Soil Phosphorus Status and Water Quality in the River Wye, Phase 2: Land Use Change and Phosphorus Balances in the Wye Catchment

Paul J A Withers, Kirsty J Forber and Shane A Rothwell
Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ UK

March 2023

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Summary

This report covers Phase 2 follow-on work for the Environment Agency (EA) aimed at further development of the evidence base linking livestock farming to phosphorus (P) surpluses, soil P status and water quality impacts in the Wye catchment, and a better understanding of the potential impact on P surpluses and water quality of future land use change. Phase 1 highlighted a strong linkage between catchment P input pressures, manure P loadings to the land surface and build-up of soil P across the English part of the Wye.

Livestock farming has had a major impact on land use patterns and P cycling in the Wye catchment over the last 150 years, traditionally with cattle and sheep farming but more recently due to the rapid expansion of the poultry industry. Annual livestock manure P loading to the soil has consistently exceeded annual catchment crop P requirements, and even in 1870 there was an estimated P surplus of over 4 kg P/ha. This increased to 23 kg P/ha in 1975 as agricultural systems intensified, but has declined since to a similar level to that in the 1920's (ca. 9 kg P/ha).

The historic analysis of surplus P loading suggests the cumulative build-up of surplus P in Wye soils has left a 'legacy' soil P reserve equivalent to 1.86 t P for every hectare of arable and productive grassland in the catchment. Only 30-60% of this legacy P input can be accounted for in the top 30 cm of soils based on a limited survey of soil total P contents of sandy and silty soils in unfarmed and farmed soils. These data suggest migration of P into the subsoil and significant losses of P to water. As surplus P inputs continue to be added each year, progressive P saturation of, and accelerated P leakage from, Wye soils is a major concern. Further work should examine the degree of subsoil P accumulation and P saturation of Wye soils across the catchment.

An updated Substance Flow Analysis (SFA) for 2021 confirms a current catchment P surplus of ca. 3000 tonnes (revised area loading of 11.4 kg P/ha) using national livestock excretion coefficients. This value is well above the UK P surplus of 5.7 kg P/ha for this year. Using local poultry P excretion coefficients supplied by the poultry industry, the catchment P surplus declines to 7 kg P/ha. A national review of livestock excretion P coefficients is warranted.

The 2021 P surplus in six sub-catchments of the English Wye varied from 1.9 kg P/ha in Yazor Brook to 16.2 kg P/ha in Garren Brook and illustrates the wide variation in manure P production across the catchment. Manure P production drives the sub-catchment P surplus and soil Olsen- P levels continue to be greatest in those catchments with the greatest manure P production. River P export (expressed as SRP) also tended to be greater in sub-catchments with higher P surpluses, but the water quality monitoring programme on which this relationship is based needs to be improved. Detailed sub-catchment maps of soil P results at 1 km^2 resolution are presented to facilitate engagement with relevant stakeholders in high-risk areas.

Scenario analysis of the impact of potential land use change on catchment P cycling and P losses to water suggests the conversion of permanent pasture to cereal cropping to provide more home-grown grain for the poultry industry would reduce the P surplus, but increase P losses to water due to the greater erosion risk. Farmscoper modelling indicated that losses to water would increase by 0.026 kg P/ha for every 10% of grassland converted. Conversion of permanent grassland to maize for anaerobic digestion plants would increase both the surplus and P losses to water; losses to water would increase by ca. 0.004 kg P/ha for every 10% of grassland converted.

1. Introduction

Soil nutrient balances, expressed as a loading of nitrogen (N) or phosphorus (P) per hectare, provide a method for estimating the annual nutrient loading of N and P to agricultural soils. They give an indication of the potential risk associated with losses of nutrients to the environment; losses which can impact on water quality. Nutrient balances are a useful high-level indicator of farming's pressure on the environment and how that will change over time with or without intervention.

Livestock farming is concentrating and intensifying in parts of England. As a result, broadly, there is a clear trend with below-average nutrient balances in the North East, East Midlands and South East in contrast to above-average nutrient balances in the North West, West Midlands and South West (Cordell et al., 2022). At a catchment level, the nutrient surpluses can be considerably higher than regional averages where livestock farming is predominant.

The Environment Agency are researching the fate of phosphorus (P) in poultry manure, and other organic manures, in the River Wye and River Lugg SAC catchments, from places of production to where the manures are recovered to land; how that is impacting on soil P indices in the catchments today and will change over time with or without intervention; and the existing links between soil P and P sources from agricultural land entering the rivers from land runoff and drainage.

A previous study and report (Phase 1) by Lancaster University summarised evidence on the current distribution of soil P levels in the Eastern (English) part of the Wye catchment and links to catchment P balances and P loading from livestock manures (Withers et al., 2022a). The Phase 1 report provided recommendations for more in-depth analysis of catchment P input pressures and their higher resolution mapping. This proposed study (Phase 2) will further develop the evidence base linking livestock farming to water quality by examining the impact of historic and potential future trends in land use on catchment P balances and cycling in the Wye catchment, and identifying potential high-risk sub-catchments based on the distribution of P input pressure, soil P levels and P loss risk to water associated with different soil types.

2. Specific Objectives/Deliverables

2.1 Overall EA objective

To investigate the potential linkages between livestock manure use, surplus P accumulation in soil and river P concentrations at existing and proposed monitoring sites in the R. Wye catchment in order to better manage P loss to water through the regulation of P inputs and soil P status. This is the wider objective of what this work forms a part.

Specific work tasks in Phase 2:

1. Undertake an historic analysis of trends in land use, livestock numbers and fertiliser use and their impact on temporal changes in agricultural P balances and legacy soil P accumulation in the Wye catchment.
2. Undertake a scenario analysis of potential future changes in land use and livestock numbers on P flows and cycling in the Wye catchment using Substance Flow Analysis.
3. Examine the current distribution of P balances and soil P levels across selected Wye sub-catchments using high resolution mapping (subject to data availability).

3. Methods

3.1 Historic analysis of surplus P loading

A historic analysis of the temporal trends in annual and cumulative surplus P loading in the Wye catchment as a result of land use change was undertaken to provide a better evidence base of the trajectory of farming pressures and manure P loading in the Wye catchment and the resultant build-up of legacy P in Wye soils.

Agricultural census data on areas and average yields of agricultural crops and numbers of livestock for the main counties within the Wye catchment (Herefordshire, Powys (Brecon, Radnorshire and Montgomeryshire prior to 1974) and Monmouthshire (largely synonymous with Gwent from 1974 to 1996)) were collated at 5-year intervals from 1870 onwards (Defra, 2023). Census data started in 1866 and are also included, but these early years are considered less reliable. Between 1974 and 1998, Herefordshire was combined with Worcestershire and during those years, the Herefordshire portion was assumed to be the same proportion of the total as in 1995, when data on each county and combined was available. In the last decade, county level census data were only available in 2013, 2016 and 2021, and all census data after 1995 were reported in somewhat less detail compared to earlier years.

Using the available census data and standard material P coefficients, the Wye catchment's annual agricultural P surplus was calculated as an annual soil P balance; the difference between annual P inputs to the soil in fertiliser and manure and annual P outputs from the soil in P offtake in all arable crops and grassland. Calculated input and output P values for a county were assumed to be evenly distributed and summed for the whole Wye catchment according to the percentage of each county within the Wye catchment boundary, and after accounting for changes in county boundaries. The three counties used in this analysis comprised 98% of the Wye catchment area. The annual P surplus was expressed as a total P loading (tonnes) and as an areal P loading (kg P/ha) across the arable and productive grassland area (excluding rough grazing). The cumulative P surplus generated over the period of analysis (1866-2021) was taken as an indication of the amount of legacy P that has accumulated in Wye soils over the last 150 years and potentially available to be exploited.

Annual overall fertiliser P inputs (kg P/ha) to arable crops and grassland from 1974 onwards were taken from British Survey of Fertiliser Practice (BSFP) data collected from the regions local to the Wye catchment (West Mercia (or Region 5 prior to 1992) and Wales (or Region 16 prior to 1992)), (Defra, 2022a). Prior to 1974, regional annual overall fertiliser P application rates were estimated from the relationship between BSFP regional overall P rate values and annual overall P rate values for the whole of England and Wales (E&W), which were based on total UK fertiliser P consumption statistics (Cooke, 1958; Thompson, 1968; Defra, 2022a). This analysis showed that rates and trends in fertiliser P use on arable and grassland in Herefordshire closely followed those in England and Wales, and that rates of fertiliser P use in Wales were ca. 80% of those used in Herefordshire.

Livestock manure P inputs were estimated as P excreted based on standard coefficients for the amounts of excreta P produced annually by each type and class of livestock in each county (Defra 2023; Rothwell et al., 2022). No adjustment was made for trends in excretal P coefficients for ruminants over the last 150 years due to changing dietary P intake, since it was assumed that temporal trends in manure P inputs to land would be driven much more by animal numbers and the volume of excreta produced rather than the P content of the excreta from healthy animals. This may be an over-simplification as cattle fed lower P diets excrete less (Ferris et al., 2010), but the level of feeding with P-rich oilcakes was already prevalent in the earlier years. Phosphorus excretion from non-ruminants is significantly less when phytase is added to the diet to breakdown phytate in cereal-base rations (Defra, 2006). For non-ruminants, current P excretion coefficients (from 2010) assume at least 70% supplementation with phytase, but phytase supplementation was not commonplace before 1995. It was therefore assumed that P excretion from pigs and poultry was 25% greater prior to 1995, 15% greater in 2000, and 5% greater in 2005 than current values from 2010 (Defra, 2006).

Annual biosolid P inputs were based on water company returns to the EA in E&W on the amounts of biosolids applied to agricultural land and their average P content. Biosolid inputs to agricultural land started in ca. 1965 (Davis, 1989), and annual application rate data were available up to 2019. Biosolid inputs to Herefordshire were assumed to be typical of those in E&W, whilst biosolids inputs in Wales were assumed to be 45% of those in E&W based on regional returns (Water UK 2010).

Offtakes of P in arable crops in each year were estimated from annual county census data on crop areas, production volumes and established P contents of harvested produce and crop residues (AHDB, 2022; Rothwell et al., 2022). Where county data on production volumes were not available, regional or average E&W or UK crop yields were used. Annual yields of temporary and mixed species permanent grass were computed from the national DM yield response to applied N in fertiliser, manures and atmospheric deposition (Qi et al., 2018), offtakes assumed 70-80% utilization established from industry recommendation (Rothwell et al., 2022), and a grass P content of 3 g/kg (AHDB, 2022), but reducing to 2.5 g/kg in the years prior to N use (Warren and Johnston, 1964). Grass production from the area of rough grazing in each county was based on Qi et al. (2018) and assumed a utilization of 25% (Haygarth et al., 1998).

Fertiliser N rates to temporary and permanent grass in each year were estimated from BSFP in the same way as for P and supplemented by an allowance for manure available N calculated from the volumes of farmyard manure and slurry spread annually and their available N content (Smith et al., 2016) together with estimates of the volumes of excretal N deposited at grazing assuming 40% of cattle and 95% of sheep excreta are deposited at grazing (Defra, 2022a). Trends in atmospheric total N deposition were taken from Fowler et al. (2004) and available N deposition was assumed to be 50% of total N based on the proportions falling as wet deposition (Phoenix et al., 2012).

Analysis of data from the Rothamsted archive suggested there was no justification for adjusting for trends in crop P content over the last 150 years. Some dilution of cereal grain P mineral density was observed when varieties changed from long straw to short straw in the mid-1960's, but impacts on phytate appear small (Fan et al., 2008).

3.2 Scenario analysis of future land use change

3.2.1 2021 baseline SFA

To provide a baseline Substance Flow Analysis (SFA) from which to assess the potential impact of future land use change, the detailed Wye catchment P SFA produced under the RePhoKUs project (Withers et al., 2022b) was updated with the latest crop and livestock census data (Defra 2023, Welsh Government pers. comm). Census data appears to significantly underestimate the poultry population in the catchment, therefore a figure of 20 million birds was used after consultation with the poultry industry.

Crop P offtake was determined on census crop areas, established crop P offtake coefficients (Rothwell et al., 2022) and regional average crop yield data (Defra, 2023). Grass P offtake was determined from census grass area, predicted grass yield using the model developed by Qi et al. (2018), utilisation and P content described above. Fertiliser input is determined from census crop areas and regional P fertiliser rates from the British survey of Fertiliser Practice (Defra, 2022a).

Livestock product (meat as live weight, milk and eggs) was estimated using the livestock population data and P content and production co-efficients established from Rothwell et al. (2022). Livestock manure P excretion was calculated from livestock population data and established livestock manure excretion coefficients (Rothwell et al., 2022). The SFA assumed that all livestock manure produced in the catchment remains in the catchment, as per the previous model. There is, however, some movement of poultry litter both into and out of the catchment area, though for the purposes of this model, they are assumed to cancel each other out. Recent investigations by the local poultry industry have produced P flows for feed, product and manure that differ from those established in this model using the current standard national Defra co-efficients. For comparison, a second baseline SFA has been produced using these industry produced data.

