Can circular strategies contribute to sustainable food production in cities? The case of nutrients circulation for urban agriculture in a metropolitan area

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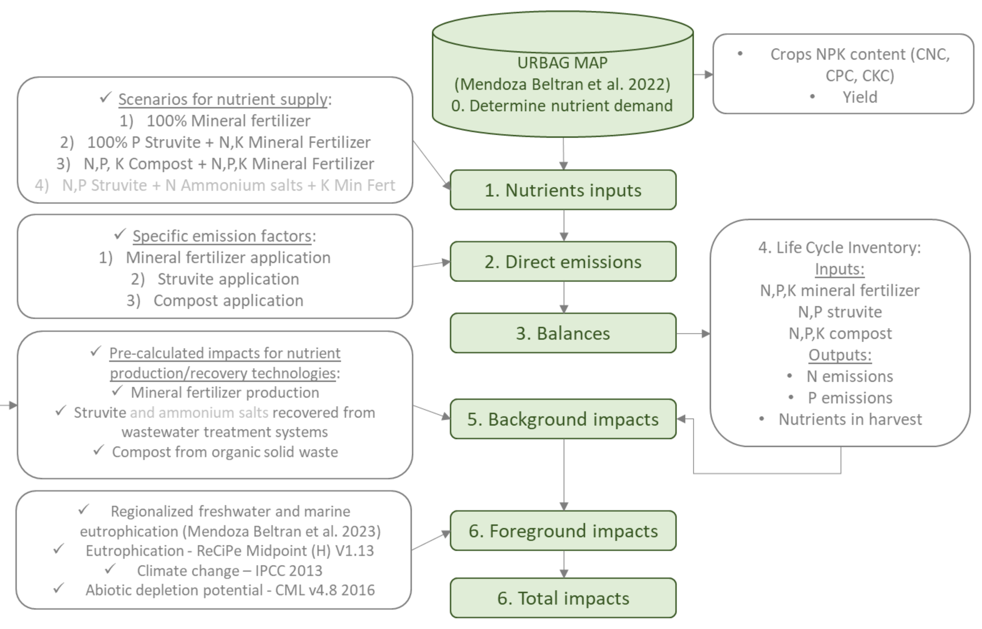
INTRODUCTION

City region food systems (CRFS) will require several transformations to become more resilient, sustainable and multifunctional systems (FAO, 2023). Such transformations include strategies to minimize the loss flows of nutrients out of the city, maximize recycling of nutrients from the city to agricultural lands and minimize the need of nutrients in food production (Metson et.al., 2022). Previous studies have found environmental benefits in coupling nutrient flows of waste and food systems in cities through different technologies to recover nutrients in different forms (Trimmer and Guest, 2018; Tonini et.al., 2019). However, specific spatial and technological patterns of individual cities, which are essential in determining the best strategies to follow, are not accounted for. Moreover, system-level dynamics e.g. implications of reduced mineral fertilizers production, avoided waste streams treatment and emissions from recovered nutrients´ application are also not always included. Finally, the focus on one nutrient such as phosphorus or nitrogen alone is also common.

In this study we take a step further to tackle these critical points and implement a **prospective-regionalized life cycle assessment (LCA) of urban agriculture (UA)** in a python based tool, where the spatial distribution of crops of the city drives the LCA. We apply this approach to the Metropolitan Area of Barcelona (AMB) in Spain. We evaluate the direct and indirect impacts of climate change, eutrophication (freshwater and marine using regionalized characterization factors (Mendoza Beltran et.al, 2023)) and abiotic resource depletion of current UA in the AMB. We evaluate technologies of plausible implementation for the city and use life cycle inventories provided by local institutions. Finally, the tool helps evaluate theoretical scenarios with the inputs of NPK in three forms: Mineral fertilizers, recovered P and N from wasterwater treatment plants in the form of struvite, recovered NPK in compost from municipal organic solid waste, and recovered N in ammonium salts from wastewater treatment plants.

