NEW
Harmonica

Material Flow Analysis Methodology Report

Authors

Shane A. Rothwell[1], Kirsty J. Ross[1], Paul J. A. Withers[1]

[1] Lancaster University

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NEW Harmonica

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EXECUTIVE SUMMARY

Material Flow Analysis (MFA) is a modelling approach commonly used to understand nutrient use in food systems at various scales. They provide a useful visual representation of nutrient imports, exports, internal movements, stores, and losses within a geographically defined area and are considered a starting point for improved nutrient stewardship. Once baseline MFA models are established, scenario models can be developed to understand the impacts of changed nutrient stewardship on the entire food system. MFA models that consider multiple nutrients, for example nitrogen (N) and phosphorus (P) are particularly useful in scenario analysis as they allow understanding of how management interventions for one nutrient may interact with the other nutrient. Additionally, the data outputs from the MFA models can be used to generate system indicator metrics that assess the environmental impact, sustainability, or efficiency of the food system.

This report presents a prototype methodology for a common, combined N and P MFA model that can be applied to the four study areas in the New Harmonica project. Initial application of this model to the Wye catchment indicates that the prototype model functions well and is appropriate for improving our understanding food system N and P in the New Harmonica study catchments.

Material Flow Analysis Methodology

Shane Rothwell, Kirsty Ross, Paul Withers

1. Introduction

Material flow analysis (MFA) is a modelling approach often used to both analyse and visualise nutrient utilisation and dynamics within food and agricultural systems. A sufficiently complete system understanding allows identification and quantification of imports, exports, accumulations, and losses of nutrients within a geographically defined system. MFA has been previously used to describe phosphorus (P) or nitrogen (N) flows at regional (e.g. Chowdhury et al., 2018, Low et al 2020), national (e.g. Rothwell et al 2022, Mayor et al 2022) and global (e.g. Vaccari et al., 2019) scales. Increasingly however, combined, multiple nutrient models are being employed to help understand the interactions between food system nutrients under different management approaches, for example N and P (Tanzer et al 2018, Vingerhoets et al., 2023).

Complete MFA models are considered a starting point for improved nutrient management by highlighting priority areas for intervention to meet future sustainability targets for nutrient stewardship (Brunner, 2010). Furthermore, when baseline nutrient MFAs are established, they can be utilised in scenario analysis to help understand the impacts of potential system change on nutrient dynamics. These are particularly insightful in multi-nutrient MFAs (e.g. N and P) where management intervention for the impacts of one nutrient may positively or negatively impact the sustainable use of other nutrients.

This project will develop and apply a common N and P MFA model for the four study catchment areas in the New Harmonica project, namely the Dutch Meuse, Flemish Meuse, Neagh Bann and Wye. This report details the development of a prototype MFA methodology for use across the New Harmonica catchments and examples its application to the Wye catchment in England and Wales. Further iteration of the methodology is anticipated as the prototype model is applied across the other three study catchments to enable a suitably harmonised model for deployment in North West Europe.

2. Methodology

2.1 MFA model and data uncertainty

The MFA model is comprised of processes and flows that represent the major uses and movements of all significant materials relating to the food system in the catchment (figure 1). Model processes represent the major sectors or industries present in the catchment that utilise or manage food system N and P and are described in more detail below. Where a sector can accumulate or lose nutrients (e.g. agricultural soil), then this is represented as an annual stock within that process. The model flows represent the imports, exports, internal flows and losses into and out of the catchment, and movement between the processes and are again described in more detail below. The model flow outputs are a Sankey style meaning that the width of the flow is proportional to the size of that flow. The system boundary for the catchment MFA model is the hydrological boundaries of the chosen catchments and 2021 has been chosen as a baseline year for data collection. Where 2021 data is not available, the nearest available years data is used, though this is recognised in an increased uncertainty for that data.

The MFA model is produced using the free software STAN (Cencic and Rechberger 2016) which applies the principles of mass conservation mass balance along with data reconciliation and error propagation to produce a balanced model according to assigned uncertainty of the data. When flow data is incomplete or there is a gross error in the flow value estimates, the model will not run successfully. With sufficiently complete data, the model will balance giving a realistic representation of food system N and P use in the catchment. The completeness of the data and success of the model can be judged by comparing the model flow input data with the STAN reconciled model output data. Where the change in value between the model input and STAN calculated flow values are less than 10% the data can be considered satisfactory.

