Supplementary Material 1- Fraction of N fertilizer applied to cropland (CF)

Estimates of the percent of synthetic N applied to major crops by country (CF) were collected from 4 major datasets:

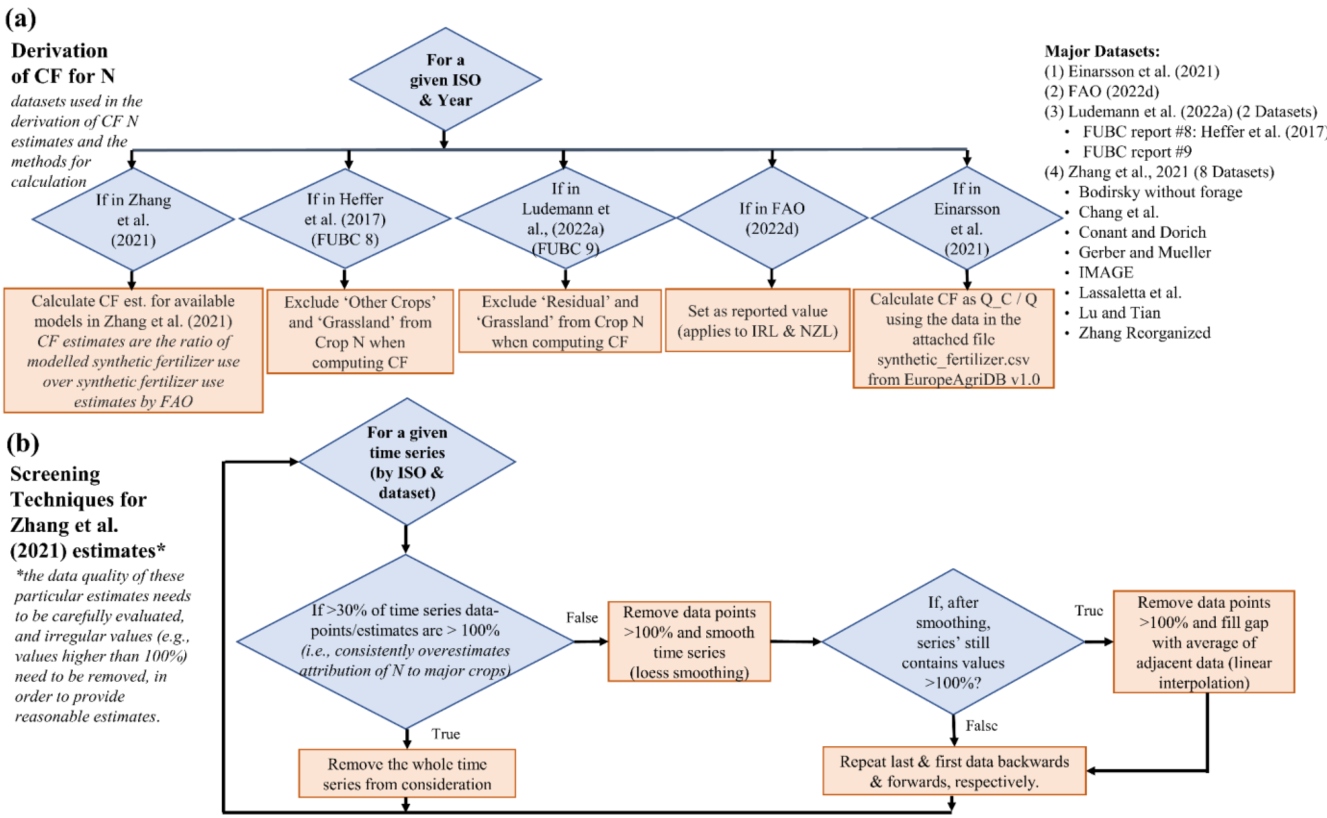
1. Fertilizer use by crop (FUBC) reports published in 2022 (Ludemann et al., 2022a) and 2017 (Heffer et al., 2017) by the International Fertilizer Association (IFA) and collated by Ludemann et al. (2022a);
2. Updated estimates from FAO for the countries of New Zealand and Ireland (FAO, 2022d);
3. Fraction estimates for European Countries from Einarsson et al. (2021); &,
4. Models of national nitrogen budgets for crop production compared in Zhang et al. (2021).

