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Phosphorus flow analysis for Malawi: Identifying potential sources of renewable phosphorus recovery

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ABSTRACT

Population growth and dietary needs changes have exerted pressure on phosphorus (P) reserves, and the future availability of P fertilisers is uncertain. Most Malawian soils have low P and farmers apply P fertilisers to harvest enough food. Scarcity of chemical P fertilisers and rising prices will affect Malawi's food security. To avert the impact of P future uncertainty a P flow analysis (PFA) was conducted to characterise and quantify sources, flows, and sinks of P to determine options for waste minimisation, recovery, and chemical fertiliser use reduction for Malawi. The PFA results highlighted that; there are 35000 Mg of recyclable organic P annually, which is over two times Malawi's annual P fertiliser demand (14000 Mg). Currently, only 16% of the organic P is recycled to agriculture. Chemical P fertiliser represents 66 % of the P fertiliser used for crop production. Manure is the most recycled organic P source (38 % recycled), followed by organic solid waste (6%), and crop residues (5%). Annually, 9000 Mg of P is transferred to faecal matter, but none is recycled. Overall, Malawian soils have a negative P balance of -4000 Mg. Malawi can reduce its dependence on imported chemical P if recycling of organic P source is adopted. However, regulations should be put in place to control the quality of organic fertilisers.

1. Introduction

1.1. Phosphorus

Just like nitrogen, phosphorus is a limiting plant nutrient (Smit et al., 2010) but the future of this critical non-renewable nutrient is uncertain. High-grade phosphorus ore could be depleted in the next 100 (Walan et al., 2014) to 350 years (Jasinski, 2013), while Cordell et al. (2009) predicted that current (2009) phosphorus ore would reach its peak in 35 years.

Between 2015 and 2017, phosphate rock processing increased from 241,000 Mg to 263,000 Mg: an 8.36% increase. A growing human population and rising demand for meat (which depends heavily on fertilised grain) will likely increase phosphorus fertiliser demand even further (Schröder et al., 2009). However, phosphate rock is a non-renewable resource and will not last forever (Cordell et al., 2009; Schröder et al., 2009; Smit et al., 2010).

The world depends on phosphate rock for phosphate fertiliser production (Smit et al., 2010); almost all phosphorus-containing fertilisers on the market today are produced from phosphate rock (Kauwenbergh, 2010). Globally, the most important phosphorus deposits are in Moroccan-occupied Western Sahara, China, Russia, United States of America (USA), Jordan, and South Africa; Morocco alone controls 75% of the world's phosphate rock deposits (USGS, 2017). Phosphate is found in igneous and sedimentary rocks ranging from 4 to 20 % but can be enriched up to 36 to 40% phosphate (Fixen and Johnston, 2012).

The so-called "peak phosphate" scenario describes the point at which the maximum production rate of phosphorus is reached followed by declining supply. Peak phosphate nearly happened in the 1980s. It was attributed to the heavy use of fertilisers in the Soviet Union, but in the 1990s, there was a reduction in fertiliser use (Daneshgar et al., 2018). Knowledge of the adverse effects of excess phosphorus in natural water bodies (i.e. eutrophication) and the disbandment of the Soviet Union was responsible for decreasing phosphate fertiliser use. Recently, changes in dietary needs/preferences and an increase in the human population has resulted in increased phosphate fertiliser use again (Daneshgar *et al.*, 2018). Another issue is geographical distribution: as only a few countries control phosphorus reserves, any political

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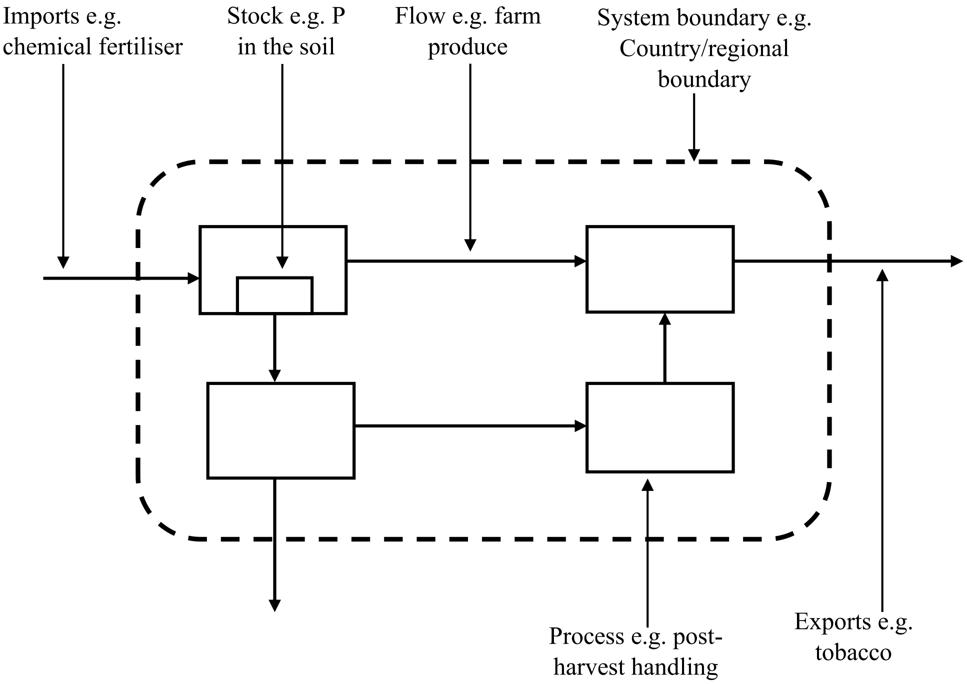

Fig. 1. A sketch of the material flow analysis system

instability or governance issues in these countries significantly affect the price and availability (Rosemarin and Ekane, 2016).

The United States Geological Survey (2017, 2018) issues annual updates on reserves, and the current phosphate reserves are approximately 70,000,000,000 Mg. The world resource of phosphate rock is over 300 billion Mg, but the reliability of this data is questionable (Cordell et al., 2009; Rosemarin and Ekane, 2016; Schröder et al., 2009). Despite conflicting views on phosphate rock reserves, the world will, at some point run out of a reliable, economically feasible, source of phosphorus and phosphorus has no replacement in agriculture (USGS, 2018).

The depletion of phosphorus reserves will affect global food security (Cordell and White, 2011) and Malawi will not be spared. Malawian farmers practice subsistence farming, and their major food crop is maize. As in most tropical countries, the soils in Malawi are infertile and highly weathered (Maida, 2013). Farmers must apply chemical fertilizers to harvest enough food to feed their families. Between 2006 and 2016, P fertiliser imports for Malawi increased by 34% (FAO, 2016) and are projected to rise. In the same period, Zambian P fertiliser imports rose by 304 per cent, Tanzania by 170%, Angola by 372%, and Uganda by 51% (FAO, 2016). The growing need for food across the African continent cannot be supported with the decreasing supply of chemical P: alternative sources of P need to be explored. Almost all the phosphorus in food/feed ends up in faeces and urine (Cordell *et al.,* 2013; Jönsson *et al.,* 2004), animal manure, and food waste, which accounts for almost 30 percent of the total food produced (FAO, 2011). However, these wastes are also potential sources of renewable phosphorus.