Loss to water from agriculture was taken from the Separate model (Zhang et al., 2014) and loss from waste water plants was estimated from balance using the P load from the human population in the catchment and a P removal efficiency established from Rothwell et al. (2022).

3.2.2 Land use change scenarios

SFA models that explore potential future land use change and their impact on the catchment P flows and overall P balance were developed. One set of scenarios were based on the conversion of grassland to cereals to supply feed for the recently-expanded poultry population. In the models the cereal production area was increased by 25, 50 and 100% from the 2021 baseline with the permanent grassland area reduced appropriately. It was assumed that the grazed livestock (cattle and sheep) produced on the converted grassland were de-stocked, so the cattle and sheep population was reduced proportional to the reduction in permanent grassland. The poultry population was assumed to remain unchanged at the 2021 baseline. All relevant material and P flows associated with the change in land use and reduced livestock population were adjusted accordingly.

A second set of scenarios based on the conversion of grassland to maize for AD feedstock were also developed. These scenarios assumed an increase in maize area in the catchment by 50, 100 and 200% from the 2021 baseline. Again, the cattle and sheep population were reduced proportional to the reduction in permanent grassland area and the poultry population remained unchanged. The baseline model assumes that 50% of the 2021 maize offtake goes to AD plants and the remaining goes to livestock feed within the catchment. In the scenarios all additional maize production above the baseline is assumed to go to AD. The digestate products of AD are assumed to be returned to agricultural land within the catchment.

Changes to losses to water from agriculture in the scenarios were estimated using Farmscoper v5 (ADAS, 2021). A baseline figure was established using the 2021 survey data and then new Farmscoper model outputs were produced for all the scenarios using the new crop and grass areas, and livestock population estimates. The percent change in the Farmscoper scenario outputs from the 2021 baseline was used to adjust the Separate model estimate used in the catchment model. Farmscoper distributes the changed land use and reduced livestock numbers across farm types based on the relative likelihood of those crops or livestock being found on certain farm types. No changes in uptake of mitigation strategies (e.g. buffer strips) were assumed in the scenarios. Farmscoper only covers the English part of the Wye catchment, so the magnitude of change was assumed to be relevant for the whole of the catchment. In the absence of more up-to-date processed-based modelling estimates, this approach provides a basic estimate of losses to water under land use change for the Wye.

To assess the impact of the land use change scenarios on P dynamics in the Wye catchment, three indicators were chosen to compare to the established baseline: Total P surplus (t), agricultural P loss to water (t) and agricultural soil P efficiency (%) which is the ratio of effective outputs from the soil surface (crops and grass) and P inputs (manure, fertiliser and biosolids).

The model is produced using STAN software (Cencic and Rechberger 2016) which applies data reconciliation and error propagation to balance the model according to assigned uncertainty of the data. Uncertainty of data flows was assessed using the systematic approach described by (Zoboli et al 2016).

3.3 High resolution mapping of soil P levels in the Wye catchment

3.3.1 Sub-catchment soil P level maps

In collaboration with local agronomists, recent analysis results for soil Olsen-P status (mg/L and P Index) across the Eastern (English) half of the Wye catchment area were collated and statistically summarised (see Phase 1 report). The sampled farms spanned the sub-catchment areas of the rivers Lugg, Frome, Monnow, Garren, Yazor and the larger river Wye. The soil P results were aggregated across 1 km^2 to give a mean P Index and assess the proportion of samples with Olsen-P values above the agronomic optiumum. Soil P data for the Arrow sub-catchment were too sparse to include.

The sub-catchment areas were matched to the location of river flow gauging stations across the Wye catchment, and boundaries of the upstream drainage area were downloaded from the National River Flow Archive (UKCEH, 2023).

3.3.2 Sub-catchment P balances

Soil P balances were determined for 6 sub-catchments of the rivers Lugg, Arrow, Frome, Monnow, Garren and Yazor (Figure 14 appendix). The methodology was the same as for the catchment SFA above using the same crop and livestock co-efficients and regional fertiliser data. Sub-catchment crop areas and livestock numbers were obtained from the Defra 2021 census and Welsh Government. However, different to the whole catchment SFA, census poultry numbers were principally used, rather than industry estimates due to difficulties assigning a spatial distribution to the whole catchment industry estimate. The only exception to this were the poultry numbers for the Yazor sub-catchment that used an industry estimate as the Defra census data returned zero broilers due to data redaction owing to the number of farms present. Biosolid P input was assumed to reflect the rate of application across the whole catchment.

The balance uses a simple input/output approach and again assumes that manure produced in the sub-catchment stays in the sub-catchment. At this scale, there is likely some export of manure out of the area, though without more detailed local investigation, determining this is difficult. The balance, particularly the manure component should therefore be treated with a degree of caution.

3.3.3 Sub-catchment P balance and water quality

To assess potential links between the catchment P surplus and river P pollution, annual river P exports at the outlet of the sub-catchments and at Redbrook (whole catchment oulet) were calculated as the product of annual average flow at the gauging station, and the average flow-weighted SRP concentration, which was based on monitored SRP concentrations at the nearest water quality monitoring station to the gauging station for the period 2010-2021. This long time series was necessary because of the low and inconsistent sampling frequency of more recent data, large data gaps and/or a marked and consistent reduction in SRP concentrations after 2010 compared to earlier years (e.g. Frome and Garren). For the Monnow and Lugg sub-catchments, available data after 2010 was either totally absent or too sparse and for these two catchments the SRP data going back to 2000 was used. These estimates of sub-catchment river P export therefore come with large uncertainty and must be treated with caution.

4. Results and Discussion

4.1 Historic analysis of land use change and surplus P loading

4.1.1 Land use change

Temporal trends in land use have been separated into the English (Herefordshire) and Welsh (Powys and Monmouth) parts of the Wye catchment in view of the distinct differences in landscape and land use characteristics between the two areas. In Herefordshire, permanent grass increased at the expense of arable land up until the second World War when much grassland was ploughed up for crop production (Figure 1b). This general increase reflects the need for grass to feed an expanding cattle and sheep population (Figure 1c). After the war, areas of permanent grass and arable crops were equal until 1975 when the grassland area decreased as cattle and later sheep numbers started to decline and the arable area increased. The expansion of the arable area was mainly as cereals until 1985 and potatoes until 2000, with maize areas increasing rapidly after 2000 (Figure 1a). Cereals also have started to increase again from 2005. Pig numbers have fluctuated wildly and are now the same as in the 1870's. In contrast poultry numbers increased exponentially to a current level of ca. 11 million birds, although it is now well known that numbers are actually much greater than this because of the inaccuracy of census data for livestock with a high turnover rate in house.

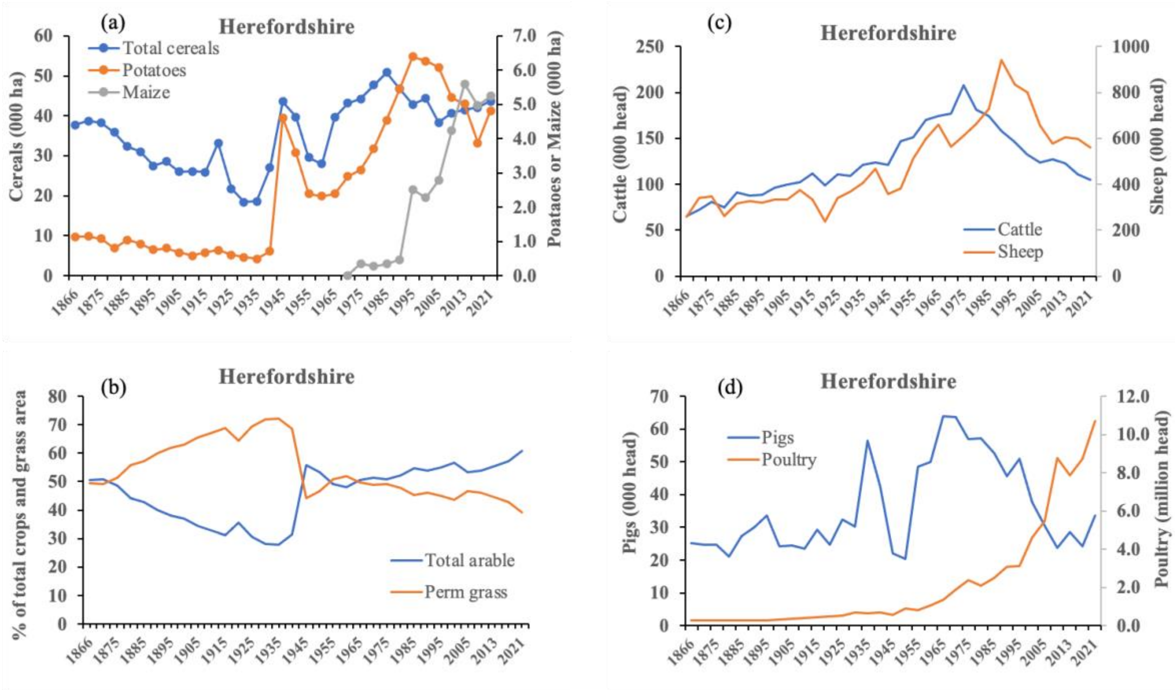


Figure 1. Temporal changes in (a) the areas of cereals, potatoes and maize; (b) the areas of arable (crops and temporary grass) and permanent grass as a proportion of the total area of crops and grass; (c) the numbers of cattle and sheep and (d) the numbers of pigs and poultry in Herefordshire from 1866-2021 using county level statistics.

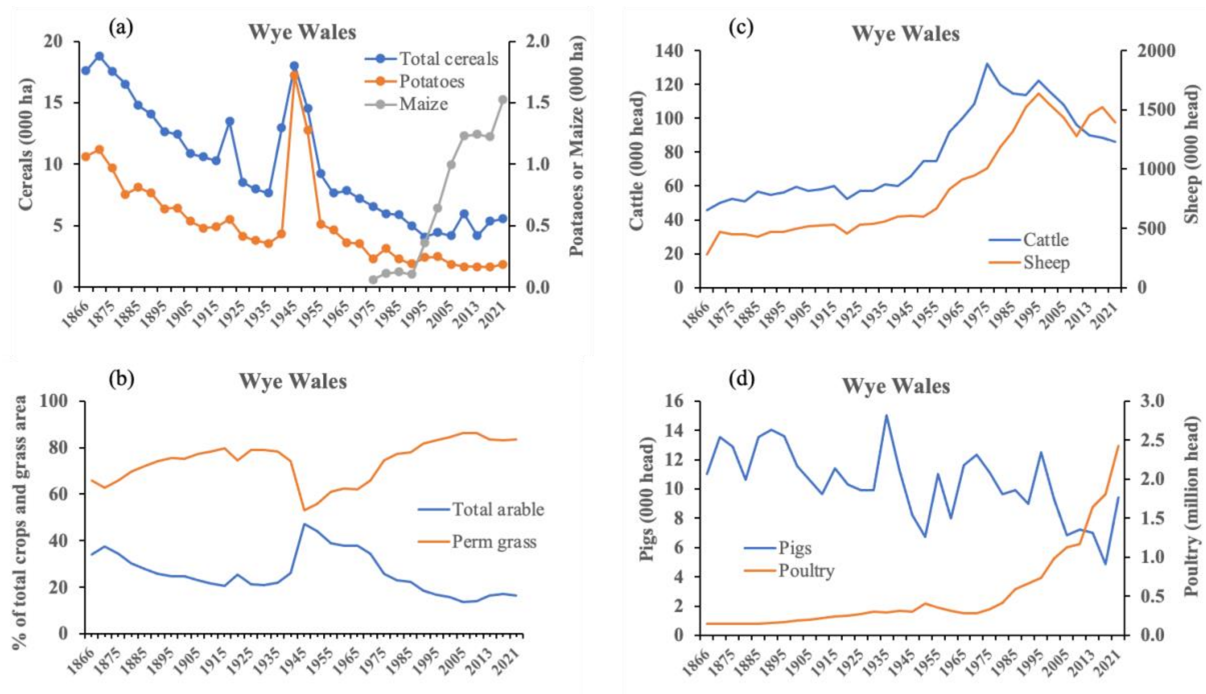


Figure 2. Temporal changes in (a) the areas of cereals, potatoes and maize; (b) the areas of arable (crops and temporary grass) and permanent grass as a proportion of the total area of crops and grass; (c) the numbers of cattle and sheep and (d) the numbers of pigs and poultry in the Wye in Wales from 1866-2021.

Temporal trends in land use in Wye Wales followed a similar pattern to those in Herefordshire up until the War as cattle and sheep numbers increased (Figure 2c). However, unlike Herefordshire, arable crops (e.g. cereals and potatoes) continued to decline after WW2 in favour of an expansion in permanent grass despite a slight fall in ruminant livestock numbers after 1995 (Figure 2a and b). Some of this grassland expansion is due to conversion of rough grazing land (as total arable and grass areas have increased in Wales), but may also be due to a trend for more production from grass rather than bought-in cereals. Of the arable crops, only maize has shown a large increase as in Herefordshire, and more recently cereal areas have started to increase again since 2000. Pig numbers have generally declined over time, but as in Herefordshire, there has been an explosion in poultry numbers, which are known to be a large underestimate.