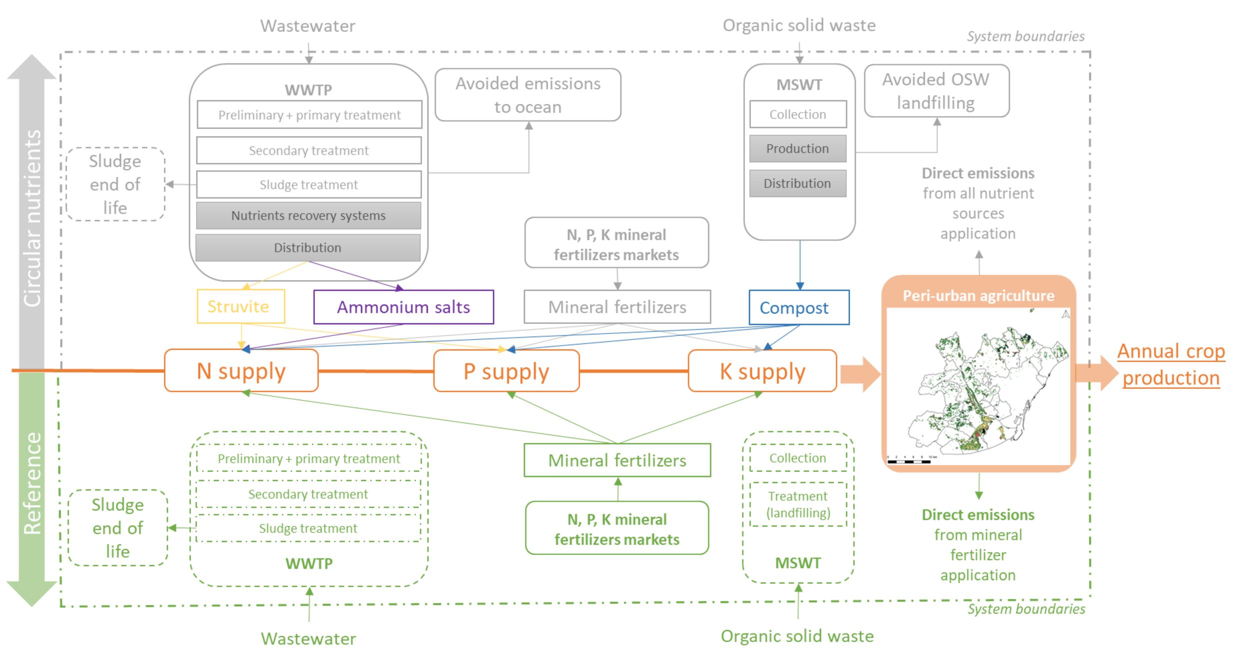
METHODS

General Methodology



Functional unit: The annual total crop production in the Metropolitan area of Barcelona (AMB) in Spain.

System boundaries



Scenarios LCI before balance:

