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Animal Production Science

Supplementary Material

Environmental impacts of Australian pork in 2020 and 2022 determined using lifecycle assessments

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Benchmarking by MMS

Environmental impacts per kilogram of liveweight were determined by production system. Key production data are outlined in Table S1. The benchmarking data for MMS breakdown, energy, water, and herd production were derived from inventory data collected for 43 piggeries in FY22. The analysis used the weighted average national herd diet composition and sourcing data. The national herd breakdown by state was applied to the electricity and water grids. In effect, the benchmarking piggeries are representative of equivalent Australian production, e.g., 100% CAP production in Australia, as opposed to 100% CAP production weighted to where 100% CAP production occurs. The data in Table S1 underpin the results reported in Table S9 and together represent average production metrics and environmental impacts for standard housing and MMS in Australia.

Table S1. Summary data for benchmarking by MMS analysis.

	Units	**100% CAP**	**Partial CAP**	**100% C, no CAP**	**DL/C**	**DL/O**	**O**
Conventional, CAP	% of production	100%	46%	0%	0%	0%	0%
Conventional, no CAP	% of production	0%	38%	100%	55%	0%	0%
Deep Litter	% of production	0%	16%	0%	45%	60%	0%
Outdoor	% of production	0%	0%	0%	0%	40%	100%
Progeny FCR	kg feed/kg LW	2.4	2.4	2.4	2.3	2.3	2.2
Herd Feed Conversion	kg feed/kg DW	3.6	3.8	3.8	3.6	3.8	4.0
Progeny sold/sow.yr	No.	22.1	20.7	21.2	20.5	17.0	19.0
DW progeny sold/sow.yr		1890.1	1656.5	1672.6	1639.4	1314.8	1332.5
Total energy on-farm (used, generated & sold)	MJ/t LW	-56.9	660.3	955.1	981.6	780.9	467.1
On-farm energy (incl. incl. renewables)	MJ/t LW	1337.1	1210.3	955.1	981.6	780.9	467.1
On-farm energy (excl. incl. renewables)	MJ/t LW	775.9	942.2	955.1	981.6	780.9	467.1
Water consumption	L/t LW	35,084	24,939	22,472	19,370	8,831	15,045
Effluent irrigation	% of total	37%	48%	37%	35%	0%	0%

Table S2. Average feedmilling inputs for FY20 and FY22, reported per 1000kg of feed milled

	FY20 Average inputs	FY20 Range	FY22 Average inputs	FY22 Range
Grid electricity (kWh)	20.8	0.2 – 41.0	20.3	0.8 – 41.0
Electricity from solar (kWh)	0.2	0.0 – 0.9	0.2	0.0 – 0.5
LPG (MJ)	17.9	0.0 – 255.0	15.9	0.0 – 255.0
Natural gas (MJ)	88.6	0.6 – 67.0	83.0	0.6 – 67.0
Diesel (L)	2.5	0.0 – 7.6	2.3	0.0 – 7.2
Petrol (L)	0.1	0.0 – 0.2	0.0	0.0 – 0.1
Freshwater (L)	44.3	23.1 – 88.7	46.3	22.9 – 88.7

Ranges between inputs in **Table S2** vary according to the major energy source used in milling, e.g., grid electricity or diesel.

Table S3. Net LU and dLUC emissions (reported in Mt CO_2-e by state and for Australia) from cropland, averaged over 10 years and excluding land use emissions from perennial woody crops

	Units	**2020***	**2021***
NSW	Mt CO_2-e	1.74	2.00
QLD	Mt CO_2-e	1.33	1.21
VIC	Mt CO_2-e	-0.28	-0.39
WA	Mt CO_2-e	-0.33	-0.43
SA	Mt CO_2-e	-1.05	-1.09
TAS	Mt CO_2-e	0.10	0.10
NT	Mt CO_2-e	0.02	0.02
Australia	Mt CO_2-e	**1.52**	**1.43**

**Data from Australia's National Greenhouse Accounts* (2023)

Primary and further processing

Table S4. Average inputs for primary processing of Australian pork, reported per tonne of HSCW, for FY20 and FY22

	FY20 Average Inputs	*FY20 Range*	FY22 Average Inputs	*FY22 Range*
Grid electricity (kWh)	148.8	*82.6 – 277.2*	147.4	*81.2 – 278.0*
LPG (MJ)	15.8	*0.0 – 87.1*	16.4	*00.0 – 87.1*
Natural gas (MJ)	228.3	*0.0 – 730.8*	347.4	*0.0 – 871.6*
Diesel (L)	0.5	*0.0 – 2.6*	0.5	*0.0 – 2.6*
Fuel oil (L)	0.8	0.0 – 4.2	0.0	0.0 – 2.1
Coal (t)	0.01	0.0 – 0.04	0.01	0.0 – 0.03
Petrol (L)	0.1	*0.0 – 0.1*	0.1	*0.0 – 0.3*
Refrigerant (kg)	0.2	*0.1 – 0.5*	0.2	*0.1 – 0.5*
Freshwater (L)	6,340	*1,525 – 12,664*	6,574	*1,530 – 9,854*