Cereals, potatoes and maize are a high-risk crop for P loss in and runoff due to their generally higher soil P status, greater erosion risk and vulnerability to compaction during harvesting. Since 2005, these crops have changed by +13%, -21% and +88%, respectively in Herefordshire and by +33%, 1% and +53%, in Wye Wales. Recent increases in the cereal area may be driven by the need for more home-grown cereals to feed the growing poultry industry, whilst increases in the maize area are being driven by the need for feedstock for anaerobic digestion (AD) plants.

4.1.2 Surplus P loading

The analysis of the annual surplus P loading to Wye soils since 1866 provides a contextual evidence base to the patterns of historic P use in the catchment, the extent of P accumulation in the Wye catchment landscape and an estimate of the likely magnitude of the total legacy soil P reserves that pose a long-term source of P loss to draining rivers. The analysis is constrained by some uncertainties: (a) the accuracy of spot census surveys in June and December each and the inconsistent reporting of this data, especially since 1980; (b) county level census statistics may not fully represent that portion of the Wye catchment in that county; (c) exports and imports of manures out of and into the catchment are not quantified and are assumed to balance out, and (d) fertiliser consumption data prior to 1966 is based on literature and industry estimates rather than actual survey data. However, these uncertainties are not considered to compromise the general trends observed or the estimation of legacy soil P reserves.

Fertiliser: Fertiliser P use increased steadily from its first use in the 1850's up to 1913 and more slowly thereafter until the early 1930s when use declined during the depression years (Cooke 1958), Figure 3a. Consumption increased again sharply after the second World War as UK agriculture intensified and reached a peak in the early 1980s with an overall application rate of ca. 15 kg P/ha. Since then, annual consumption has shown a general decline, probably reflecting reduced farm profit margins and greater farmer awareness of the financial benefits of better nutrient planning and increased efficiencies of P use (Figure 3a). Significant falls in consumption occurred in individual years due to the oil crisis in the early 1950s, and in 1975 and in 2008 when the cost of phosphate rock increased sharply (+400%) due to a combination of market forces, rising energy costs and/or export bans (Brownlie et al., 2023). The industry is currently experiencing another large price hike in fertiliser costs, with further uncertainties over future supplies due to the Ukraine war. Current overall inorganic P fertiliser inputs across the catchment for arable crops and grass average only 5 and 2 kg P/ha, respectively for the English Wye and 10 and 4 kg P/ha, respectively for the Welsh Wye.

Manures: Phosphorus inputs to Wye soils in livestock manures increased relatively slowly up to 1945 (with small declines during the 1880 and post WW1 depression years), but then increased sharply up to ca. 1980 and the early 1990s as the livestock industry expanded (Figure 3b). Thereafter annual manure P inputs have remained fairly static at around 5000 tonnes tempered by a succession of major disease outbreaks (BSE in the 1980s and foot and mouth in 2001) and a general fall in animal numbers, except for poultry. The poultry industry is the only sector which is still expanding.

Biosolids: Inputs of P from wastewater biosolids applied to land commenced in the 1960's and gradually increased, rising more sharply after the ban on dumping of sewage to sea in 1998. Total biosolid P inputs reached an apparent peak in 2005 (Figure 3b), but after accounting for some misreporting of volumes spread, are typically just over 300 tonnes. Although application rates of biosolid P are very high where they are spread (over 100 kg P/ha), their overall contribution to the total catchment manure P is very small (ca. 6%) because of the relatively small area of land receiving biosolids.

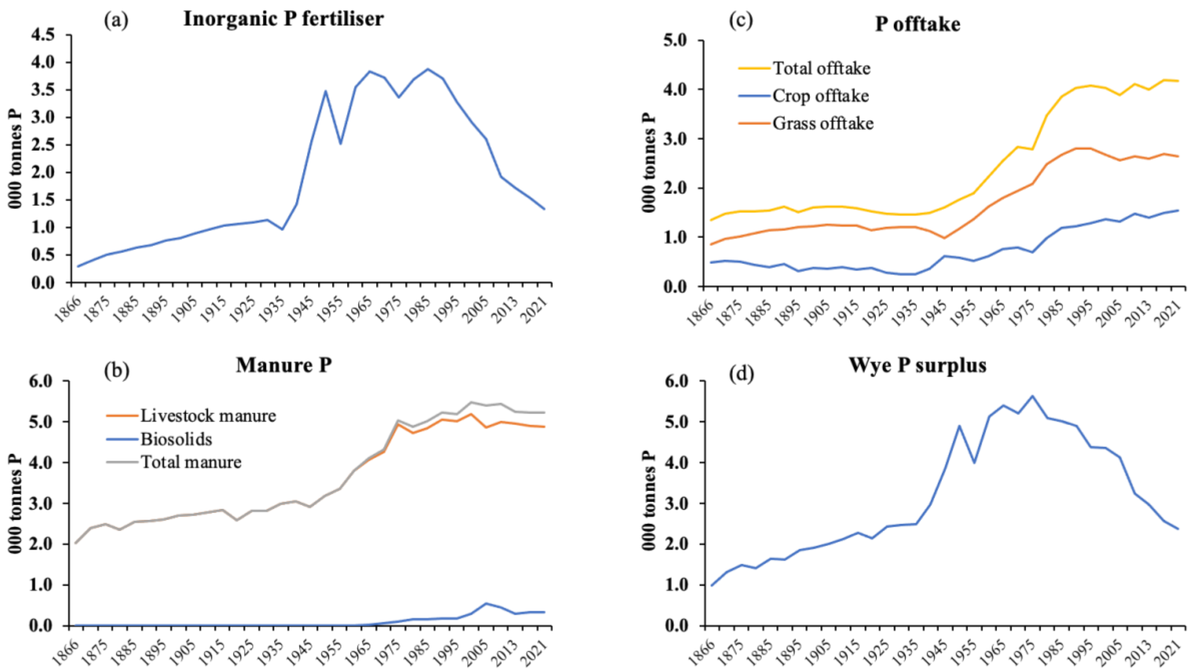


Figure 3. Temporal trends in the amounts of phosphorus (P) cycling annually in the Wye catchment as (a) fertiliser, (b) manures, (c) crop offtake and (d) in surplus accumulating in soils from 1866 to 2021.

Crop Offtake: Amounts of P removed in arable crops and grassland across the Wye catchment remained fairly constant until after the second World War when crop P offtakes increased exponentially with the introduction of new higher yielding varieties, increased nitrogen (N) use, better disease control and streamlined soil and crop management (Dungait et al., 2012). Total P offtake reached a peak in the 1990s and has remained relatively constant since. The temporal trends in P offtake were similar for both arable crops and grassland, with the latter accounting for approximately 70% of total P offtake in the Wye catchment (Figure 3c).

Surplus P loading: Even in 1870, there was a surplus of P inputs to the Wye catchment area of ca. 1000 t (4 kg P/ha), reflecting the continuing contribution of animal production in the region and low amounts of crop P offtake, largely due to N and to a lesser extent P limitation (Figure 3d). In the late 19th century, P was already being applied in bones, guano and superphosphate (Thompson, 1968), whilst inorganic fertiliser N use on crops and grass did not commence until after the second World War. Similarly, there were large imports of oilseed cake to supplement grass intake and animal feed rations to sustain an expanding livestock industry (Thompson, 1968). Surplus P increased steadily until 1940 (12 kg P/ha) and then more rapidly when N and P fertilisers use increased. Surpluses of P reached a peak in 1975 (23 kg P/ha), and have steadily declined since to a current level (ca. 9 kg P/ha) that is the same as in the 1920's. Note that these current estimates of surplus are based on county level census statistics, and will be different to the more accurate P surplus calculated in the SFA (see section 4.2). The current UK P surplus for 2021 is estimated at 5.7 kg P/ha (Defra, 2022b).

4.1.3 Legacy phosphorus

The total amount of surplus P that has accumulated in the Wye catchment soils over the last 150 years can be calculated at over 500,000 tonnes (Figure 4), and represents a potential reserve of legacy soil P that can be relied upon to sustain crop and grassland production when inorganic fertiliser imports become prohibitively expensive. For example, the sharp 2008 fertiliser price increase resulted in farmers taking a 'P holiday', leading to a decline in national fertiliser P consumption but without any reduction in agricultural output. This cumulative surplus equates to an average legacy soil P reserve over the cropped and productive grassland area of the Wye catchment in 2021 of ca. 1.86 t P/ha. The value of these legacy P reserves in sustaining crop yields was reported in the RePhoKUs project

(Withers et al., 2022b). Interpretation of the results from the pot based legacy P trial undertaken at the Lancaster Environment Centre suggest that a typical arable crop rotation could be sustained for between 2 and 10 years on the farms analysed without any P input before experiencing yield penalty.

If this total soil P reserve was distributed over 30 cm depth of soil, and taking account of average soil bulk density (1.3 g/cm^3), the cumulative surplus P loading would be expected to increase the soil total P content by 465 mg/kg. A recent but limited study of topsoil total P concentrations in farmed and unfarmed areas in the Wye catchment suggested an accumulation of 286 mg/kg total P in very sandy soils and 134 mg/kg in silty soils. These data suggest that there has been significant migration of surplus P into the subsoil and/or substantial loss of P to the wider environment. Subsoil P enrichment will increase the risk of P mobilisation and loss in drain flow during storm events and/or lead to P leaching into groundwater. These data also question the degree to which intensely farmed Wye soils are already saturated with P sufficiently to cause P migration down the soil profile and a reduced capacity to absorb further additions of P without significant P leakage to water (Chakraborty and Prasad, 2021).

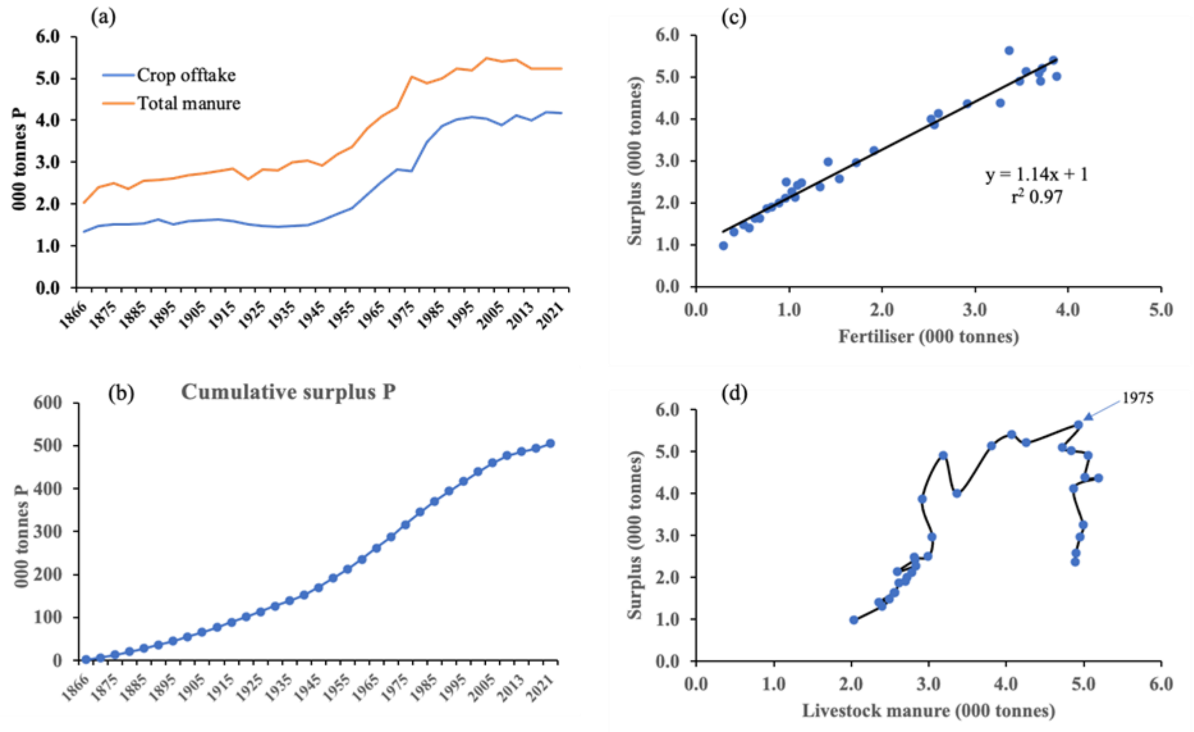


Figure 4. The temporal trend in the amounts of (a) annual total manure inputs relative to crop annual P offtake and (b) the cumulative P surplus that has accumulated in Wye soils since 1866. Annual surpluses correlate strongly with inorganic fertiliser inputs (c) but the main driver of the annual P surplus is the pattern of livestock farming (d).