CF cropland fraction estimates for N were derived by Heffer et al. (2017) as the fraction of crop N-use excluding 'Grassland' and 'Other Crops;' whereas, Ludemann et al. (2022a) estimates were derived as the fraction of crop N-use excluding 'Grassland' and 'Residual.' Fractions from Einarsson et al. (2021) calculated N share to cropland as Q_C/Q (total agriculture use of fertilizer to cropland/Total quantity of synthetic N fertilizer applied; Supplementary Figure 1a). Models compared in Zhang et al. (2021) reported N synthetic fertilizer inputs for major crops; thus, CF was derived by dividing these modelled input amounts over the total amount of N fertilizer use reported by FAO for each given country and year. This method resulted in some fraction estimates greater than 100% which required additional screening of data before determining our final report on suggested CF estimates. The initial screening applied to CF estimates from models compared in Zhang et al. (2021) followed the following sequence of steps for data screening, smoothing, and gap filling (See also Supplementary Figure 1b):

1. For each country, identify data points >100%
   a. If these data points account for >30% of the time series (i.e., consistently overestimate the attribution of N to major crops), then remove the whole time series from consideration. If these data points account for >0% and <=30%, then smooth the time series (loess smoothing). After smoothing and if the series' still have values >100%, remove, and fill the gap with the average of adjacent data (linear interpolation).
2. Following our final selection of fraction estimates, we proceeded to repeat last and first data backwards and forwards, respectively for each selected time series.

For those countries that we believe an update is needed (Supplementary Table 1) and that have multiple time series estimates from various data sources, we recommended the appropriate data source by considering the following criteria:

1. the time series' closest to FAO or IFA estimates in recent years were considered to be a more accurate data source; and
2. the smoother time series with smaller year-to-year fluctuations should be prioritised .



Supplementary Figure 1: Decision trees detailing initial derivation of fraction of N fertilizer applied to cropland (CF) estimates for N based on the major datasets considered for this analysis, and (b) additional data screening steps for cropland fraction estimates derived from Zhang et al (2021) datasets.

Supplementary Table 1: Outlined methods of data preparation for N fraction estimates for 21 specific country time series (1961-2020). All analyzed models are from the Zhang et al., 2021, dataset received the same standard, initial data preparation and initial screening techniques.

ISO3 country code	Data Preparation Steps	Source
AUS	(1) Standard filtering, gap-filling, and interpolation methods*	Lassaletta et al. (2014); Lassaletta et al. (2016)
AUT	(1) Projected first (oldest) & last (most recent) data backwards and forwards, respectively.	Einarsson et al. (2021)
BRA	(1) Standard filtering, gap-filling, and interpolation methods	Bouwman et al. (2013)
CAN	(1) Standard filtering, gap-filling, and interpolation methods; followed by (2) removal of post-2011 values and projection of 2011 value forwards through time.	Zhang et al. (2021)
CHL	(1) Standard filtering, gap-filling, and interpolation methods; followed by (2) removal of post-2011 values and projection of 2011 value forwards through time.	Zhang et al. (2021)
DEU	(1) Projected first (oldest) & last (most recent) data backwards and forwards, respectively.	Einarsson et al. (2021)
FIN	(1) Standard filtering, gap-filling, and interpolation methods.	Lassaletta et al. (2014); Lassaletta et al. (2016)
FRA	(1) Projected first (oldest) & last (most recent) data backwards and forwards, respectively.	Einarsson et al. (2021)
GBR	(1) Projected first (oldest) & last (most recent) data backwards and forwards, respectively.	Einarsson et al. (2021)
IRL	(1) Projected first (oldest) & last (most recent) data backwards and forwards, respectively.	Einarsson et al. (2021)

JPN	(1) Standard filtering, gap-filling, and interpolation methods; followed by (2) removal of post-2011 values and projection of 2011 value forwards through time.	Zhang et al. (2021)
LUX	(1) Projected first (oldest) & last (most recent) data backwards and forwards, respectively.	Einarsson et al. (2021)
MAR	(1) Standard filtering, gap-filling, and interpolation methods; followed by (2) removal of post-2011 values and projection of 2011 value forwards through time.	Zhang et al. (2021)
NLD	(1) Projected first (oldest) & last (most recent) data backwards and forwards, respectively.	Einarsson et al. (2021)
NZL	Applied 8% across the time series.	FAO (2022d).
POL	(1) Projected first (oldest) & last (most recent) data backwards and forwards, respectively.	Einarsson et al. (2021)
SVN	(1) Projected first (oldest) & last (most recent) data backwards and forwards, respectively.	Einarsson et al. (2021)
URY	(1) Standard filtering, gap-filling, and interpolation methods; followed by (2) removal of post-2011 values and projection of 2011 value forwards through time.	Zhang et al. (2021)
USA	(1) Standard filtering, gap-filling, and interpolation methods.	Zhang et al. (2021)
ZAF	(1) Standard filtering, gap-filling, and interpolation methods; followed by (2) removal of post-2011 values and projection of 2011 value forwards through time.	Zhang et al. (2021)