Table S5. Average inputs for further processing of Australian pork, reported per tonne of CCW, for FY20 and FY22

	FY20 Average Inputs	*FY20 Range*	FY22 Average Inputs	*FY22 Range*
Grid electricity (kWh)	252.6	*131.7 – 522.4*	233.9	*131 – 6341*
LPG (MJ)	6.7	*0.0 – 19.7*	6.7	*0.0 – 19.7*
Natural gas (GJ)	405.8	*255.3 – 683.5*	280.0	*255.3 – 1950.0*
Refrigerant (kg)	0.1	*0.05 – 0.1*	0.1	*0.05 – 0.1*
Freshwater (L)	1,372	*480 – 2,154*	1,372	*480 – 2,154*

Table S6. Summary data used to model environmental impacts per kilogram of pork at the retail shelf for FY20 and FY22

	Units	**FY20**	**FY22**
Transport to warehousing	km	366.9	366.9
Transport to retail	km	188.5	189.0
Fossil energy consumption	MJ/kg pork	2.74	2.79
Waste	kg/kg pork	0.14	0.15
Water consumption*	L/kg pork	0.6	0.6
Emission intensity#	kg CO_2-e/kg pork	0.75	0.75

**Water consumed at warehousing and retail sites.*

[#]Scope 1, 2 and 3 emissions from operation of warehousing and retail facilities (excludes emissions from waste treatment and product transport).

Sensitivity analysis methodology

Producers were surveyed regarding major source regions for Australian feed grains and proteins. Where possible, regionally specific background processes from AusLCI (ALCAS 2017) were used and irrigation water application rates were determined from published data. The sensitivity of the national herd and individual farms' freshwater consumption impacts to these regionally specific irrigation rates was tested.

The sensitivity of the model was tested for assumptions regarding feed waste (% of total feed fed). Producers were surveyed and asked to provide an estimate of feed waste. However, given that feed waste cannot be measured, there was a degree of uncertainty associated with these estimates. For verification, industry experts were consulted regarding average feed waste for different housing or feeding systems (Sara Willis & Alan Skerman, pers. comms). Industry estimates were then compared with estimates from PigBal (Skerman *et al.* 2015), which calculates predicted feed waste. For a 100% conventional piggery, the sensitivity of a reported feed waste of 4% was compared with a predicted feed waste of 10%.

The sensitivity of the emission intensity (and eutrophication potential) of outdoor pig production to dietary crude protein (CP) was also tested. The national average grower diet for FY22 was 17.8% crude protein. Analysis of a 16.5% crude protein grower diet (see Pomar et al. (2021)) was conducted to compare nitrous oxide emissions from manure and N eutrophication potential.

Table S7. Environmental impacts for the National Herd for FY20 and FY22, reported per kilogram of liveweight

	Units	**National Herd FY20**	**2.SD (±)**	**National Herd FY22**	**2.SD (±)**
GHG emissions	kg CO_2-e	3.0	0.1	3.0	0.1
GHG emissions - LU & dLUC	kg CO_2-e	0.4	0.07	0.3	0.03
Total GHG emissions	**kg CO_2-e**	**3.4**	**0.2**	**3.3**	**0.2**
Fossil energy use	MJ	12.9	0.5	13.4	0.5
Renewable energy generated and consumed	MJ	0.1	0.0	0.1	0.0
Freshwater consumption	L	93.8	24.9	52.5	15.7
Water stress	L H_2O-e	68.4	18.1	43.2	12.9
Land occupation	m^2	12.0	3.2	12.7	3.8
Total freshwater eutrophication potential	kg P	2.1e-04	2.5e-05	2.3e-04	3.6e-05
Total marine eutrophication potential	kg N	7.6e-03	2.8e-04	9.9e-03	4.3e-04

Water scarcity ranged from 14.3±3.2 to 13.6±3.5 in FY20 and FY22, respectively.

Table S8. GHG emissions for the National Herd for FY20 and FY22, reported per kilogram of liveweight, as Scope 1, 2 and 3 emissions

	Units	**National Herd FY20**	**National Herd FY22**
Scope 1 - Enteric methane	kg CO_2-e	0.2	0.2
Scope 1 - Emissions from MMS	kg CO_2-e	1.4	1.5
Scope 1 - Emissions from energy	kg CO_2-e	0.1	0.1
Scope 2 - Grid electricity	kg CO_2-e	0.1	0.1
Scope 3 - Emissions from energy & grid electricity	kg CO_2-e	0.0	0.0
Scope 3 - Feed and transport	kg CO_2-e	1.1	1.2
Subtotal	kg CO_2-e	***3.0***	***3.0***
Scope 3 - LU & dLUC	kg CO_2-e	0.4	0.3
Total	kg CO_2-e	**3.4**	**3.3**

Table S9. Environmental impacts per kilogram of liveweight produced in standard housing and manure management systems in FY22