4.2 Updated catchment SFA and scenario analysis of future land use change

4.2.1 Catchment SFA

The 2021 Wye catchment SFA model output (Figure 5) shows that the catchment imported ca. 6500 t P and exported ca. 3500 t P. The largest P import into the catchment is as livestock feed (ca. 5300 t) and mineral P fertiliser use in the catchment imports ca. 1200 t P. The largest internal flow of P is as livestock manure (ca. 5300 t) and the catchment exports ca. 3500 t P in agricultural products. Agricultural soil P efficiency for the catchment is around 52% meaning that nearly half of applied P is accumulating as legacy P or lost to the aquatic environment. For comparison, UK national soil P efficiency is around 65% (Rothwell et al., 2022). The input/output balance leaves and annual P surplus of ca. 3000 t P yr for the catchment, this is an average of 11.4 kg/ha across managed agricultural land in the catchment. This areal average value is different from previous estimates (Withers et al., 2022b) due to different agricultural land areas reported from different data sources used in different years. However, the total catchment P surplus remains consistent. Losses to water are estimated at ca. 93 t P from waste water treatment and ca. 225 t from agricultural sources. However, the agricultural data from the Separate model uses 2010 agricultural census data so is outdated.

Using the poultry industry supplied data (Figure 15, appendix), the catchment imports reduce to ca. 5500 t P of which ca. 4200 t P was in livestock feed. The P in manure flow reduces to ca. 4000 t P and catchment exports increase slightly to ca. 3700 t P. Soil P efficiency is calculated as 65% using these data which is the same as the national average. Using these data, the catchment surplus reduces to ca. 1700 t P yr which is the equivalent of an average 7 kg P/ha across the catchment.

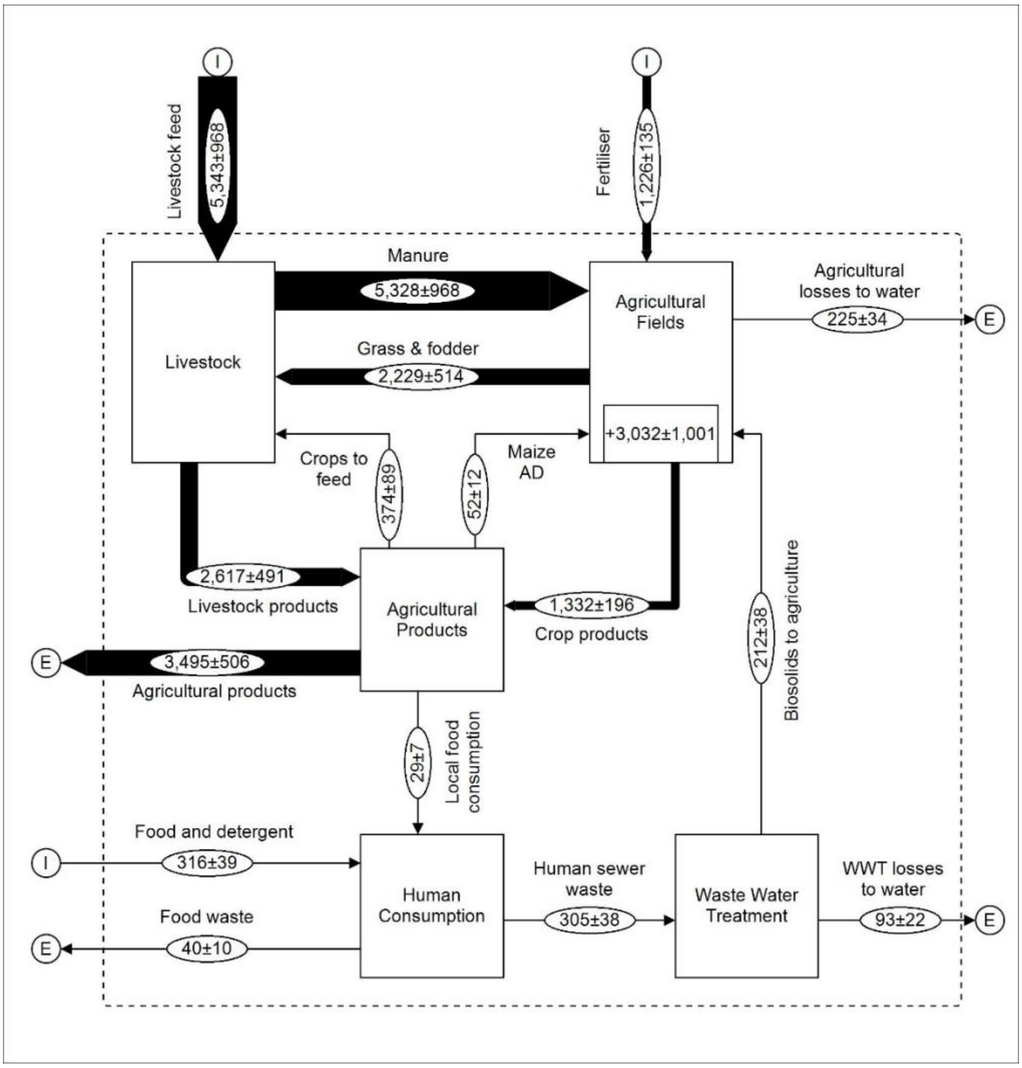


Figure 5. Substance Flow Analysis (SFA) for the Wye catchment. All flows are ± uncertainty (t/P/yr) for the year 2021.

The industry argues that feed conversion efficiency has increased considerably in recent years. Their bird excretion estimates are based on recorded feed volumes, numbers of birds produced and samples of poultry litter (including bedding) from 120 farms, and wet chemistry was used to establish P contents of the feed and manure. With this, P flows in feed, product and manure were estimated. The industry generated numbers vary significantly from those generated using the current Defra co-efficients, but have yet to be substantiated and clearly warrants further investigation. Whether these are representative of the wider poultry industry also remains unclear.

4.2.2 Land use change scenarios

The land use change scenario analysis indicated that an increase in cereal production to supply the poultry industry (Figures 16, 17, 18, appendix) would reduce total catchment agricultural P imports from the 2021 baseline to between ca. 6400 (-2.4%) and 5700 t (-13%). This is likely because less feed P is required by the reduced ruminant population (Table 1) and more of the poultry feed demand is met by grain produced in the catchment area. The system indicators (Table 2) suggest that the catchment P surplus decreases with increased cereal area by between 136 and 790 t/yr to a lowest value of ca. 2200 t P with a 100% increase in cereal production from the 2021 baseline. This is likely due to the shift from livestock production to arable (Table 1), which is generally much more efficient in its P use (Rothwell et al., 2022), and less manure production. Importantly though, these scenarios assume that the poultry population remains at its 2021 level. Any increase in the catchment poultry population would likely limit any reduction in surplus due to the increased manure production.

Farmscoper analysis suggests that the increase in cereal area is likely to increase agricultural losses to water by 0.026 kg P/ha for every 10% of grassland converted (up to an additional 76 t/yr in the 100% cereal increase). This is likely due to the increased risk of soil erosion from tillage-based agriculture over permanent pasture, although the risk of soil erosion can be reduced by good management practices (which were not included in this analysis). Ploughing up permanent grassland also increases N leakage, and greatly reduces soil carbon stocks, especially in the first few years after conversion (Whitmore et al., 1992; Johnston et al., 2009). Catchment soil P efficiency increases with the larger cereal area, increasing from the 2021 baseline by between 3 and 16% up to a maximum of 61% in the 100% cereal change scenario.

Table 1. Changes to relevant crop and grass areas, and livestock populations in the land use change scenarios.

	2021 Baseline	Cereals 25%	Cereals 50%	Cereals 100%	Maize 50%	Maize 100%	Maize 200%
Permanent grass area (ha)	177,856	167,217	156,579	135,301	174,884	171,911	165,965
Cereal production area (ha)	42,556	53,195	63,834	85,111	42,556	42,556	42,556
Maize production area (ha)	5,946	5,946	5,946	5,946	8,919	11,891	17,837
Cattle population (head)	173,632	165,126	156,620	139,608	171,255	168,878	164,125
Sheep population (head)	2,230,870	2,121,583	2,012,296	1,793,723	2,200,332	2,169,794	2,108,718

Converting grassland to maize land use for AD would slightly increase the total catchment agricultural P import by around 2.5% in all three scenarios, with likely increases in fertiliser import slightly outweighing reductions in feed P import from the reduced ruminant population (Figures 19, 20, 21, appendix). The system indicators (Table 2) show that the catchment P surplus is slightly higher than the 2021 baseline in all three scenarios, with the highest surplus (3172 t P) occurring with a 50% increase in maize area. This surplus increase is most likely due to the increased P fertiliser import and use to meet the maize crop demand. The surplus then actually decreases slightly with increasing maize area, likely due to the increasing influence of reducing the ruminant population which is inherently P inefficient (Rothwell et al., 2022).

Losses to water from agriculture are predicted to increase by 0.004 kg P/ha for every 10% of grassland converted to maize (up to an additional 22 t/yr in the 200% maize scenario), again likely due to the increased risk of erosion from bare soils typical with maize production. However, again, good management practice can mitigate some of these impacts. Agricultural soil P efficiency is not significantly altered in these maize scenarios increasing up to a maximum of 55% in the maize 200% scenario.

Table 2. Impact of the land use change scenarios on the three system indicators. Change from the 2021 baseline is shown as both a mass change (t P) where relevant and a % change.

		Land use change scenarios								
Indicator	**2021 baseline**	**Indicator value**	**Mass change**	**% change**	**Indicator value**	**Mass change**	**% change**	**Indicator value**	**Mass change**	**% change**
Cereal scenarios		**Cereals 25%**			**Cereals 50%**			**Cereals 100%**		
Surplus (t P)	3032	2896	-136	-4.5	2683	-349	-12	2242	-790	-26
Ag loss to water (t P)	225	244	19	8.4	259	34	15	301	76	34
Ag soil efficiency (%)	52	54	n/a	2.9	56	n/a	7.2	61	n/a	16
Maize scenarios		**Maize 50%**			**Maize 100%**			**Maize 200%**		
Surplus (t P)	3032	3172	140	4.6	3148	116	3.8	3102	70	2.3
Ag loss to water (t P)	225	231	6	2.7	237	12	5.3	247	22	10
Ag soil efficiency (%)	52	52	n/a	-1.0	53	n/a	0.6	55	n/a	4.8

4.3 High resolution mapping of soil P levels in the Wye catchment

4.3.1 Distribution of soil Olsen-P

The distribution of soil Olsen-P Indices across the Eastern (English) half of the Wye catchment at 1 km^2 resolution is shown in Figure 6, and more detailed sub-catchment maps of soil P results are presented in Figures 7-11 to facilitate engagement with farmers and relevant stakeholders in high-risk areas of P loss related to elevated soil P levels and erosion-prone soils. The mean soil P Index and percentage of sample results above the agronomic optimum (P Index 2) was high in the Garren Brook (4.1 and 94%, respectively), and relatively similar across other sub-catchment areas (2.1-2.6 and 37-56%, respectively).