MFA studies are done to quantify phosphorus sources and flows and identify areas where phosphorus is lost or accumulates in the system. These types of balances help to identify areas from which phosphorus can be recovered and recycled as an alternative source of phosphorus fertiliser and to assess the potential of human excreta as a source of plant nutrients. Due to variations in the agricultural and food systems in different countries, the effects of phosphorus scarcity will be felt differently (Cordell et al., 2013); therefore, each country must assess its alternatives sources of phosphorus. Phosphorus accumulate in manure (Cooper and Carliell-Marquet, 2013; Cordell et al., 2013; Klinglmair et al., 2015), organic waste (Thitanuwat et al., 2016), and WWTPs (Álvarez et al., 2018) which have all been identified as potential areas of phosphorus recovery.

Although phosphorus flow analysis has been done for a range of contexts, no work has been done at the national level in Africa. Lederer et al. (2015) and Xiong et al. (2020) did an MFA at the regional level in Uganda and Tanzania, respectively, while Xiong et al. (2020) just considered P flow at household level through food consumption. MFAs completed at the national level were done in industrialized countries that are socially and economically different from Malawi and other Sub-Saharan countries. These industrialised countries depend on P imports; have well-developed sewer and solid waste collection systems; and practice intensive animal productions systems which all store and transfer P in very different ways than in most African contexts. Therefore, this paper presents the first phosphorus (material) flow analysis with the aim of characterising and quantifying the sources, flows, and sinks of phosphorus to determine options for waste minimisation, recovery potential, and chemical fertiliser reduction in one of the poorest, most agriculturally dependent, and landlocked countries in the world. Uniquely, this work explores the importance of pit latrines, free-range livestock management, and unauthorised waste dumping for phosphorus security for a landlocked country with no local phosphorus fertiliser production. This work is important to demonstrate the potential to implement circular economy programs using renewable sources of phosphorus in Malawi.

2. Methodology

2.1. Material flow analysis (MFA)

MFA describes a group of material accounting tools that use mass balance concepts to assess the movement of materials in and out of a unit area defined in space and time. Space can be a household, company, region, or country while the time can be a day, a week, a month, or a year. The tool choice depends on the goal of the MFA. For example, substance flow analysis is used primarily to understand the movement of the periodic table elements (Cu, Cd, Pb, P, etc.) and other compounds like chlorofluorocarbon (CFC) and carbon dioxide (Brunner and Rechberger, 2016). Material system analysis (MSA) deals with the sustainability and environmental concerns of raw materials or semi-finished products. In contrast, life cycle analysis (LCA) is concerned with the materials required for the production of a specific product, the life cycle of the products and the impact on the environment (Brunner and Rechberger, 2016; Cordell et al., 2013; OECD, 2008).

An MFA is based on a system that has set boundaries, imports, exports, process(s), flows, and stocks/sinks. In this case, Malawi, with its political boundary, is the system (Fig. 1).

Imports are materials crossing into the system boundary; exports are materials that leave. A process is where materials or substances are stored or transformed. A flow is the movement of the material/substance from one process to another, and the materials/substances stored within the process over time are called stocks (Brunner and Rechberger, 2016).

In this case of phosphorus flow analysis, the political boundary of Malawi is the system boundary. Imports are all the materials containing phosphorus coming into the country, for example, fertilisers and food items. At the same time, exports are all the foods (beans, fish, meat) containing phosphorus that Malawi sells/exports to other countries. The processes include crop or animal production. In crop production, inorganic phosphorus in fertiliser is transformed into the organic phosphorus in plant biomass. The movement of crop products from crop production to households or crop residues to animal production are flows and the phosphorus stored in soils is a stock.

2.2. Malawi

Malawi has almost 18 million people with an annual growth rate of 2.9 (NSO, 2019). Agriculture contributes to almost 80% of jobs and 90% of foreign currency earnings (Government of Malawi, 2010, 2007; NSO, 2017). Nearly 80% of Malawian farmers practice subsistence farming; their major food crop is maize though a few farmers grow legumes like soybean, pigeon peas, and groundnuts for income (IFDC, 2013). As in most tropical countries, Malawi's soils are infertile and highly weathered (Maida, 2013). Subsistence farmers must apply chemical fertilisers to harvest enough food to feed their families (Omuto and Ronald, 2018). However, the current fertiliser consumption (180,000 Mg/year) is below half of the potential consumption (Government of Malawi, 2007; IFDC, 2013). Malawi imports almost all its fertilisers (280,000 Mg/year) and is a landlocked country. The price of chemical fertilisers is too high for most smallholder farmers, and prices are expected to continue rising (IFDC, 2013). Malawi already has a fragile economy and struggles with food security which means it will be heavily affected by the depletion of the world's phosphate reserves.

The increasing human population will result in both increased food demand and an increased quantity of waste. As food moves from production to consumption, waste materials containing phosphorus are generated. The phosphorus in the waste materials is either from external inputs (fertilisers) or soil reserves. These organic waste materials, together with human excreta and animal manure, are potential sources of phosphorus. The four major cities in Malawi (Blantyre, Lilongwe, Zomba, and Mzuzu) generate around 500,000 Mg of solid waste per year. Almost 80 per cent of the waste materials are organic (Government of Malawi, 2014; ICLEI, 2016) but the city councils only collect about 30 per cent of the total solid waste generated (Government of Malawi, 2014). Almost 99 per cent of the population is not connected to the sewer system, with the majority using pit latrines (NSO, 2017). Additionally, the country also has over 30 million heads of livestock (FAOSTAT, 2016). All of these agricultural and human factors affect phosphorus in the country and no previous attempts have been made in Malawi to assess the phosphorus flows and how phosphorus from organic sources can contribute to sustainable nutrient management and agriculture production.

2.3. System description

The MFA covers the whole of Malawi in 2016, including the water bodies. Currently, Malawi does not produce or export phosphate fertilisers. Phosphorus leaves the country through the export of agricultural products, wastewater, landfill discharge (which leaves through water bodies) and, agricultural soils (through soil erosion). P in groundwater contribution to the model was considered insignificant and was excluded from the model. In this model, phosphorus flows within the country from agriculture production, imports, waste management, and recycling are all traced. The phosphorus form presented here is phosphorus pentoxide (P_2O_5) in Mg and 2016 is the reference year, although when data were not available in 2016 other years were used. Substance flow analysis software (STAN) (version: 2.6.801) software was used to perform this phosphorus flow analysis.

2.4. STAN software

STAN is a free resource developed by the Technical University of Vienna to supporting material flow analysis (Cencic and Rechberger, 2008). STAN incorporates data uncertainty and several material flow analysis features like graphical modelling, data management, calculations, and graphical presentation of results for the substance/material under investigation. STAN procedures conform to the Austrian standard ÖNORM S 2096 (Cencic and Rechberger, 2008). Several studies that have been done on phosphorus flow analysis in Europe, Asia, and Africa at different district/regional, country and continent levels, for example, various studies from the UK. (Cooper and Carliell-Marquet, 2013), Spain (Álvarez et al., 2018), Denmark (Klinglmair et al., 2015), Vietnam (Anh et al., 2016), Netherlands (Smit et al., 2010), and Uganda at district level (Lederer et al., 2015) all used STAN.