	Units	**100% CAP**	**Partial CAP**	**100% C, No CAP**	**C/DL**	**O/DL**	**O**
GHG emissions	kg CO_2-e	1.8	2.7	4.4	3.4	2.0	2.1
GHG emissions - LU & dLUC	kg CO_2-e	0.3	0.3	0.3	0.3	0.3	0.3
Total GHG emissions	**kg CO_2-e**	**2.1**	**3.0**	**4.7**	**3.7**	**2.3**	**2.4**
Fossil energy use	MJ	11.7	12.6	13.1	15.1	12.7	12.6
Renewable energy generated and consumed	MJ	0.56	0.28	0.04	0.02	0.01	0.01
Renewable energy generated and sold	MJ	0.27	0.01	0.00	0.00	0.00	0.00
Freshwater consumption	L	63.6	52.9	51.3	49.5	38.4	47.6
Water stress	L H_2O-e	49.7	43.1	41.7	40.5	33.6	40.5
Land occupation	m^2	12.4	12.7	12.5	12.4	12.8	14.4
Total freshwater eutrophication potential	kg P	1.6e-04	1.7e-04	1.7e-04	1.7e-04	5.2e-04	1.2e-03
Total marine eutrophication potential	kg N	1.1e-02	1.0e-02	1.1e-02	9.4e-03	9.5e-03	1.1e-02

Table S10. Total emissions (incl. LU and dLUC) for the Australian pork industry in FY20 and FY22, reported by gas

	Units	**FY20**	**FY22**
Carbon dioxide (CO_2)	t CO_2-e	546,676	604,030
Nitrous oxide (N_2O)	t CO_2-e	221,076	243,500
Methane (CH_4)	t CO_2-e	796,167	903,672
Other minor gases	t CO_2-e	3,145	3,431
Carbon dioxide (LU & dLUC)	t CO_2-e	229,804	161,029
Total	**t CO_2-e**	**1,796,869**	**1,915,661**

Table S11. Greenhouse gas emissions for the Australian pork industry in FY20 and FY22, reported as totals and net (of traded ACCUs), including LU and dLUC emissions

	Units	**FY20**	**FY22**
GHG emissions, excl. LU & dLUC	*t CO_2-e*	1,567,064	1,754,632
GHG emissions – LU & dLUC[#]	*t CO_2-e*	174,852	161,029
Total GHG emissions	*t CO_2-e*	*1,796,869*	*1,915,661*
ACCUs generated & sold to private market	*No.*	8,560	73,716
Net GHG emissions	*t CO_2-e*	**1,805,429**	**1,989,377**

Table S12. Total emissions (incl. LU and dLUC) for the Australian pork industry, reported as Scope 1, 2 and 3 emissions, and sectoral emissions (Scope 1 & 2) for FY20 and FY22

	Units	**National Herd FY20**	**National Herd FY22**
Scope 1 - Enteric methane	tonnes CO_2-e	96,199	103,453
Scope 1 - Emissions from MMS	tonnes CO_2-e	767,603	848,959
Scope 1 - Emissions from energy	tonnes CO_2-e	29,684	33,574
Scope 2 - Grid electricity	tonnes CO_2-e	76,735	77,509
Scope 3 - Emissions from energy & grid electricity	tonnes CO_2-e	17,422	17,024
Scope 3 - Feed and transport	tonnes CO_2-e	579,422	674,113
Subtotal	tonnes CO_2-e	***1,567,064***	***1,754,632***
Scope 3 - LU & dLUC	tonnes CO_2-e	229,804	161,029
Total	tonnes CO_2-e	**1,796,869**	**1,915,661**
Total sectoral emissions (Scope 1 & 2)	tonnes CO_2-e	1,016,858	1,016,858
ACCUs generated & sold to the private market	No.	**8,560**	**73,716**
Net sectoral emissions (Scope 1 & 2)	tonnes CO_2-e	978,781	1,137,211

Table S13. Environmental impacts per kilogram of pork ready for distribution to retail for Australia for FY20 and FY22

	Units	**Australia FY20**	**2.SD (±)**	**Australia FY22**	**2.SD (±)**
GHG emissions	kg CO_2-e	5.3	0.2	5.4	0.2
GHG emissions - LU & dLUC	kg CO_2-e	0.7	0.1	0.4	0.1
Total GHG emissions*	**kg CO_2-e**	**5.9**	**0.4**	**5.8**	**0.3**
Fossil energy use	MJ	26.1	0.8	26.5	0.9
Renewable energy generated & consumed	MJ	0.2	0.0	0.2	0.0
Freshwater consumption	L	160.4	42.5	74.9	27.7
Water stress	L H_2O-e	116.7	30.9	22.7	6.8
Land occupation	m^2	18.8	5.0	20.2	6.0
Total freshwater eutrophication potential	kg P	3.5e-04	1.3e-04	3.9e-04	4.4e-05
Total marine eutrophication potential	kg N	1.2e-02	4.4e-04	1.6e-02	6.5e-04