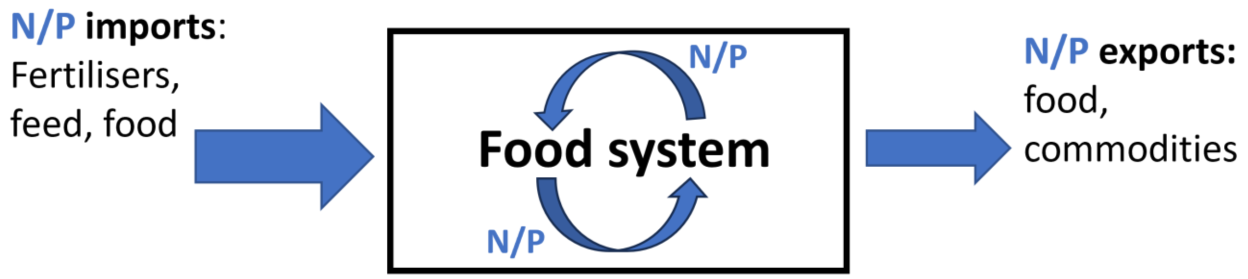

Figure 1. A simple conceptual Substance Flow Analysis (SFA) figure. The SFA assesses the imports, flows, stocks and exports of a particular material (in this case phosphorus (P) and nitrogen (N)) from a defined system using a mass balance approach.

Uncertainty of data flows is assessed using the systematic approach fully described by Zoboli et al (2016). In brief, an evaluation score is assigned to a range of quality indicators that are translated into coefficients of variation (CVs) for that quality indicator. The quality indicators are: *Reliability*, *Completeness*, *Composition*, *Temporal correlation, Geographical correlation* and *Further correlation*. A final quality indicator, *Expert judgement* is used where expert opinion is used to assign a flow. Each quality indicator is assigned a score between 1 and 4 where 1 represents the most reliable data and 4 the worst, though *Composition*, *Temporal*, *Geographical* and *Further correlation* are subject to a further sensitivity assessment based on the subjective opinion of the user. Three sensitivity levels are available from *Highly sensitive*, *Sensitive* to *Not sensitive* which then determine the CV assigned to each score. The CVs assigned to each quality indicator score and sensitivity used in this study and as determined by Zoboli et al (2016) are shown in table 1.

Table 1 Coefficient of variation scores with quality indicators and sensitivity and to assign uncertainty to the MFA data flows.

Quality indicator	Sensitivity	Score (%CV)			
		1	2	3	4
Reliability	n/a	4	10	22	50
Completeness	n/a	0	10	22	50
Composition *Temporal correlation* *Geographical correlation* *Further correlation*	Highly sensitive	0	10	22	50
	Sensitive	0	5	11	22
	Not sensitive	0	2	4	8
Expert judgement	n/a	10	20	40	80

2.2 Processes and flows

2.2.1 Model processes

The MFA model processes that represent the sectors or industries that represent significant uses or handling of nutrients the food system are:

Process 1 is *Livestock* which includes all livestock grown for the purpose of food production or breeding, notably, beef and dairy cattle, sheep and lambs, pigs and poultry.

Process 2 is *Agricultural Soil* that represents the soil-based agriculture that produces all tillage crops, horticultural produce, and grass for both grazing and silage/hay. This process includes a stock value (presented in a box within the process) that represents the annual accumulation of N or P within the agricultural soil.

Process 3 is *Agricultural Products* that deals with the internal movements and export of agricultural products and food produced in the catchment.

Process 4 is *Human Consumption* that includes all food consumed or wasted in households, institutions, and the food service sector, and P coming from detergent and that added to drinking water to prevent plumbosolvency.

Process 5 is *Wastewater Treatment* that represents the processing of wastewater arising from households and industry and includes both WWTW and septic tanks.

2.2.2 Model flows

There are 20 flows in the MFA that represent the internal movement of N and P between processes and catchment import and export. The model flows and a brief description are given in table 2. Where possible, flow N and P data is determined by inputting the mass of the material (e.g. manure), and the N and P content of that material, STAN then calculates the elemental N and P mass flow. However, for some flows it is not possible or practical to take the mass and N/P content approach, e.g. when estimating gaseous N flows or N and P losses to water from agriculture or wastewater. In these cases, the elemental mass of N and P is inputted directly into the STAN model. All flows are ultimately outputted in the model as elemental N or P per year ± uncertainty.

