PACSAN

Phosphorus and Climate Smart Agriculture Network

PACSAN INTERACTIVE MODEL: Background and Assumptions

PHOSPHORUS USE & GREENHOUSE GAS EMISSIONS IN THE FOOD SYSTEM

AUSTRALIA AND CHINA

2024

This report provides the assumptions behind v1 of the interactive PACSAN model which can be found online at https://model.pacsan.online/

This forms part of the larger PACSAN project, led by the Institute for Sustainable Futures, University of Technology Sydney, and funded by the National Foundation for Australia China Relations, 2023-24 grant, Australian Government.

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1 Model Description

The PACSAN model is structured around two integrated sub-models, each addressing critical aspects of sustainability in food systems:

- The first sub-model, the **Greenhouse Gas (GHG) emissions model**, evaluates GHG emissions across various stages of the food chain, such as *fertilizer manufacturing, livestock production,* and *food waste*.

- The second sub-model, the **Phosphorus (P) model**, focuses on the supply-risk of phosphorus from a food security perspective and explores alternative demand solutions, targeting sectors like *agriculture*, *aquaculture*, and *livestock*. Additionally, it considers innovative supply strategies, such as phosphorus recovery from *food waste* and *manure*.

Both sub-models are focused on assessing the potential impact of eight measures which represent interventions, as described in the following table:

Table 1: Measures applied across the model

Measure	Description
1. Renewable fertilizer	• Ammonia produced with renewable hydrogen • Recovery and recycling of phosphorus from manures, crop waste and sewage
2. Nutrient productivity	• On farm efficiency of fertilizer • Smart agriculture • Tapping legacy phosphorus, soil testing and mapping
3. Soil carbon sequestration	• Lock-up carbon in soils
4. Crop type	• Rice varieties to reduce greenhouse emissions • Crop varieties that maximise nutrient use efficiency
5. Livestock feed additives	• Feed additives for ruminants to reduce methanogenesis • Phytase additives to maximise phosphorus uptake
6. Energy productivity	• Improving energy productivity along the food chain, • Electrification incl mobility, food processing • increased renewables in the grid
7. Sustainable food choices	• Shifting food consumption from livestock to plant-based
8. Food waste avoidance	• Reducing avoidable food waste across the food chain

Each measure is assigned an impact coefficient, ranging from 0 to 1, which reflects its potential impact on specific categories of emissions or phosphorus use or sectors within the model. The impact coefficient is an estimate of the extent to which a particular measure can affect its corresponding stages or sectors of the food chain (for the GHG sub-model) and phosphorus-demanding sectors (for the P sub-model). For instance, an impact coefficient of 1 signifies that the measure could achieve its full potential impact, while lower values suggest reduced influence. The simultaneous application of these measures across both the GHG and P models allows for a holistic assessment of sustainability interventions across the food supply chain. These impact coefficients are equivalent to elasticity coefficients between two variables. For example, converting all nitrogen fertilizer production to renewable ammonia and renewably sourced electricity would impact on the emissions from the fertilizer manufacturing sector with an impact coefficient of 1.0, but for all other sectors it would be 0. Reducing livestock numbers in Australia would have an impact factor on crop production of less than 1 because only about 40% of crop production in Australia supplies livestock feed.

2 Greenhouse Gas Emissions Sub-model

The greenhouse gas (GHG) emissions model relied on several key data sources. For its baseline, the data was collected from the Food and Agriculture Organization of the United Nations (FAOSTAT) Agrifood System Emissions (FAOSTAT, 2024). Relevant FAO reports and publications offered detailed methodologies and guidelines on how these emissions have been estimated. The data used ranged from 1961 to 2021 for historical insights, with forecasts extending to 2030 and 2050 where available. In cases where FAO forecasts were unavailable, extrapolation techniques such as Exponential Smoothing (ETS) and logistic functions were applied to project emissions up to 2050. To enable a more granular analysis, some FAO categories were presented with disaggregated emissions (e.g. rice cultivation from crop production), allowing for a detailed assessment of the sources and processes contributing to GHG emissions across the food supply chain.

Moreover, data for the Land Use Change in Australia has been collected from the DCCEW – Australia's emissions projections 2023 (Australian Government, 2023). This category includes emissions from “Agricultural and other land” and “Forest conversion to agriculture and other land”. It does not consider carbon sequestration from forests.

The detailed FAOSTAT datapoints used, how they’ve been labelled in the PACSAN model, the available FAOSTAT projections, and the forecasting techniques used (when applicable) are presented in Figure 1 and Figure 2 for Australia and China, respectively.

Figure 1: Data structure, data sources, disaggregation levels, FAO projections and forecasting function used for the Australian GHG model