2.5. Processes, flows, and stocks

Depending on the objective of the MFA and the system under study, different processes, flows and stocks are considered (Álvarez et al., 2018; Cordell et al., 2013; van Dijk et al., 2016; Lederer et al., 2015; Senthilkumar et al., 2012; Smit et al., 2010). In terms of phosphorus, chemical fertilisers, imported food products, and washing chemicals are the common flows into a country (Álvarez et al., 2018; Cordell et al., 2013; van Dijk et al., 2016; Smit et al., 2010). Chemical phosphorus in the fertilisers and the phosphorus from the soil reserves are taken up into crop products. Animals and people consume these products, and some are exported (Cooper and Carliell-Marquet, 2013). Farm products (including animal products), waste materials produced along the farm products value chain, and household waste are the most important phosphorus flows (Álvarez et al., 2018; Bittman et al., 2017; Klinglmair et al., 2015; Lifset, Eckelman, Harper, Hausfather, and Urbina, 2016). For example, Cooper and Carliell-Marquet (2013) and Li et al. (2015) identified fertilisers, crop uptake, animal manure, crop and animal products, animal feed, food, and feed processing waste, waste to landfill, sewage sludge to agriculture, soil erosion, and imported food and feed as some of the possible flows of phosphorus. In addition to flows, processes where phosphorus may accumulate, pass through, or be depleted also need to be identified. The most explored processes are agricultural soils, households/humans, WWTPs, landfills, water bodies, animals, and incineration plants (Bi et al., 2013; Cooper and Carliell-Marquet, 2013; Klinglmair et al., 2015; Li et al., 2015; Smit et al., 2010; Thitanuwat et al., 2016) and pit latrines (Lederer et al., 2015).

This MFA was based on the approach described above but considering that most of these phosphorus flow analyses were done in developed countries, some flows/processes were either added or dropped to suit Malawi's situation. For example, there is no (engineered) waste incineration in Malawi, the majority of the population use pit latrines (NSO-Malawi, 2017), most animals feed on natural pasture (Chintsanya et al., 2004), people still practise open defecation (NSO-Malawi, 2017), and city councils collect only 30 per cent of the waste generated (Government of Malawi, 2014). Therefore, this MFA is designed to describe the situation in Malawi and may also be adaptable for many developing countries in Sub-Saharan African. Additional processes flows and stocks

Table 1
Process description

Process	Description
Imported fertiliser	The mass of P imported in the form of chemical fertiliser meant for crop production.
Cropland soils	Agricultural soils on which crops are grown and absorb P. In addition to inherent P in soil, P is added through chemical fertiliser, manure, decomposing mulch, ash after crop residues are burnt, and faecal sludge, and compost. Furthermore, some P is lost to water through soil erosion.
National crops	The collection of all P containing crops produced locally (from cropland soils) including crop biomass. The crop residues are used as animal feed and soil mulch. The P-containing crop products go to post-harvest handling (processing, transporting, storage, etc.)
Food products processing and handling	P from both locally produced and imported crop products and animal products arrive here. As the crops are processed, transported, or stored, there are organic waste materials produced. These P-containing waste materials end up at the waste collection process. Another part of P leaves the country through exports of crop products, e.g. tea and tobacco.
Waste collection	All organic waste materials from food handling, food processing and households converge here. The waste materials go either to official landfills or unauthorised dumping sites.
Unauthorised dumping site	Places not designed for waste dumping: roadsides, public markets, private yards, rivers, etc. The organic waste here are mixed with plastics and other inorganic materials. P is lost from here through leaching, the loss of ash from burning, and erosion.
Landfills	The designated places for waste materials dumping. P is lost from the landfills to water bodies through leachate.
Households	It is the place where people consume crop and animal products after post-harvest handling and processing.
People	People consume P-containing crop and animal products and fish. The body absorbs some of the P while the rest is excreted. When humans die, the phosphorus they contain is transferred to the soil when they are buried.
Pit latrines	Pit latrines are one of the onsite sanitation facilities where human excreta are contained. Some of the P is lost from the pit latrines when they flood or are emptied.
WWTPs	Some human excreta go to WWTPs through the sewer system, while the excreta that is emptied from pits and septic tanks are delivered mechanically. The P-containing wastewater is discharged into rivers.
Septic tanks	Septic tanks are one of the onsite sanitation facilities where human excreta are contained. P leaves the septic tanks through emptying and leaching.
Livestock	Animals consume P-containing feed from processed crop products, crop residues, and natural pasture. P leaves livestock through animal products like eggs and meat, and also through manure, feathers, and bones.
Burning	Crop residues are burnt for fuel, tobacco curing, field clearing, and mice hunting, among other reasons. Some of the P is returned to the soil in the form of ash and used by the crop but the rest is lost to water bodies by wind and water erosion.
Natural pasture	Naturally growing pasture without intentional, external P application. The pasture utilises P from the soil reserves and livestock droppings. P leaves the natural pasture to livestock through grazing and the animals fertilise the pasture through droppings as they graze.
Collected manure	Animals are normally housed during the night and the night droppings are easily collected. Some of the collected manure is left unused while some are applied to soils for crop production. P is lost from unused manure mostly through leaching.
Water bodies	All rivers and lakes in Malawi to which P is lost from processes through water and wind erosion. Some P goes back to the household for consumption through fish; some P leaves the country through rivers that run beyond the country boundaries.

almost certainly exist but have been excluded from the MFA on the grounds that they are assumed to be irrelevant within the context of the magnitude of error inherent in this analysis.

2.6. Phosphorus flow analysis

All the flows and data sources used in this analysis and how they were calculated are presented in appendix (Table 1). The flows are categorised into three: imports (into Malawi), internal flows, and exports (out of Malawi). Just like any other material flow analysis, the law of conservation of mass is observed, **input = change in stock + output**.

2.5. Data uncertainty and errors

Data uncertainty and error always occur in MFA and need to be acknowledged (Cooper and Carliell-Marquet, 2013b). In experiments that involve replications, it is easy to calculate errors and standard deviations, but in MFA most of the data are from one source or the available data are not independent (Hedbrant and Sorme, 2001). It is difficult to determine the original uncertainties but several methods and approaches are available to deal with data uncertainty in MFA like those used by Cooper and Carliell-Marquet (2013), Álvarez et al. (2018), Klinglmair et al. (2015) and Laner et al. (2015). Almost all studies in MFA base their uncertainty calculation on the procedure developed by Hedbrant and Sörme (2001). The method, which was developed through experience with their data, showed that uncertainty differs depending on the source of the data (official statistics, published literature, and expert judgment) and Antikainen et al. (2005) modified this approach according to their data. These authors categorised data sources into different levels (1 to 8), and then assigned different uncertainty intervals to each data level. For example, data in Level 1, which is data from official statistical offices at the national level e.g. human population, are multiplied or divided by 1 (× ÷1). Level 2 also includes data from national statistics at national level e.g. an agricultural land area, and are multiplied or divided by 1.05 and so on up to level 8 which contains data from literature e.g. N_2O emissions with the uncertainty of × ÷4.