Table 2 Details of flows contained in the catchment STAN model including associated process, flow name and a brief description.

Flow number	Process	Flow Name	Flow description
1.01	Livestock	Livestock emissions to atmosphere	Gaseous nitrogen losses from housed livestock and stored manure as NH3, N2O and NO2
1.02		Manure to fields	All manure coming from livestock that stays in the catchment and goes to agricultural fields from both spread manure from housed animals or directly deposited during grazing
1.03		Livestock product to food processing	All livestock products produced in the catchment including meat as live weight, milk and eggs
1.04		Import Feed	Feed imported into the catchment to meet livestock feed requirements
2.01	Agricultural soil	Field emissions to atmosphere	Gaseous nitrogen losses from agricultural soil as NH3, N2O and NO2. Includes loss from fertiliser, manure, biosolid and AD spreading; emissions from grazed livestock; and mineralisation from managed cropland. Both direct and indirect losses are considered
2.02		N fix to agricultural soil	Atmospheric nitrogen fixed in the agricultural soil from legume crops
2.03		Atmospheric deposition	Deposition of both naturally occurring and anthropogenic N and P onto agricultural land in the catchment
2.04		Import fertiliser	Fertiliser imported into the catchment for application to agricultural fields
2.05		Crop products	All crops produced in the catchment for human or livestock consumption
2.06		Grass	All grass grown in the catchment that is either harvested as silage or hay, or grazed
2.07		Ag losses to water	Total losses from agriculture in the catchment to water
3.01	Food processing & agricultural products	Crops to feed	Crops grown in the catchment that are used to feed livestock produced in the catchment
3.02		Food and ag product export	Agricultural products (livestock and crops) grown of produced in the catchment that are exported as either raw product or processed food stuffs
3.03		Local product consumption	Food consumed by the catchment population that is grown in the catchment

4.01	Human consumption	Human to WWT	All human effluent waste that is going to waste water treatment works or privately owned septic tanks
4.02		Food waste	Proportion of the food wasted by the population in the catchment
4.03		Import food (& detergent P)	Food imports and for phosphorus, detergent imports and phosphorus added to drinking water to prevent plumbosolvency
5.01	Wastewater Treatment (inc. septic tanks)	Biosolids to ag fields	Biosolids recovered from WWTWs that are applied to agricultural land in the catchment
5.02		STW losses to water	Loss to water from all wastewater sources (WWTWs, combined sewer overflow, storm tank overflow and septic tanks)
5.03		STW emissions to atmosphere	Nitrogen loss to atmosphere during the wastewater treatment process

2.3 Flow values and coefficients

2.3.1 Human and wastewater

2.3.1.1 N and P consumption

The human population in the catchment is determined from national census data, (ONS 2021). Total human dietary N and P intake for the catchment is then estimated using daily per person intake coefficients. For the Wye catchment this is calculated using an estimate of food purchased using UK dietary survey data (OHID 2023) and the N and P content of that food taken from McCance and Widdowson (Finglass et al 2015). A percentage of purchased food is usually wasted and not consumed which needs to be accounted for. For the UK this data comes from WRAP and is estimated at 17% (WRAP 2020) and includes domestic household, service sector (e.g. schools and hospitals) and hospitality food waste.

There is also P entering the food system from detergent use and P added to drinking water to prevent plumbosolvency that must be accounted for as it ultimately ends up in the wastewater sector and consequently either reapplied to land via biosolids or contributes to the losses to water. This is estimated using per capita coefficients for detergent P and plumbosolvency P derived from Rothwell et al (2022).

2.3.1.2 Waste water losses to water

As the STAN model does not calculate losses to water it is reliant on data from other modelled outputs. For the Wye catchment, point source losses to water of P are currently applied from the Separate model (Zhang et al 2014) that gives an annual loss from WWTWs, septic tanks, combined sewer overflows and storm tank overflows. N loss to water is estimated from assumed N removal efficiency of 79% (Coppens et al 2016). However, emission estimates from the modelling exercise in New Harmonica task 2.3 will ultimately provide the data to input into the MFA for N and P losses to water.