Sensitivity analysis results

Assumptions regarding water related impacts were found to be highly sensitive to source region for grain. The presence of irrigated grain within a region had a dramatic effect on piggery freshwater consumption. Because few piggeries were able to confirm exact amounts of grain sourced from farms that utilised irrigation, regional averages were used that reflected water use and grain production reported in regional statistics. Only a very small fraction of grain supply arose from irrigated sources (for example, 9.7% in NSW) and market data were unclear regarding whether feed grain was irrigated at the same rate as other grain types (for example, grain for human consumption or export). Consequently, the attributed water was uncertain. To examine the impact, we revised the assumption to reduce the grain sourced from irrigation down by 50%, which resulted in a 30% decrease in freshwater consumption at the national level for 2020. For individual farms in the southern grain region this was even more sensitive: reducing the source of grain from irrigation from the regional average to “zero” (assuming a farm could conceivably source all grain from dryland farms only), resulted in an 58% reduction in freshwater consumption use for highly irrigation exposed farms.

In 100% C production, GHG emissions were shown to be sensitive to assumptions regarding the fraction of feed waste. A reported feed waste fraction (farm estimate) of 4% was compared with a PigBal (Skerman *et al.* 2015) estimate of 10%. GHG emissions per kilogram of liveweight were 18% higher in the latter case (see Table S14), compared with the 4% feed waste analysis, and 14% higher than the average for 100% conventional production (see **Table S9**). Given this degree of sensitivity, ongoing work is needed to monitor and minimise feed waste in C systems. Other housing/MMS were much less sensitive to feed waste.

The model was found to exhibit some sensitivity to dietary CP in O production (see Table S15). A 16.5% CP grower diet (compared with 17.8% in **Table S9**) resulted in 2.5% lower GHG emissions (excl. LU & dLUC) per kilogram of LW.

Table S14. Environmental impacts per kilogram of liveweight for a 100% conventional piggery with 4% and 10% feed waste

	Units	**4% feed waste**	**10% feed waste**
GHG emissions	kg CO_2-e kg LW^{-1}	4.3	5.1
GHG emissions - LU & dLUC	kg CO_2-e kg LW^{-1}	0.3	0.3
Total GHG emissions	**kg CO_2-e kg LW^{-1}**	4.6	5.4
Fossil energy use	MJ kg LW^{-1}	13.1	13.1
Renewable energy generated and consumed	MJ kg LW^{-1}	0.0	0.0
Freshwater consumption	L kg LW^{-1}	51.3	51.3
Water stress	L H_2O-e kg LW^{-1}	41.7	41.7
Land occupation	m^2 kg LW^{-1}	12.5	12.5
Total freshwater eutrophication potential	kg P kg LW^{-1}	1.7e-04	1.7e-04
Total marine eutrophication potential	kg N kg LW^{-1}	1.1e-02	1.1e-02

Table S15. Environmental impacts per kilogram of liveweight for outdoor production with a low crude protein grower diet.

	Units	**Outdoor (low CP grower diet)**
GHG emissions	kg CO_2-e kg LW^{-1}	2.1
GHG emissions - LU & dLUC	kg CO_2-e kg LW^{-1}	0.3
Total GHG emissions	**kg CO_2-e kg LW^{-1}**	**2.3**
Fossil energy use	MJ kg LW^{-1}	12.6
Renewable energy generated and consumed	MJ kg LW^{-1}	0.0
Freshwater consumption	L kg LW^{-1}	47.6
Water stress	L H_2O-e kg LW^{-1}	40.5
Water scarcity	m^3 kg LW^{-1}	14.5
Land occupation	m^2 kg LW^{-1}	14.4
Total freshwater eutrophication potential	kg P kg LW^{-1}	1.2e-03
Total marine eutrophication potential	kg N kg LW^{-1}	1.1e-02

Table S16. Comparison of total eutrophication potential, phosphate equivalent, of Australian retail pork with international studies

	Reference	*Units*	Eutrophication Potential
Australia	This study	g PO_4-eq/kg LW	4.1 – 5.3
Australia	This study	g PO_{4eq}/kg retail pork	7.1 – 8.8
Spain (Galicia)	Noya et al. (2017)	g PO_4-eq/kg LW	24.6
Denmark	Dorca-Preda et al. (2021)	g PO_4-eq/kg LW	15.5
Northern Germany	Reckmann et al. (2013)	g PO_{4eq}/kg pork	23.3
Netherlands^	Rougoor et al.(2015)	g $PO_{4\text{-}eq}$ /kg carcass weight	18.4 – 31.1
Great Britain#	Fry and Kingston (2009)	g PO_{4eq}/kg pork	57

Table S17. Resource use and impacts for Australian pork for FY20 and FY22, reported per kilogram of boneless, fat-corrected pork ready for distribution to retail