For example, if the national statistics reported that a country has 10,000,000 people, then its uncertainty is × ÷1, but if national crop yield was 200,000 Mg, then its uncertainty is × ÷1.1. In situations where data sets are being added or multiplied, the uncertainty was calculated using equations outlined by Antikainen et al. (2005). Data uncertainty increases when data sets are multiplied and decreases when data sets are added (Antikainen et al., 2005).

Multiplication:

$$Uncertainty\ factor = 1 + \sqrt{(f_a - 1)^2 + (f_b - 1)^2}$$ (Antikainen et al., 2005)

f_a = assigned uncertainty interval for the P flow 1
f_b = assigned uncertainty interval for the P flow 2

For example, if 500,000 × ÷1.2 kg of maize was harvested in 2016 in Malawi and maize's phosphorus is content 250 × ÷1.25 mg/kg then the amount of phosphorus was 125 kg, and the uncertainty can be calculated as follows:

$$Uncertainty\ factor = 1 + \sqrt{(1.2 - 1)^2 + (1.25 - 1)^2} = 1.32$$

The final value of phosphorus will be 125 × ÷1.32

Addition

$$Uncertainty\ \ factor = 1 + \frac{\sqrt{[m_a.(f_a - 1)]^2 + [m_b.(f_b - 1)]^2}}{m_a + m_b}$$

(Antikainen et al., 2005)

m_a = Mass phosphorus 1
m_b = Mass phosphorus 2 and f = assigned uncertainty interval

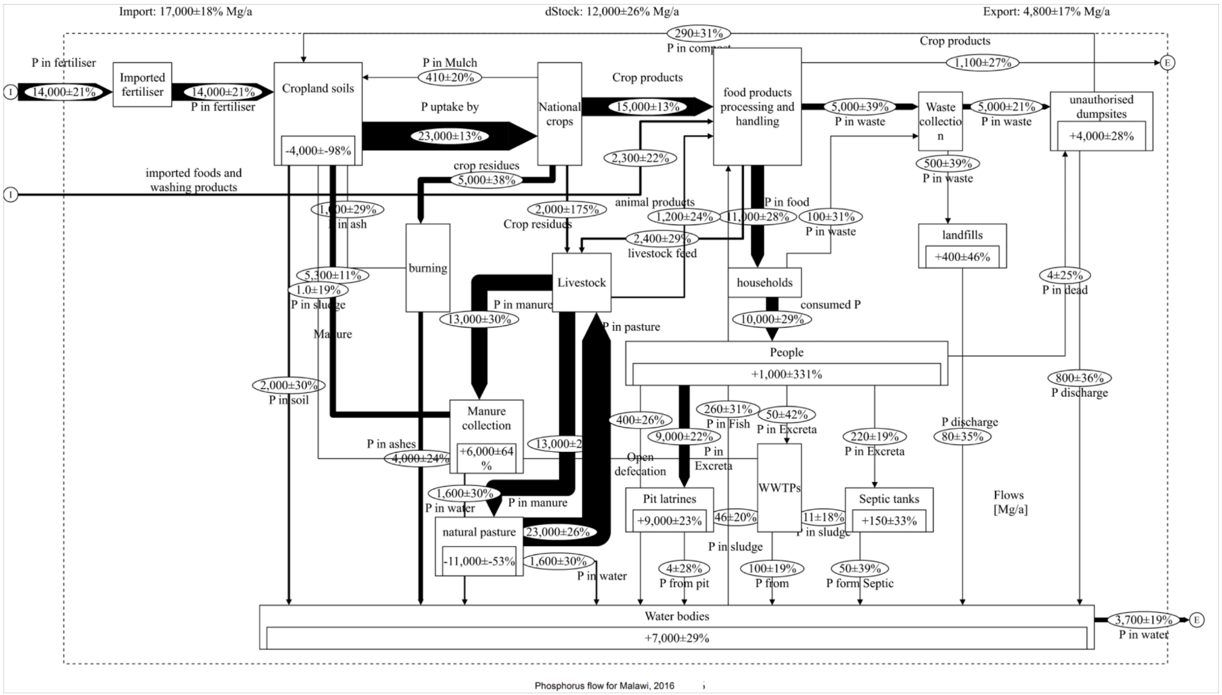

Fig. 2. The Malawian phosphorus flow model V1.0 shows the primary inputs (Mg/year), outputs (Mg/year), internal flows (Mg/year), processes, and stocks/sinks (Mg) of phosphorus in Malawi in 2016.

For example, if phosphorus applied to crops through manure is manure is 300 × ÷1.4 kg and through fertiliser is 2000 × ÷1.2 kg then total phosphorus applied is 2300 kg, and the uncertainty can be calculated as follows:

$$Uncertainty\ \ factor = 1 + \frac{\sqrt{[300.(1.4-1)]^2 + \ [2000.(1.2-1)]^2}}{300+2000}$$

$$= 1.18$$

Then phosphorus applied is 2300 × ÷1.18

Cooper and Carliell-Marquet (2013b) converted the × ÷ uncertainty range to ± range to simplify the model balancing and the entering of the uncertainties in STAN software. The × ÷1.32 was changed to ±32%, then × /÷1.18 to ±18%, this method maintains the upper limit but extends the lower limit (Cooper and Carliell-Marquet, 2013).

In the current study, we used official data from FAOSTAT, the Malawi National Statistical Office, the United States Department of Agriculture, literature from national and international sources, personal communications, and experts' assumptions. Data uncertainty was dealt with by following the approach used by Antikainen et al. (2005) and (Cooper and Carliell-Marquet, 2013). Just like previous studies, we adapted the data to different uncertainty levels depending on data sources (Table 3). In STAN software, data uncertainty is incorporated by using the Gauss error propagation for independent variables method to calculate uncertainty values (Cencic, 2016) for flows and stocks.

3. Results and discussion

3.1. Material flow analysis

Overall Phosphorus flow in Malawi The MFA (Fig. 2) showed that P enters Malawi mainly through imported chemical fertilisers and imported food products. In the year 2016, Malawi imported approximately 17,000 Mg of P of which 14,000 came through chemical fertilisers and, 2,300 Mg came through imported foods and washing products.

Crop production in Malawi used almost 21,000 Mg of P, which were applied to the soils. The P in chemical fertilisers contributed 66% of the P applied to the soils for Malawi's crop production. Approximately 5300 Mg of P, which represents 25% of the P applied to the soils for crop production came from animal manure. In contrast, faecal sludge, compost, P in wastewater and decayed mulch contributed to the remaining 9% of the P applied. Although 21,000 Mg of P was applied to the soils, 25,000 Mg of P left the soils of which 2,000 Mg went to water bodies through soil erosion and 23,000 Mg were utilised by crops. This showed that extra 4,000 Mg of P were taken from the soil reserves every year translating into 1 kg of P mined per hectare per year from the agricultural land.