2.3.2 Livestock

2.3.2.1 Livestock product

Livestock product as meat, milk and eggs, is estimated by multiplying up the catchment livestock population by established per head production coefficients. For the Wye catchment, the livestock population is established from agricultural census data (Defra 2021) selected for the catchment area. To estimate livestock product coefficients at the catchment scale, we used UK national statistics on livestock population and product to extrapolate per head product coefficients for meat, milk and eggs as a mass of product. The N and P content of the various livestock product is taken from Defra (pers comm.) and a single weighted average N and P content coefficient for livestock product is used in the model.

2.3.2.2 Livestock manure

Livestock manure excretion is estimated from established coefficients for the different livestock classes (Defra pers. Comm.), and the values are multiplied by the livestock population census data to give a total mass of manure produced in the catchment. The manure N and P content values are taken from established sources (AHDB 2022). The model usually assumes that all livestock manure produced in the catchment remains in the catchment and any minor movements of manure both into and out of the catchment cancel each other out. If any major imports or exports of manure are identified these can be quantified with new import or export flows in the model.

2.3.2.3 Livestock feed

Livestock manufactured feed use is estimated by balance within the STAN model i.e. if the grass and fodder input to the livestock system (as N and P) and the livestock product and manure coming out of the livestock system (as N and P) are known, the difference must equal the feed input. A proportion of feed will likely come from grain crops grown in the catchment. Local farmer expert knowledge in the Wye catchment would suggest this is around 30% of grain production. By subtracting this locally grown feed input we can estimate the catchment level feed import.

2.3.3 Crops and grass

2.3.3.1 Yield and offtake data

Crop and grass offtake is calculated from 2021 agricultural census data for the area of the different crops grown in the catchment, and established yield (Defra 2022a) and N and P crop content coefficients (Defra pers. Comm.). The total mass of arable crops harvested is calculated by multiplying crop area by a yield coefficient, and a single weighted average N and P content for those crops is applied to the model. Coefficients for average annual yields of arable crops are either obtained locally, regionally, or nationally, whatever data is best available.

National yield data for grass production (t/ha) is not available in the UK, so for the Wye catchment we used a grass DM production model developed by Qi *et al* (2018) at Rothamsted that uses predicted regional baseline DM production values for temporary and permanent grass that are adjusted for nitrogen input from fertiliser and manure for the relevant year. The N and P content coefficient for grass is taken from AHDB (2022).

2.3.3.2 Fertiliser data

For the Wye catchment, The British Survey of Fertiliser Practice (Defra 2022b) regional overall average fertiliser use rates (kg/ha) for both N and P (P is converted from P2O5) were used. These are then multiplied up by the catchment crop and grass census data areas to give us an estimated total fertiliser input of N and P. Where catchment-specific fertiliser input data is available, this can be used instead.

2.3.4 Losses to water from agriculture

Similarly to the point sources, the STAN model does not calculate losses to water from diffuse sources, so is again reliant on additional modelled estimates for N and P. For the Wye catchment, estimated P losses to water from agriculture come from the Separate model (Zhang et al 2014), and N is currently estimated for an assumed N/P loss ratio of 13.3 which is the average value of those found by Le Noe et al (2017), Tanzer et al (2018), and Antikainen et al (2005). New Harmonica task 2.3 will again provide updated estimates of both N and P losses to water to input into the MFA model.

2.3.5 Gaseous N losses from agriculture

This data is split into losses from 'housed livestock and stored manure' and 'field-based losses' that include spreading of fertiliser, manure and other organic inputs, and direct deposition of manure at grazing. Losses include nitrogen oxides (NOx and NO2), nitrous oxide (N2O) and ammonia (NH3) and are all converted to elemental N for the model input. Both direct losses from livestock and agricultural land and indirect (off-site) losses, mostly from agricultural N leaching and runoff (Tian et al 2019) are accounted for. We use national level emission data from the National Atmospheric Emissions Inventory (NAIE 2023) and national statistics on land area and livestock populations (Defra 2021) to produce emission coefficients for agricultural land (grassland and arable as kg/N/ha), and livestock classes (cattle, sheep, pigs, poultry, and other as kg/N/head). These coefficients are then multiplied up by the catchment land use and livestock census data to give atmospheric N losses from agriculture for the catchment.

2.3.6 Atmospheric deposition and nitrogen fixation

Atmospheric N and P deposition rates (kg/ha) are taken from Tipping et al (2014) and are multiplied up by the census agricultural area to give total N and P deposition. Fixing of atmospheric N in legume crops and pasture is estimated using established relationships between N offtake at harvest and the proportion of that derived from symbiotic N fixing (Anglade et al 2015). It was assumed that 25% of managed grassland contained clover (Le Noe et al 2017).