	Units	National Herd FY20	2.SD (±)	National Herd FY22	2.SD (±)
GHG emissions	kg CO_2-e	7.8	0.3	8.0	0.3
GHG emissions - LU & dLUC	kg CO_2-e	1.0	0.2	0.7	0.1
Total GHG emissions	**kg CO_2-e**	**8.7**	**0.5**	**8.7**	**0.4**
Fossil energy use	MJ	38.5	1.2	39.1	1.3
Renewable energy generated and consumed	MJ	0.3	0.0	0.3	0.0
Freshwater consumption	L	236.6	62.8	136.5	40.8
Water stress	L H_2O-e	172.1	45.6	110.6	33.1
Land occupation	m^2	27.7	7.3	29.8	8.9
Total freshwater eutrophication potential	kg P	5.2e-04	1.9e-04	5.7e-04	6.5e-05
Total marine eutrophication potential	kg N	1.8e-02	6.5e-04	2.4e-02	9.6e-04

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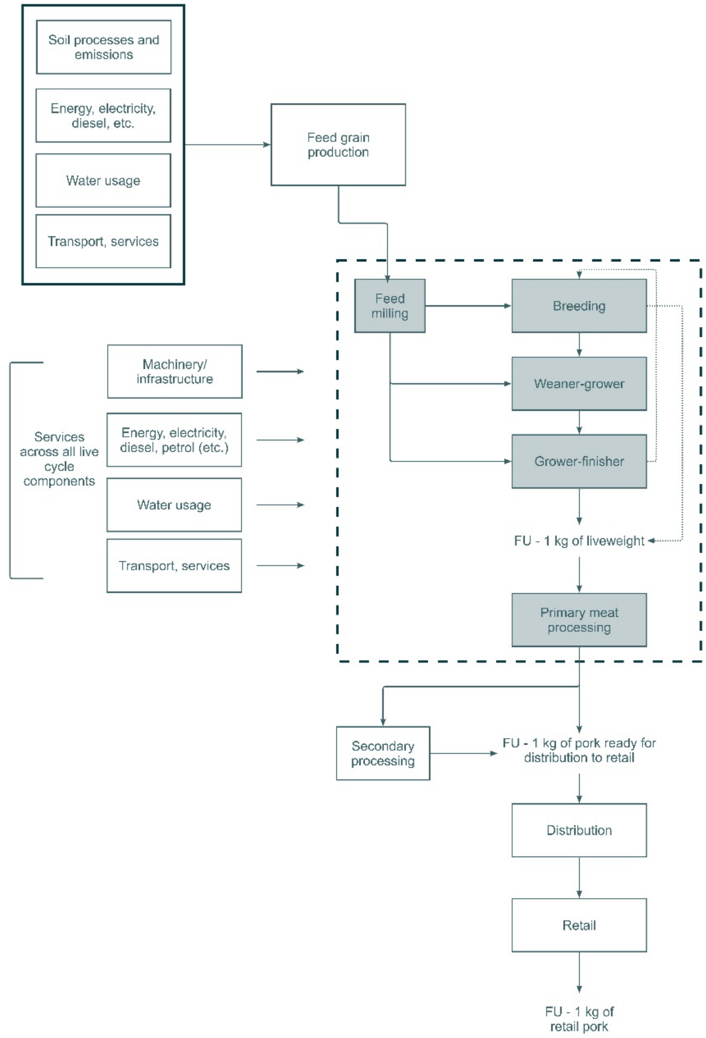

Figure S1. System boundary for Australian pork production (dashed line denotes foreground system)