Supplementary Material 2- Biological nitrogen fixation (BNF)

For grain legumes, biological nitrogen fixation (BNF) was estimated using a non-linear model described by Herridge et al. (2022). The model calculates fixation in grain legumes as the total plant N content multiplied by the proportion of N derived from the atmosphere (Ndfa). The total plant N content is calculated from the grain harvest using a harvest index (HI), defined as grain (or pod for groundnut) yield (moisture content 11-14%) as a proportion of total shoot dry matter; shoot N concentration; and a below-ground N factor (BGF), defined as the ratio of total plant N to above-ground plant N. In summary,

$fixation = harvest \times \frac{1}{HI} \times\ shoot\ N\ concentration\ \times\ BGF\ \times Ndfa$ (2).

The full model (Equation 4) is non-linear since the HI, and for soybeans also the shoot N concentration, is assumed dependent on crop yield Y:

HI = a + b * ln(Y) (3),

and

shoot N concentration = c + d * Y/HI,

where ln() is the natural logarithm and the yield Y is expressed in metric tonnes per hectare harvested. The yield is the grain yield, except for groundnuts, where the pod yield is used.

The full model can therefore be written

$fixation = harvest \times \frac{c+d\times\left(\frac{Y}{a+b ln ln\, Y}\right)}{a+b\ ln ln\ Y} \times BGF \times Ndfa$ (4).

Note that each factor of this equation is dimensionless except the harvest. The fixation therefore gets the same unit as the harvest e.g., as in the paper by Herridge et al. (2022) if the harvest is given in million metric tonnes (Tg), then the fixation is in Tg N. The parameters provided by Herridge et al. (2022) are summarized in the table below.

Supplementary Table 2: Coefficients used in the estimation of crop biological nitrogen fixation (BNF), where a, b, c and d indicates non-linear coefficients as described in Equation 4, BGF indicates below-ground N factor, and Ndfa indicates the proportion of N derived from the atmosphere.

Crop	a	b	c	D	BGF	Ndfa
Soybean	0.2775	0.1178	0.03913	-0.00118	1.4	0.44 (Europe); 0.61 (North America, Africa, Asia, South America except Brazil, Oceania); 0.73 (South/Central America); 0.78 (Brazil)
Groundnut	0.2614	0.1343	0.027	0	1.4	0.62
Common bean	0.2839	0.0804	0.025	0	1.4	0.38
Chickpea	0.2839	0.0804	0.019	0	2.0	0.62
Pigeon pea	0.1647	0.0517	0.019	0	2.0	0.74
Faba bean	0.2839	0.0804	0.025	0	1.4	0.74
Lupin	0.2839	0.0804	0.027	0	1.4	0.74

All other grain legumes	0.2839	0.0804	0.025	0		1.4	0.62

For non-legume crops, BF was estimated following fixed per-hectare coefficients. Rice was assumed to have a BF coefficient of 25 kg N ha^{-1} $year^{-1}$. This coefficient was based on multiple lines of evidence. Smil (1999) suggested a N fixation of 20-30 kg N per hectare per cropping season from free-living cyanobacteria, and 50-90 kg N per hectare per cropping season in rice fields with azolla (Genus: Azolla). Assuming 2% of rice fields have azolla and 1.25 rice crops per year, these numbers lead to a total fixation of approximately 33 kg N per hectare per year, which is the estimate used by Herridge et al. (2008). However, since the FAOSTAT production data implicitly accounts for multi-cropping in its harvested areas, the factor 1.25 was not needed. Moreover, as Ladha et al. (2016) characterize azolla and legume green manures in rice as “negligible” and “insignificant” at present, Smil’s estimate of 20-30 kg N ha^{-1} $year^{-1}$ from cyanobacteria appears to be an appropriate coefficient. This is in line with 22kg N ha^{-1} $year^{-1}$ fixation estimation based on crop N budgets by Ladha et al. (2016), and the 10-50 kg N ha^{-1} $year^{-1}$ range reported by Ladha et al. (2022) based on ^{15}N isotope methods.