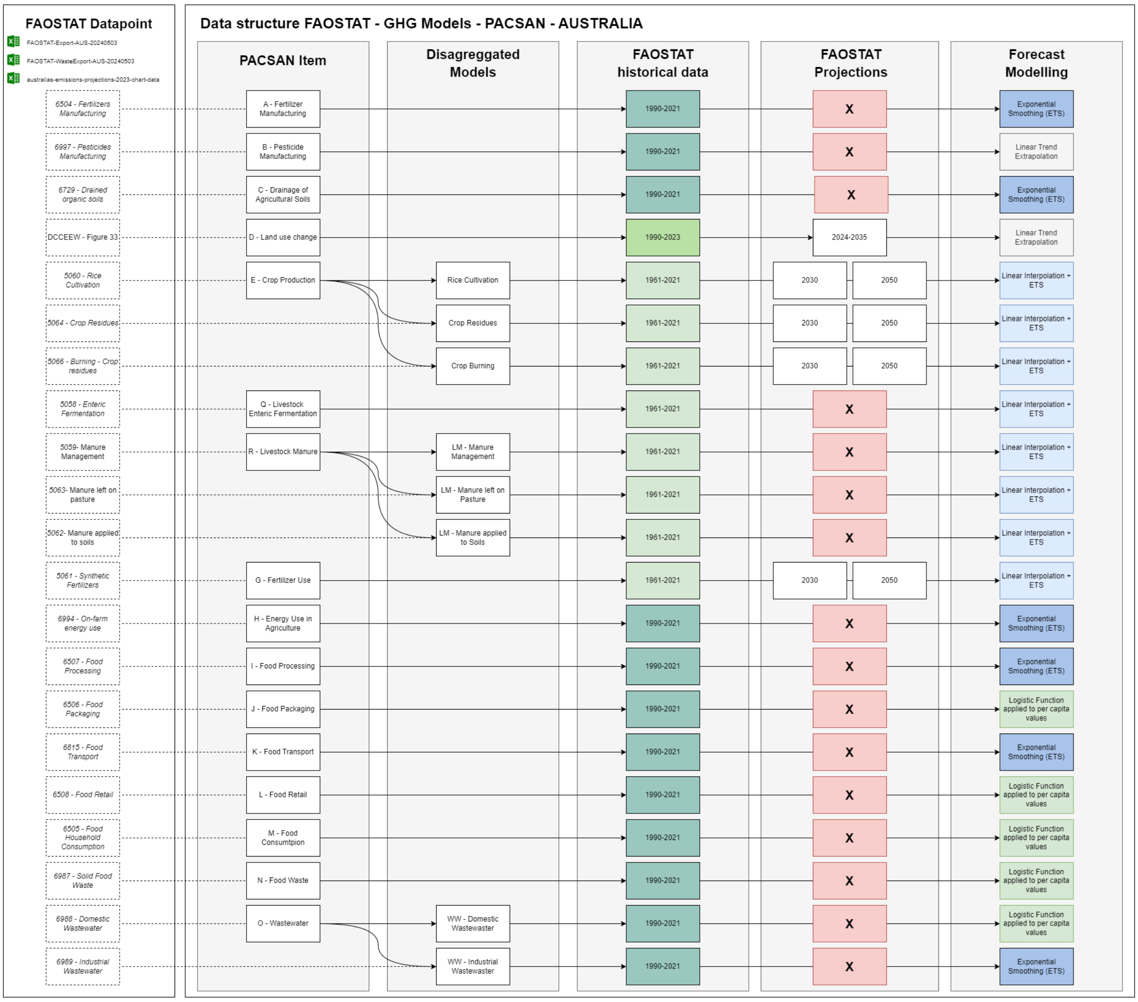
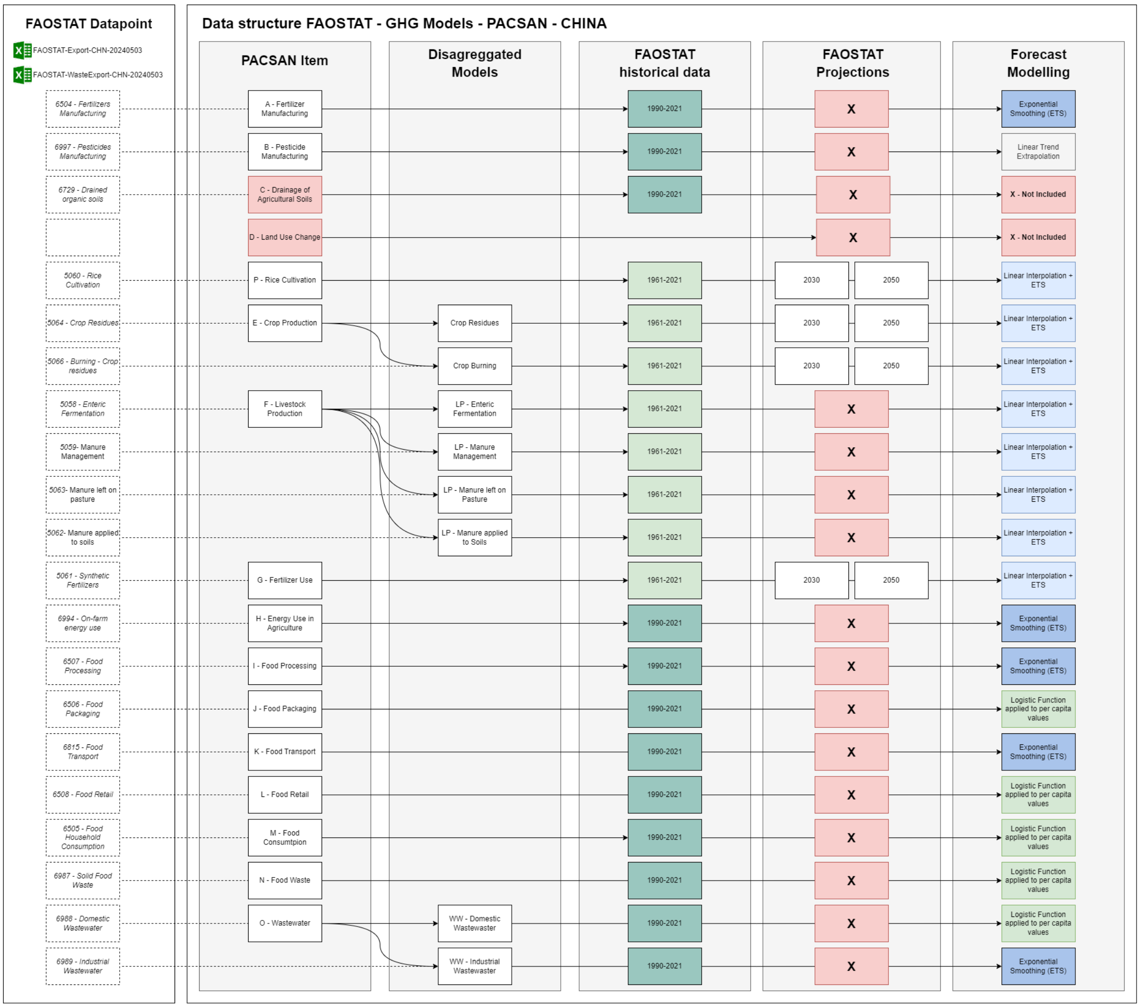


Figure 2: Data structure, data sources, disaggregation levels, FAO projections and forecasting function used for the Chinese GHG model



2.1 Emission categories

The FAOSTAT data provides comprehensive estimates of GHG emissions across various stages of agrifood systems. This includes emissions generated within the farm gate, emissions related to land use changes, as well as those associated with pre- and post-production food processes (FAOSTAT, 2023). **Table 2** offers an overview of these processes, categorized according to FAO classifications.

Table 2: Categories covered under the FAO Emissions dataset and Land use change description based on DCCEEW.

FAO Category	Description	Gases Covered
Fertilizer manufacturing	Critical input in crop production with significant energy use in ammonia production via the Haber-Bosch process. Emissions primarily from energy-intensive manufacturing processes.	CO_2; N_2O
Pesticide manufacturing	Energy consumption and emissions associated with producing pesticides.	CO_2; CH_4; N_2O
Drainage of agricultural soils	Greenhouse Gas (GHG) Emissions from Drained Organic Soils consist of the N2O and CO2 losses to the atmosphere due to the oxidation of the organic matter when organic soils are drained for agricultural activities	CO_2; N_2O
Land use change	This category includes emissions from *"Agricultural and other land"* and "*Forest conversion to agriculture and other land"* from the DCCEEW Emissions forecast. It does not consider carbon sequestration from forests.	CO_2; CH_4; N_2O
Crop production	*Rice Cultivation*: Methane emissions from anaerobic decomposition in paddy fields. *Crop Residues*: N_2O emissions from decomposing residues. *Crop Burning*: CH_4 and N_2O emissions from burning agricultural residues.	CH_4; N_2O
Livestock production	*Enteric Fermentation*: Methane emissions from digestion in ruminants. *Manure Management*: Emissions from manure handling and storage.	CH_4; N_2O
Fertilizer use	Direct and indirect N_2O emissions from nitrogen applied to soils.	N_2O
Energy use in agriculture	Emissions from the use of machinery, irrigation, and other energy-consuming agricultural activities.	CO_2; CH_4; N_2O
Food processing	Energy use and emissions from transforming raw agricultural commodities into consumable food products.	CO_2; CH_4; N_2O
Food packaging	Emissions linked to producing packaging materials like glass, plastic, aluminium, and paper.	CO_2; CH_4; N_2O
Food transport	Emissions from transporting food products across various stages of the supply chain.	CO_2; CH_4; N_2O
Food retail	Energy consumption and emissions from retail operations, including refrigeration and lighting.	CO_2; CH_4; N_2O; F-gases
Food consumption	Household emissions from cooking, refrigeration, and food preparation.	CO_2; CH_4; N_2O
Food waste	Methane emissions from anaerobic decomposition of organic waste in landfills.	CO_2; CH_4; N_2O
Wastewater	*Domestic Wastewater*: Emissions from wastewater generated by households. *Industrial Wastewater*: Emissions from wastewater generated in food-related industrial processes.	CH_4; N_2O