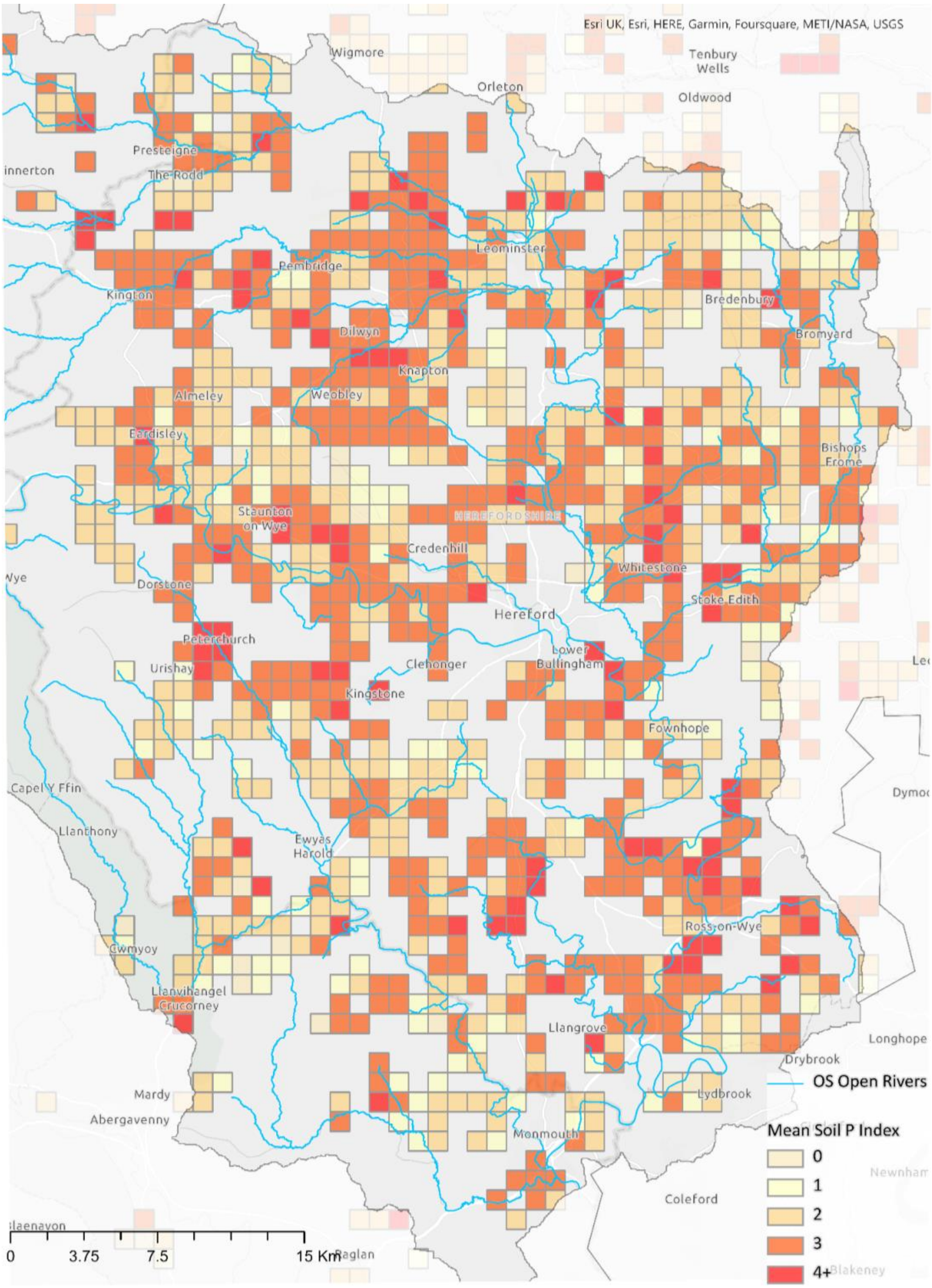
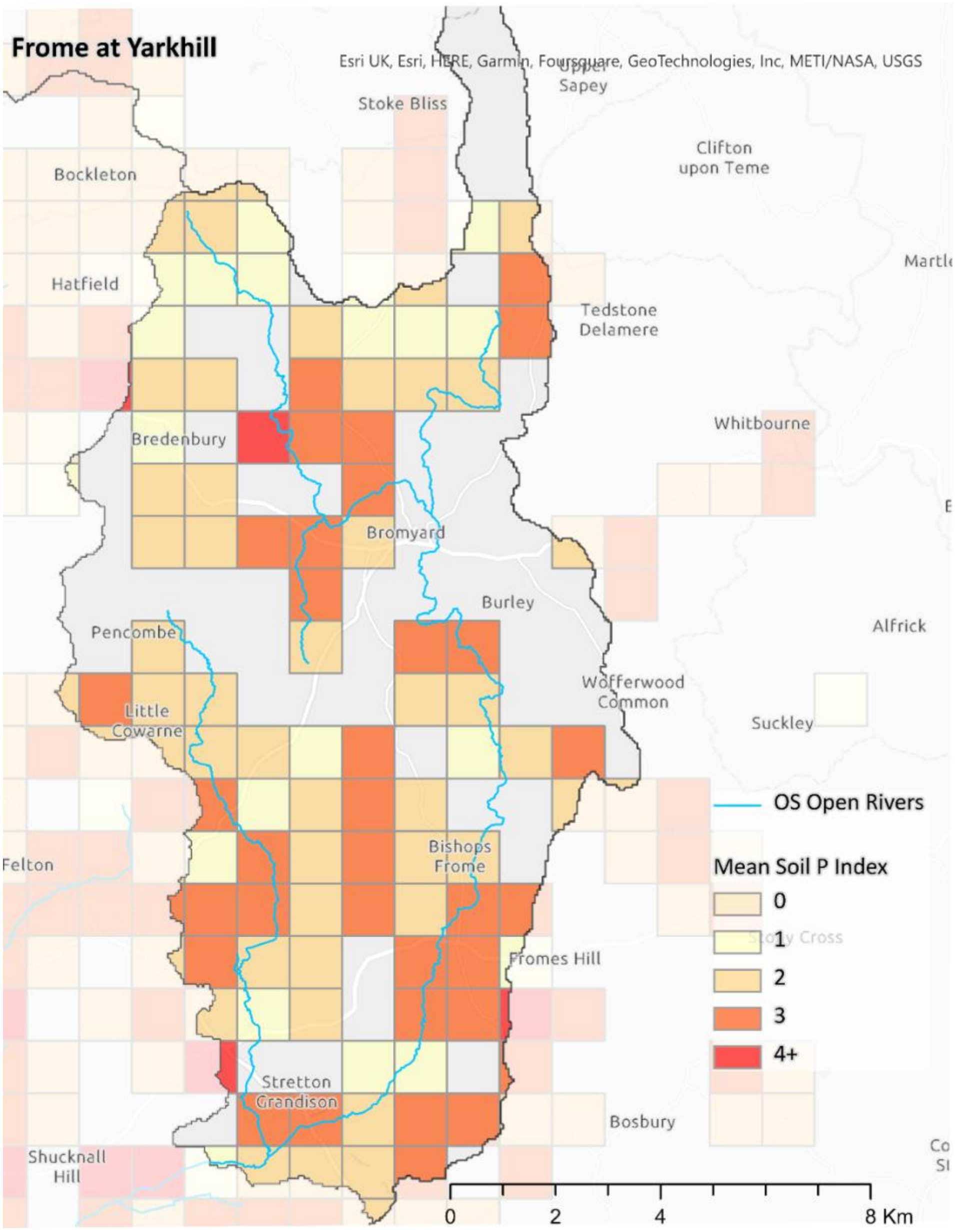


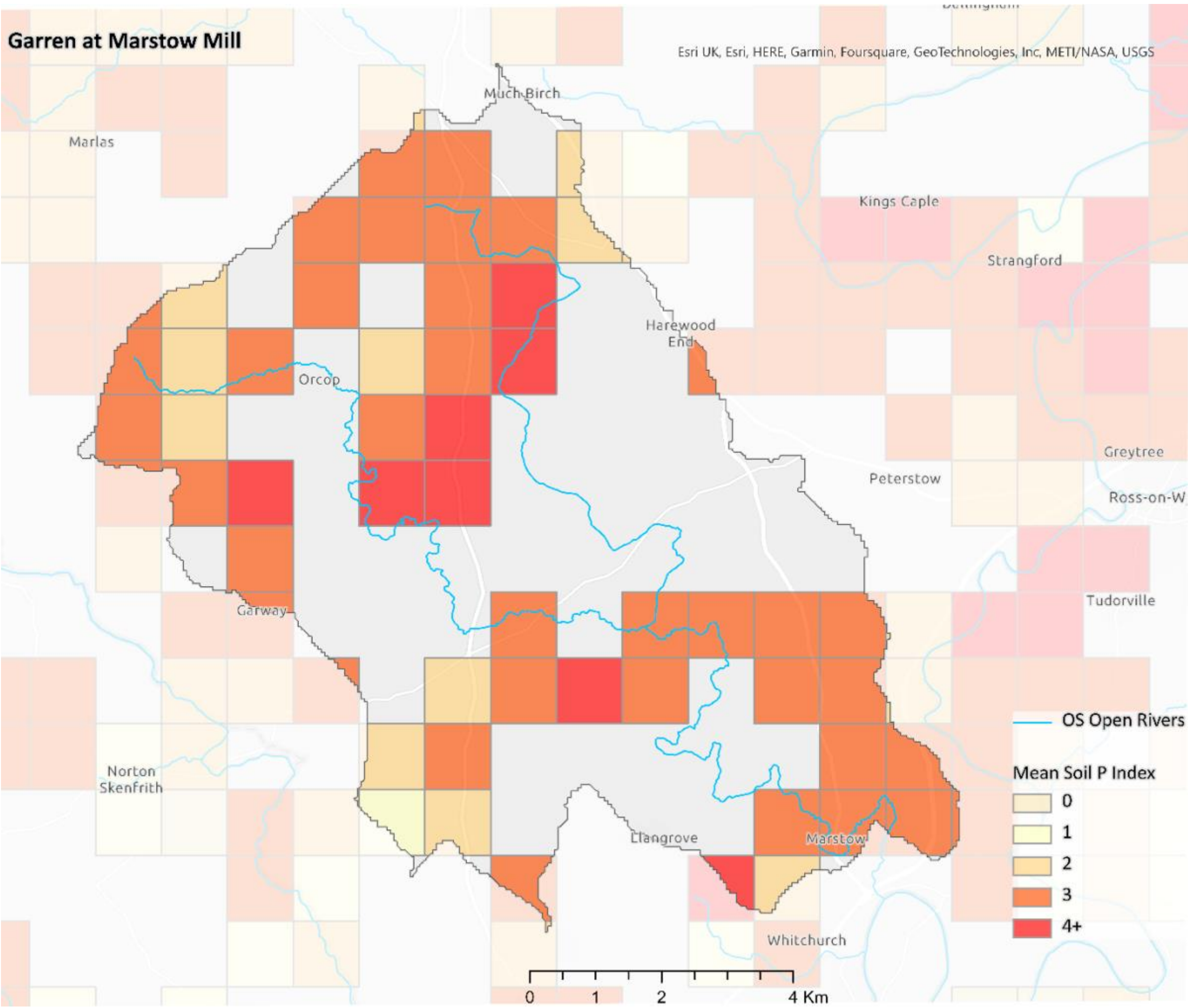
Figure 6. Wye mean Soil P Index distribution at 1 km^2

4.3.2 Subcatchment soil P maps



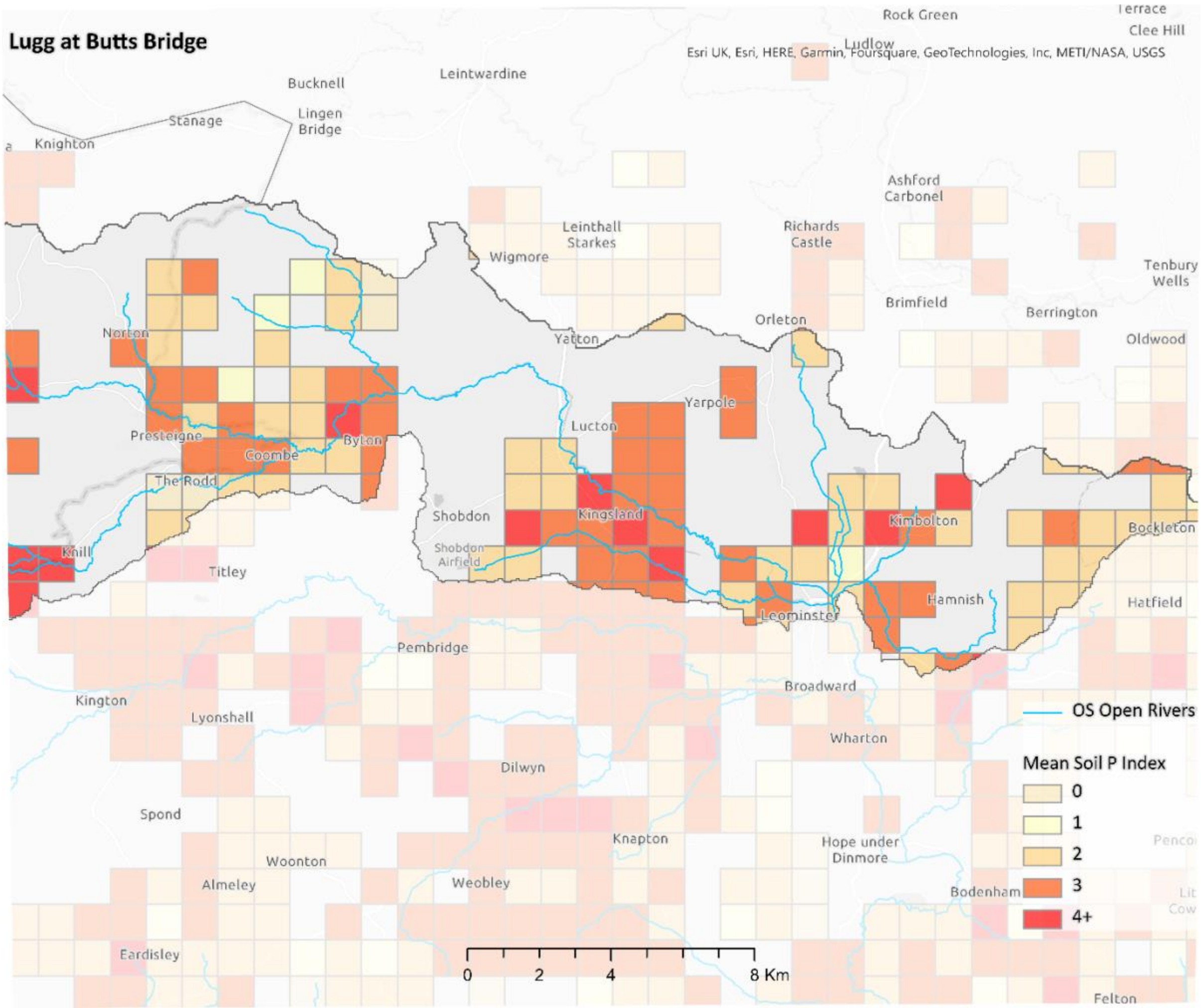
	P Index	Ha	No. samples	% distribution of P index
Frome at Yarkhill	0	21	6	1
	1	427	74	17
	2	1159	191	45
	3	765	133	30
	4	190	26	7
	5	6	2	0
Area weighted mean soil P index	2.3			
% area above agronomic optimum				37