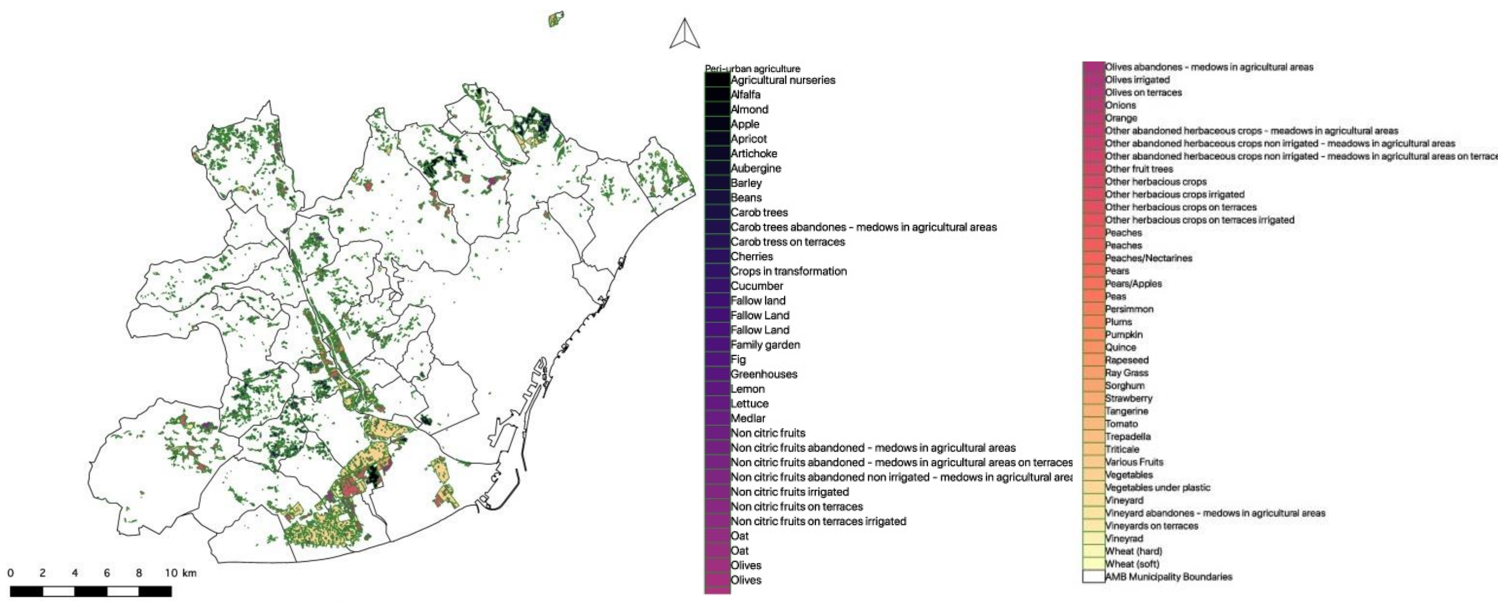
Scenario	Input**	N*	P*	K*	Background inventory source
S0_MinFert	Mineral Fertilizer	CNC	CPC	CKC	ecoinvent v3.8: market for inorganic nitrogen fertilizer, as N, P2O5 and K2O
	Struvite***	0	0	0	Rufí-Salís et al (2020)
	Compost****	0	0	0	Arosema et al (submitted)
	N fixation#	CNC			
S0_Struvite_P	Mineral Fertilizer	CNC - CPC * Struvite N to P content	0	CKC	ecoinvent v3.8: market for inorganic nitrogen fertilizer, as N, P2O5 and K2O
	Struvite***	CPC * Struvite N to P content	CPC	0	Rufí-Salís et al (2020)
	Compost****	0	0	0	Arosema et al (submitted)
	N fixation#	CNC			
S0_Compost	Mineral Fertilizer	CNC * (1 - Frac_N_compost_supplied)	CPC * (1 - Frac_P2O5_compost_supplied)	CKC * (1 - Frac_K2O_compost_supplied)	ecoinvent v3.8: market for inorganic nitrogen fertilizer, as N, P2O5 and K2O
	Struvite***	0	0	0	Rufí-Salís et al (2020)
	Compost****	CNC * Frac_N_compost_supplied	CPC * Frac_P2O5_compost_supplied	CKC * Frac_K2O_compost_supplied	Arosema et al (submitted)
	N fixation#	CNC			
S0_Struvite_P_Ammonium_salts	Mineral Fertilizer				Under development
	Struvite***				Under development
	Compost****				Under development
	m_Salts				Under development

Scenario	Outputs (emission factors)	N: Mineral Fertilizers	N: Struvite	N: Compost	P: Mineral Fertilizers	P: Struvite	P: Compost	K: Mineral Fertilizers	K: Struvite	K: Compost	Emission factors source: Mineral Fertilizers	Emission factors source: Struvite	Emission factors source: Compost
S0_MinFert	NH3 to air	0.04			-						PEFCR		
	NOx to air	0.012			-						EEA (2013)		
