Modelling multi-year phosphorus flow at the regional scale: the case of Gippsland, Australia

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ABSTRACT

Phosphorus (P) is an essential element for global food production, but it is geographically limited, non-substitutable, and non-renewable. In the traditional P management system, there exist a number of challenges to the sustainability of this vital resource, which, if not properly tackled, may lead to global P scarcity and hinder global food security. In order to provide effective policy and management response to overcome these challenges, and to safeguard global P sustainability, there is need for a sound understanding of the nature and magnitude of P flow through different systems at various geographical and temporal scales. An in-depth review of the available P flow analyses at different geographical and temporal scales has revealed that the regional scale which is significant in terms of the magnitude of P flow, has received limited attention in the multi-year analysis of P flow. Thus, there is a knowledge gap regarding the nature and magnitude of P flow over several years at the regional scale, but this understanding is essential for providing long-term and effective P management decisions. Therefore, utilizing the Substance Flow Analysis (SFA) method that relies on the mass balance principle, this study has performed a quantitative modelling of P flow over multiple years at the regional scale. In this regard, this study has developed SFA model of P in MATLAB/Simulink® software platform that can be utilized for analysing the nature and magnitude of multi-year P flow at the regional scale. This model takes into account both structurally and operationally, all the relevant P flows and storage associated with all key systems, subsystems, processes or components, and associated interactions of P flow to represent a typical P flow system at the regional scale. The main advantage of this model over available regional scale SFA models is that it is capable of analysing the trends or dynamic changes in P flow and storage over many years at an annual time step, whereas the available P flow models are static and can analyse P flow only for a particular year at a time. The unique capability of the model to comprehensively analyse various P flows and storage in a system, subsystems, or/and different components within subsystems and sub-subsystems while taking into account all interactions of P flow render it as a robust and powerful tool for the regional scale P flow analysis. This study has utilized this model in the case of Gippsland region in Australia to analyse the nature and magnitude of P flow and storage over a six-year period (2008-2013). This analysis has revealed that approximately 29% (4,445 tonnes) of the

mean annual total inflow (15,349 tonnes) of P in this region eventually exited the system, indicating a substantial amount (10,904 tonnes) of P storage. The inflow of P mainly occurred as commercial fertilizer (10,263 tonnes) and livestock feed (4,443 tonnes), and the outflow mainly occurred as livestock products (4,181 tonnes); whereas the majority (66% or 7,218 tonnes) of P storage occurred in soils of the livestock farming system. The analysis has also revealed that the majority (approximately 90%) of the P flow and storage in this region was associated with the livestock farming subsystem. A significant annual variation in the magnitude of nearly all P flow and storage has been observed in the case of the main system (Gippsland region) and all subsystems. These variations in annual P flow and storage implies that making judgement based on a single year analysis may not represent the true picture of the magnitude of P flow, and therefore, emphasises the significance for multi-year analysis. This analysis also indicates that over the study period, a total of about 3,241 tonnes P were lost as soil erosion and runoff from different subsystems to water bodies in this region, eventually causing a substantial environmental and economic damage. Over the study period, a total of approximately 65,424 tonnes P storage (mainly in soils of the livestock farming subsystem) occurred in this region, which is more than the total quantity of P imported as commercial fertilizer into this region in that period. The accumulation of P in this manner over several years may lead to a massive stock of P in soils, which may ultimately intensify the risk of P loss as soil erosion and runoff. The findings of this analysis could be effectively utilized for making better P management decisions towards achieving P sustainability in this region. However, this study suggests that future research should investigate the reasons for the variations and trends in multi-year P flow as identified in the case of Gippsland region.

DECLARATIONS

This is to certify that:

i. *the thesis comprises only my original work towards the PhD,*

ii. *due acknowledgement has been made in the text to all other material used,*

iii. *the thesis is fewer than 100000 words in length, exclusive of tables, maps, bibliographies and appendices.*

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Chapter-1

INTRODUCTION

This chapter presents an in-depth assessment of the key sustainability challenges for the global phosphorus (P) resource and their consequences for global food security, and based on that assessment, it identifies the needs for research to find appropriate solution towards mitigating these challenges. It consists of four sections viz. *General statement*- which briefly outlines the importance of P for global food production, and addresses the significance for sustainable management of this vital element; *Statement of the problem at the global scale*- which explains the key sustainability challenges for P at the global scale, and outlines how these challenges could lead to global P scarcity and hinder global food security; *Statement of the problem at the country scale*- which briefly describes the key sustainability challenges for P at the country scale, and outlines how these challenges could hamper P security and food security in a country, and *General research needs*- which briefly outlines the type of research required to formulate effective policy and management response towards achieving global P sustainability.