Figure 7. Frome at Yarkhill mean Soil P Index at 1 km^2 (catchment boundary from National River Flow Archive (UKCEH, 2023))



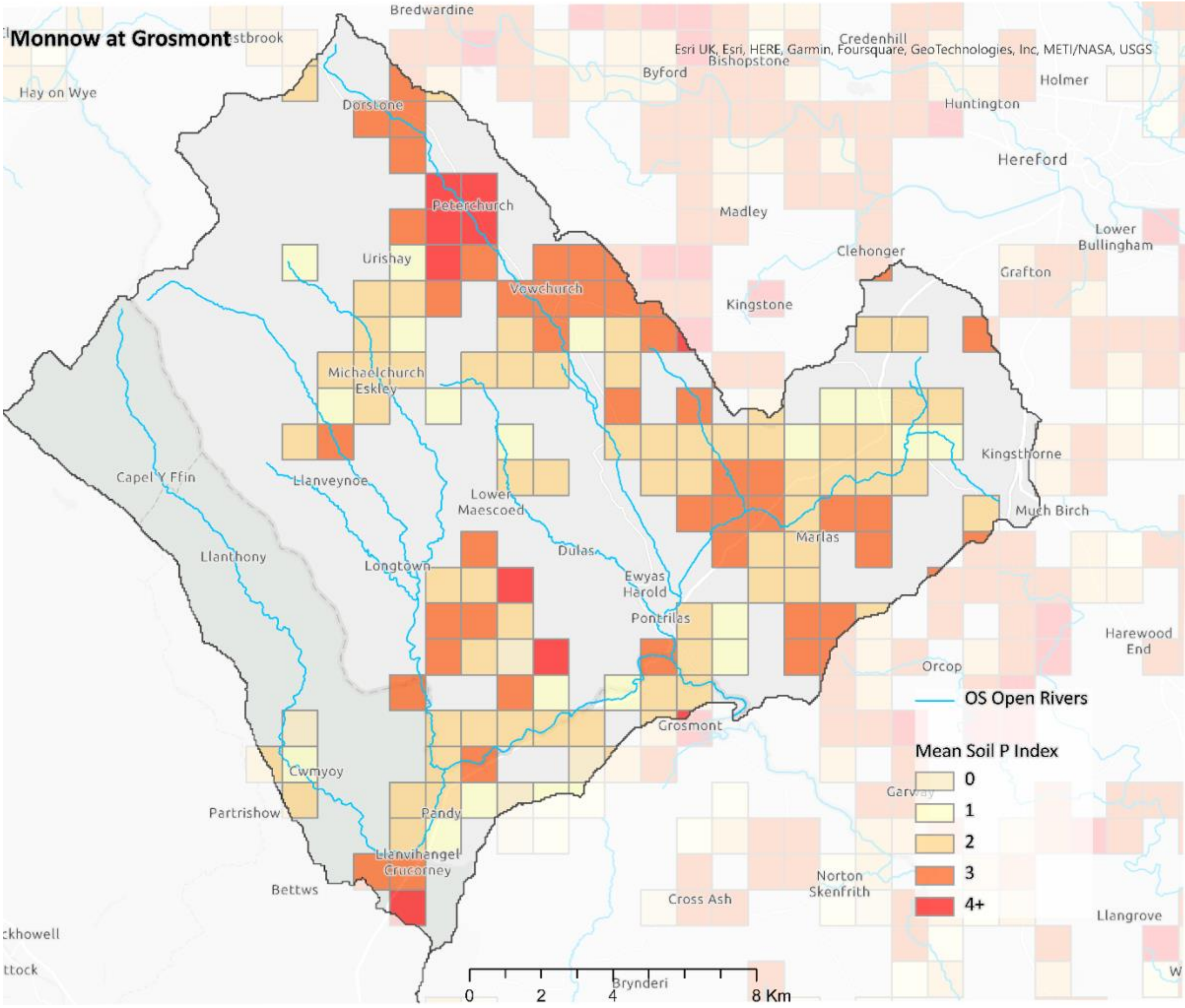
	P Index	Ha	No. samples	% distribution of P index
Garren at Marstow Mill	1	9	3	1
	2	61	14	5
	3	223	56	18
	4	567	134	45
	5	343	51	27
	6	47	8	4
Area weighted mean soil P index	4.1	3	1	0
% area above agronomic optimum				94

Figure 8. Garren at Marstow Mill mean Soil P Index at 1 km^2 (catchment boundary from National River Flow Archive (UKCEH, 2023))



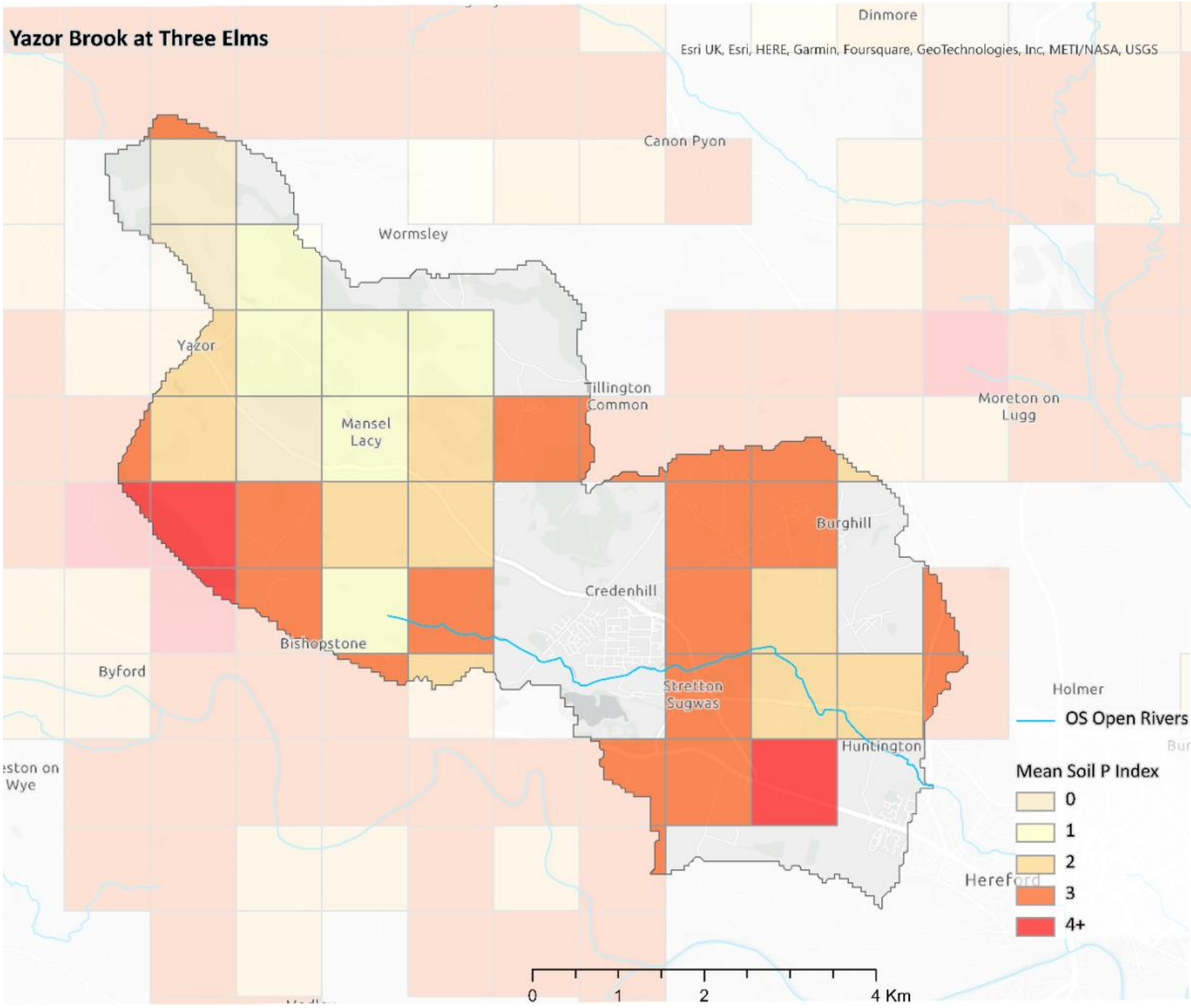
	P Index	Ha	No. samples	% distribution of P index
Lugg at Butts Bridge	0	87	18	3
	1	265	70	10
	2	768	164	30
	3	991	186	39
	4	371	63	15
	5	43	8	2
	6	6	1	0.2
Area weighted mean soil P index	2.6			
% area above agronomic optimum				56

Figure 9. Lugg at Butts Bridge mean Soil P Index at 1 km^2 (catchment boundary from National River Flow Archive (UKCEH, 2023))



	P Index	Ha	No. samples	% distribution of P index
Monnow at Grosmont	0	53	18	1
	1	457	134	12
	2	1538	369	40
	3	1479	289	39
	4	257	52	7
	5	26	5	1
Area weighted mean soil P index	2.4			
% area above agronomic optimum				46

Figure 10. Monnow at Grosmont mean Soil P Index at 1 km^2 (catchment boundary from National River Flow Archive (UKCEH, 2023))



	P Index	Ha	No. samples	% distribution of P index
Yazor Brook at Three Elms	0	106	18	10
	1	247	34	23
	2	281	42	26
	3	338	70	32
	4	93	22	9
Area weighted mean soil P index	2.1			
% area above agronomic optimum				40

Figure 11. Yazor Brook at Three Elms mean Soil P Index at 1 km^2 (catchment boundary from National River Flow Archive (UKCEH, 2023))

4.3.3 Sub-catchment P balances

There was a large variation in the soil P balances across the sub-catchments (Table 3), the largest being around 16.2 kg/ha in the Garren, the lowest was 1.9 kg/ha for the Yazor Brook. Manure P production within the sub-catchment was a strong predictor of P balance with areas of highest manure P production having the largest P surplus (Table 3). Similarly, those sub-catchments with highest manure P production had the highest mean soil P Index (Figure 12) suggesting that manure P production may be associated with high soil P status. The high manure P production in the Garren sub-catchment was largely attributed to poultry (67% of total manure P), whilst in most other sub-catchments poultry manure represented 24-34% of manure P production, except in the much smaller Yazor Brook sub-catchment where it accounted for 61%. However, as we assume all manure produced in the sub-catchment remains in the sub-catchment this result should be treated with caution as there is likely some export out of the sub-catchment which cannot be accounted for in this case.

4.3.4 Linking catchment P surpluses to river water quality

Calculated river SRP export across the sub-catchments varied from 0.14 to 0.43 kg/ha, and there was a significant positive (but weak) relationship between the sub-catchment P surplus and river P export (Figure 13). Whilst consistent with previous research (Withers et al., 2022b), insufficient river water quality monitoring data makes it difficult to evidence this linkage with more certainty.

Table 3. Sub-catchment P inputs and offtakes, total and areal soil P balances, all values are per year for 2021

Sub-catchment	**P input (t)**		**P offtake (t)**		**Ag area ex. rough grazing (ha)**	**P balance (t)**	**P balance (kg/ha) ag area**	**P balance (kg/ha) total land area**
Monnow	Fertiliser	37	Crops	102	24361	129	5.3	3.6
(354 km^2)	Manure	377	Grass	203				
	Biosolids	15.3						
Lugg	Fertiliser	63	Crops	167	27880	115	4.1	3.1
(371 km^2)	Manure	411	Grass	213				
	Biosolids	10.2						
Frome	Fertiliser	41	Crops	36	12657	114	9	7.9
(144 km^2)	Manure	261	Grass	5.24				
	Biosolids	9.6						
Garren	Fertiliser	26	Crops	75	8542	138	16.2	15.2
(91 km^2)	Manure	236	Grass	55				
	Biosolids	6.5						
Arrow	Fertiliser	8	Crops	12	8902	100	11.2	7.9
(126 km^2)	Manure	186	Grass	88				
	Biosolids	2.3						
Yazor	Fertiliser	11	Crops	41	2908	5	1.9	1.3
(42.3 km^2)	Manure	40	Grass	8				
	Biosolids	2.2						

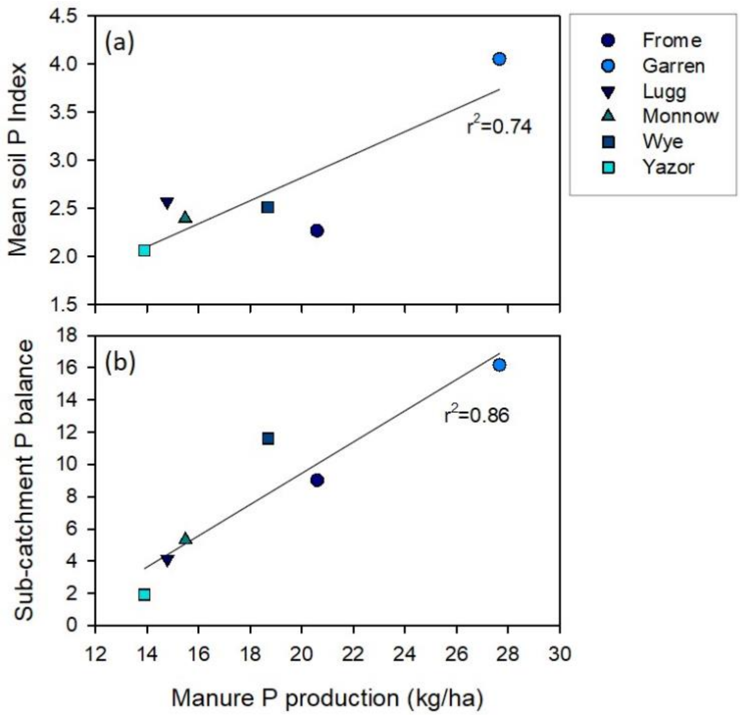


Figure 12. Relationship between manure P production and mean soil P index (a) and manure P production and P balance (b) for selected sub-catchment areas. The overall values for the entire Wye catchment are included for reference.

