Supplementary Materials

Supplementary Methods 1. Estimating recoverable urban and rural N and P quantities

Potentially recoverable N and P was estimated using the methodology of Trimmer and Guest[1]. This uses regional data of protein supply quantity (expressed in g capita^{-1} day^{-1}) derived from The Food and Agriculture Organization Corporate Statistical Database[2], hereafter referred to as FAOSTAT. N and P excretion rates are assumed to equal protein N and P consumption rates. We expect 2-3% of N and P consumed will become hair and nails, but as much of this is likely to enter sanitation systems anyway, we assume excretion is 100% of intake. Values for all aggregated food items were taken from FAOSTAT, except 'spices' 'stimulants' and 'miscellaneous', as no waste data is available for these items. As protein supply quantity data does not include waste, we incorporate regional estimates of food waste given by FAO[3]. This estimate (given as a percent) was subtracted as a food waste value from 100%, with the difference then multiplied by supply to estimate actual consumption. Values for the N and P protein percentage in consumed supply were then incorporated to estimate N and P consumption and excretion. These values were 13% for N, 2.2% for vegetable P and 1.1% for animal P. Maximum expected recovery rates from excreta, calculated by Trimmer & Guest as 90% for N and 95% for P, were also included. Data expressed in national g capita^{-1} day^{-1} was converted to total annual figures by multiplying by the population given by FAOSTAT and 365. Population projections for 2020, 2030 and 2050 were taken from FAOSTAT. These calculations are given in equations S1-S2.

$$Urban\ N_{exc} = \sum i\left[(Prot_i)(Waste_i)(0.13)(Pop_i)(365)\right] \tag{S1}$$

$$Urban\ P_{exc} = \sum a,p\left[(Prot_a)(Waste_a)(0.011) + (Prot_p)(Waste_p)(0.022)\right](365)(Pop_i) \tag{S2}$$

Urban N$_{exc}$ and *P*$_{exc}$ are the potential recoveries of N and P in urban areas; *Prot* represents protein supply for selected food group (meat, grain, oilseeds etc), with *a* and *p* referring to animal and plant in the case of P; *Waste* represents the fractions of N and P lost as food waste.

FAOSTAT regional groupings and SDG regions do not exactly match geographically. SDG regional data were calculated where necessary as follows. Sub-Saharan Africa includes Western Africa, Eastern Africa, Middle Africa and Southern Africa. Oceania includes Melanesia, Micronesia and Polynesia. Latin America and The Caribbean includes Central America, The Caribbean and South America. All others are as described, i.e. Eastern and South Eastern Asia from FAOSTAT includes the Eastern and South Eastern Asia SDG region. These groupings were applied to all calculations.

Supplementary Methods 2. Estimating application rates and crop requirements of N and P fertilizers

Application rates of N and P fertilizers in 2019 (the most recent available year) were taken from FAOSTAT. A simple compound interest formula was used to estimate 2020, 2030 and 2050 projections using predicted annual increases found in Alexandratos and Bruisma[4]. N and P fertilizer requirements were estimated using a simplified version of the method of Trimmer et al[5], which we summarize here. Seventeen key crops representing 76% of global agricultural productivity were selected (barley, cassava, groundnut, maize, millet, oil palm, potato, rapeseed, rice, sorghum, soybean, sugar beet, sugar cane, sunflower seed and wheat). Median values for N and P fertilizer requirements for these crops, given by IFA[6], were then multiplied by the number of hectares harvested for each crop as given by FAOSTAT. The result was summed to give an estimate of key crop N and P requirements in each region.