1.1. General statement

Phosphorus is a non-substitutable fundamental chemical element requirement for the cellular processes of all living organisms including plants, animals and microorganisms. It is a vital component of DNA (genetic memory unit of all living organisms) and RNA (which reads the DNA genetic code for building proteins and other compounds necessary for physical structure, reproduction and genetic transfer). It is also an important component of ATP (Adenosine triphosphate), which is the main source of energy for all living organisms. Application of P fertilizers to soil is part and parcel of conventional farming practices that produce food for billions of people (UNEP, 2011). Unfortunately, the global reserves of extractable phosphate rock, a non-renewable but very crucial resource for the manufacture of all forms of commercial P fertilizer is limited. According to the available estimates (Smil, 2000; Fixen, 2009; Vaccari, 2009; Cordell et al., 2009; Van Kauwenbergh, 2010; Cooper et al., 2011), the lifetime of the global phosphate rock reserves (that is extractable with current economic and technological facilities) may range from one to a few hundred years. Moreover, the anthropogenic influences on this limited resource such as excessive mining, increasing demand, increasing price, geopolitical constraints, excessive wastage, and high discharge to water bodies tend to hinder the sustainable management of this finite resource (FAO, 2008; Cordell et al., 2009; Gilbert, 2009; Vaccari, 2009; FAO, 2011; Schröder et al., 2010; Dawson and Hilton, 2011; Childers et al., 2011; UNEP, 2011; Elser, 2012; Neset and Cordell, 2012; Science Communication Unit, 2013; Wyant et al., 2013; Sutton et al., 2013; Scholz et al., 2014). Advances in technology, public health, and food production over the last couple of centuries have fundamentally interrupted the natural global P cycle (Ashley et al., 2011). Phosphate rock reserves have been mined to feed the green revolution, which generated a mostly one-way flow of P from mine to farms to oceans, ultimately impairing freshwater and coastal ecosystem functions (Elser and Bennett, 2011). The unbalancing of the global P cycle is not only causing environmental and economic problems but also leading to the gradual depletion of finite P resource, eventually risking future global food security (Sutton et al., 2013).

1.2. Statement of the problem at the global scale

As presented in **Fig. 1.1**, the key sustainability challenges for the global P resource are dwindling fossil reserves, increasing demand, geopolitical constraints, excessive wastage and loss, and high discharge to water bodies and associated harmful consequences. This section presents an in-depth and systematic assessment of these challenges along with their anticipated impact on global food security.

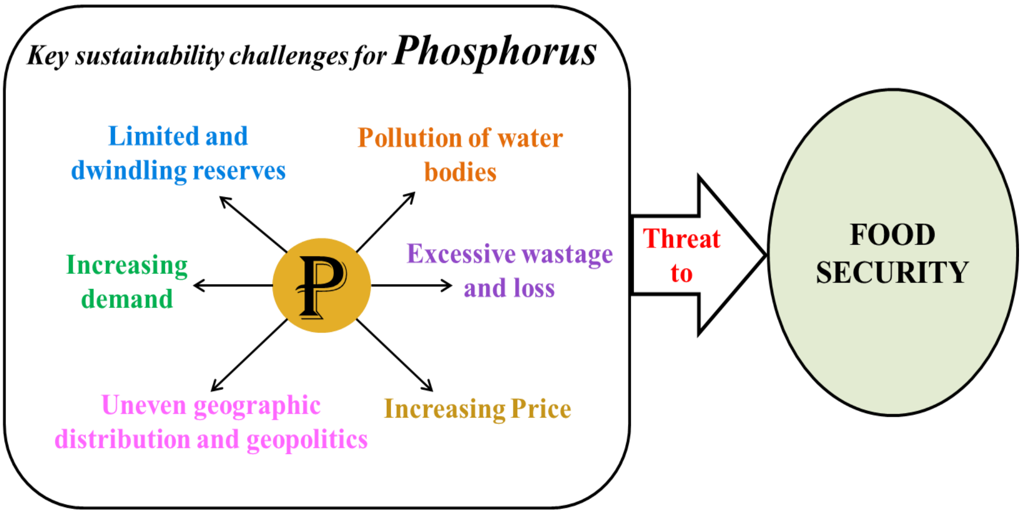


Fig. 1.1 Key sustainability challenges for the global P resource and their anticipated impact on global food security.