Sugar cane was assume to have a BF of 25 kg N per harvested hectare. This coefficient was suggested by Herridge et al. (2008) based on consideration of multiple lines of evidence. The fixation in sugar cane is subject to a considerable uncertainty. Smil (1999) suggested that endophytic microbes in sugar cane fix at least 50 kg N/ha/year, maybe up to 150 kg N ha^{-1} $year^{-1}$ or more. Such high rates have clearly been demonstrated on some fields using various methods (see, e.g., Herridge et al. (2008); Urquiaga et al. (2012);Baptista et al. (2014); Martins et al. (2020)) but were considered unlikely by Herridge et al. (2008) as an average. The coefficient 25 kg N ha^{-1} $year^{-1}$ harvested used here is considered as a conservative estimate which may be revised upwards in the future.

Supplementary Material 3- Crop removal (CR) coefficients

Supplementary Table 3: Crop nutrient removal coefficients (in kilograms of nitrogen (N), phosphorus (P) or potassium (K) per tonne of commodity (to 2 significant figures).

Item	FAO code	N	P	K
Almonds, with shell	221	39	11	71
Anise, badian, fennel, coriander	710	8.8	1.3	16
Apples	515	2.2	0.7	4.5
Apricots	526	3.7	0.7	2.2
Areca nuts	226	7.8	NA	NA
Artichokes	366	3.2	NA	NA
Asparagus	367	4.8	0.9	4.2
Avocados	572	2.7	0.9	NA
Bambara beans	203	26	5.1	15
Bananas	486	1.4	0.4	8.9
Barley	44	18	3.2	5.8
Bastfibres, other	782	4.3	1.1	3.3
Beans, dry	176	42	5.7	20
Beans, green	414	4.1	0.7	2.2
Berries nes	558	1.6	NA	NA
Blueberries	552	1.1	0.0	0.8
Brazil nuts, with shell	216	11	NA	NA
Broad beans, horse beans, dry	181	30	5.1	15
Buckwheat	89	17	2.2	3.7
Cabbages and other brassicas	358	3.8	0.4	3.0
Canary seed	101	20	2.9	11
Carobs	461	2.6	NA	NA
Carrots and turnips	426	2.1	0.5	2.3
Cashew nuts, with shell	217	12	NA	NA
Cashewapple	591	1.3	NA	NA
Cassava	125	2.7	3.3	2.6
Castor oil seed	265	14	NA	NA
Cauliflowers and broccoli	393	4.0	0.9	3.2
Cereals nes	108	15	2.9	4.4
Cherries	531	1.8	NA	NA
Cherries, sour	530	1.4	NA	NA
Chestnut	220	2.9	NA	NA
Chick peas	191	28	5.1	15
Chicory roots	459	1.8	NA	NA
Chillies and peppers, dry	689	12	1.2	9.5
Chillies and peppers, green	401	2.2	0.5	2.2
Cinnamon (cannella)	693	12	1.3	16

Item	FAO code	N	P	K
Cloves	698	19	4.0	18
Cocoa, beans	661	23	6.0	36
Coconuts	249	19	3.8	6.6
Coffee, green	656	23	3.5	18
Cow peas, dry	195	30	5.1	15
Cranberries	554	0.6	NA	NA
Cucumbers and gherkins	397	1.5	0.5	1.6
Currants	550	2.2	NA	NA
Dates	577	2.4	NA	NA
Eggplants (aubergines)	399	2.8	0.8	2.9
Fibre crops nes	821	4.3	1.1	3.3
Figs	569	3.0	NA	NA
Flax fibre and tow	773	14	3.5	6.4
Fonio	94	13	2.2	4.2
Fruit, citrus nes	512	1.5	0.3	2.4
Fruit, fresh nes	619	1.9	0.4	2.0
Fruit, pome nes	542	3.0	0.7	2.0
Fruit, stone nes	541	2.2	0.7	2.0
Fruit, tropical fresh nes	603	2.8	0.7	2.0
Garlic	406	6.4	0.9	2.7
Ginger	720	16	1.3	16
Gooseberries	549	1.4	NA	NA
Grapefruit (inc. pomelos)	507	1.8	NA	NA
Grapes	560	3.6	0.7	5.4
Groundnuts, with shell	242	34	6.0	8.2
Gums, natural	839	150	NA	NA
Hazelnuts, with shell	225	5.3	0.4	1.7
Hemp tow waste	777	3.1	1.1	3.3
Hempseed	336	35	NA	NA
Hops	677	19	1.3	16
Jojoba seed	277	NA	NA	NA
Jute	780	2.7	1.1	3.3
Karite nuts (sheanuts)	263	11	NA	NA
Kiwi fruit	592	1.4	NA	NA
Kola nuts	224	14	NA	NA
Leeks, other alliaceous vegetables	407	3.1	0.9	2.7
Lemons and limes	497	1.8	NA	NA
Lentils	201	36	4.4	16
Lettuce and chicory	372	2.4	0.4	2.9
Linseed	333	29	NA	NA
Lupins	210	44	5.1	15
Maize	56	12	3.4	4.3