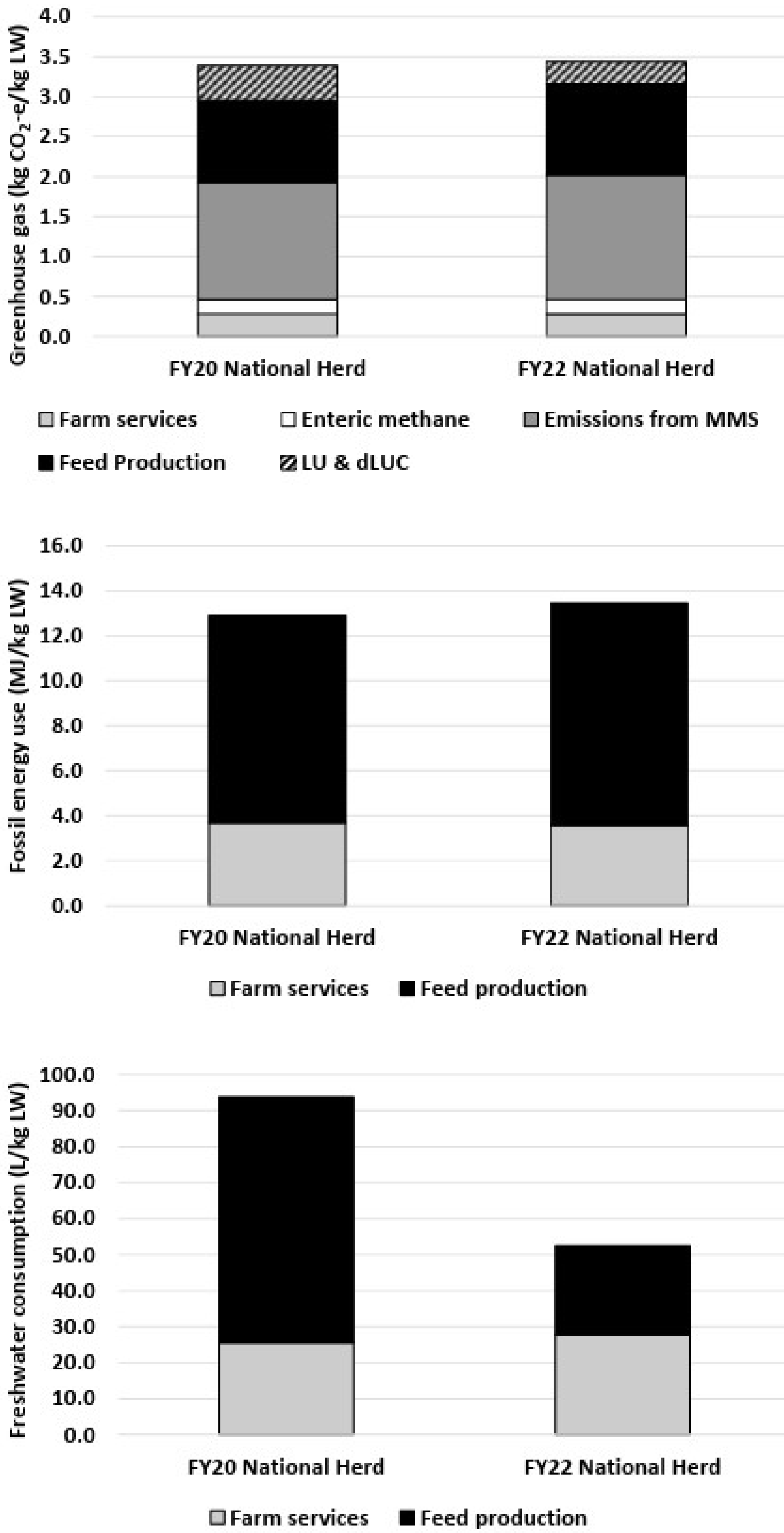

Figure S2. Greenhouse gas emissions (incl. LU and dLUC), fossil energy use, and freshwater consumption for the national herd for FY20 and FY22 reported per kilogram of liveweight