Supplementary Methods 3. Estimating recoverable urban C quantities

Potentially recoverable C was also estimated using FAOSTAT. Food supply data (measured in kg capita^{-1} year^{-1}) was used to estimate C excretion. ‘Spices’, ‘stimulants’ and ‘miscellaneous’ were again omitted and the same food waste fraction as that used for N and P was used. Estimated percentage C and dry matter (DM) for each food item, given by Wolf et al[7], were included to estimate the C and DM content of each food group. As most dietary C is excreted as CO_2 through respiration, an excretion factor of 12% was applied, given by West et al[8]. This value will change slightly with regional variations in lifestyle, fiber consumption etc, but we expect these differences to be minor and apply this factor to all regions. These calculations are given in equation S3.

$$Urban\ C_{exc} = \sum i\left[(Food\ Supply_i)(Waste_i)\left(\frac{C\%_i}{100}\right)\left(\frac{DM_i}{100}\right)(Exc/100)\right] \tag{S3}$$

Food Supply represents supply data for all food items; *UF* refers to the urban factor; *Waste* represents the fraction of C wasted; *C%* refers to mass percentage C per item; *DM* refers to dry matter mass percentage per item, and *Exc* refers to estimated excretion C fraction (12%). $Urban\ C_{exc}$ and $Rural_{exc}$ then converted to total estimates in the same fashion as $Urban\ N_{exc}$ and $Urban\ P_{exc}$.

Supplementary Methods 4. Estimating annual GHG emissions associated with mineral N and P production and application

GHG emissions from mineral N and P fertilizer production were estimated using the methodology of Blonk Consultants[9]. This method estimates the CO_2 (and/or CO_2 eqv – hereafter $CO2_2$ e) emitted per kg N synthesized or P_2O_5 mined. Regional percentage use of each fertilizer product (ammonium nitrate, triple superphosphate etc) were also taken from Blonk Consultants[9]. These calculations are given in equation S4.

$$CO_2\ e\ emissions = \sum n,p\left[(Fertilizer_{n,p})(Use_{frac})(CO_{2emitted})\right] \tag{S4}$$

$Fertilizer_{n,p}$ is the total regional application of N and P_2O_5 (taken from FAOSTAT); Use_{frac} is the estimated regional use of each fertilizer product; and $CO_{2emitted}$ is the estimated volume of CO_2 emitted per kg N synthesized or P_2O_5 mined. Regional fertilizer production quantities given by FAOSTAT were to used to calculate regional GHG emissions from fertilizer production and we use the same compound interest formula to calculate fertilizer production GHG emissions in future projections.

The regions given by Blonk Consultants are Western Europe, Russia and Central Europe, North America, China, India and rest of the world. We expect Chinese industry will account for most fertilizers produced in Eastern and South-Eastern Asia, and we assign this SDG region to the China category given by Blonk Consultants. We expect the same for Indian industry in Central and Southern Asia and assign this SDG regions to the India category. Other SDG regions were assigned the geographical region given by Blonk Consultants, apart from Central America, South America and The Caribbean, which were assigned the values reported for 'rest of the world'.

Annual GHG emissions from N fertilizer application (NO_2 expressed as CO2e) were estimated using FAOSTAT. These estimates are the sum of 'direct emissions' of nitrous oxide taking place from the field of application and 'indirect emissions' of nitrous oxide from additional sites following volatilization, redeposition or leaching of N from the field of application. Estimates for these emissions for 2020 were calculated by applying the Tier 1 default emission factor from IPCC (1%) to regional N fertilizer use data for 2021, previously calculated. Estimates for 2030 and 2050 are given directly by FAOSTAT. Nitrous oxide emissions are not applicable to P_2O_5 application. An emission factor of 1.16% was applied to prospective human excreta-derived fertilizers, as described by a global meta analysis of organic amendment emission factors[10].

Regional estimates for annual potential C sequestration of croplands are taken from the medium rate scenario described by Zomer et al[11].

Supplementary Methods 5. Estimating GHG emissions associated with sanitation systems

GHG emissions associated with sanitation systems were estimated using the Tier 2 methods described by IPCC[12], with some minor adjustments and supplementary information from the World Health Organization Joint Monitoring Program (JMP)[13] for improved accuracy. The wastewater treatment process itself is a globally significant source of GHGs (about 1.6% of total emissions)[14] but here we focus on emissions from sanitation services prior to treatment. The IPCC method for estimating methane emissions from sanitation services is described here in Box S1 and our modifications are described afterwards.

$$CH_4 emissions = \sum_j \left[(TOW_j - S_j) \cdot (EF_j - R_j)\right] \tag{S5.1}$$