Of the 23,000 Mg of P absorbed by the crops, approximately 7,410 Mg of P were in crop residues. Almost 410 Mg of the P in crop residues were retained in the fields through mulching, 5,000 Mg were burnt in crop residues, 2,000 Mg were fed to animals. Out of the 5,000 Mg of P in burnt residues, 4,000 Mg were lost to water bodies and 1,000 Mg were returned to the soil. Almost 15,000 Mg of phosphorus went into post-harvest handling processes (processing, storage, distribution/transportation), which includes the P in fish, animal products, and P in imported food products. Approximately, 19,000 Mg of P entered into the post-harvesting processes, and from these post-handling processes, 5000 Mg of P ended up in food waste, 1100 Mg of P were exported through crop and animal products, 2400 Mg of P were in animal feed and, 10000 Mg of P were in food for human consumption within the country. Out of the 10000 Mg of P for human consumption, 100 Mg were lost to food waste.

The P in organic waste materials are taken to official landfills and unofficial landfills (roadsides, rivers and other undesignated places). Approximately 5,100 Mg of P are in waste materials every year, and 4500 Mg were dumped at unofficial landfills. The remaining 500 Mg were dumped at official landfills. Out of the 5,000 Mg of P that were dumped at the landfills, 800 Mg from unofficial dumpsites and 80 Mg from landfills were lost to water bodies through liquid discharging. The MFA shows that there are almost 4000 Mg and 400 Mg of P accumulating every year in unofficial and official landfills.

People utilised nearly 10,000 Mg of P yearly, of which 1000 Mg were incorporated into the bodies. Dead people take 4 Mg of P away with them when they are buried. The rest of the consumed P was excreted, of which, approximately, 91% was deposited in pit latrines and the remaining 9% went to septic tanks, WWTPs, and water bodies through open defecation. Almost all P that went to pit latrines accumulated (9000 Mg) as there is little P lost to water bodies through overflowing in the rainy season or as faecal sludge which is taken to WWTPs. In addition to receiving P from people through the sewer system, WWTPs receive P through septic tanks and pit latrines emptying. All the P (107 Mg) that arrived at the WWTPs left the facility to water bodies (106), and some (1 Mg) were recycled to agriculture. The septic tanks received almost 220 Mg of P yearly. Through emptying, 11 Mg went to WWTPs while 50 Mg went to water bodies due to the dumping of faecal sludge from septic tanks into rivers. Almost 159 Mg remain of P remain in the septic tanks

Livestock consumed 27000 Mg of P, of which 2000 Mg came from crop residues, 2400 Mg came from the processed feed, and the rest came from natural pasture. P left livestock through animal products (eggs, meat, and milk), bones, feathers and manure. The manure was either dropped directly onto natural pasture while grazing or dropped when the animals are housed at night. In total, 26000 Mg of P left the livestock through the manure of which 13000 Mg went to natural pasture, and the other 13000 Mg went to manure collection. Of the manure collected, 5000 Mg were applied to the soils for crop production, 2000 Mg were lost to water bodies and 6000 Mg remained unused. Natural pasture received 13000 Mg of P from manure and 1600 Mg were lost to water bodies. Animal grazing consumed almost 23000 Mg of P from natural pasture.

In this MFA, water bodies in Malawi received P from WWTPs, cropland soils, and landfills among other processes. Yearly, the water bodies receive almost 11000 Mg P from landfills, WWTPs, septic tanks, manure, pit latrines, ashes, unauthorised dumpsites, soil erosion and open defecation, of which 3700 Mg went beyond the MFA system boundary through flowing water and 260 Mg were in harvested fish. This means there were almost combined 7000 Mg of P in sediments and in Malawian water bodies.

3.2. Crop production, phosphorus inputs and recycling

The results show that 33% of the phosphorus used in Malawi comes from renewable sources. Malawi depends mostly on imported inorganic phosphorus which contributes 66% of the total P used for crop production every year. The over-dependence on imported inorganic phosphorus, which is a non-renewable resource, puts the dependent countries' food security at risk (Rosemarin and Ekane, 2016; Schröder et al., 2009; P. Walan et al., 2014; Petter Walan, 2013). Malawi's farming sector is dominated by the resource-poor smallholder farmers who are already struggling to buy fertiliser and depend on the government farm input subsidy programme (FISP) to access fertiliser. The FISP is not sustainable, and the Government of Malawi (2007) and (2010) emphasised the need for recycling and the use of organic fertiliser.

The country produces approximately 35000 Mg of organic P annually that can be recycled and used for crop production. The P that can be recycled is almost over two times the P that Malawi imports in chemical fertilisers for crop production. Currently, only 16% of the organic P is recycled to agriculture with animal manure contributing 14%. There is little or no recycling of P from municipal organic waste, crop residues, or faecal sludge (Table 4).

Although Malawi depends on imported chemical fertiliser as a source of P, the mass of P imported does not meet the crop demand which resulting in a negative P balance in the soil. There almost 4000 Mg of P mined from the soil every year which translate to -1 kg P/ha. These results agree with previous studies which found negative P balances. Henao and Baanante (1999) reported -16 kg P/ha, Stoorvogel and Smaling (1990) reported -10 kg P/ha and Sheldrick and Lingard (2004) reported -4 kg P/ha soil balances for Malawi which are higher than the value calculated here. The previous studies used crop nutrient uptake indeces (Henao and Baanante, 1999) to estimate P output in crops while the current study used the P content in crops to estimate P output from the soils. Furthermore, this study used chemical fertilisers, manure, mulch, compost, ash, and sewage as the inputs for P. It was only Sheldrick and Lingard (2004) who included sewage in addition to chemical fertilisers, manure and deposition as inputs for P, (Henao and Baanante, 1999) and Stoorvogel and Smaling (1990) used chemical fertiliser, manure, and deposition as inputs sources for P. It is also important to note the increase in animal population from 13 million in 1990 to around 30 million in 2016 (FAO, 2016) which may imply increased manure production and utilisation in Malawi.

Although P is mined every year from the cropland, almost 30,000 Mg of P in organic waste materials are left unused. If recycling is promoted, the P in organic sources in long run will be able to offset the negative soil P balance in the cropland soil. Table 4 shows that there is no recycling of P from landfills, pit latrines, septic tanks and WWTPs. Animal manure and crop residues are the only sources of P that are currently recycled.

3.3. Phosphorus accumulation and loss

Just considering available P at 20 cm depth, the soil has 241,000 Mg±72000, which is the most extensive stock of all. As noted earlier, the available soil P content in Malawi is not enough to fully support crop growth, and as such, external P has to be applied (Omuto and Ronald, 2018). However, the P inputs that go into the soil are less than the output (Table A2 in Appendix). It means that in addition to the P from the external sources, the crops are also using P from the soil reserves. If the P inputs and outputs are not balanced, it will lead to the depletion of the soil reserves and the soil will not be able to support crop growth in years to come.