2.2 GHG cumulative emissions business-as-usual forecast

The cumulative emissions, in kilotons of carbon dioxide equivalent (kt of CO2-eq), from 2025 to 2050 are presented in **Figure 3** for Australia, and **Figure 4** for China.

The aggregation / disaggregation between countries might be slightly different, in accordance with the data structure presented in **Figure 1** and **Figure 2**.

Figure 3: Australia: Cumulative kt of CO2-eq from 2025 to 2050, per model category

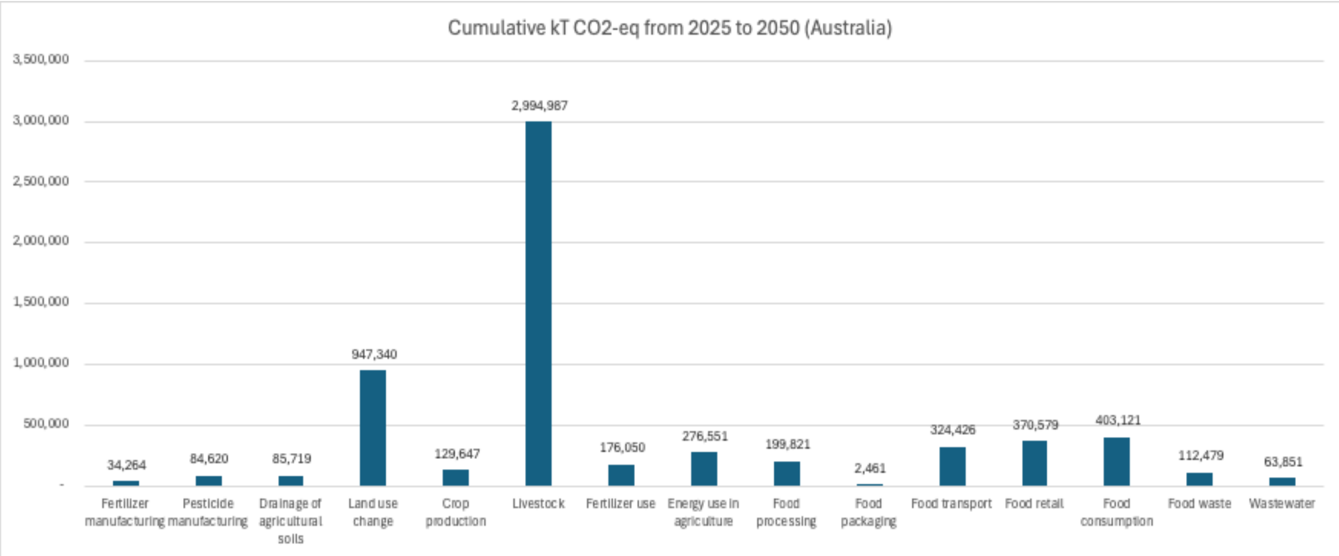
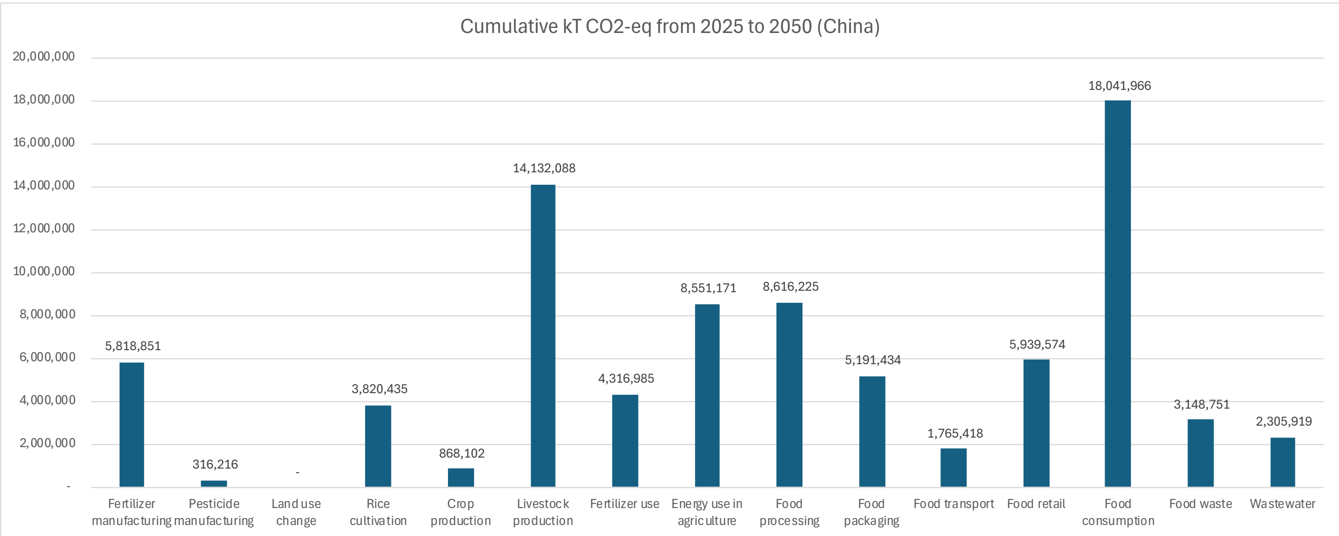


Figure 4: China: Cumulative kT of CO2-eq from 2025 to 2050, per model category



2.3 Impact coefficients

The following figures showcase the combinations of measures and sectors, highlighting the impact coefficient values applied to these combinations, which quantify the potential impact of each measure on its respective model sector.

This indicates the strength of the relationship of a measure applied to different sectors in the food value chain.