Item	FAO code	N	P	K
Maize, green	446	3.6	0.8	2.8
Mangoes, mangosteens, guavas	571	3.0	0.6	3.8
Manila fibre (abaca)	809	2.9	1.1	3.3
Melonseed	299	29	NA	NA
Millet	79	20	4.2	5.4
Mushrooms and truffles	449	9.3	NA	NA
Mustard seed	292	40	NA	NA
Nutmeg, mace and cardamoms	702	13	1.3	16
Nuts nes	234	11	NA	NA
Oats	75	22	3.6	4.5
Oil palm fruit	254	3.6	0.7	4.1
Oilseeds nes	339	13	4.6	22
Okra	430	2.8	0.5	3.0
Olives	260	7.3	11	10
Onions, dry	403	2.6	0.7	2.2
Onions, shallots, green	402	2.6	0.5	1.8
Oranges	490	3.1	0.4	4.6
Papayas	600	60	18	140
Peaches and nectarines	534	2.2	0.4	3.3
Pears	521	1.8	0.4	2.6
Peas, dry	187	38	8.7	9.8
Peas, green	417	17	3.3	10
Pepper (piper spp.)	687	9.8	1.3	16
Peppermint	748	11	1.3	16
Persimmons	587	1.0	NA	NA
Pigeon peas	197	NA	NA	NA
Pineapples	574	1.0	0.2	1.4
Pistachios	223	17	NA	NA
Plantains and others	489	3.3	0.3	5.0
Plums and sloes	536	2.4	NA	NA
Poppy seed	296	29	NA	NA
Potatoes	116	2.5	1.0	6.2
Pulses nes	211	26	4.2	13
Pumpkins, squash and gourds	394	2.7	0.4	3.2
Pyrethrum, dried	754	14	1.3	16
Quinces	523	0.3	NA	NA
Quinoa	92	19	NA	NA
Ramie	788	4.0	1.1	3.3
Rapeseed	270	31	5.9	NA
Raspberries	547	1.4	NA	NA
Rice, paddy	27	13	2.8	3.0
Roots and tubers nes	149	4.4	0.3	2.9

Item	FAO code	N	P	K
Rubber, natural	836	7.2	1.3	4.4
Rye	71	21	3.6	4.6
Safflower seed	280	30	5.4	19
Seed cotton	328	56	11	32
Sesame seed	289	26	5.1	9.7
Sisal	789	5.0	1.1	3.3
Sorghum	83	15	4.5	4.2
Soybeans	236	59	8.1	18
Spices nes	723	13	1.0	8.8
Spinach	373	4.0	0.6	3.7
Strawberries	544	5.5	1.7	8.3
String beans	423	3.0	0.7	2.2
Sugar beet	157	2.1	0.5	2.3
Sugar cane	156	4.7	0.3	1.3
Sugar crops nes	161	0.0	NA	NA
Sunflower seed	267	24	3.9	6.5
Sweet potatoes	122	3.4	0.8	6.9
Tallowtree seed	305	NA	NA	NA
Tangerines, mandarins, clementines, satsumas	495	1.9	0.4	1.3
Taro (cocoyam)	136	3.7	1.1	3.3
Tea	667	19	2.6	15
Tobacco, unmanufactured	826	42	6.6	48
Tomatoes	388	1.4	0.2	2.4
Triticale	97	17	2.9	4.2
Tung nuts	275	48	NA	NA
Vanilla	692	8.5	1.3	16
Vegetables, fresh nes	463	5.6	0.9	2.6
Vegetables, leguminous nes	420	4.9	1.1	3.3
Vetches	205	34	4.0	17
Walnuts, with shell	222	22	4.4	10
Watermelons	567	1.8	NA	NA
Wheat	15	21	4.2	5.2
Yams	137	2.1	NA	NA
Yautia (cocoyam)	135	3.9	1.1	3.3

Supplementary Material 4- Uncertainties of Cropland Nutrient Budget components quantified as coefficients of variation.