	NO3- to water	0.24			-						IPCC		
	N2O Direct to air	1***			-						Tier 2 (Mendoza Beltran et al 2022)		
	N2O indirect volatilization to air	0.01			-						IPCC Tier 1		
	N2O indirect leaching to air	0.011			-						IPCC Tier 1		
	PO43- to water	-			0.0025						Ecoinvent2 P-SALCA model		
	N in harvest	CNC											
	P in harvest				CPC								
	K in harvest							CKC					
S0_Struvite_P	NH3 to air	0.04	0.04		-	-					PEFCR	Wang et al (2023)##	
	NOx to air	0.012	0.012		-	-					EEA (2013)	EEA (2013)	
	NO3- to water	0.24	0		-	-					IPCC	Wang et al (2023)##	
	N2O Direct to air	1***	0.1929		-	-					Tier 2 (Mendoza Beltran et al 2022)	[illegible]	
	N2O indirect volatilization to air	0.01	0.01		-	-					IPCC Tier 1	IPCC Tier 1	
	N2O indirect leaching to air	0.011	0		-	-					IPCC Tier 1	Wang et al (2023)##	
	PO43- to water	-	-		0.0025	0					Ecoinvent2 P-SALCA model	Wang et al (2023)##	
	N in harvest	CNC											
	P in harvest				CPC								
	K in harvest							CKC					
S0_Compost	NH3 to air	0.04		0.016	-		-				PEFCR		Brunn et al (2006)#
	NOx to air	0.012		-	-		-				EEA (2013)		
	NO3- to water	0.24		0.41	-		-				IPCC		Brunn et al (2006)#
	N2O Direct to air	1***		0.016	-		-				Tier 2 (Mendoza Beltran et al 2022)		Brunn et al (2006)#
	N2O indirect volatilization to air	0.01		-	-		-				IPCC Tier 1		
	N2O indirect leaching to air	0.011		-	-		-				IPCC Tier 1		
	PO43- to water	-		-	0.0025		0.1				Ecoinvent2 P-SALCA model		Brunn et al (2006)#
	N in harvest	CNC											
	P in harvest				CPC								
	K in harvest							CKC					