Figure 5: Impact coefficients applied to the Australian GHG model

Code	A	B	C	D	E	Q + R	G	H	I	J	K	L	M	N	O
Sector	Fertilizer manufacturing	Pesticide manufacturing	Drainage of agricultural soils	Land use change	Crop production	Livestock	Fertilizer use	Energy use in agriculture	Food processing	Food packaging	Food transport	Food retail	Food consumption	Food waste	Wastewater
1. Renewable fertiliser	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2. Nutrient productivity	0.80	0.10	0.10	0.10	1.00	0.10	1.00	0.10	-	-	-	-	-	-	0.10
3. Soil carbon	0.10	0.10	0.10	1.00	0.10	0.05	0.20	-	-	-	-	-	-	-	-
4. Crop type	0.10	0.10	0.10	0.10	1.00	0.10	1.00	0.10	-	-	-	-	-	-	-
5. Livestock feed additives	-	-	-	-	-	0.80	-	-	-	-	-	-	-	-	-
6. Energy productivity	0.10	0.50	-	-	-	-	-	1.00	1.00	1.00	1.00	1.00	1.00	-	-
7. Sustainable food choices	0.10	0.10	0.10	0.50	0.30	1.00	0.50	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
8. Food waste avoidance	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.50	0.50	1.00	0.50

Figure 6: Impact coefficients applied to the Chinese GHG model

Code	A	B	D	P	E	F	G	H	I	J	K	L	M	N	O
Sector	Fertilizer manufacturing	Pesticide manufacturing	Land use change	Rice cultivation	Crop production	Livestock production	Fertilizer use	Energy use in agriculture	Food processing	Food packaging	Food transport	Food retail	Food consumption	Food waste	Wastewater
1. Renewable fertiliser	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2. Nutrient productivity	0.80	0.10	-	1.00	1.00	0.10	1.00	0.10	-	-	-	-	-	-	0.10
3. Soil carbon	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4. Crop type	0.10	0.10	-	0.10	1.00	0.10	1.00	0.10	-	-	-	-	-	-	-
5. Livestock feed additives	-	-	-	-	-	0.80	-	-	-	-	-	-	-	-	-
6. Energy productivity	0.10	0.50	-	-	-	-	-	1.00	1.00	1.00	1.00	1.00	1.00	-	-
7. Sustainable food choices	0.10	0.10	-	0.50	0.30	1.00	0.50	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
8. Food waste avoidance	0.10	0.10	-	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.50	0.50	1.00	0.50

Universal assumptions:

- Fisheries and aquaculture were excluded from the model

Table 3: Assumptions and references for GHG model

Measure	Description	Assumptions (impact coefficients)	References
1. Renewable fertilizer	• Ammonia produced with renewable hydrogen	• Nitrogenous fertilizer could, in principle, be fully derived from green hydrogen or from nitrogen fixing crops • This measure impacts solely on the *Fertilizer manufacturing* sector • Fossil fuel use in mining and processing of phosphorus fertilizer can be electrified (diesel and gas) and provided by renewable sources	Butler and Denis-Ryan (2024) Wang, et al (2022)
2. Nutrient productivity	• On farm efficiency of fertilizer • Smart agriculture	• Improved efficiency of application of nitrogenous fertilizers will have the greatest impact on N2O emissions from *Fertilizer use*, as well as *Crop production*, and also from *Fertilizer manufacturing*, due to reduced demand for fertilizer • Impact coefficients for other primary production categories will be much lower	Karatay and Meyer-Aurich, (2018)

Measure	Description	Assumptions (impact coefficients)	References
3. Soil carbon sequestration	• Lock-up carbon in soils	• Soil sequestration of carbon will have the greatest impact in the *Land use change* sector in the Australian GHG accounts, and minor impacts across the primary production, as improved soils will reduce emissions from N2O through improved efficiency of N use	Lal (2016)
4. Crop type	• Rice varieties to reduce methane emissions	• Changing crop varieties to improve nutrient uptake will have the greatest impact on the category of *Crop production* and *Fertilizer use* • There will be a minor impact on other primary production sectors	Carlson et al. (2017)
5. Livestock feed additives	• Feed additives to reduce methanogenesis	• This measure will have an impact on the *Livestock* sector	Hegarty et al. (2021)
6. Energy productivity across food value chain	• Improving energy productivity along the food chain • Electrification including mobility, food processing increased renewables in the electricity supply	• This measure will impact across all the energy using sectors, where the majority of emissions arise from energy use, except for f-gases for cold chain which are relatively minor relative to energy use • The *Fertilizer manufacturing* and *Pesticide manufacturing* sector will have lower coefficients as they have emissions due to the use of fossil fuels for their chemical properties, which are covered under a separate measure	Australian Alliance for Energy Productivity (2017)
7. Sustainable food choices	• Shifting food consumption from livestock to plant-based	• This measure will have the largest impact on the *Livestock* sector, and on the *Crop production* sector due to feed for livestock, as well as a lower coefficient for other sectors e.g. as a result of reduced *Fertilizer manufacturing* and cold chain requirements in the food system	Xue, Q. et al. (2017) Willett W. et al. (2019)
8. Food waste avoidance	• Reducing avoidable food waste across the food chain	• Food waste avoidance impacts back up the entire food chain to varying degrees, with lower coefficients as a result of food exports from e.g. Australia	FIAL (2021)

3 Phosphorus Sub-model

The phosphorus (P) model draws on both historical and forecasted P demand values for Australia and China, using different sources to each geography. For Australia, the demand values were based on a model devised by Mohr, S. et al (UTS:ISF 2014), while the values for China were inferred from the work of Jiang et al (2019). These data points provide a baseline for understanding both current and future phosphorus usage in these countries.

The model integrates a range of sustainable P measures, categorized into *Demand Measures* and *Supply Measures*, as defined by Cordell and White (2013). Demand measures target reducing phosphorus demand by mitigating phosphorus use, e.g. by changing diets or improving agricultural efficiency. Supply measures, on the other hand, focus on alternative sources of phosphorus that do not rely on phosphate rock. For example, phosphorus can be recovered from human excreta or agricultural waste, reducing dependency on traditional phosphate rock mining. These categories allow for a comprehensive assessment of phosphorus supply risks, exploring both the potential to curb demand and identify alternative, more sustainable phosphorus supply routes.

The PACSAN model applies the same measures described in **Section 1** to both the demand-side and supply-side interventions for phosphorus in Australia and China.

3.1 Phosphorus demand forecast

The cumulative total phosphorus demand, in kilotons of phosphorus (kt of P) from 2025 to 2050 are presented in **Figure 7** for Australia, and **Figure 8** for China. These have been disaggregated into phosphorus used in *fertilizer for agriculture, livestock, aquaculture,* and *"non-food phosphorus use".* For Australia, no values for aquaculture have been considered.