2.4 System analysis

The data outputs from the MFA model can be used to generate system indicator metrics that can be used to assess the environmental impact, sustainability or efficiency of the catchment food system. For example, overall catchment food system nutrient use efficiency can be calculated, which is expressed as the ratio between the N or P in food and products produced and N and P imports (van Dijk et al 2016). Low food system efficiency means that N or P is either being lost from the system, likely causing environmental pollution, and/or is accumulating unused in the system, so is a good over arching indicator of nutrient stewardship. Similarly, the efficiency of nutrient use in the soil based agricultural system can be assessed from the crop and grass output to the nutrient inputs to the soil surface. The overall system N and P pressure on the catchment (in kg/ha) can be assessed by estimating the Net Anthropogenic Nitrogen/Phosphorus Input (NANI/NAPI) which are commonly correlated with riverine losses of N and P (e.g. Howarth et al 2011, Metson et al 2017). The theoretical potential of secondary nutrient sources (e.g. manures) produced in the catchment to meet (or exceed) catchment crop and grass demand can also be assessed, which can indicate scope for improved nutrient circularity and reduced need for fertiliser imports. Examples of these and further indicator metrics are shown in table 3.

2.5 Data and coefficient harmonisation

The coefficients described here mostly relate specifically to the Wye catchment and UK based data. An important component of this work is to determine if standard coefficients can be used across all four catchment areas or whether catchment specific coefficients will be needed. The next phase of this work will collate relevant coefficients from each catchment area to understand how variable they are and make a judgement on the most appropriate approach.

2.6 Scenario analysis

Scenario MFA models can be produced to understand the system level impacts of proposed changes to N and P stewardship on N and P loss to water. These will capture any major changes to the food system, for example reduced fertiliser use, changes in land use or livestock population or significant export of livestock manures. To do this, the values for the changed flows are estimated and inputted into the model, and any additional flows, for example manure export, are added. With a complete scenario model, new indicator metrics can be generated to compare the magnitude of impact against the baseline MFA model. This approach is particularly insightful in the combined N and P model as the impact of mitigation measures or system change for one nutrient can be assessed for the other nutrient.

3. Preliminary MFA results for River Wye Catchment

3.1 N and P MFAs

The MFA baseline model outputs for N and P in figures 1 and 2 and analysis in table 3 show that in 2021 the food system imported a total of 56344 t N/yr and 6928 t P/yr into the Wye catchment, and 24838 t N/yr and 4139 t P/yr were exported in food and agricultural products or consumed locally. Overall food system efficiency for the Wye catchment, assessed as the ratio of N or P in food or product produced in the catchment to total N and P imports was therefore 51% for N and 60% for P, suggesting a highly inefficient food system.

The largest catchment import for both N and P was in animal feed (26756 t N/yr and 5496 t P/yr) which represented 55% and 80% of total catchment imports for N and P respectively. The largest internal flows of N and P were in animal manure (32486 t N/yr and 5987 t P/yr), which suggests that N and P flows are predominantly related to livestock production. Fertiliser import and use in the catchment was 20897 t N/yr and 1224 t P/yr which represented 43% and 18% of total N and P catchment import respectively.

Total agricultural input of N and P from manure, fertiliser, biosolids, atmospheric deposition and N fixation to the soil was 61166 t N/yr and 7331 t P/yr while total offtake in crops and grass was 32910 t N/yr and 4630 t P/yr leaving respective agricultural surpluses above crop requirements of 28256 t N/yr and 2701 t P/yr. Normalised over the productive agricultural area in the catchment (excluding rough grazing), this equates to an average surplus of 99 kg N/ha and 9.5 kg P/ha which is slightly higher than the UK average for N of 93 kg N/ha, but considerably higher than the UK average P surplus of 5.7 kg P/ha for 2021 (Defra 2022c). Agricultural losses to water from agriculture were estimated at 3007 t N/yr and 225 t P/yr, so the combined surplus application above crop requirement and loss to water meant agricultural soil nutrient use efficiency was only 54 % for N and 63 % for P.