The subscript j refers to each type of sanitation service (sewer, latrine etc); TOW is the total organics loading in wastewater for sanitation service j in units of kg BOD yr^{-1} (described below in Eq S5.3); S is the organic component removed as sludge from sanitation service j in kg BOD yr^{-1}; EF is the methane emission factor in sanitation service j (described in Eq 5.2) and R is the volume of methane recovered or flared from sanitation service j.

$$EF_J = B_o \cdot MCF_j \tag{S5.2}$$

EF_j is the emission factor in kg CH_4/kg BOD; j is the fraction using each treatment/discharge system; B_o is the maximum CH_4 producing capacity in kg CH_4/kg BOD (a default value of 0.6 is proposed) and MCF_j is the methane correction factor (the fraction of C likely to become CH_4 in each sanitation system).

$$TOW = P \cdot BOD \cdot 0.001 \cdot 365 \cdot I \tag{S5.3}$$

TOW is the total organics in wastewater in inventory in kg BOD yr^{-1}; P is the country population; BOD is the regional per capita BOD (a range of 37-85 g cpt^{-1} day^{-1} is given for different regions); 0.001 is applied to convert unit of g BOD to kg BOD; I is a correction factor for additional industrial BOD discharged into wastewater (for collected the default is 1.25, for uncollected the default is 1).

IPCC (2019) IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 6: Wastewater

Box S1. IPCC methods for calculating annual methane emissions from sanitation systems

In the IPCC method U_i and $T_{i,j}$ refer to population fractions in different income brackets and degree of utilization for each service (latrine, septic tank, sewer etc). Here we instead use data given by the Joint Monitoring Program (JMP)[15] regarding service in urban and rural areas of SDG regions (Annex 7.2 JMP). We use this data because it is much more comprehensive than that offered by IPCC and gives data for more sanitation services. These services are split into ‘improved’ (latrines, septic tanks and sewers) and ‘basic’ (limited or shared, unimproved and open defecation). This was done to improve the accuracy of the estimates, as they are given for each SDG region.

EF_j is calculated by multiplying the default maximum methane producing capacity (BO value - 0.6 kg CH_4/kg BOD) by a selected MCF_j (Methane Correction Factor – explained below). The BO value is an estimate of the maximum amount of C contained in the excreta which may become methane in anaerobic conditions. IPCC guidelines[12] for this estimate are to use region-specific data when available, and if unavailable to use the default value of 0.6 (or 60%). Regional estimates are unavailable to our knowledge. BO is mostly used in the context of livestock studies, as different animals and different diets produce manure of varying lignin content, which affects BO[16], as lignin is unavailable for anaerobic microbial metabolism. Human digestion and diet will not differ to the same extent, so we use the default value of 0.6 for all regions, as other studies have done[17].

Suggested MCF values for different sanitation services are given by IPCC[12]. The MCF indicates the extent to which the methane producing capacity is realized in each service. Here we use the IPCC values as a guideline, with minor adjustments. The IPCC assign a value of 0.11 kg CH_4/kg BOD to open discharge; we assume this will be equal to open defecation and therefore assign an MCF of 0.11 to open defecation. For septic tanks IPCC suggest an MCF of 0.5, but we believe this may be an overestimate, as research using real gas flux chambers in field conditions calculated a value of 0.22[18]. This value may fluctuate with different types of tanks, input rates, frequency of desludging etc, but data on septic tank management is scarce at the time of study[15]. This is the only study we are aware of which offers empirical MCF values from field research, so we use this value for septic systems.

Methane emission factor data for sewer conditions is also scarce. The IPCC guidelines suggest a value of 0 for fast moving, clean sewer systems and 0.5 for stagnant or open sewers, as stagnant conditions can generate anaerobic environments, particularly in warm areas. Here we assign a value of 0 to all sewer services in developed SDG regions (Europe, North America, Australia & New Zealand), as we assume sewer systems here will largely be closed and fast moving with minimal anaerobic activity. The extent to which sewers in developing SDG regions are stagnant, open and warm is unknown and we accordingly take the lowest value of the range described for open and stagnant sewers by IPCC[12] (0.4).