* Crop nitrogen content (CNC), Crop phosphorus content (CPC), Crop potassium content (CKC) described in Mendoza Beltran et al (2023) as the N and P removed with the harvest. K was added from the same sources for all crops
** Agricultural residues and manure inputs are considered to be zero as theoretical scenarios are explored to study the maximum potentials
*** Wastewater treatment plant considered for the AMB is the Llobregat plant (Rufí-Salís et al, 2020)
**** Compost plants considered for the AMB are: Sant Cugat open air compost plant, Torrelles open air compost plant and the Zona Franca Ecoparc (anaerobic digestion)
# Average for Loam and Sand soils
No leaching from struvite application in open air agriculture, according to Wang et al (2023)
For floating crops only

METHODS

URBAG MAP (Peri-urban agriculture at the Metropolitan Area of Barcelona)

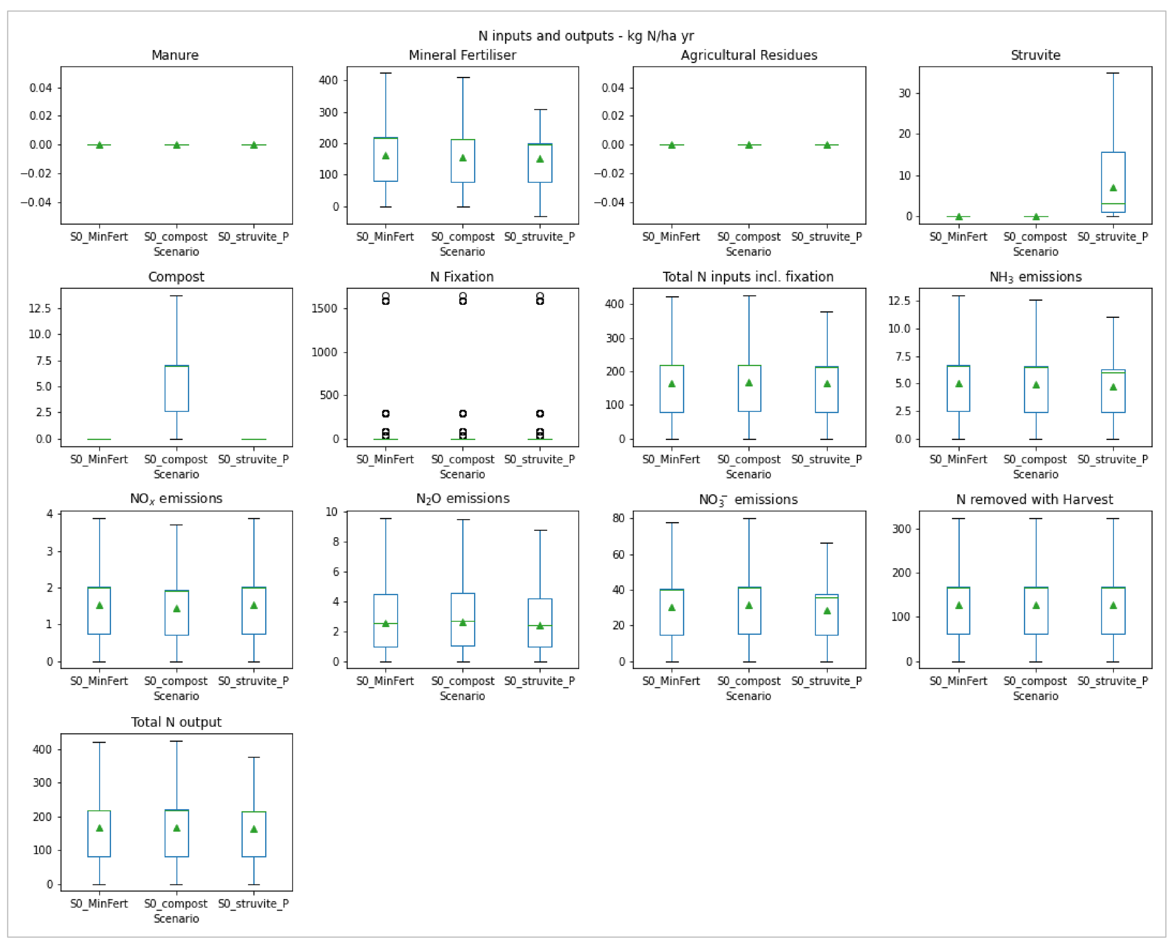


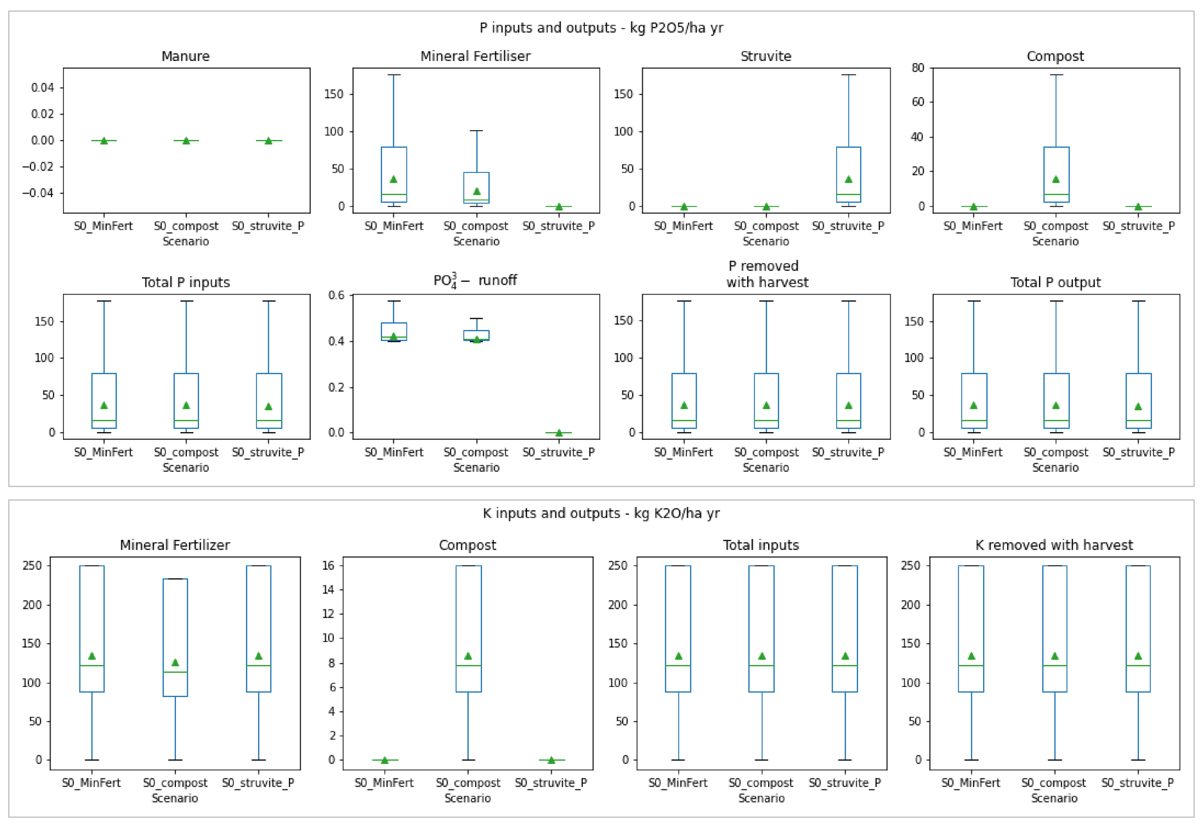
LCIs after balance

Inventories after balance			Scenario			%Change vs MinFert		
Nutrient	Input	Units	S0_MinFert	S0_Struvite_P	S0_Compost	S0_Struvite_P	S0_Compost	Assumption
NITROGEN	N_MinFert	N tons yr-1	963.2	904.1	935.6	-6%	-3%	Adjusted