Supplementary Table 4: Estimates of coefficient of variation percentages (CV%) for important items* from components of the Cropland Nutrient Budget .

Component of budget	Item	FAO value for 2020	Units	Other reported values (and sources of data used)	CV%
Cropland area (Area)		1562	Million ha	1215-2002 (range), 1540 (mean) +/- 370 (sd) (Tubiello et al., 2023)	24%
Crop production (Prod) (select main crops only)	Total grains	3007	Million t	2725-3007 (range), 2866 (mean) +/- 199 (sd) (FAO, 2022b; USDA, 2023)	7%
Livestock numbers (Livestock n) for manure applied to soils (MAS) (select main livestock classes only)	Cattle	1523	Million head	1281-1523 (range), 1403 (mean)+/-121 (sd) (FAO, 2022b; USDA, 2023)	12%
	Swine/pigs	938	Million head	938-1090 (range), 1014 (mean)+/-77 (sd) (FAO, 2022b; USDA, 2023)	11%
Livestock manure coefficients for manure applied to soils (MAS) (N content)	Dairy cattle	47	kg N head^{-1} year^{-1}	47-98 (range), 80 (mean) +/- 29 (sd) (Sheldrick et al., 2003; IPCC, 2006b)	36%
	Non-dairy cattle	14	kg N head^{-1} year^{-1}	14-101 (range), 61 (mean) +/- 36 (sd) (Sheldrick et al., 2003; IPCC, 2006b)	59%
	Swine (sows, boars and to slaughter)	34	kg N head^{-1} year^{-1}	11-38 (range), 23 (mean) +/- 11 (sd) (Sheldrick et al., 2003; IPCC, 2006b)	48%
Synthetic fertilizer use (SF)	N	532	Million tonnes year^{-1}	(FAO, 2022b; IFA, 2022a)**	21%

Component of budget	Item	FAO value for 2020	Units	Other reported values (and sources of data used)	CV%
	P	97	Million tonnes $year^{-1}$	(FAO, 2022b; IFA, 2022a)**	28%
	K	147	Million tonnes $year^{-1}$	(FAO, 2022b; IFA, 2022a)**	28%
Fraction of SF applied to cropland (CF)	N	97	%	Across all countries: 10-100 (range), 97 (mean) +/- 11 (sd) (Table 1)	11%
	P	98	%	Across all countries: 10-100 (range), 98 (mean) +/- 9 (sd) (Table 1)	9%
	K	98	%	Across all countries: 10-100 (range), 98 (mean) +/- 10 (sd) (Table 1)	10%
N deposition (ND)	Various based on models	6.7	kg N ha^{-1} $year^{-1}$	Across all countries: 0.5-17 (range), 5.1 (mean) +/- 3.5 (sd) (estimates from Vishwakarma et al. (2022) AH model: ACCMIP and HYDE)	69%
	Various based on models	6.7	kg N ha^{-1} $year^{-1}$	Across all countries: 0.7-17 (range), 5.5 (mean) +/- 3.5 (sd) (estimates from Vishwakarma et al. (2022) AL model: ACCMIP and LUH2)	64%
	Various based on models	6.7	kg N ha^{-1} $year^{-1}$	Across all countries: 0.4-35 (range), 6.8 (mean) +/- 5.2 (sd) (estimates from Vishwakarma et al. (2022) WH model: Wang et al and HYDE)	76%