The MCF value (Eq. S5.2) for latrines is determined by the depth to the water table, as latrine molecular oxygen (O_2) levels will deplete when contents are submerged in water. Flooded latrines may become anaerobic when the O_2 dissolved in the water becomes depleted. A water table depth of >3m can be classified as dry/above water table, whilst a depth of <3m can be classified as wet/below water table, as latrines are typically dug to a depth of 2-3 meters[17]. Global groundwater table depth has been estimated using national data and modelling by Fan et al[19]. We combine continental estimates of water table depth from this study and IPCC guidelines to incorporate this consideration into the MCF in the latrine service. IPCC guidelines suggest 0.1 for dry climate with water table lower than latrine, 0.5 for dry climate with water table lower than latrine but many users, and 0.7 for wet climate with ground water table higher than latrine. We assume the water table is lower than latrine level at 3 m. An MCF of 0.1 is also suggested for routinely emptied latrines, but data on this is absent[15]. Based on estimating average water table depth in SDG regions from Figures S12-16 in Fan et al[19], we assign the following MCF values for latrines in the improved sanitation category, and 'shared' and 'unimproved' sanitation in the unimproved category. We assume 'shared' and 'unimproved' will mostly refer to informally dug latrines and septic tanks shared between families and communities. We select MCF values of 0.1 for North America and Europe, 0.35 for Latin America and the Caribbean, 0.25 for Central and South Asia, 0.25 for Eastern and South-Eastern Asia, 0.1 for Western Asia and North Africa, 0.3 for Sub-Saharan Africa, 0.2 for Australia and New Zealand and 0.3 for Oceania. Conservative estimates are deliberately taken due to the uncertainly associated with this assessment.

'Shared' services are given the same MCF value as the dominant sanitation service in that region and 'unimproved' services are assigned the same MCF value as pit latrines, as 'unimproved' services are defined by JMP[15] as poorly constructed or maintained pit latrines.

We use the JMP[15] value for wastewater treatment to account for the S value suggested by IPCC[12] (organic component removed as sludge). For example, 87% of wastewater is treated in North America in Europe; here we applied an 'untreated fraction' of 0.13. IPCC[12] also suggest an R value (Eq. S5.1) to account for recovered methane from sanitation systems, which may be significant in estimations from WWTPs, but will be minimal from latrines etc. Some septic systems are equipped with biogas recovery systems, but how many and how efficient these are is unknown and this is not included in this study. The modifications are summarized in Eq S.7.

$$CH_4 emissions = \sum_i \left[U_i \cdot EF_i \cdot TOW \cdot Frac_{untreated_i}\right] \tag{S.7}$$

U_i refers to the fraction of the urban/rural population using each sanitation service; EFi is the selected emission factor; TOW is the total organics in wastewater and $Frac_{untreatedi}$ is the fraction of untreated wastewater in each region. CH_4 emissions were converted to CO_2 e by applying a GWP of 28, NO_2 emissions were converted to CO_2 e by applying a GWP of 301[20]. Sanitation systems can also generate nitrous oxide and we use the IPCC[12] methods to estimate these, with minor modifications. The IPCC methods for estimating nitrous oxide emissions are described in Box S.2.

Box S.2 IPCC* methods for calculating nitrous oxide emissions from sanitation systems

$$N_2O\ emissions = N_{effluent} \cdot EF_{effluent} \cdot {}^{44}/_{28} \tag{S8.1}$$

Where $N_{effluent}$ is the N in the effluent discharged into aquatic environments, $EF_{effluent}$ is the emission factor for N_2O emissions from $N_{effluent}$, and 44/28 is a conversion factor (kg N_2O-N into kg N_2O).

IPCC (2019) IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 6: Wastewater Treatment and Discharge

The IPCC methods cited in Box S.2 describe N inputs of industrial pollution and food waste to sanitation systems, but as this study is only concerned with human waste, we exclude these inputs. For $N_{effluent}$ we substitute N_{exc} (calculated previously in SM.1). Emission factors suggested by IPCC were applied to all sanitation services (0.005 for open defecation, 0.019 for developing world sewers, 0 for developed world sewers, 0 for latrines, 0.0045 or septic tanks).