Figure 7: Cumulative demand, in kilotons of P from 2025 to 2050 in Australia, per model category

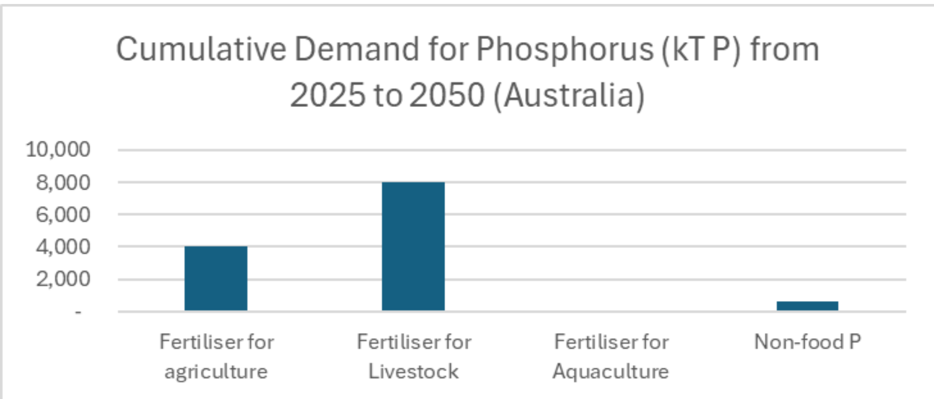
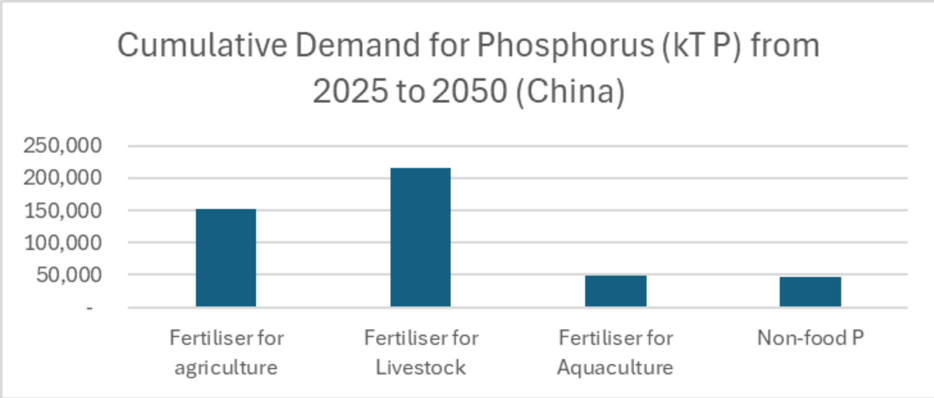


Figure 8: Cumulative demand, in kilotons of P from 2025 to 2050 in China, per model category



3.2 Coefficients applied

The following figures showcase the combinations of measures and *demand-* or *supply-side* strategies, highlighting the impact coefficient values applied to these combinations.

Figure 9: Impact coefficients applied to the Australian P model

Code	D-A	D-B	D-C	D-D	S-A	S-B	S-C	S-D
Sector	Fertiliser for agriculture	Fertiliser for Livestock	Fertiliser for Aquaculture	Non-food P	Crop Residue	Food Waste	Human Excreta	Manure
1. Renewable fertiliser	-	-	-	-	0.06	0.04	0.02	0.18
2. Nutrient productivity	0.25	0.25	-	0.10	-	-	-	-
3. Soil carbon	-	-	-	-	-	-	-	-
4. Crop type	0.10	0.10	-	0.10	-	-	-	-
5. Livestock feed additives	-	0.03	-	-	-	-	-	-
6. Energy productivity	-	-	-	-	-	-	-	-
7. Sustainable food choices	- 0.20	0.50	-	-	-	-	-	-
8. Food waste avoidance	0.40	0.10	-	-	-	-	-	-

Figure 10: Impact coefficients applied to the Chinese P model

Code	D-A	D-B	D-C	D-D	S-A	S-B	S-C	S-D
Sector	Fertiliser for agriculture	Fertiliser for Livestock	Fertiliser for Aquaculture	Non-food P	Crop Residue	Food Waste	Human Excreta	Manure
1. Renewable fertiliser	-	-	-	-	0.19	0.19	0.13	0.38
2. Nutrient productivity	0.45	0.20	0.30	0.50	-	-	-	-
3. Soil carbon	-	-	-	-	-	-	-	-
4. Crop type	0.20	0.08	0.10	0.20	-	-	-	-
5. Livestock feed additives	-	0.02	-	-	-	-	-	-
6. Energy productivity	-	-	-	-	-	-	-	-
7. Sustainable food choices	- 0.20	0.40	0.10	-	-	-	-	-
8. Food waste avoidance	0.45	0.20	0.50	-	-	-	-	-

Universal assumptions:

- **Fisheries and aquaculture** were included in the China model, but excluded from the Australia model (due to a lack of data availability)

- **Phosphate rock** supply is fixed at 30% of demand. This percentage is somewhat arbitrary, and rather is indicative that we need to diversify sources of phosphorus (away from dominant reliance on phosphate rock – especially imports - due to environmental, economic and geopolitical risks). The actual percentage is a point for discussion. E.g. Australia has a relatively high dependence on imports - it is currently the world's 5th largest importer of phosphate rock. China is the largest producer, however some estimates indicate that domestic production is forecast to peak by 2045 (Jiang et al, 2019).

- **Fertiliser use for crops versus pastures** has been fixed at a ratio of 37% usage on crops and 63% usage on pastures for Australia, based on previous phosphorus flow modelling through the Australian food system (Cordell et al, 2013). Fertiliser use for food versus non-food has been assumed at 90% food, 10% non-food crops (cotton etc).

Table 4: Assumptions and references for P model

Measure	Relevance for phosphorus	Assumptions (co-efficients)	References
1. Renewable fertiliser	• Recovery and recycling of phosphorus from manures, crop waste, food waste and sewage	• All organic waste by-products are theoretically available as raw feedstocks to produce renewable fertilisers. This model however includes: crop residues, manures, food waste, human excreta. • The availability of crop residues, manures, food waste, excreta in kt has been extrapolated from 2013. • The model assume that these renewable sources meet renewable fertiliser demand in a fixed ratio (for simplicity, however in reality this would be more dynamic and dependent on many market and technical factors).	Cordell et al (2013)
2. Nutrient productivity	• On farm efficiency of fertiliser • Smart agriculture • Tapping legacy phosphorus, soil testing and mapping	• Maximum Phosphorus Use Efficiency (PUE) for fertiliser use has been assumed the same for crops and pastures, however in reality these are different.	As above; Simpson et al 2011.
3. Soil carbon sequestration	• N/A	• Soil sequestration was considered not to have an impact, however in reality, it is likely that improved soil health will increase carbon sequestration and impact on phosphorus mobility	PACSAN Sydney workshop expert participant
4. Crop type	• Crop varieties that maximise nutrient use efficiency	• Efficiency gains associated with crop types is assumed the same for all crop types (e.g. grains vs pasture). In reality these will differ and could be modelled as such with future available data.	Richardson et al 2009; Gamuyao et al 2012; Cornish 2009.