In 2021 the human population in the Wye catchment consumed 1189 t N/yr and 153 t P/yr in food, detergents and plumbosolvency P and wasted 164 t N/yr 18 t P/yr in food waste. This means 1025 t N/yr and 135 t P/yr went to wastewater, of which 162 t N/yr and 52 t P/yr were recovered in biosolids. For N 648 t N/yr were lost to atmosphere at wastewater treatment meaning losses to water from all wastewater sources (WWTW, CSO, storm tanks and septic tanks) were 215 t N/yr and 83 t P/yr. Source apportionment of N and P losses to water from the food system in the catchment are therefore 7% wastewater and 93% agriculture for N and 27% wastewater and 73% agriculture for P. The NANI/NAPI input pressure for the catchment was 79 kg/N/yr and 6.8 kg/p/yr.

Secondary N and P sources generated in the catchment (manure and biosolids) totalled 32648 t N/yr and 6039 t P/yr. Therefore, theoretically crop and grass N demand in the catchment could be almost entirely met (99%) by secondary sources alone without fertiliser use. Secondary P sources in the catchment actually exceeded crop and grass P demand by 30% indicating that catchment agricultural surplus and inefficiency is driven by manure N and P loading to the catchment soils.

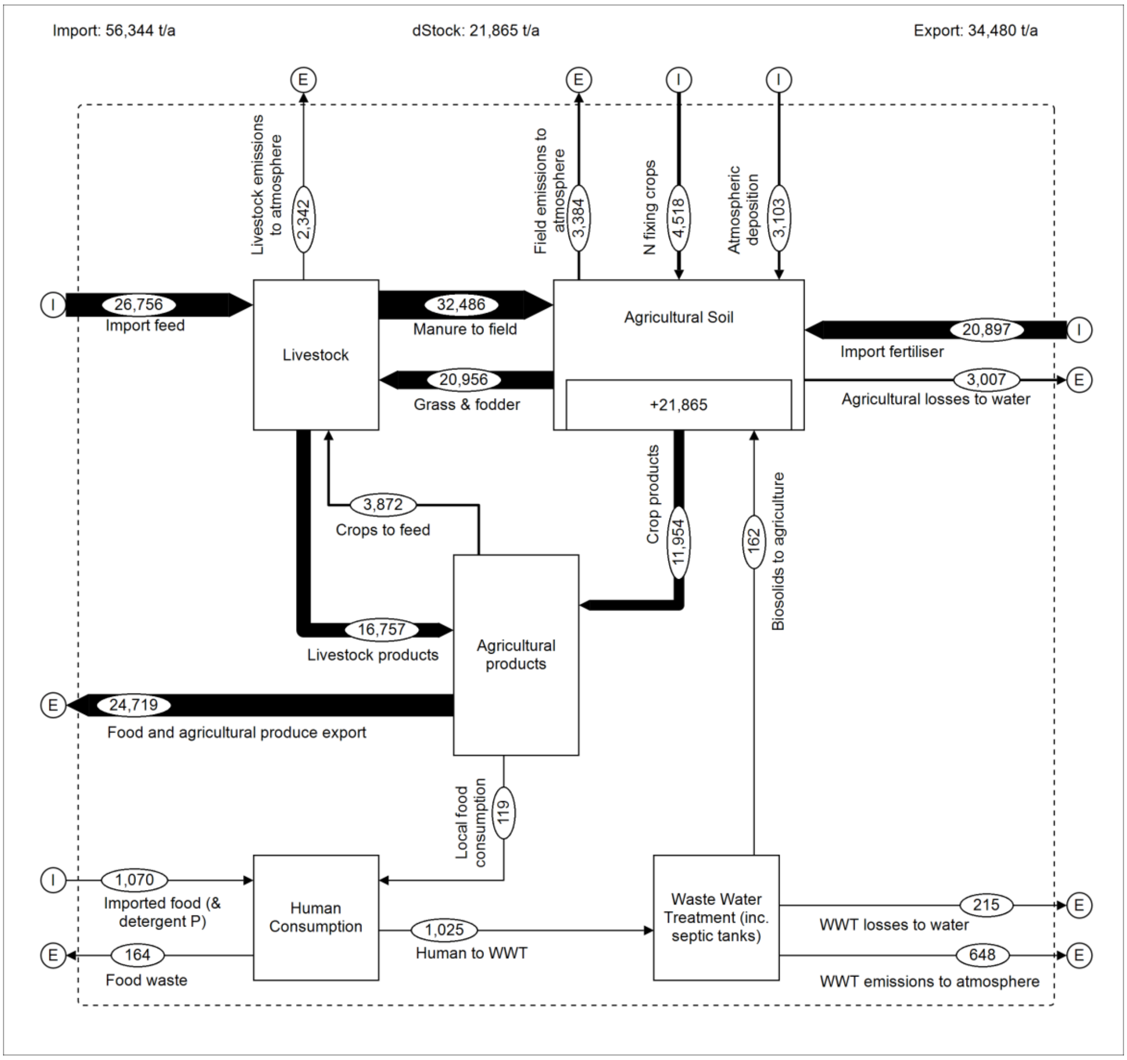

Figure 1 Nitrogen (N) Material Flow Analysis (MFA) for the river Wye catchment. All flows are ± uncertainty (t/N/yr) for the year 2021. The boxed value in the Agricultural Soil process represents the annual accumulation of N in the agricultural soil.