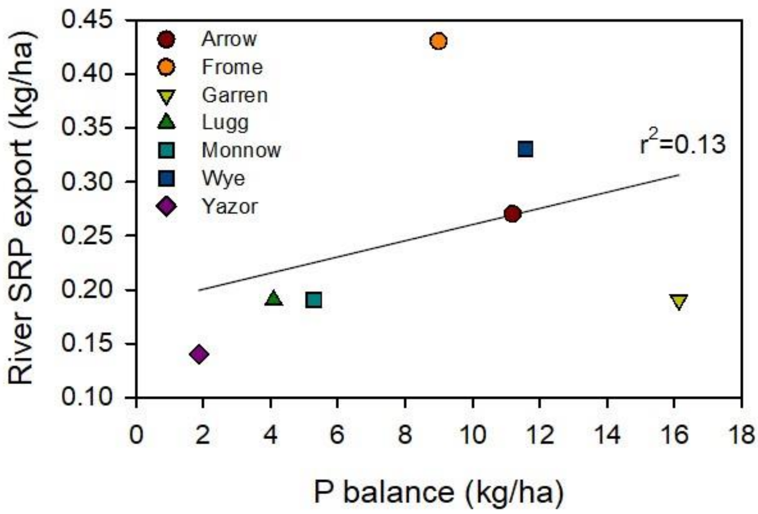


Figure 13. Catchment annual P surplus is positively but weakly related to the average annual SRP export at sub-catchment outlets.

5. Conclusions

1. An historic analysis of census-derived land use and livestock numbers indicates the Wye catchment has been in P surplus for the last 150 years. From a value of 4 kg P/ha in 1870 to 8.6 kg P/ha in 2021, peaking in 1975 (23 kg P/ha) coincident with rapid agricultural intensification after the second World War. The current surplus is the same as it was in the 1920s. Trends in the annual P surplus were related most to the amount of fertiliser P imported into the catchment because manure P loading to soils is more than sufficient to meet crop P requirements.

2. The cumulative accumulation of surplus P over the last 150 years amounts to an average of 1.86 tonnes for every hectare of crop and productive grassland in the catchment. This legacy P input would be expected to increase soil total P content to a depth of 30 cms in Wye soils by 465 mg/kg. This is considerably more than the difference in total P content between unfarmed and farmed topsoils from recent (albeit limited) sampling, and suggests that there has been considerable movement of P into the subsoil. This is a particular concern for long-term mobilisation of P in drain flow and potentially leaching to groundwater.

3. An updated 2021 SFA for the Wye catchment confirmed livestock feed as the major P input leading to an annual surplus of 3000 tonnes or 11.4 kg P/ha using national excretion coefficients for poultry. However, local poultry industry data suggest lower P excretion rates from broilers and layers and using these figures, feed P inputs and the annual P surplus drops to 1750 t and 6.8 kgP/ha, respectively. Both estimates are above the 2021 UK average of 5.7 kg P/ha.

4. Scenario analysis that explored the conversion of permanent grassland to cereals saw a reduction in total catchment P surplus of between 136 and 790 t/yr at 25% and 100% land use change respectively from the 2021 baseline. Catchment average losses to water from agriculture were predicted to increase by 0.026 kg P/ha for every 10% of grassland converted to cereals. Scenario analysis of converting permanent grassland to maize predicted very small increases in catchment P surplus from the 2021 baseline and an increased catchment average agricultural loss to water by 0.004 kg/ha for every 10% land area conversion.

5. There was a wide distribution of P surpluses (1.6 to 16.2 kg P/ha calculated as a soil P balance) across six sub-catchments of the Wye (Arrow, Frome, Garren, Lugg, Monnow, and Yazor). Sub-catchment P surpluses were driven by the manure production and those catchments with higher P surpluses tended to have higher soil P status and to a lesser extent greater river P export.

6. Recommendations

1. Catchment nutrient mapping using SFA is a valuable tool to assess nutrient input pressures and cycling, and for examining potential scenarios of system and land use change to reduce river nutrient pollution. It relies on high resolution and accurate catchment data and relevant material nutrient coefficients. Local data supplied by the poultry industry in the Wye suggests that Defra's national P excretion coefficients for poultry, which are based on 2006-2010 research may be too high. It is therefore recommended that these national coefficients need to be reviewed and that higher resolution catchment census data is made more available.

2. The historic analysis of the annual P soil P balance and limited soil total P analysis of unfarmed and farmed soils suggests shows that the cumulative surplus that has accumulated in the Wye catchment soils over the last 150 years cannot all be accounted for in the topsoil. This suggest that Wye soils may be more P-saturated and that legacy soil P has migrated to the subsoil. This needs further investigation as it increases the risk of further P loss to water in drain flow and to groundwater.

3. Current inconsistencies in river water quality monitoring programmes are confounding understanding of the impact of variable farming pressures and P surpluses on river P pollution. Relationships between farm and catchment P surpluses and river P pollution need better evidencing with improved and consistent water quality monitoring programmes going forward.

Acknowledgements

The help and support of Cobb-Agri Ltd in obtaining farm soil analysis records within the river corridor and wider catchment, and of Lancrop Laboratories Ltd in providing specific data summaries of relevant soil analysis results for the years 2017-2021 are gratefully acknowledged. The help and support of Ken Stebbings, Paul Walsh and Neil in Welsh Government in providing agricultural census data and useful discussion is gratefully acknowledged.

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Appendix

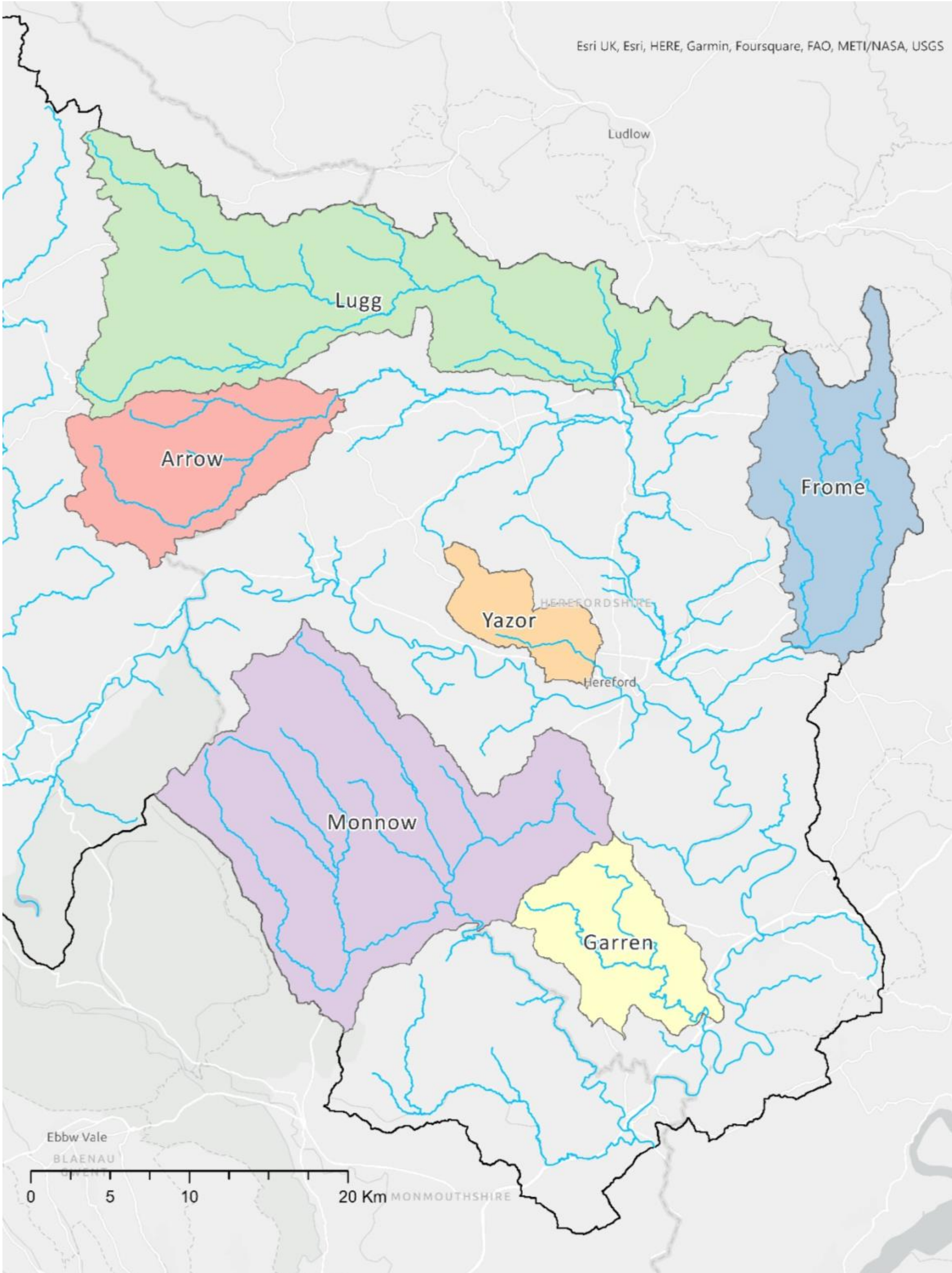

Figure 14. The chosen sub-catchments in the Wye catchment. Catchment boundaries for the Lugg, Arrow, Frome, Yazor, Monnow and Garren are from the National River Flow Archive (UKCEH, 2023).

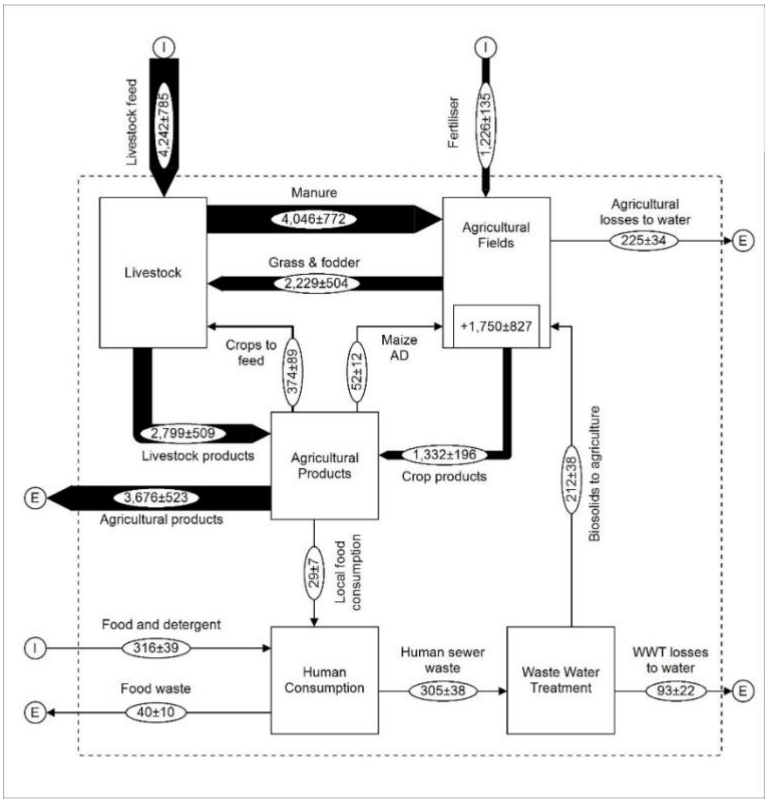

Figure 15. Wye catchment SFA using the industry produced P data related to poultry production. All flows are t/P/yr ± uncertainty for the year 2021.