	N_struvite	N tons yr-1	0.0	45.6	0.0	4564%	0%	
	N_compost	N tons yr-1	0.0	0.0	32.4	0%	3243%	
	N_fixation	N tons yr-1	46.4	46.4	46.4	0%	0%	
	N_inputs	N tons yr-1	1009.6	996.1	1014.4	-1%	0%	
	Output							
	N2O to air	N tons yr-1	16.0	15.2	16.5	-5%	3%	
	NH3 to air	N tons yr-1	30.8	28.9	30.0	-6%	-3%	
	NOx to air	N tons yr-1	9.2	9.2	8.8	0%	-4%	
	NO3 to water	N tons yr-1	184.6	173.6	190.1	-6%	3%	
	N_Harvest	N tons yr-1	769.1	769.1	769.1	0%	0%	Fixed
	N_outputs	N tons yr-1	1009.6	996.1	1014.4	-1%	0%	
PHOSPHORUS	Inputs							
	P_MinFert	P2O5 tons yr-1	234.6	0.0	134.5	-100%	-43%	Adjusted
	P_struvite	P2O5 tons yr-1	0.0	232.2	0.0	23220%	0%	
	P_compost	P2O5 tons yr-1	0.0	0.0	100.0	0%	10000%	
	P_inputs	P2O5 tons yr-1	234.6	232.2	234.5	-1%	0%	
	Outputs							
	PO43 leaching	P2O5 tons yr-1	2.4	0.0	2.3	-100%	-4%	
	P_Harvest	P2O5 tons yr-1	232.2	232.2	232.2	0%	0%	Fixed
	P_outputs	P2O5 tons yr-1	234.6	232.2	234.5	-1%	0%	
POTASSIUM	Inputs							
	K_MinFert	K2O tons yr-1	709.3	709.3	664.1	0%	-6%	
	K_Compost	K2O tons yr-1	0.0	0.0	45.2	0%	4520%	
	K_inputs	K2O tons yr-1	709.3	709.3	709.3	0%	0%	
	Outputs							
	K_Harvest	K2O tons yr-1	709.3	709.3	709.3	0%	0%	Fixed