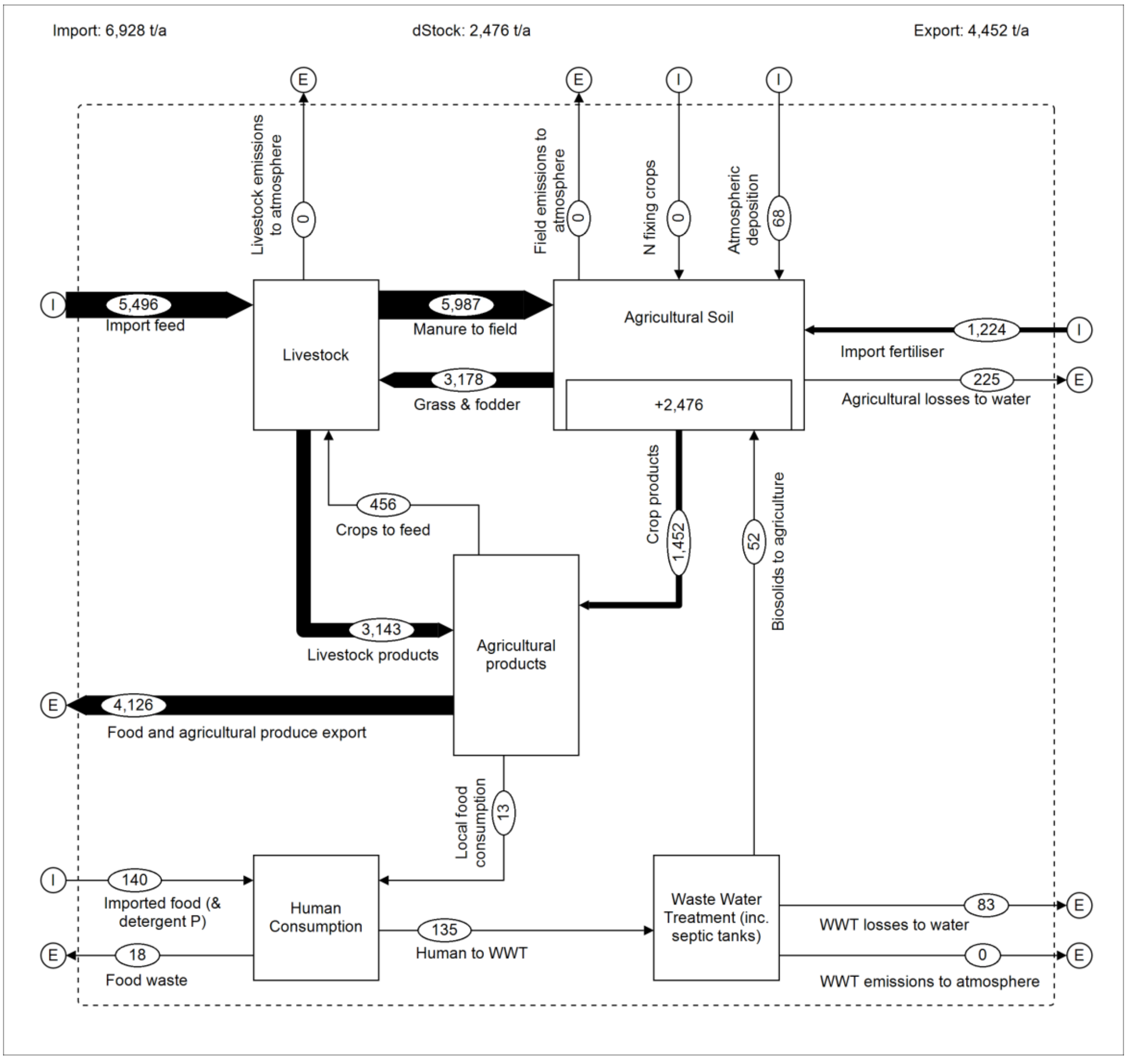

Figure 2 Phosphorus (P) Material Flow Analysis (MFA) for the river Wye catchment. All flows are ± uncertainty (t/P/yr) for the year 2021. The boxed value in the Agricultural Soil process represents the annual accumulation of P in the agricultural soil.

Table 3 System analysis of MFA output with indicator metrics for N and P use in the river Wye catchment.

Sector	Metric	N	P
Agricultural soil	Utilised agricultural area (ex. Rough Grazing) (ha)	285133	285133
	In (t/yr)	61166	7331
	out (t/yr)	32910	4630
	Agricultural soil surplus (t/yr)	28256	2701
	Surplus (kg/ha ex. RG)	99	9.5
	Soil efficiency (%)	54	63
	Manure input (kg/ha ex. RG)	114	21
Agricultural loss to water	t/yr	3007	225
	kg/ha (ag area ex. RG)	10.5	0.79
	kg/ha (full catchment area)	7.5	0.56
Agricultural N loss to atmosphere	t/yr	4976	n/a
	kg/ha (ag area ex. RG)	17	n/a
	kg/ha (full catchment area)	12	n/a
Total Agricultural loss (atmosphere + water)	t/yr	7983	225
	kg/ha (ag area ex. RG)	28	0.79
	kg/ha (full catchment area)	20	0.56
Wastewater loss to water	Population	222400	222400
	WWTW (t/yr)	140	55
	CSO (t/yr)	18.7	7.3
	Storm tank (t/yr)	26.7	10.4
	Septic tank (t/yr)	27.7	10.8
	Total (t/yr)	215	83
	Removal efficiency %	79	39
	Loss (kg/PP)	0.97	0.37
	Loss (kg/ha) (full catchment)	0.54	0.21
Wastewater loss to atmosphere	Total (t/yr)	648	0
	Loss (kg/PP)	2.9	0
	Total (t/yr)	863	83

Total wastewater loss (atmosphere + water)	Loss (kg/PP)	3.9	0.37
NANI/NAPI	Total catchment area (km2)	4017	4017
	Total (t/yr)	31625	2716
	kg/ha (full catchment)	79	6.8
Loss apportionment to water	Agriculture (%)	93	73
	Wastewater (%)	7	27
Catchment food system	Import total (t/yr)	48723	6860
	Import % as feed	55	80
	Import % as fertiliser	43	18
	Import % as food/detergent	2.2	2.0