Supplementary Materials 6. Water Availability and Requirement

Water availability and requirement was taken from AQUASTAT[21]. The most recently available national data from variables 'Total Renewable Water Resources', 'Renewable Internal Water Resources', 'Freshwater Withdrawal' and 'Agricultural Withdrawal' data points were taken. National data was aggregated into the SDG regional groupings and projections for 2030 and 2050 were done by adjusting for the predicted population in each SDG Region in the same fashion as excreted N, P and C described previously.

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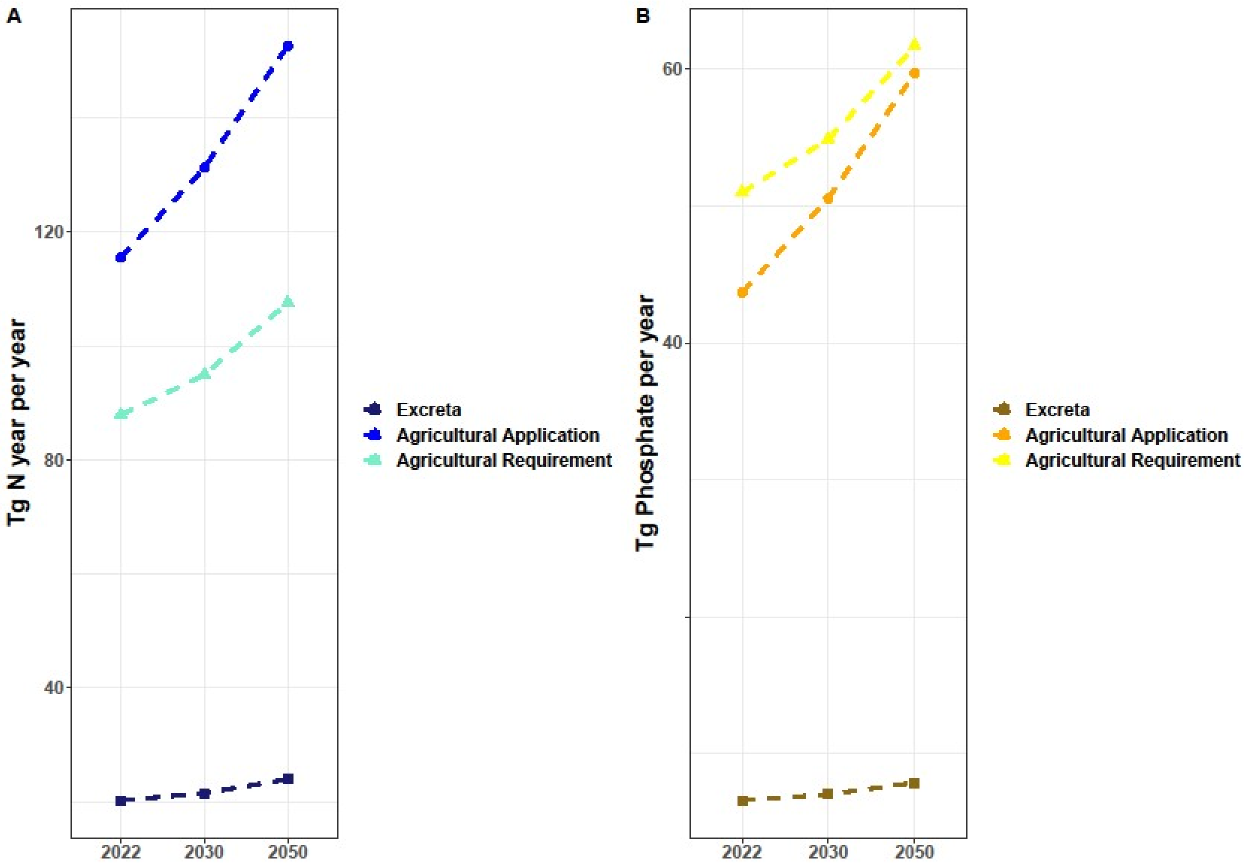

Figure S1. Global nitrogen (A) and phosphate (B) available for recovery in human excreta, total nitrogen and phosphate fertilizer applied to agriculture and nitrogen, and nitrogen and phosphate fertilizer requirement of 17 key crops in Sustainable Development Goal Regions in 2022 with projections to 2030 and 2050. Units are Tg N year-1 and Tg P2O5 year-1.