Component of budget	Item	FAO value for 2020	Units	Other reported values (and sources of data used)	CV%
	Various based on models	6.7	kg N ha^{-1} $year^{-1}$	Across all countries: 0.4-35 (range), 6.7 (mean) +/- 5.2(sd) (estimates from Vishwakarma et al. (2022) WL model: Wang et al and LUH2)	78%
Biological N fixation	Soybeans	Various, region and yield dependent	kg N fixed tonne DM^{-1}	16-89 (range) 55 (mean) +/-17 (sd) (Peoples et al., 2021; Herridge et al., 2022)***	32%
	Sugar cane	25.0	kg N ha^{-1}	25-150 (range), 75 (mean) +/- 66 (sd) (Peoples et al., 2021; Herridge et al., 2022)	88%
	Rice	25.0	kg N ha^{-1}	20-90 (range), 39 (mean) +/- 27 (sd) (Peoples et al., 2021; Herridge et al., 2022)	69%
Crop removal coefficients	Maize	12.4	kg N tonne $product^{-1}$	8-18 (range) 14 (mean) +/-3 (sd) (Ludemann et al., 2023a)	19%
	Rice, paddy	12.9	kg N $product^{-1}$	11-12 (range) 11 (mean) +/-0 (sd) (Ludemann et al., 2023a)	3%
	Soybeans	59.3	kg N $product^{-1}$	53-83 (range) 59 (mean) +/-12 (sd) (Ludemann et al., 2023a)	20%
	Wheat	20.9	kg N $product^{-1}$	17-27 (range) 21 (mean) +/-3 (sd) (Ludemann et al., 2023a)	14%
	Maize	3.4	kg P $product^{-1}$	1-5 (range) 2 (mean) +/-1 (sd) (Ludemann et al., 2023a)	21%
	Rice, paddy	2.8	kg P $product^{-1}$	1-4 (range) 2 (mean) +/-0 (sd) (Ludemann et al., 2023a)	17%
	Soybeans	8.1	kg P $product^{-1}$	4-8 (range) 6 (mean) +/-1 (sd) (Ludemann et al., 2023a)	24%

Component of budget	Item	FAO value for 2020	Units	Other reported values (and sources of data used)	CV%
	Wheat	4.2	kg P product^{-1}	1-5 (range) 3 (mean) +/-1 (sd) (Ludemann et al., 2023a)	19%
	Maize	4.3	kg K product^{-1}	2-10 (range) 3 (mean) +/-1 (sd) (Ludemann et al., 2023a)	18%
	Rice, paddy	3.0	kg K product^{-1}	1-4 (range) 2 (mean) +/-1 (sd) (Ludemann et al., 2023a)	22%
	Soybeans	18.3	kg K product^{-1}	16-27 (range) 22 (mean) +/-7 (sd) (Ludemann et al., 2023a)	34%
	Wheat	5.2	kg K product^{-1}	3-7 (range) 4 (mean) +/-1 (sd) (Ludemann et al., 2023a)	13%

*Items were selected based on relative contribution to each component of the Cropland Nutrient Budget and availability of data.

**IFA did not have fertilizer data for every country. Therefore the CV% was based on variation in estimates of fertilizer use by country for countries that had data available from IFA *and* FAO.

***Raw data from Peoples et al. (2021) were used for estimating the CV% (Giller, K, pers.comms November 2022).

Supplementary Material 5- Case studies

The CNB currently attributes manure from livestock across each country to cropland area based on the proportions shown in Table 1. However, as described in Supplementary Material 1, these proportions are based on apportioning the fraction of total fertilizer used in a country to that applied to cropland. In addition, none of the nutrient outputs in removed herbage from permanent and temporary meadows and pastures or maize for silage are accounted for in the CNB, nor does it account for manure exported from one country to another. Therefore several countries were examined more deeply as case studies to quantify some of the methodological limitations of the current cropland nutrient budget. These countries included the Netherlands, Ireland, Denmark and New Zealand and were chosen based on those having a significant number of livestock and areas of permanent and temporary meadows and pasture and maize for silage relative to the total size of agricultural land. Of these case study countries, the Netherlands exports a significant percentage of its manure from livestock to other countries (~10%) (CBS, 2023) and so it was used for the most detailed analysis.

To account for the 10% of manure from livestock exported from the Netherlands, scenario b (Supplementary Table 5) was modelled by decreasing N inputs by the equivalent of 10% of the quantity of total manure N from livestock for the country. This resulted in a 10 kg N ha^{-1} year^{-1} decrease in N inputs to cropland and a ~7% (~2 percentage point increase to 32%) increase in N use efficiency, across cropland area compared with the current CNB (Supplemental Table 5, columns a and b).