In Malawi, almost 80% of the livestock feed on unmanaged pasture (Chintsanya et al., 2004). The unmanaged pasture utilises P from the soil reserves. The size of the P stock in the soils supporting the natural pasture is unknown, and almost 11,000 Mg of P are removed every year through animal grazing (Table A2 in Appendix). In the long run, these soils will be unable to support pasture growth, leading to a reduction in the animal population, especially goats and cattle. Although we assumed that P in animal manure (dropped during grazing), decay plant materials, soil erosion and flooding water replenishes P absorbed by plants that are consumed by the animals. Still, P is incorporated in animal bodies, and manure which are excreted away from the pasture (in confinement at night). Annually, there is almost 25,000 (Table A2 in Appendix) Mg of P from the natural pasture of which 13,000 Mg are in manure that can be used for crop production. Natural pasture play a significant role in moving phosphorus from the soils through animals, but the lack of circular movement of P to replace the removed P poses a threat to the future ability of the ranges to support livestock production.

Human excreta in pit latrines, septic tanks is another source of P. The P stock in pit latrines and septic is almost 9200 Mg every year. The pit latrines represent 98% of the P in human excreta. Despite that 91% of Malawians use pit latrines (NSO-Malawi, 2017), 97% of the sludge dumped at the wastewater treatment plants in Blantyre is from septic tanks (Yesaya and Tilley, 2021), i.e. pit latrines are rarely emptied, or if they are, the sludge is not disposed of safely. These results agrees with the finding of Collet et al. (2018) and WaterAid Malawi (2018) which found 24% and 64% of faecal matter unemptied in Blantyre and Kasungu respectively. To have a clear picture of the P stock in pit latrines and septic tanks, we used the current (2016) accumulations of 9000 Mg for latrines and 140 Mg for septic tanks of P and assumed constant accumulation in the past ten years (from 2006 to 2016). As of 2016 Malawi had 91,500 Mg of P in faecal sludge buried under the ground. In the past 12 years (2006 to 2018), Malawi imported 19,000 Mg of P on average every year (FAO, 2016): in the past 10 years (2006 to 2016) there has been an accumulation of P in faecal sludge which is equivalent to almost 5 years of P imports to Malawi.

Approximately 38% of P from collected manure is used for crop production, which is higher than the 5% from crop residues and 6% from

Table 2
Uncertainty levels and data sources (Antikainen et al., 2005)

Level	Uncertainty factor	Data source	Example data
1	×÷1	Official statistics on the national level	Human population
2	×÷1.05	Official statistics on the national level	Foreign trade, amount of produced milk and eggs, area of agricultural land, fertilisation
3	×÷1.1	Official statistics on the national level. Information from facilities subjected to permit requirement Values from literature	Number of animals, crop yield Mass of Nitrogen (N) and P in treated wastewaters Mass of N and P in treated wastewaters
4	×÷1.2	Official statistics on the national level Values from literature	Feed consumption in balance sheets for food commodities N and P contents in products (e.g. hay, horses, poultry)
5	×÷1.33	Modeled data Values from literature	N deposition on soil N and P contents in products (e.g. fur animals, fish, organic waste)
6	×÷1.5	Monitored data Values from literature	P deposition on soil NH$_3$ emission factors, leaching from agricultural soil
7	×÷2	Factors from literature	Biological N fixation, N$_2$O emission factors
8	×÷4	Factors from literature	N$_2$O emission factors

Table 3
Data uncertainty interval

Level	Interval factor	Data source	Example data
1	×÷1.2	Official statistics from the Food and Agriculture Organisation of the United Nations and Malawi National Statistics Office	Fertiliser imports, human population, crop production, and livestock statistics.
2	×÷1.25	Data from the local and international literature	Phosphorus content in food products. Phosphorus content in manure
3	×÷1.33	Expert guesses and assumptions	Manure and compost being recycled to agriculture.

Adapted from (Cooper & Carliell-marquet, 2013)

organic market waste (Table 4). However, over 6000 Mg of P in manure accumulated in the year 2016. Assuming ten years (2006 to 2016) of accumulating, the current P in manure would be equivalent to Malawi's P import demand of 3 years.

Organic waste materials generated in households and markets are other sources of P (Davila et al., 2019). The councils in Malawi collect 30 per cent of the waste produced (Government of Malawi, 2014) meaning landfills are not the critical stock of P in organic waste. The landfills contain 10 % of the total P in organic waste material produced in Malawi, the rest is in unauthorised dumpsites (backyard, markets, river, roads etc.). Annually, there is accumulation of 4000 Mg of P in unauthorised dumpsites and 400 Mg of P in landfills. Assuming ten years at the same accumulation rate, then approximately 44000 Mg of P will have accumulated which is equivalent to 2 years of chemical P imports.

Water is the sink for almost all P lost from the other stocks and processes. Nearly 11,000 Mg of P went into the water bodies. Although P supports life in the water, an excess of it causes eutrophication. In the last ten years (2006 to 2016), almost 70,000 Mg of P has built up the water bodies (bulk water, sediments, and living organisms) in Malawi. Unlike other stocks, P in water bodies can be either in a soluble form, a solid form after reacting with other elements, or incorporated into tissues of aquatic animals and plants.

Table 4
Potential and actual P recycled in Malawi

Subsystem	Potential P (Mg) that can be recycled per year	P containing material	P recycled to agriculture	
			Mg P/ year	%
National crops	7600	Crop residues	400	5
Manure production	13000	Manure	5000	38
Landfills	500	Municipal organic waste	0	0
Unauthorised dumping	5000	Municipal organic waste	290	6
Pit latrines	9000	Faecal sludge	0	0
WWTPs	100	Wastewater and faecal sludge	0	0
Septic tank	220	Wastewater and faecal sludge	0	0
Total	35420		5690	16

The P outputs presented in Appendix (Table 2) include P, which is goes to water bodies. If the flows of P to water bodies are prevented or reduced, the P stocks (soil, manure, WWPTs etc) would increase. For example, out of the 25000 Mg P output from the soil, 6000 Mg of P went to water bodies through soil erosion (2000 Mg) and ashes erosion (4000 Mg) after burning of crop residues. All the P output from landfills went to water bodied while 68% of the output from unauthorised dumpsites went to water bodies. Just like landfills, P output from pit latrines and septic tanks went to water bodies. 29% of the P output from manure went to water. The model depicts that the output of P from water bodies is through fish and water running beyond the system's boundary. However, irrigation brings P from the water to the crops, but irrigation only covers 2 % of the cropland in Malawi (FAO, 2016).

Applying organic fertiliser does not only improve soil nutrients status but also soil aggregates (Carbonell et al., 2011; Giannakis et al., 2014; Soma et al., 2018) through the binding effects of organic matter. Well aggregated soil has reduced erosion potential which means even P lost through erosion from the fields will be reduced if organic fertiliser is used. Reducing the losses of P from the stocks and processes will not only increase the amount of P to be recycled to agriculture but also reduce water contamination.

The Malawian government encourages the use of organic fertilisers (Government of Malawi, 2007) but the lack of fertiliser policy, and specifically the lack of policy for organic fertilisers, makes its enforcement a problem: the potential of organic fertiliser remain unrealised in Malawi (Simtowe, 2016).