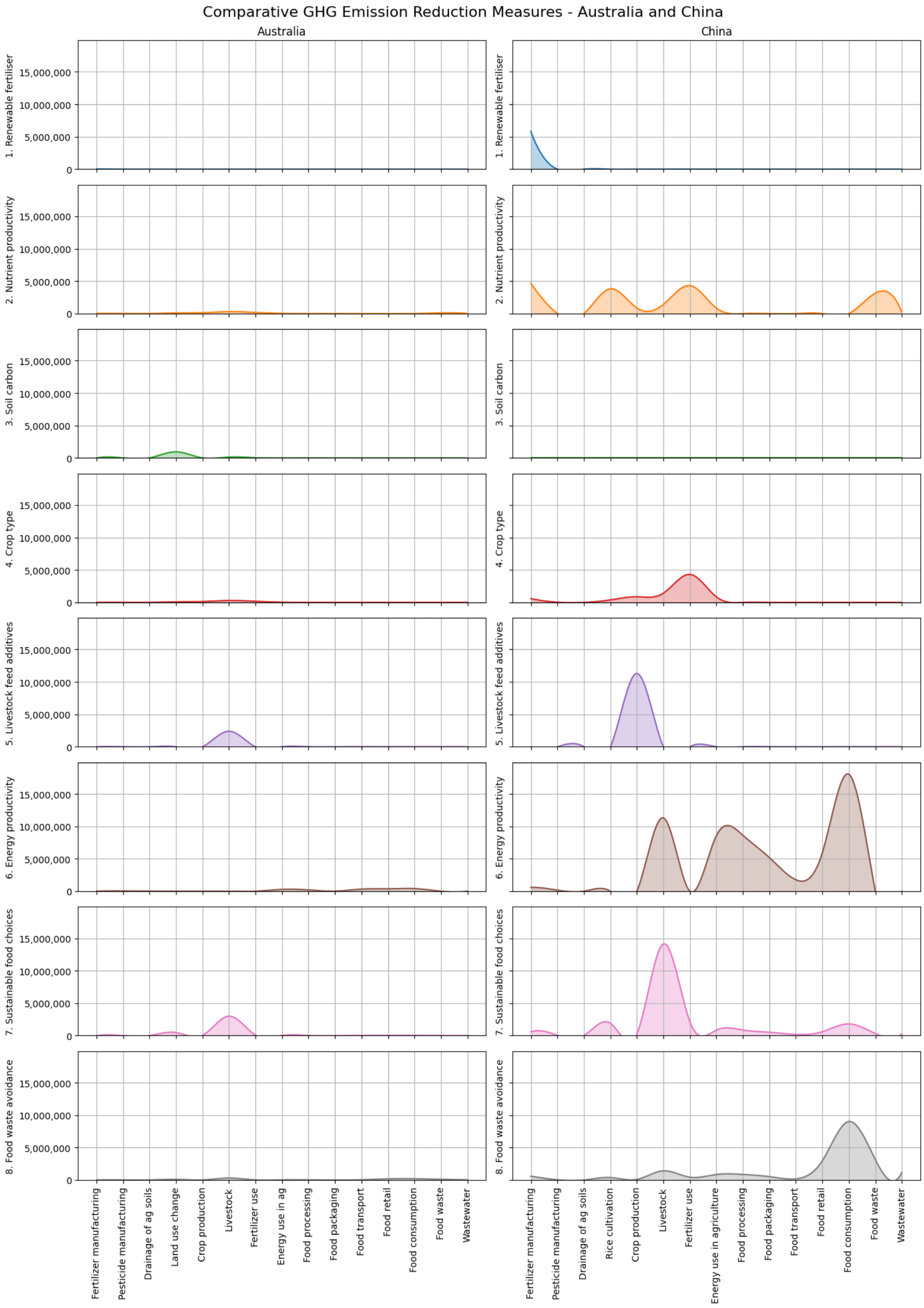
Measure	Relevance for phosphorus	Assumptions (co-efficients)	References
5. Livestock feed additives	• Phytase additives to maximise phosphorus uptake	• The use of phytase reduces overall phosphorus demand as a result of improved efficiency of feed absorption, hence reducing or eliminating the need for P feed additives	Afinah et al (2010)
6. Energy productivity across food value chain	• N/A	• There is no significant impact of improving energy productivity on phosphorus demand or use.	
7. Sustainable food choices	• Shifting food consumption from livestock to plant-based	• Reduction in phosphorus demand	Metson et al (2012)
8. Food waste avoidance	• Reducing avoidable food waste across the food chain	• Reduction in phosphorus demand back up the food value chain	FIAL (2021)

4 Synthesis

4.1 Cumulative GHG emissions reduction potential

The ridge plots in **Figure 11** illustrate the cumulative potential for reducing greenhouse gas (GHG) emissions through the application of various measures across different stages of the food supply chain. These plots highlight the total potential GHG emission reduction of each measure within both Australia and China.

