. Although not all crops can be fertilized using digestate[11,28,102], the majority of crops in the region (corn and hay grown for animal consumption) are suitable. We assumed modest crop-specific target yield and optimal soil testing results to determine the total amount of P recommended for application (Data derived from Tables 7.4 and 4.2 in ref. 61), thus indicating crop P demand and soil nutrient capacity after converting from P_2O_5. Although the yield and recommended fertilizer application rates were based on Wisconsin, yields are similar between the two states (average grain corn yields: Wisconsin 176 bushels per acre[103] and NY 167 bushels per acre[104]). P-containing fertilizer applied in excess of these guidelines was assumed to be at risk of runoff. Derived P demand factors by crop type were applied to the CropScape dataset to provide a geospatial indication of region-wide nutrient application requirements, referred to as P demand. The anticipated phosphorus capacity for a hectare of crop per year was converted to 30 m × 30 m cell equivalents to coincide with the raster grid.

Digestate in the study region is typically moved from the generation site to the fields where it is applied by drag lining or tanker truck. Prior studies suggest maximum economically viable distances of about 3[33] and 10 km[34,35], respectively, for these two modes of digest transport, but there is uncertainty in the economic and environmental gains or losses from shorter or longer transportation distances. The total phosphorus capacity of available fields within a defined transportation radius from each cell was calculated using the focal statistics tool[86]. We varied the radial transportation distance from 2 to 20 km in order to assess the relationship between distance and overall field acceptance capacity and present detailed geospatial images for both 10 and 20 km.

Comparison of digestate phosphorus and land capacity

For each viable AD site, we estimated the net phosphorus deficit or surplus for land within the specified transportation radius by comparing the potential phosphorus generated in digestate at that site (from WF plus manure, or from WF only) to the acceptance capacity of surrounding fields. For this analysis, phosphorus availability was calculated using a sourcing radius of 40 km for WF and 20 km for manure. Similarly, the total field acceptance capacity was calculated using distances of 10 and 20 km. In reality, the heterogeneity and complexity of cropland use and ownership will limit field acceptance capacity, and thus, our results may overestimate acceptance capacity.

While co-AD of WF and manure is currently more common in our study region, WF-only digestion technology is an emerging technology space. However, if digesters are constructed to handle WF alone, appropriate siting will need to take into account pre-existing manure production and management systems that may already saturate field capacity. Thus, for a WF-only scenario, we assumed that existing manure production was land applied on fields near the CAFO generation site to illustrate locations currently saturated with manure-derived phosphorus relative to those with residual acceptance capacity where WF-only AD development may be favorable.

Phosphorus runoff potential

We evaluated potential runoff risk for two scenarios that represent the decision-making extremes for constructing new AD facilities: maximum WF (Max WF) availability and maximum cropland phosphorus acceptance capacity (Max Phosphorus Capacity) (above and in SI Fig. S8). Both scenarios used 40 and 20 km sourcing radius to estimate total WF and manure availability, respectively, and a 20 km transportation radius for field application of digestate. The Max WF scenario reflects optimization of potential economic benefit by maximizing WF sent to AD and minimizing transportation distance and associated costs. The potential site is located in a high-density commercial region on the western side of the WNY study area. The Max Phosphorus Capacity scenario is centered in a highly agricultural area in the economically and environmentally important Finger Lakes Region and reflects a scenario where a high capacity for phosphorus application may minimize potential ecological risk.

Agricultural land within the digestate transportation radius of each location was assigned a hydrologic group (A–D) using the soil (SSURGO) database (NRCS classification). Curve numbers (CNs) were then assigned from the Technical Release 55 (TR-55) manual based on these soil hydrological groups, crop type, cover type, and treatment[105]. Based on the CN for each crop type, we assigned the runoff depth, referring to the discharge model of 1965–2014 for Rochester, NY, and assumed a consistent runoff depth across the study region. Runoff depth was calculated for each crop distribution based on pixel count within the 20 km digestate transportation radius. To estimate total phosphorus load from each location, we multiplied these crop distribution categories by an event mean concentration value typical of agricultural land use (1.3 mg P L^{-1})[74], to produce an estimate of the total areal phosphorus loss to waterways from agricultural land surrounding each focal point. See SI Table S4 for GIS data sources.

Data availability

Data are available at https://doi.org/10.6084/m9.figshare.31009600.

Code availability

Model data and code are available at https://doi.org/10.6084/m9.figshare.31009600.

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Author contributions

W.A.: Conceptualization, formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing; S.S.: Conceptualization, formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing; B.M.T.: Writing review and editing, conceptualization, and methodology; C.W.B.—Conceptualization, methodology, writing—review and editing, supervision, and funding acquisition; A.C.T.: Conceptualization, methodology, supervision, project administration, and writing review and editing.

Competing interests

The authors declare no competing interests.

Additional information

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