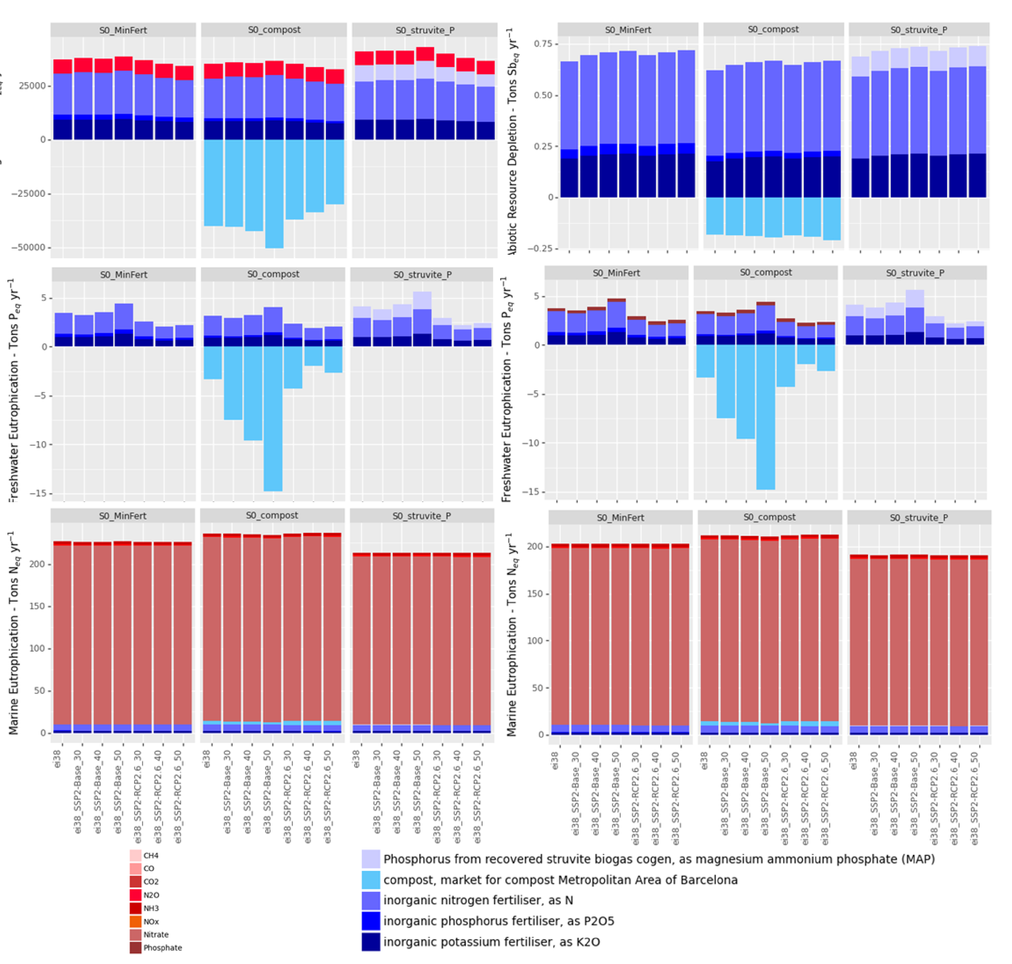
RESULTS

Boxplots for NPK inventories of all individual farms





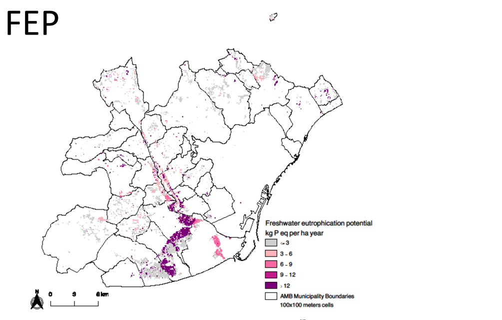
LCIA



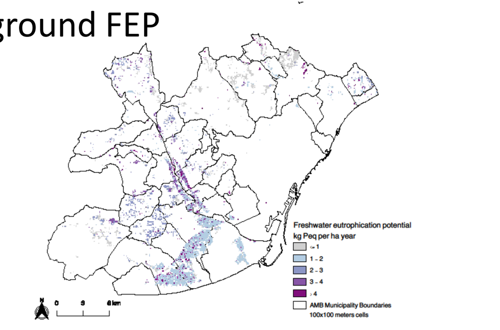
Per functional unit of 68716.3 tons of food per year in 5568.5 HA					
	Absolute impacts			% change vs MinFert	
ADP - tons Sbeq/yr	S0_MinFert	S0_struvite_P	S0_compost	S0_struvite_P	S0_compost
ei38	0.66	0.69	0.44	3%	-34%
ei38_SSP2-Base_30	0.69	0.71	0.46	3%	-34%
ei38_SSP2-Base_40	0.71	0.73	0.47	3%	-34%
ei38_SSP2-Base_50	0.72	0.74	0.47	3%	-35%
ei38_SSP2-RCP2.6_30	0.69	0.71	0.46	3%	-34%
ei38_SSP2-RCP2.6_40	0.71	0.73	0.47	3%	-34%
ei38_SSP2-RCP2.6_50	0.72	0.74	0.46	3%	-36%
FE - Tons Peq/yr					
ei38	3.78	4.10	0.14	9%	-96%
ei38_SSP2-Base_30	3.56	3.86	-4.19	8%	-218%
ei38_SSP2-Base_40	3.88	4.34	-6.03	12%	-255%
ei38_SSP2-Base_50	4.76	5.65	-10.40	19%	-319%
ei38_SSP2-RCP2.6_30	2.95	2.96	-1.58	0%	-153%
ei38_SSP2-RCP2.6_40	2.45	2.22	0.35	-9%	-86%
ei38_SSP2-RCP2.6_50	2.58	2.41	-0.31	-6%	-112%
FE_Reg - Tons Peq/yr					
ei38	3.43	4.10	-0.19	20%	-106%
ei38_SSP2-Base_30	3.21	3.86	-4.52	20%	-241%
ei38_SSP2-Base_40	3.53	4.34	-6.37	23%	-280%
ei38_SSP2-Base_50	4.41	5.65	-10.74	28%	-344%
ei38_SSP2-RCP2.6_30	2.60	2.96	-1.91	14%	-174%
ei38_SSP2-RCP2.6_40	2.10	2.22	0.02	6%	-99%
ei38_SSP2-RCP2.6_50	2.23	2.41	-0.64	8%	-129%
GWP100 - Tons CO2eq/yr					
ei38	37077.90	40748.62	-4969.42	10%	-113%
ei38_SSP2-Base_30	37835.12	41186.06	-4375.14	9%	-112%
ei38_SSP2-Base_40	37601.33	41145.01	-6871.05	9%	-118%
ei38_SSP2-Base_50	38688.12	42875.15	-13710.42	11%	-135%
ei38_SSP2-RCP2.6_30	36987.55	39972.07	-2055.05	8%	-106%
ei38_SSP2-RCP2.6_40	35315.10	37891.59	-0.78	7%	-100%
ei38_SSP2-RCP2.6_50	34264.63	36516.74	2691.31	7%	-92%
ME - Tons Neq/yr					
ei38	203.17	191.43	212.23	-6%	4%
ei38_SSP2-Base_30	202.98	191.20	211.78	-6%	4%
ei38_SSP2-Base_40	203.00	191.24	211.47	-6%	4%
ei38_SSP2-Base_50	203.15	191.47	210.64	-6%	4%
ei38_SSP2-RCP2.6_30	202.83	190.97	212.40	-6%	5%