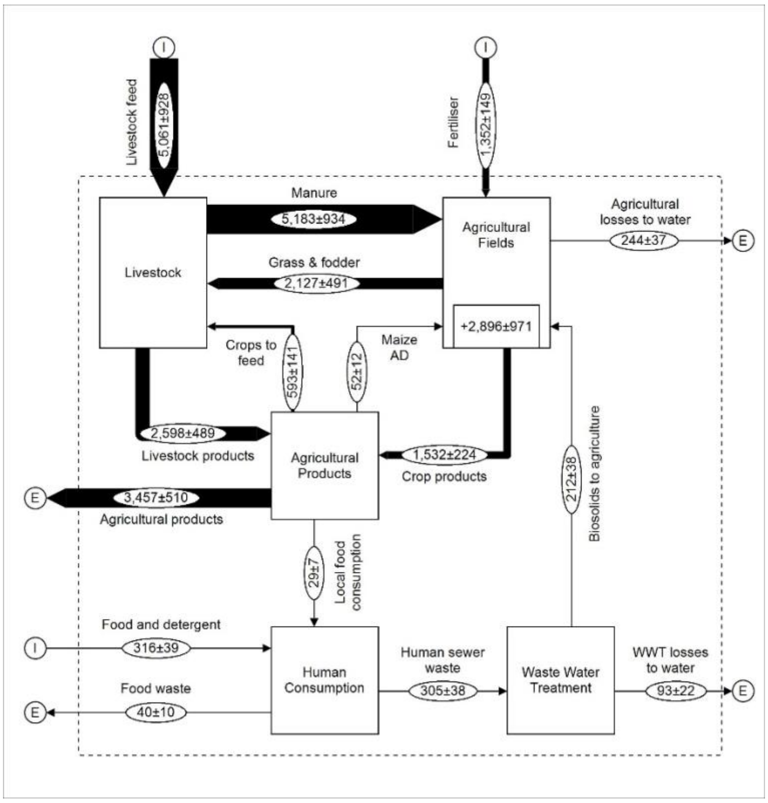

Figure 16. Wye catchment SFA for the cereals 25 scenario. All flows are t/P/yr ± uncertainty using the 2021 SFA as the reference year for scenario change.

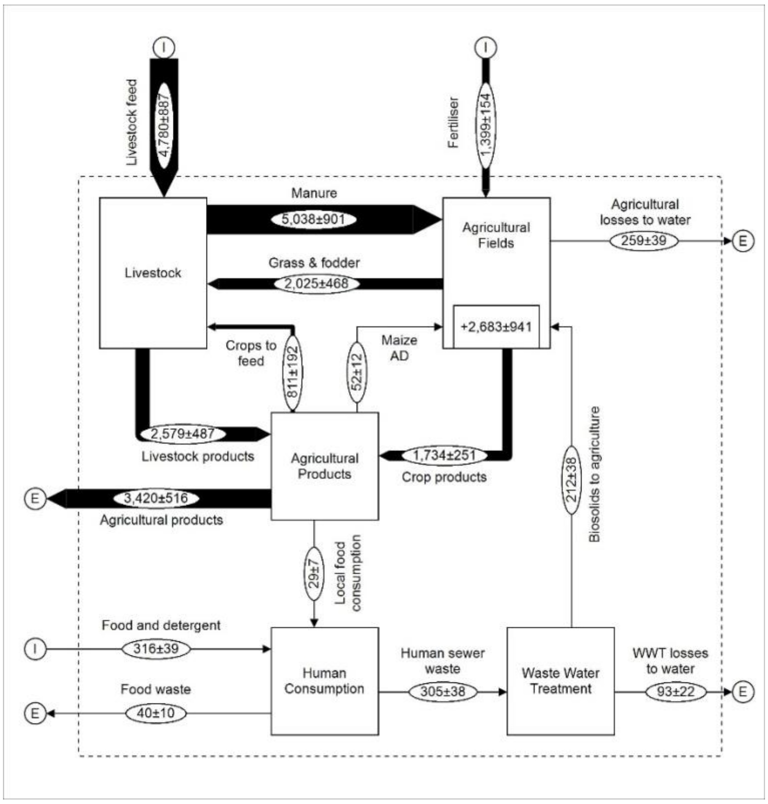

Figure 17. Wye catchment SFA for the cereals 50 scenario. All flows are t/P/yr ± uncertainty using the 2021 SFA as the reference year for scenario change.

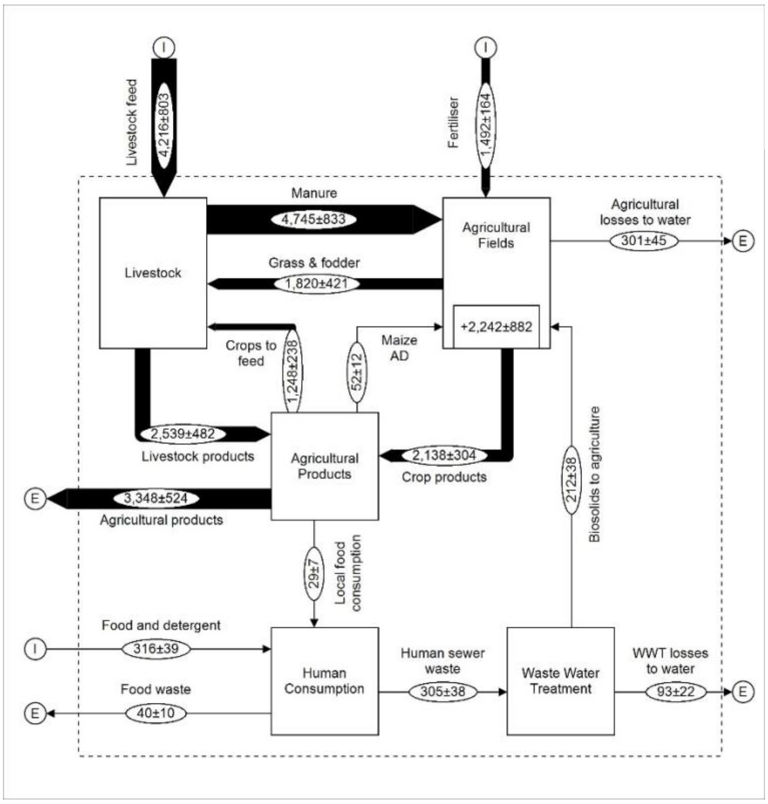

Figure 18. Wye catchment SFA for the cereals 100 scenario. All flows are t/P/yr ± uncertainty using the 2021 SFA as the reference year for scenario change.

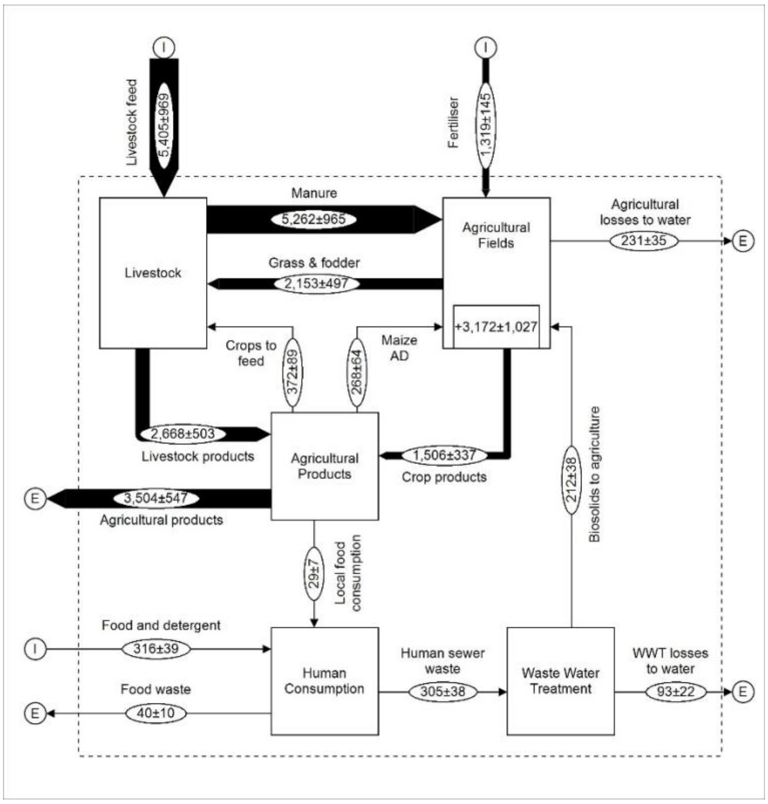

Figure 19. Wye catchment SFA for the maize 50 scenario. All flows are t/P/yr ± uncertainty using the 2021 SFA as the reference year for scenario change.

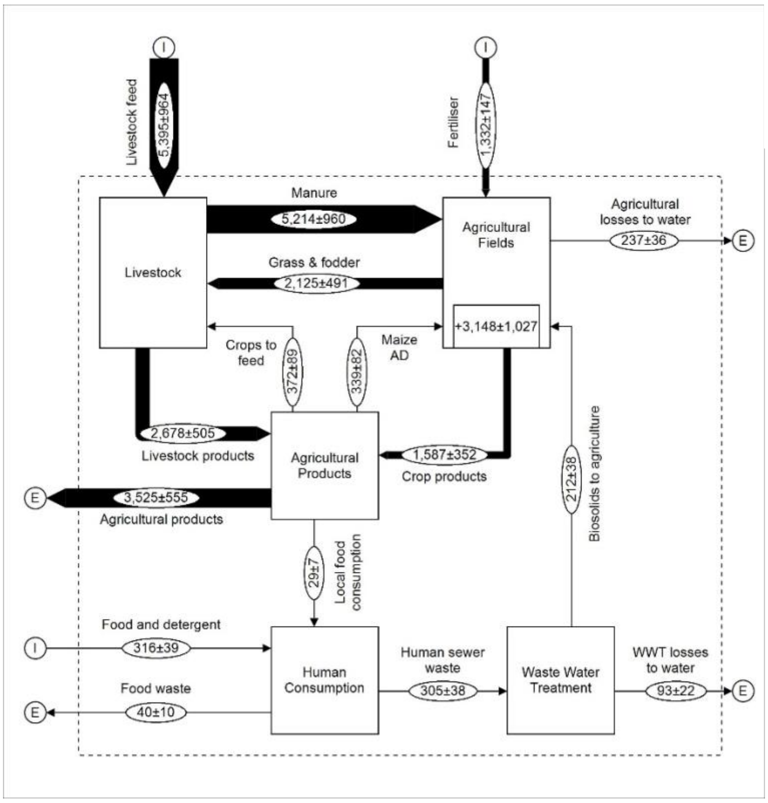

Figure 20. Wye catchment SFA for the maize 100 scenario. All flows are t/P/yr ± uncertainty using the 2021 SFA as the reference year for scenario change.

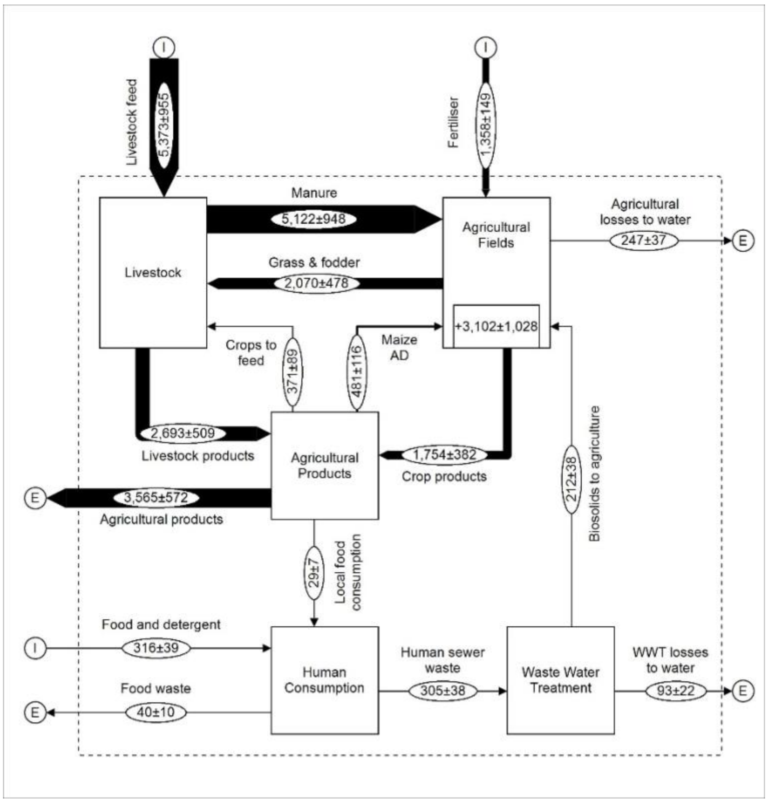

Figure 21. Wye catchment SFA for the maize 200 scenario. All flows are t/P/yr ± uncertainty using the 2021 SFA as the reference year for scenario change.