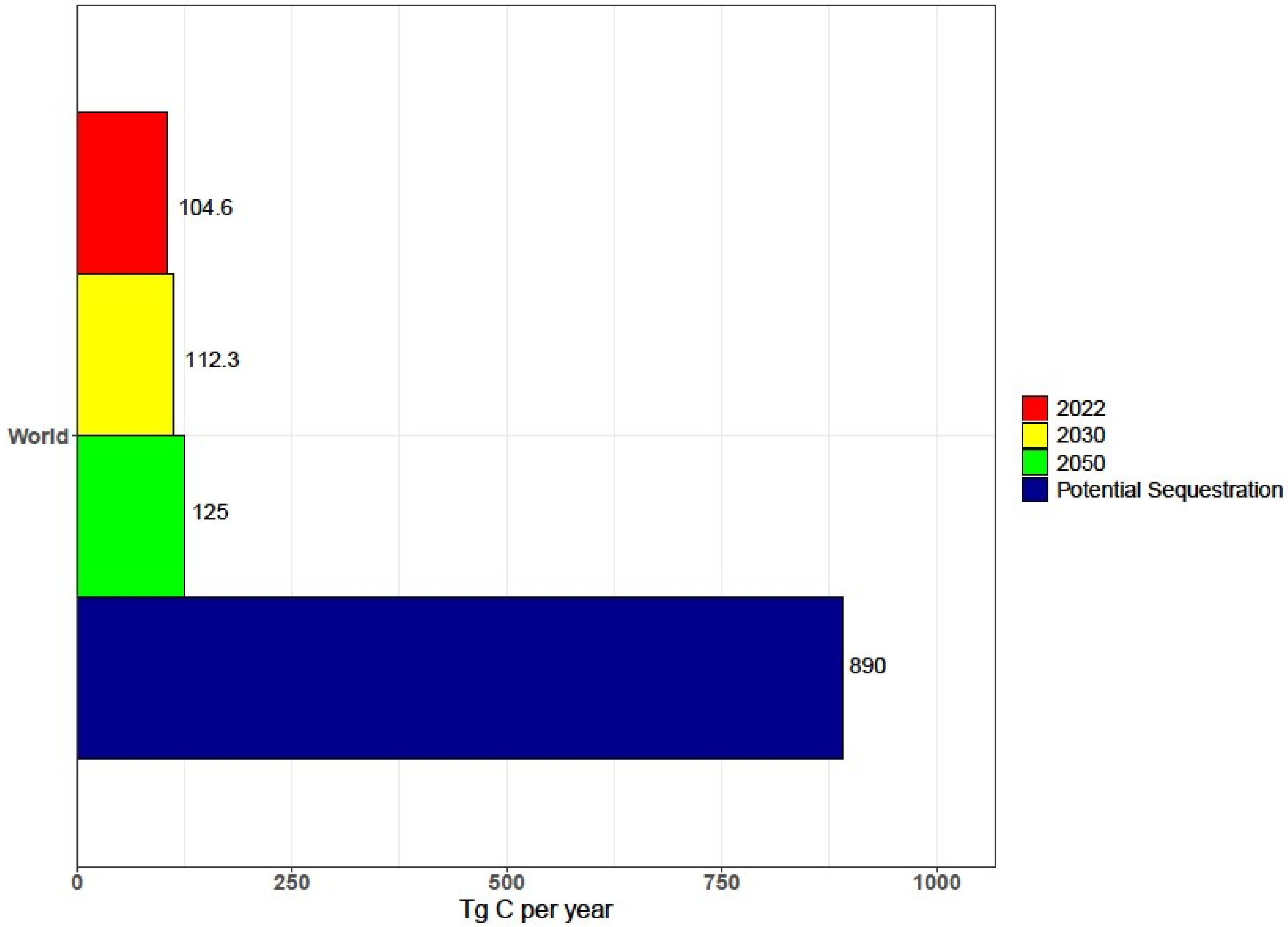

Figure S2. Figure S2. Global excreta C in 2022, 2030 and 2050 and global potential cropland sequestration in cropland. All units are Tg C per year

