Supplementary Information:
Phosphorus in Ontario's economic sectors: mapping flows and assessing recovery and recycling potential

Université Laval team[a,*], McGill University team[b], University of Waterloo team[c]

[a] *Université Laval*
[b] *McGill University*
[c] *University of Waterloo*

Contents

1 Phosphorus recovery processes **1**

1.1 Scaling CAFOs phosphorus recovery processes 1

1.2 Scaling municipal wastewater phosphorus recovery processes 2

2 Distribution of CAFOs size in regions of the the Great Lakes area **2**

1. Phosphorus recovery processes

1.1. Scaling CAFOs phosphorus recovery processes

We refer the reader to Martín-Hernández et al. (2021) for a detailed description on estimating the phosphorus recovery costs of processes from phosphorus recovery from livestock facilities. Capital costs are annualized through the application of an annual capital charge ratio ($ACCR$) as defined by Towler and Sinnott (2013), shown in Eq. 1, assuming a typical interest rate i of 5% and a plant lifetime n of 20 years.

$$ACCR = \frac{i\left(1+i\right)^{n}}{\left(1+i\right)^{n}-1} \quad (1)$$

*Corresponding author
Email address: edgar.martin-hernandez.1@ulaval.ca (Université Laval team)

1.2. Scaling municipal wastewater phosphorus recovery processes

Data on processes for phosphorus recovery from municipal wastewater is taken from Egle et al. (2016). We assume that, similarly to other industrial activities (Dysert and Pickett, 2005), the phosphorus recovery cost from municipal wastewater in function of the plant capacity shows an exponential behavior. In consequence, the cost-to-capacity method (Baumann, 2014) is used to estimate phosphorus recovery cost from municipal wastewater in function of the plant capacity, as shown in Eq. 2, where x denotes the scale factor 'facility 2' refers to the facility which cost is required while 'facility 1' denotes the facility whose data is known. The scale factor x is estimated based on the data for different capacities reported by Egle et al. (2016) through the transformation of Eq. 2 by applying natural logarithms to both sides of the equation, as shown in Eq. 3. The scale factor obtained are shown in Table 1. The capacity magnitude has been normalized to the mass of phosphorus recovered.

$$\frac{\text{Cost}_{\text{facilitiy 2}}}{\text{Cost}_{\text{facilitiy 1}}} = \left(\frac{\text{Capacity}_{\text{facilitiy 2}}}{\text{Capacity}_{\text{facilitiy 1}}}\right)^{x} \tag{2}$$

$$x = \frac{\ln\left(\frac{\text{Cost}_{\text{facilitiy 2}}}{\text{Cost}_{\text{facilitiy 1}}}\right)}{\ln\left(\frac{\text{Capacity}_{\text{facilitiy 2}}}{\text{Capacity}_{\text{facilitiy 1}}}\right)} \tag{3}$$

2. Distribution of CAFOs size in regions of the the Great Lakes area

The size distribution of Ontario's CAFOs is not reported by public databases, but the number of animals is aggreggated at Census Division level REF, REF. As an approximation, the size distribution of CAFOs of other regions in the vicinity of the Great Lakes area reporting the size of CAFOs is calculated and extrapolated to the province of Ontario. The size distribution of CAFOs is determined for the US states of Ohio REF, Pennsylvania REF, Indiana REF, Michigan REF, and Wisconsin REF. The distribution of CAFOs size has been fit to a truncated normal distribution, since the possible size of livestock facilities is bounded between 300 animal units for being considered

Table 1: Estimation of scale factors for municipal wastewater phosphorus recovery systems.

Inflow	Technology	Type	P recovery potential (% related to inflow)	P inflow (kg P/year)	Annual processing cost (EUR)	Scale factor x
WWTPs (liquid phase)	Crystalactor	Struvite/Calcium phosphate	38	65700 328500	305920 795893	0.59
	Ostara Pearl	Struvite	20	65700 328500	130856 235234	0.36
	P-RoC	Calcium phosphate	27	65700 328500	75970 266025	0.78
	REM-NUT	Struvite	47	65700 328500	977933 4417171	0.94
	AirPrex	Struvite	15	65700 328500	74195 137693	0.38
	PRISA	Struvite	18	65700 328500	186923 371578	0.43
WWTPs	Stuttgart process	Struvite	40	65700 328500	581730 2419407	0.89
	Gifhorn process	Struvite	40	65700 328500	400384 1491509	0.82
	PHOXNAN	Struvite	51	65700 328500	891667 3468902	0.84
	Aqua Reci	Calcium phosphate	61	65700 328500	939605 3529595	0.82
	MEPHREC	P rich slag	68	65700 657000	1154473 4715866	0.61

as an intensive livestock production facility REF, and 10,000 animal units in order to remove extra-large CAFOs that are outliers in the size distribution, avoiding excessive long tails distorting the distributions. The probability density distribution of a truncated normal distribution is shown in Eq. 4, where μ, σ^2, a, and b denote the mean, variance, and lower and upper bounds respectively, while Θ denotes the probability density distribution of the standard normal distribution, as shown in Eq. 5, and Φ denotes the cumulative distribution function of the standard normal distribution, as shown in Eq. 6. Figure 1 represent the distribution of CAFOs using the kernel density estimation (KDE) REF, and Table 2 collect the truncated normal distribution fitting parameters for each evaluated region.

$$f\left(x\right) = \frac{1}{\sigma}\frac{\Theta\left(\frac{x-\mu}{\sigma}\right)}{\Phi\left(\frac{b-\mu}{\sigma}\right) - \Phi\left(\frac{a-\mu}{\sigma}\right)} \tag{4}$$

$$\Theta\left(\xi\right) = \frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}\xi^2} \tag{5}$$

$$\Phi\left(\xi\right) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{\frac{-\xi^2}{2}}d\xi \tag{6}$$

Table 2: Truncated normal distribution fitting parameters for the distribution of cAFOs sizes in regions of the Great Lakes area.