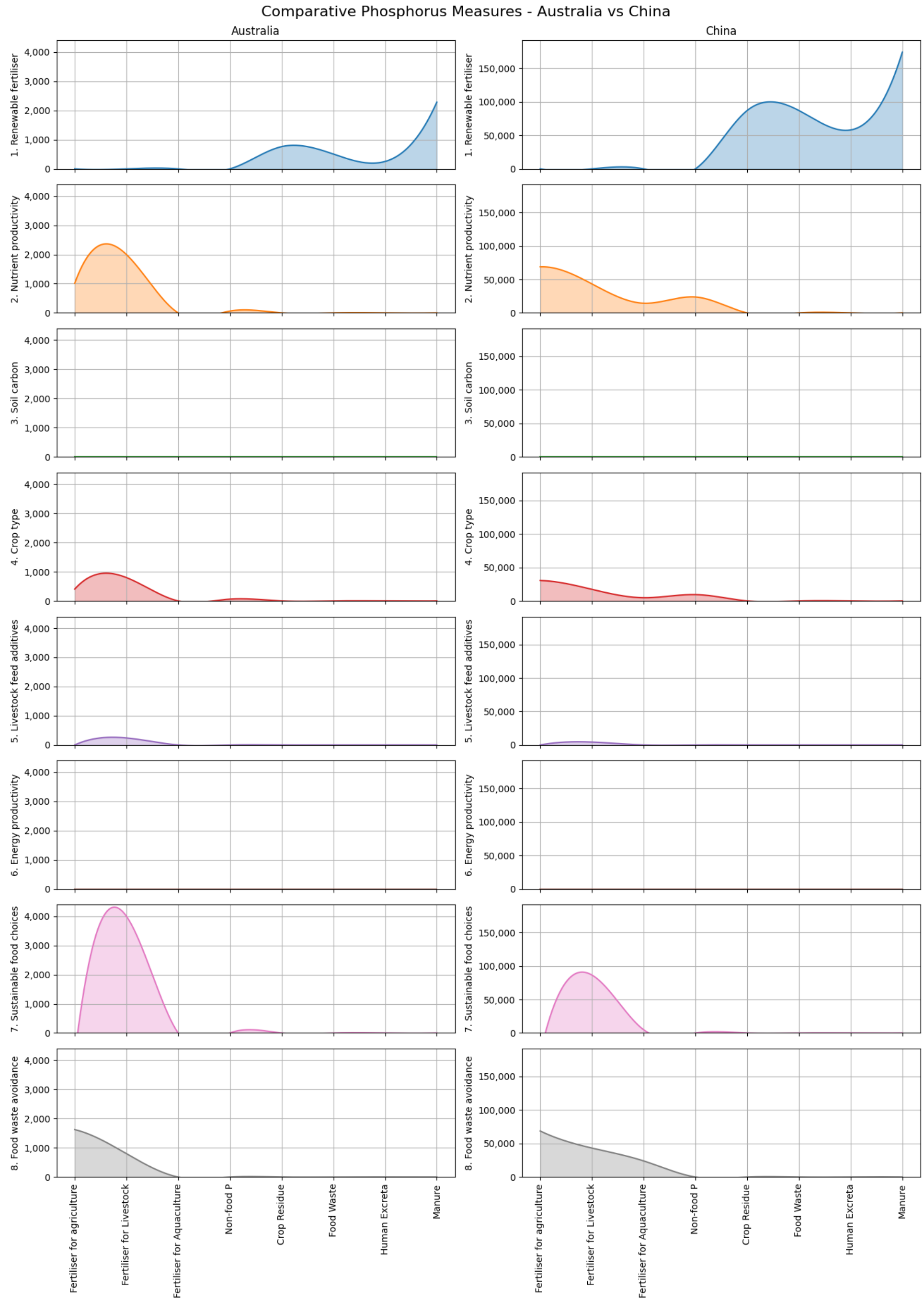
Figure 11: Cumulative potential for GHG emissions reduction by measure across food supply chain sectors in Australia and China.



4.2 Cumulative P demand reduction, supply alternatives and impact coefficients

The ridge plots depicted in **Figure 12** illustrate strategies for reducing phosphorus demand through measures 2 to 8 and enhancing alternative supply sources with measure 1. Specifically, measure 1 quantifies the maximum amount of phosphorus that can be recovered, assuming no alterations in current demand levels – meaning no demand-side measures are applied. Due to the significant differences in scale between Australia and China, two plots with distinct Y-axes values have been provided.

Figure 12: Cumulative potential for P demand reduction by measure across food supply chain sectors in Australia and China. Due to the significant differences in scale between the two countries, the plots are presented with distinct Y-axis values.



4.3 Synthesis of measures across impact categories and countries

To evaluate the combined potential for reducing GHG emissions and phosphorus (P) demand through the application of each measure, we:

- **Assumed Full Implementation Potential:** Considered each measure as being applied to its maximum feasible extent.
- **Analysed Dual Impact**: Assessed the impact of each measure on both GHG emissions and P demand for Australia and China.
- **Quantified the Distribution of Potential Reductions**: Evaluated the potential impact as a percentage within each sub-model (either GHG or P), reflecting the measure's effectiveness in reducing emissions or demand.

The results are summarised on **Table 3** and **Table 4** and **Figure 13.**

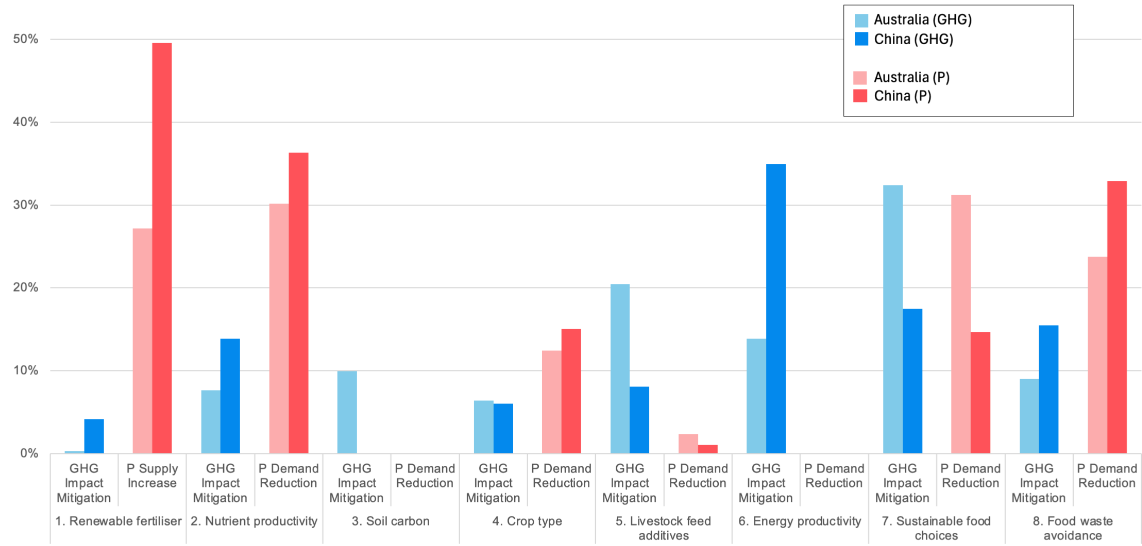
Table 5: GHG emissions' reduction potential and P demand reduction potential across Australia and China - % of total

	GHG Reduction Potential		P Demand Reduction Potential	
Measure	**Australia**	**China**	**Australia**	**China**
1. Renewable fertiliser	0%	4%	27%	50%
2. Nutrient productivity	7%	12%	22%	18%
3. Soil carbon	10%	0%	0%	0%
4. Crop type	6%	6%	9%	8%
5. Livestock feed additives	21%	8%	2%	1%
6. Energy productivity	14%	36%	0%	0%
7. Sustainable food choices	33%	18%	23%	7%
8. Food waste avoidance	9%	16%	17%	17%

Table 6: GHG emissions' reduction potential and P demand reduction potential across Australia and China (kt for 2025-2050)

	GHG reduction potential kt of CO_2-eq (2025-2050)		P demand or supply potential kt of (2025-2050)	
	AUSTRALIA	CHINA	AUSTRALIA	CHINA
1. Renewable fertiliser	34,264	5,818,851	3,808	406,552
2. Nutrient productivity	778,415	16,191,142	3,078	150,175
3. Soil carbon	1,165,724	-	-	-
4. Crop type	748,045	8,448,963	1,269	62,162
5. Livestock feed additives	2,395,990	11,305,670	240	4,325
6. Energy productivity	1,622,696	48,845,780	-	-
7. Sustainable food choices	3,791,365	24,430,781	3,186	60,776
8. Food waste avoidance	1,056,843	21,632,173	2,424	136,035
Total	11,593,342	136,673,360	14,005	820,026

Figure 13: Distribution of GHG emissions' reduction potential and P demand reduction potential (2025-2050).