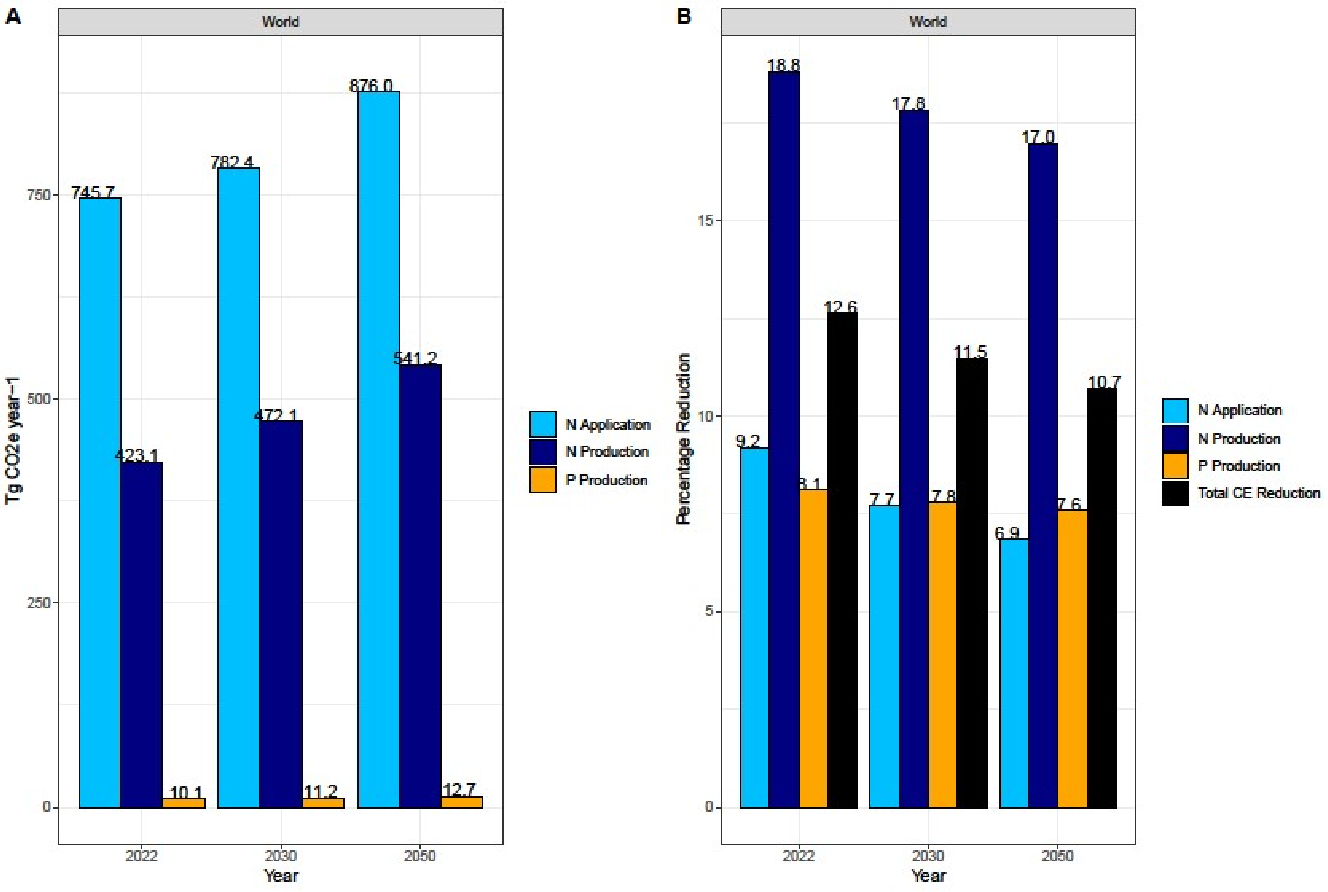

Figure S3. Global GHGs from mineral fertilizer production and application (A) and percentage reduction offered by the circular economy (B)