Parameters	Ohio	Michigan	Wisconsin	Pennsylvania	Indiana
mean	2415.245	2461.528	2393.431	1398.358	1529.522
std	1588.247	1333.813	1457.033	1076.217	1541.599
a	820.000	420.000	396.000	328.000	310.000
b	9800.000	7601.000	9979.000	7533.000	7040.000

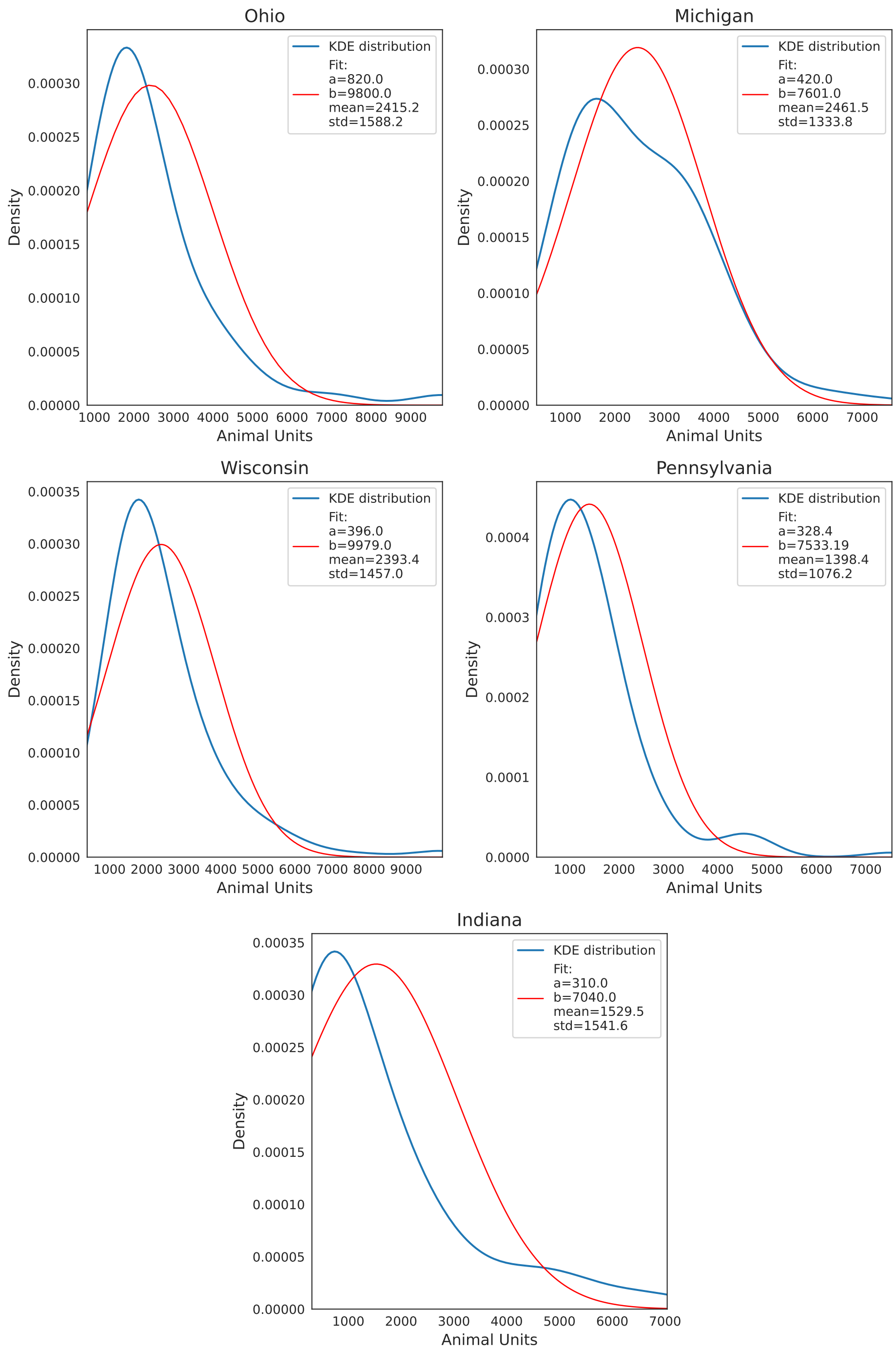

Figure 1: Distribution of CAFOs size in regions of the the Great Lakes area.

References

Baumann, C., 2014. Cost-to-capacity method: applications and considerations. M&TS J 30, 49–56.

Dysert, L.R., Pickett, T.W., 2005. So you think you're an estimator? Cost Engineering 47, 30.

Egle, L., Rechberger, H., Krampe, J., Zessner, M., 2016. Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. Science of The Total Environment 571, 522–542. URL: https://linkinghub.elsevier.com/retrieve/pii/S0048969716314656, doi:10.1016/j.scitotenv.2016.07.019.

Martín-Hernández, E., Martín, M., Ruiz-Mercado, G.J., 2021. A geospatial environmental and techno-economic framework for sustainable phosphorus management at livestock facilities. Resources, Conservation and Recycling 175, 105843.

Towler, G., Sinnott, R., 2013. Chemical engineering design: principles, practice and economics of plant and process design. Butterworth-Heinemann.