Scenarios c and d aimed to quantify the effects on N surpluses and NUE if N in herbage removed from 'temporary meadows and pastures', and 'maize as silage' were included in the total quantity of N outputs respectively. Scenario e quantified the combined effect of scenarios c and d. Accounting for these scenarios made a greater effect on N surplus and NUE estimates than when manure exports were accounted for. Accounting for N outputs from herbage removed from temporary meadows and pastures resulted in a NUE of 50% (20 percentage points greater than results from the current CNB) and a 50kg ha^{-1} year^{-1} lower N surplus compared with the current CNB (Supplementary Table 5). Accounting for additional N outputs from herbage removed from maize for silage resulted in a NUE of 58% (28 percentage points greater than the current CNB) and a 70kg ha^{-1} year^{-1} lower N surplus compared with the current CNB (Supplementary Table 5). Accounting for N outputs from herbage removed from temporary meadows and pastures and maize for silage resulted in a NUE of 77% (47 percentage points greater than results from the current CNB) and a 113 kg ha^{-1} year^{-1} lower N surplus compared with the current CNB (Supplementary Table 5). Unsurprisingly values from scenarios c, d and e are more comparable (than the original CNB values) with results from surveys of Dutch farms (with values of 54% and 52% for NUE for arable and dairy farms respectively, www.agrimatie.nl) considering results from the Dutch surveys had more refined land area coverage.

The Netherlands is an extreme case in how it is effected by the limitations of the current methodology for the CNB. Ireland, Denmark and New Zealand are other examples of countries whose NUE may be effected by the limitations of the current CNB methodology. Currently they have NUE values of 38%, 55% and 50% respectively (Supplementary Table 6). NUE values for countries like these may increase in the future if nutrients removed as fodder and forage crops are better accounted for. Overall, this shows that accounting for N outputs from temporary meadows and pastures and short term fodder crops (such as maize for silage), (and to a lesser extent manure exports on total N inputs) can substantially increase estimates of NUE. This highlights the importance of properly accounting for N outputs from fodder and forage crops in future iterations of the CNB, especially for countries with significant areas of these fodder or forage crops and numbers of livestock.

Supplementary Table 5: Comparison in estimates of cropland N budget (CNB) components and nitrogen use efficiency (NUE) % for the Netherlands for 2019 based on current cropland nutrient budget data (a), accounting for 10% of livestock manure exported (b), accounting for N outputs as temporary meadows and pastures (c), accounting for N outputs as maize silage (d), accounting for N outputs as permanent meadows and pastures*.

Item	Scenario				
	a) Current CNB	b) CNB accounting for 10% exported manure	c) CNB accounting for N outputs from temporary meadows and pastures	d) CNB accounting for N outputs from maize silage	e) CNB accounting for scenario c and d combined
N inputs (tonnes)	260000	250,000	260000	260000	260000
N outputs (tonnes)	79000	79000	130000	150,000	200000
N surplus (tonnes)	181000	171,000	130000	110000	60,000
N inputs (kg ha^{-1} year^{-1})	250	240	250	250	250
N outputs (kg ha^{-1} year^{-1})	75	75	120	140	190
N surplus (kg ha^{-1} year^{-1})	170	160	120	100	57
NUE (%)	30%	32%	50%	58%	77%
% change in N surplus relative to Current CNB	0%	-6%	-28%	-39%	-67%

% change in NUE relative to Current CNB	0%	7%	67%	93%	157%

*Values are rounded to 2 significant figures, Scenario b assumed 10% of manure from livestock in the Netherlands was exported (CBS, 2023), scenario c assumed 216,000ha temporary meadow and pastures, 11,000kg DM ha^{-1} production (Schils et al., 2020) , 0.7 utilization of production, 0.032 kg N kg^{-1} herbage nutrient concentration, scenario d assumed 187,000ha maize silage (CBS, 2023), 14,000kg DM ha^{-1} production, 0.7 utilization of production 0.036 kg N kg^{-1} (Supplemental Table 5) herbage nutrient concentration.

Supplementary Table 6: Agricultural land area (1000 ha) and nitrogen use efficiency (NUE) % for a selected group of countries with significant areas of permanent meadows and pastures and number of livestock for 2019.

Item	Netherlands	Ireland	Denmark	New Zealand
Land under temporary crops	787	355	1794	414
Land under temp. meadows and pastures	216	87	525	63
Land with temporary fallow	8	1	77	69
Land under permanent crops	38	1	23	74
Cropland	**1049**	**444**	**2419**	**620**
Perm. meadows & pastures – Cultivated	691	3559	207	NA
Perm. meadows & pastures - Nat. growing	77	522	0	NA
Land under perm. meadows and pastures	**768**	**4080**	**207**	**9725**
NUE%	31%	38%	55%	50%
Maize area for silage	~187 (CBS, 2023)	~17 (CSO, 2023)	186 (Stadbank, 2023)	~55 (FAR, 2020)
Silage maize area as % of cropland	18%	4%	10%	13%