3.4. Limitations and challenges of the current MFA

Although the current MFA has revealed the magnitude of flow, and sinks/stocks of P in Malawi, it does not indicate the stocks' location. Furthermore, this MFA does not specify how much of the P in the stock can be recycled and the challenges that may be encountered in the attempt to recover the P from the accumulation sites. For example, out of the current or yearly P in human excreta, landfills, manure how much can be recovered and the drawbacks.

Data used on P content in crop and animal products (soybean, pigeon peas, beef, fish, etc.) were collected from the U.S. Department of Agricultural database (https://fdc.nal.usda.gov). The data may not necessarily represent the Malawi situation and also resulted in using higher uncertainty values.

The MFA shows the P that is in different organic sources and can be potentially used for crop production. However, is not all the P in organic sources that is readily available for crop uptake and mineralisation and availability of P in these products depend on soil pH, texture and presence of oxides (Al and Fe oxides)

Table A1
Flows description, calculations and data sources

Flow	Flow description	From	To	Data used	Data sources	Calculations, assumptions
Import flows						
Chemical fertiliser	P imported in chemical fertiliser	Outside Malawi	Imported fertiliser	• P in fertiliser, Mass of imported fertiliser	FAOSTAT, 2016	Mass of P in NPK fertiliser
Imported foods and washing products	P imported in food and washing products	Outside Malawi	Food processing/ distribution and retailers	• Mass of imported fruits, processed food, wheat flour, fish, etc. • Mass of imported washing products • P content of imported food • P content in washing products	FAOSTAT, 2016, WITS, 2019 USDA, 2019 (Pattusamy et al., 2013)	Mass of Food imported x P content (mg/kg)
Internal flows						
Chemical fertilisers	P in chemical fertiliser applied to crops	Imported fertiliser	Cropland soils	• P fertiliser used in agriculture	FAOSTAT, 2016	The difference between P applied (chemical fertilisers, manure, and compost) and P lost (soil erosion) and absorbed (crops) from the soil to the soils Produced by STAN mass balance
Crops	Nationally produced P-containing crops including residues (maize, wheat, and rice)	Cropland soils	National crops	• Mass of harvested cereals, legumes, fruits, vegetables, etc. • Hectarage under maize production • P content of each crop product • P content in maize residues • Mass of maize residues per ha	FAOSTAT, 2016 USDA, 2019 FAO, 2006 Kabambe *et al.,* 2018	Crop and residues harvested x P content
Crop products	P in crop products that go to post-harvest handling	National crops	Crop /animal products processing and handling	• Mass of P in crop products • Mass of P in crop residues (mostly maize)		Mass of P from cropland (soils) – Mass P in crop residues (feed, mulch, and burnt)
Mulch (residues)	P returned to the soil through soil mulching	National crops	Cropland soils	• Hectarage under conservation agriculture (C.A.)	Kassam *et al.,* 2015	The area under C.A. x maize residues yield x P content
Crop residues (animal feed)	P consumed by animals from crop residues, e.g. maize stalks	National crops	Livestock	• Mass of maize crop residues		Assumption: 20% of the total P in crop residues
Crop residues	P in crop residues to be burnt for fuel, nursery curing, mice hunting, and land clearing.	National crops	Burning	• Mass of burnt crop residues • P in crop residues	FAO, 2016 FAO, 2006	Mass of residues burnt x P content
Ash	P in ash after burning of crop residues	Burning	Water bodies	• Percentage of nutrient loss from burnt biomass • Mass of biomass burnt	Dobermann & Fairhurst, 2002 FAOSTAT, 2016	Assumption: 80% of P in burnt biomass
Ash	P in ash after burning of crop residues	Burning	Cropland soils	• Percentage of nutrient loss from burnt biomass • Mass of biomass burnt	Dobermann & Fairhurst, 2002 FAOSTAT, 2016	Assumption: 20% of P in burnt biomass
Food products	P in food products going into households	Crop/animal products processing and handling	Households	• Mass of food products		The difference between the mass of P in food products (in post-harvest handling) and the mass of P in food waste, feed, and food exports. Produced by STAN mass balance
Waste materials	P in organic waste	Crop/animal products processing and handling	Waste collection	• Percentage of food waste for Sub-Saharan Africa in four processes (agriculture, post-harvest handling, processing, distribution,) • P content in food	FAO, 2011b USDA, 2019	Amount of wasted food x P content
Waste materials	P in organic waste	Households	Waste collection	• Percentage of food waste for Sub-Saharan Africa in during consumption	FAO, 2011	Percentage of food waste x total in household
Waste materials	P in organic waste	Waste collection	Landfills	• Mass solid waste composition data • Percentage of waste collected in city councils	ICLEI, 2016 Government of Malawi, 2014	Assumption:10% of the total P in organic waste
Waste materials	P in organic waste	Waste collection	Unauthorised dumpsites	• Mass solid waste composition data Percentage of waste collected in city councils	ICLEI, 2016 Government of Malawi, 2014	Assumption:90% of the total P in organic waste
Consumed P	P in food consumed by people	Households	People	• Mass of food products going to households	FAO, 2011	Percentage of food waste at household x mass of food going to

(*continued on next page*)

Table A1 (*continued*)