5 Readiness-to-implement workshop outcomes

The following table shows the outcomes of discussions by workshop participants for the Shanghai and Sydney workshops, related to the eight measures.

Measure	Readiness to implement (Participant views/perspectives)
1. Renewable fertilizer	**China**: Emphasis on phosphorus recovery from waste and recycling. Stakeholders mentioned phosphorus inefficiencies and recovery from organic sources as key strategies. **Australia**: Fertilizer manufacturing, especially low-emission options, was noted, including a need for local production and infrastructure to handle phosphorus recovery.
2. Nutrient productivity	**China**: Smart agricultural practices and improving resource efficiency, especially phosphorus use efficiency is needed. **Australia**: The role of legumes in nutrient-specific crops is crucial, and the importance of soil mapping for targeted nutrient application necessary.
3. Soil carbon sequestration	**Australia**: Soils as a carbon sink were highlighted, and carbon management in soils was a priority, with a note that soil carbon and nutrient management are interconnected.
4. Crop type	**China & Australia**: No comments.
5. Livestock feed additives	**China**: Livestock emissions are a key focus, with targets for methane reduction. Potentially achieved through additives. **Australia**: Emphasis on livestock emissions reductions through feed additives and faster time to slaughter to reduce overall emissions seem to be considered.
6. Energy productivity across food value chain	**China & Australia**: Renewable energy integration into the food system, including improving energy productivity is a key strategy.
7. Sustainable food choices	**China**: Promoted a plant-forward diet as a key solution for reducing food-related emissions. **Australia**: Discussion on shifting consumer behaviour toward plant-based diets was highlighted as essential but challenging.
8. Food waste avoidance	**China**: Addressed the need to reduce food waste at various stages of the food system, particularly on the consumption side. **Australia**: Extensive focus on reducing food waste, particularly in households, and the role of packaging and food waste recovery strategies.

References

Afinah, S.; Yazid, A.M.; Anis Shobririn, M.H.; Shuhaimi, M. Phytase: Application in food industry: Review article. Int. Food Res. J. 2010, 17, 13–21.

Australian Alliance for Energy Productivity (2017) Innovation to Improve Energy Productivity in the Food Value Chain. www.a2ep.org.au

Australian Government, Australia's emissions projections 2023 - DCCEEW, E. Department of Climate Change, the Environment and Water, Editor. 2023

Butler, C. & Denis-Ryan, A. (2024). How mining could ignite Australia's green hydrogen boom. Institute for Energy Economics and Financial Analysis.

Carlson, K., Gerber, J., Mueller, N. et al. (2017) Greenhouse gas emissions intensity of global croplands. Nature Climate Change 7, 63–68 (2017). https://doi.org/10.1038/nclimate3158

Cordell, D. and S. White, Sustainable Phosphorus Measures: Strategies and Technologies for Achieving Phosphorus Security. Agronomy, 2013. 3(1): p. 86-116.

Cordell, D., Jackson, M. White, S. (2013), Phosphorus flows through the Australian food system: Identifying intervention points as a roadmap to phosphorus security, Environmental Science & Policy, 2(9) 87–102.

Cornish, P. Research directions: Improving plant uptake of soil phosphorus, and reducing dependency on input of phosphorus fertiliser. Crop Pasture Sci. 2009, 60, 190–196.

FAOSTAT. FAOSTAT - Food and Agriculture Organization of the United Nations. [cited 2024; Available from: https://www.fao.org/faostat/en/#data.

FAOSTAT. FAOSTAT Domain Emissions Totals. Methodological note, release October 2023. 2023 [cited 2023; Available from: https://files-faostat.fao.org/production/GT/GT_en.pdf.

FIAL (2021) The National Food Waste Strategy Feasibility Study – Final Report www.fial.com.au/sharing-knowledge/food-waste

Gamuyao, R.; Chin, J.H.; Pariasca-Tanaka, J.; Pesaresi, P.; Catausan, S.; Dalid, C.;Slamet-Loedin, I.; Tecson-Mendoza, E.M.; Wissuwa, M.; Heuer, S. The protein kinase Pstol1 from traditional riceconfers tolerance of phosphorus deficiency. Nature 2012, 488, 535–541.

Hegarty, R.S. et al. (2021) An evaluation of emerging feed additives to reduce methane emissions from livestock. Edition 1. A report coordinated by Climate Change, Agriculture and Food Security (CCAFS) and the New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC) initiative of the Global Research Alliance (GRA)

Jiang, S. et al. Phosphorus footprint in China over the 1961–2050 period: Historical perspective and future prospect, Science of The Total Environment, Volume 650, Part 1, 2019, pp 687-695.

Karatay, Y. N. and Meyer-Aurich, A. (2018). A model approach for yield-zone-specific cost estimation of greenhouse gas mitigation by nitrogen fertilizer reduction. Sustainability, 10(3), 710. https://doi.org/10.3390/su10030710

Lal, R. (2016) Soil health and carbon management, Food and Energy Security 5(3): 212–222

Metson, G. S., Bennett, E. M., & Elser, J. J. (2012). The role of diet in phosphorus demand. Environmental Research Letters, 7(4). https://doi.org/10.1088/1748-9326/7/4/044043

Richardson, A.E.; Hocking, P.J.; Simpson, R.J.; George, T.S. Plant mechanisms to optimise access to soil phosphorus. Crop Pasture Sci. 2009, 60, 124–143.

Simpson, R.; Oberson, A.; Culvenor, R.A.; Ryan, M.; Veneklaas, E.; Lambers, H.; Lynch, J.; Ryan, P.; Delhaize, E.; Smith, A.; et al. Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems. Plant Soil 2011, 349, 89–120.

UTS:ISF (2014), Adapting to future phosphorus scarcity: investigating potential sustainable phosphorus measures and strategies, Phase II of the Australian Sustainable Phosphorus Futures project, Institute for Sustainable Futures, prepared for Rural Industries Research & Development Corporation, 31st May, 2012, pp.57.

Wang, C., Walsh, S., Longden, T., Palmer, G., Lutalo, I., & Dargaville, R. (2022). Optimising renewable generation configurations of off-grid green ammonia production systems considering Haber-Bosch flexibility. https://doi.org/10.31223/x5vp9g

Willett W. et al. (2019) Food in the Anthropocene: the EAT Lancet Commission on healthy diets for sustainable food systems. Lancet; 393 (10170): 447-92 https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(18)31788-4/fulltext#

Xue, Q. et al. (2017) Mitigating greenhouse gas emissions in agriculture: From farm production to food consumption, Journal of Cleaner Production 149 (2017) pp1011-1019