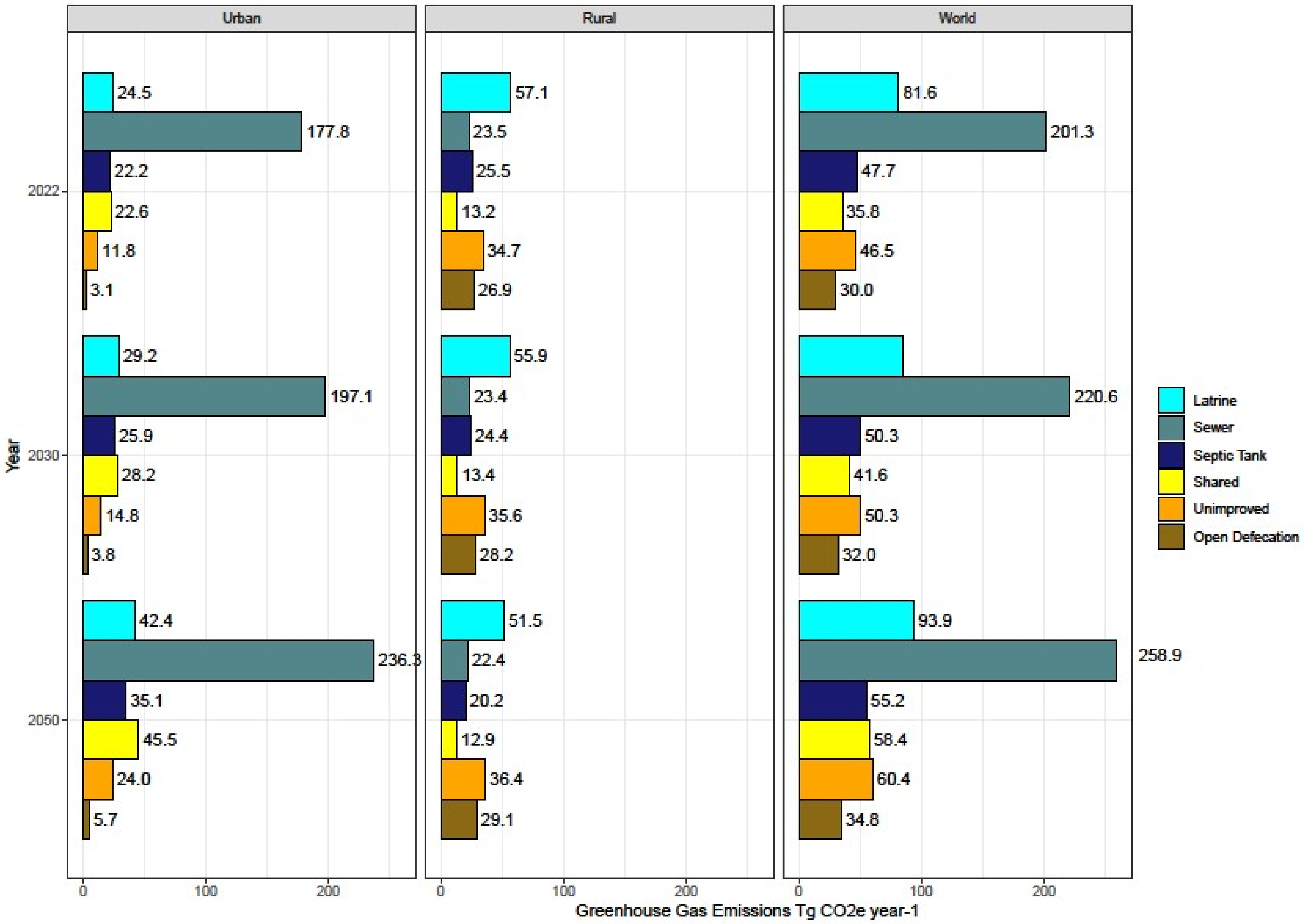

Figure S4. Global greenhouse gas emissions (urban, rural and total) in Sustainable Development Goal Regions in 2022 with projections to 2030 and 2050. Improved services are given in blue, unimproved services are given in yellow/tan. All units are Tg CO2 year-1.