Flow	Flow description	From	To	Data used	Data sources	Calculations, assumptions
						households STAN mass balance
Excreta	P excreted from humans to pit latrines	People	Pit latrines	• Percentage of P absorbed by the human body • Percentage of the population using pit latrines	Jönsson et al., 2004 NSO, 2017	P consumed by people - P absorbed by the human body. Then the difference multiplied by the percentage of the population using pit latrines
Excreta	P excreted from humans to WWTPs	People	WWTPs	• Population connected to an off-site sanitation system	NSO, 2017	Percentage of people using off-site sanitation x P in human excreta
Excreta (septic tanks)	P excreted from humans to septic tanks	People	Septic tanks	• Population using septic tanks	NSO, 2017	P in human excreta x percentage of the population using septic tanks
Excreta (open defecation)	P excreted by humans onto open land/water	People	Water	• Population with no sanitation facility		P in human excreta x percentage of the population using no sanitation facilities
Animal Products	P in animal products	Livestock	Crop/animal products processing and handling	• Mass of meat and chickens, the volume of milk, etc • P content in meat products	NSO, 2017 USDA, 2019	Sum of the tonnage of meat products multiplied by their P content minus P in waste food
Livestock feed	P in feed for animals	Crop/animal products processing and handling	Livestock	• Mass of crop products used for animal feed	FAO, 2006	Mass of crop products used x P content in the crop products
Manure	P excreted by animals	Livestock	Collected manure	• Livestock population • Mass manure production per cow • Mass manure production per goat • Mass manure production per 1000 heads of chickens • P content in manure	NSO, 2017 Onmeremadu et al., 2007 Osuhor et al., 2002 Williams, n.d. Neina et al., 2016; Ryssen, 2001	Livestock population x manure production per animal x manure P content
Manure	P excreted by animals	Livestock	Natural pasture (soils)	• Livestock population • Mass manure production per cow • Mass manure production per goat • Mass manure production per 1000 heads of chickens • P content in manure	NSO, 2017 Onmeremadu et al., 2007 Osuhor et al., 2002 Williams, n.d. Neina et al., 2016; Ryssen, 2001	Livestock population x manure production per animal x manure P content
Pasture	P in grazing pasture	Natural pasture (soils)	Livestock	• Livestock management	Chintsanya et al., 2004	STAN mass balance
Manure	P in manure applied to cropland	Manure collection	Cropland	• Mass of manure collected		Assumption: 20% of the P in manure collection
Soil erosion	P carried by water from agricultural fields to water bodies	Cropland soils	Water bodies	• Hectares of agricultural land • Mass of P lost per hectare per year through soil erosion	FAO, 2016 Omuto & Ronald, 2018	Land area x P lost per hectare
Leachate discharge	P leaving unauthorised dumpsites	Unauthorised dumpsites	Water bodies	• P content leachates	Cheng et al, 2011	Assumption: 20 % of P in unauthorised dumpsites
Leachate discharge	P leaving official landfills	Landfills	Water bodies	• P content leachates	Cheng et al, 2011	Assumption: 20 % of P in landfills
Faecal sludge	P in human excreta emptied from pit latrines	Pit latrines	WWTPs	• Population using pit latrines • Percentage of pit emptied	NSO, 2019 Manda, 2009 *Chipeta et al.,* 2017	Assumption: 0.5% of P in pit latrines
Faecal sludge	P from septic tank emptying	Septic tanks	WWTPs	• Percentage of septic tank emptied	Collet *et al.*, 2018 WaterAid Malawi, 2018	5% of P in Septic tanks
Wastewater	P from leaving WWTPs	WWTPs	Water bodies	• Percentage of wastewater treated	Government of Malawi 2014 The World Bank, 2017	Assumption: 99% of P at WWTPs
Leachate discharge from manure	P in leachates from manure	Manure collection	Water bodies	• Percentage of P loss from uncovered manure	Nicholson, Rollett, & Chambers, 2011 Tittonell, Rufino, Janssen, & Giller, 2010	P loss factor multiplied by P in unused manure

(*continued on next page*)

Table A1 (*continued*)

Flow	Flow description	From	To	Data used	Data sources	Calculations, assumptions
Fish	P from water bodies through fish	Water bodies	Crop/animal products processing and handling	• Mass of fish harvested • P content in fish, tilapia as reference	FAO, 2017 USDA, 2019	Mass of fish harvested multiplied by P content (mg/kg)
Compost	P in compost applied to cropland soils	Waste collection	Cropland	• Mass of solid organic waste		Assumption: 5% of P in unauthorised dumping sites
Discharge	P from flooding pit latrines	Pit latrines	Water bodies	• Percentage of P discharge from pit latrines	Kiptum and Ndambuki, 2012, Manda 2009	Assumption: 0.4% of P in pit latrines
Faecal sludge (Septic tank emptying)	P from septic tank emptying	Septic tanks	Water bodies	• Percentage of septic tank emptied	Collet et al., 2018 Water Aid Malawi, 2018	23 % of P in septic tanks (based on Kasungu district data)
Faecal sludge	P from WWTPs that is used for crop production.	WWTPs	Cropland soils	• Mass of P in WWTPs		Assumption: 1 % of P from WWTPs
P in water	P lost from manure dropped during grazing	Natural pasture land	Water bodies	• Mass of P in manure	Nicholson, Rollett, & Chambers, 2011 Tittonell, Rufino, Janssen, & Giller, 2010	Assumption: 50% of the P in manure dropped
Cadavers	P in dead human bodies	Peoples	Unauthorised dumpsites	• Number of dead people	U.N. 2016	Percentage of dead people x total P absorbed by people.
Export flows (P leaving the country)						
Crop/animal products (exports)	P in exported crop/ animal products	Crop/animal and fish products processing and handling	Outside the country	• Mass of exported crop products • P content in crops	FAO, 2017 USDA, 2019	Mass of crop products exported x P content
Water	P in water leaving the country	Water bodies	Outside the country	• Flowrate in Shire river • P content in Shire river water	Shela 2000	Amount of water leaving flowing in a year multiplied by P content in water

4. Conclusion

This MFA has revealed that there is P mining in Malawian soils caused by low input of P and high output of P through crop uptake. The situation is like to be exacerbated by P fertiliser's continued rising prices, limiting smallholder farmers' access to chemical P fertilisers. Furthermore, around 66 per cent of P used in crop production is imported chemical P. The high dependency on imported P is likely to affect Malawi's food security. However, P in solid organic waste, faecal matter, manure, and crop residues can be recycled back to agriculture. The yearly (from 2016) accumulation of P in manure, faecal sludge, and organic solid waste is almost two times annually P imported in chemical fertiliser. If the stocks are ranked based on yearly P accumulation, then the faecal matter would come first followed by manure and organic solid waste materials

Although this study showed that Malawi has organic P stocks, still some issues need to be addressed. Currently, Malawi has no regulations addressing the production or quality of organic fertiliser products. An organic fertiliser policy must be formulated to define criteria for producers to follow to ensure high quality (nutrient-dense, hygienic) recycled P fertilisers if Malawi's soils and food security are to be sustained in the face of increasingly expensive imported P and a growing population. The government should promote the sorting of organic waste materials at source to reduce the cost of compost production from market waste. Furthermore, extension outreach and training should be promoted to encourage farmers to adopt the production and use of organic fertilisers.

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Table A2

Existing stocks, inputs, and outputs of phosphorus in Malawi (as of 2016)

Process name	References	Stock calculations and assumptions	Existing stock (Tg)	Inputs (Tg/ yr.)	Outputs (Tg yr.)	Accumulation (Tg/yr.)
Agricultural land (soils)	Mloza-Banda, Makwiza, & Mloza-Banda, 2016; Njoloma, Sileshi, Geoffrey, Nalivata, & Nyoka, 2016; FAOSTAT, 2016	Soil bulk density x soil depth (20cm) x crop ha x available P (20cm depth)	241±72	21±3	25±3	-4±4
Unauthorised dumping sites	Based on the current P flow analysis	4000 Mg of P accumulating per year.	40±11	5±1	1±3	4±1
Landfills	Based on the current P flow analysis	400 Mg of P accumulating per year.	4±2	.5±0.2	.0100±0.04	0.4±0.2
Pit latrines	Based on the current P flow analysis	9000 Mg of P accumulating per year in latrines.	90±21	9±2	0.05±0.01	9±2.
Septic tanks	Based on the current P flow analysis	9000 Mg of P accumulating per year in latrines.	1.5±0.5	0.200±0.04	0.060±0.02	0.140±0.5
Collected manure	Based on the current P flow analysis	6000 Mg of manure accumulating every year.	60±38	13±4	7±.8	6±4
Water	Based on the current P flow analysis	7000 Mg of P accumulating per year.	70±20	11±1.4	4±.7	7±2
Natural pasture		No data	Unknown	13±3	25±6	-11±6

Key: Tg = Teragram

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

See Table A1.

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