ei38_SSP2-RCP2.6_40	202.67	190.75	212.90	-6%	5%
ei38_SSP2-RCP2.6_50	202.71	190.81	212.70	-6%	5%
ME_Reg - Tons Neq/yr					
ei38	226.58	213.65	236.33	-6%	4%
ei38_SSP2-Base_30	226.38	213.41	235.88	-6%	4%
ei38_SSP2-Base_40	226.40	213.46	235.58	-6%	4%
ei38_SSP2-Base_50	226.56	213.69	234.74	-6%	4%
ei38_SSP2-RCP2.6_30	226.23	213.19	236.51	-6%	5%
ei38_SSP2-RCP2.6_40	226.08	212.97	237.01	-6%	5%
ei38_SSP2-RCP2.6_50	226.11	213.03	236.80	-6%	5%

LCIA Regionalized (example)

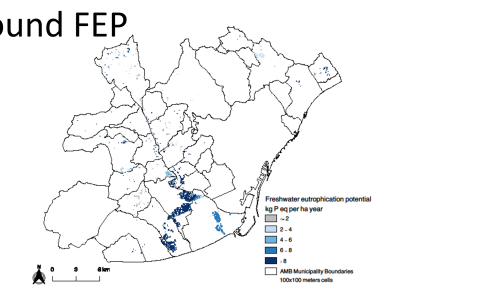
Total FEP



Background FEP



Foreground FEP



DISCUSSION AND CONCLUSIONS

- Circular nutrient strategies can contribute to sustainable production of CRFS at present and in the future.
- However, this depends on:
  - City crops patterns - determine the demand of nutrients, as well as impacts of nutrient redistribution.
  - City available technologies for nutrient recovery in different forms.
  - City local physical conditions – can make the impact of an emissions of a substance or a resource use more or less relevant.
- CRFS nutrient inputs need to be considered in terms of their life cycle as alternatives to mineral sources of nutrients and as a "shift" in waste management to capture their full potential.
- The python tool developed to quantify the impacts of different strategies could be adapted for other cities.
- For the AMB, compost production brings benefits in GWP, FE and ADP, while struvite use to replace P mineral fertilizer reduces ME.
- Replacing N mineral fertilizer application if essential to reduce impacts in the AMB – struvite and compost are not concentrated sources of N and thus not the best to replace N mineral fertilizer. Further we will consider recovering ammonium salts from wastewater treatment.
- Avoiding greener electricity production in the future (e.g. from anaerobic digestion to produce compost) leads to positive footprints in two degree scenarios towards 2050.

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