	Import % as manure	n/a	n/a
	Import % as biosolids	n/a	n/a
	Export total (t/yr)	24719	4126
	Export % as ag products and food	100	100
	Export % as manure	n/a	n/a
	Export % as biosolids	n/a	n/a
	Balance (t/yr)	24004	2734
	Balance (kg/ha)	60	7
	Efficiency %	51	60
Secondary P (manure + biosolids)	Total input	32648	6039
	% of total ag input	53	82
	% manure of total input	53	82
	% biosolids of total input	0.26	0.71
	% of crop and grass offtake (demand met)	99	130

4. CONCLUSIONS

Here we have presented a prototype methodology for producing a combined N and P MFA model for the four catchment areas covered in the New Harmonica project using STAN software. This represents a starting baseline model that covers the major imports, exports, internal stocks and flows required to understand food system N and P stewardship in the catchments. Preliminary findings for the Wye catchment suggest that the N and P model balances and functions well. The model has scope for further adaption if any new major flows are identified or as existing flows are improved and can be utilised for scenario analysis of proposed system change or nutrient mitigation measures. Establishing whether common N and P coefficients can be applied to all four catchment areas is a critical next step. Once baseline MFA outputs have been generated for each of the study catchments, scenario analysis will be deployed in WP3 to assess the impact of potential system-wide changes on a range of sustainability metrics. Outputs from the catchment MFAs will also be compared with the outputs of the Miterra model (Velthof et al 2009) applied to each catchment so that the effects of N and P stewardship on the carbon balance can be estimated.

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