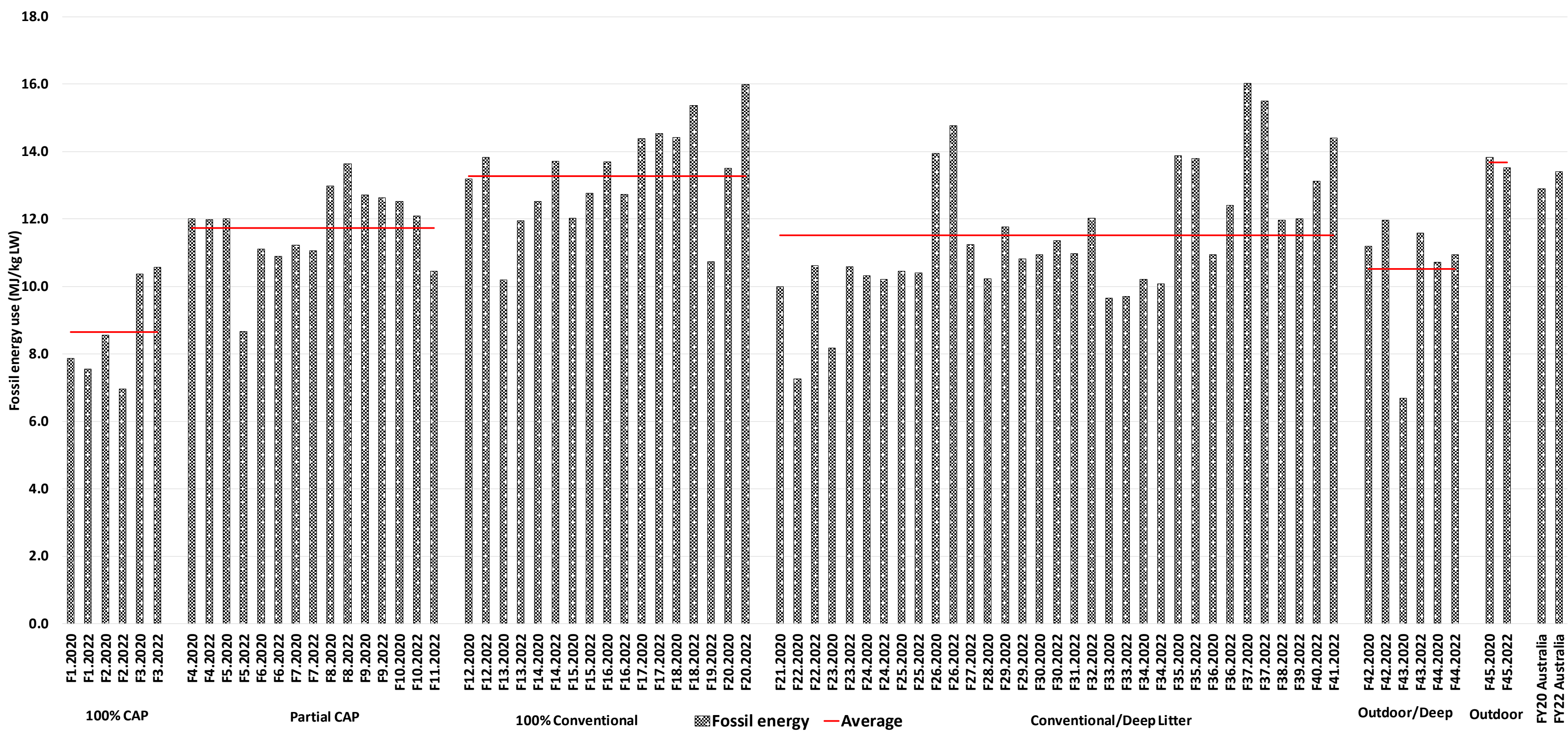

Figure S3. Total fossil energy use (direct and indirect) per kilogram of liveweight for surveyed farms for FY20 and FY22, presented alongside national average results for each housing and manure management system, and national average results for FY20 and FY22

Note that the averages in the figure are the simple averages of the results for each housing/MMS for both years.

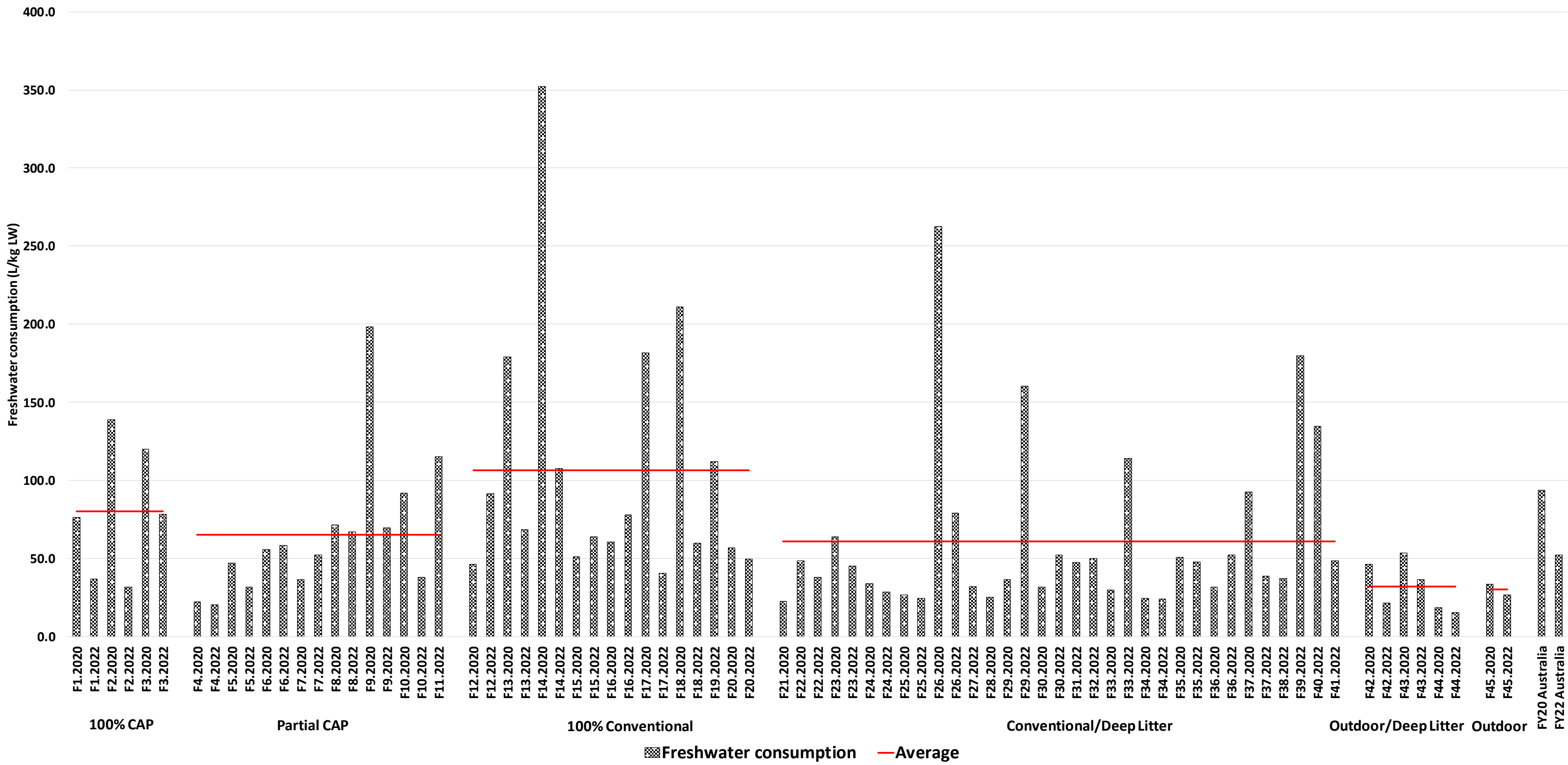

Figure S4. Freshwater consumption per kilogram of liveweight for surveyed farms for FY20 and FY22, presented alongside national average results for each housing and manure management system, and national average results for FY20 and FY22

Note that the averages in the figure are the simple averages of the results for each housing/MMS for both years

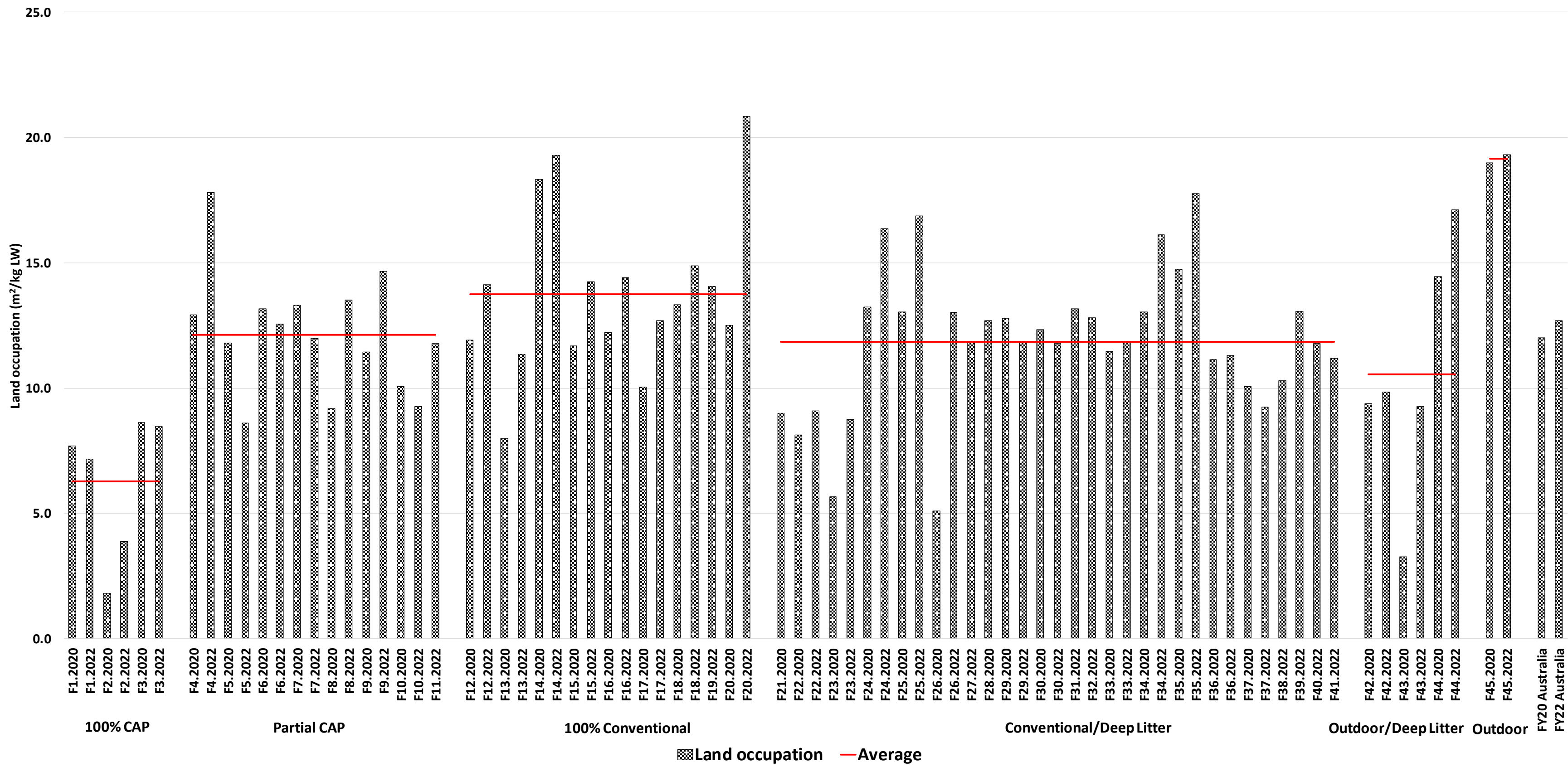

Figure S5. Land occupation per kilogram of liveweight for surveyed farms for FY20 and FY22, presented alongside national average results for each housing and manure management system, and national average results for FY20 and FY22

Note that the averages in the figure are the simple averages of the results for each housing/MMS for both years