1.2.1. Phosphorus and global food security

According to the 1996 World Food Summit, "food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets dietary needs and food preferences for an active and healthy life" (FAO, 1996). This definition is based on five pillars viz. "Availability: sufficient supply of food for all people at all times; Accessibility: physical and economic access to food at all times; Acceptability: access to culturally acceptable food which is produced and obtained in ways that do not compromise people's dignity, self-respect or human rights; Adequacy: access to food that is nutritious, safe and produced in environmentally sustainable ways; and Stability: reliability of food supply" (PMSEIC, 2010, p. 9). In the modern era, the global food crisis has emerged as one of the major concerns for human existence and development (FAO, 1996; FAO, 2008;

Bush, 2010; Sneyd et al., 2013). In response, nations have already attempted a number of collective initiatives towards alleviating the global food crisis. For instance, at the 1996 UN World Food Summit, representatives from 185 countries and the European Community promised to achieve global food security and reaffirmed, "the right of everyone to have access to safe and nutritious food, consistent with the right to adequate food and the fundamental right of everyone to freedom from hunger." This meeting resolved to remove hunger and malnutrition from all countries with a time-bound, measureable goal of decreasing the number of starving people by 50% by 2015 (FAO, 1996). Later, this goal was formally agreed as one of the key commitments of the Millennium Development Goals (MDGs) by 191 nations (UN, 2000).

Although a number of international initiatives have already been taken over the last two decades to tackle the global food crisis, the achievements observed so far in this regard are not satisfactory. A considerable time period has passed after the agreement of the MDGs, but a large proportion of the global population is still undernourished, and eradication of hunger remains a huge global challenge (FAO, 2013). According to the FAO Statistical Yearbook (2014), the total number of undernourished people in the world is estimated to be about 842 million (about 14% of global population) in 2011-2013. A revision of progress in 2010 towards attaining the MDG’s by 2015 revealed that hunger and malnutrition rose globally between 2007 and 2009 partly reversing the initial progress (UN, 2010). This reversal could be attributed to the global food crisis of 2007-2008. According to FAO (2008), the global food price index doubled between 2002 and 2008 with a sharp rise in 2006-2007 and a dramatic increment of 64% above 2002 levels in mid-2008. This global ‘food price shock’ caused severe food crisis in 47 countries (27 in Africa, 10 in Asia and 10 in other continents) ultimately requiring emergency food support (FAO, 2008). In 2008, the global food crisis culminated in violent food riots in several countries, especially Haiti, Egypt, Bangladesh, Mozambique, Ivory Coast, Senegal, Yemen, and Mexico (CNN, 2008; Topping, 2008; Bush, 2010; Sneyd et al., 2013). A number of causes of the global food price shock in 2007-2008 have been identified and these include; poor harvest due to extreme weather events (droughts and floods); decreasing food stocks; high petroleum and energy prices; increased mineral fertilizer prices; lack of investment in the agricultural sector; extensive biofuel production; traders hedging and building up storage; and export restrictions on food grains (FAO, 2008; FAO, 2009; FAO, 2013).

The increased price of phosphorus fertilizer was among the various causes of the global food price shock in 2007-2008 (FAO, 2008; FAO, 2011a). According to Minemakers Limited

(2008), the global phosphate rock price showed a 400 % increase in just one year, from US$ 50 per tonne in January 2007 to US$ 200 per tonne in January 2008. The global Di-ammonium phosphate (DAP) price also increased from US$ 265 per tonne in March 2007 to US$ 1040 in May 2008 (ACCC, 2008). A number of factors viz. increased price of oil and energy necessary for production and transportation of P fertilizers mainly DAP and MAP, significant decline in fertilizer production of US (a major P producing country), imbalances in demand and supply, decline in crop production due to unfavourable weather, excessive demand for fertilizer for biofuel production, and increasing tax on phosphate fertilizer exports were responsible for the rapid increase in the global P price (FAO, 2008; Topping, 2008; FAO, 2011b; Scholz et al., 2014a). The global food crisis observed in the same period also contributed to global P price shock by increasing P fertilizer demand to produce more food (Scholz et al., 2014a). Due to the sudden rise in DAP and other fertilizer prices, in 2008, fertilizer riots were observed in many developing countries (Vidal, 2008). Despite P being a crucial resource for supporting global food production, the potential for P scarcity has been overlooked in many international agreements directed at achieving global food security (Cordell et al., 2009; Elser and Bennett, 2011). This lack of recognition is likely to be one of the limitations preventing progress towards the MDG's. A number of studies (Cordell et al., 2009; Schröder et al., 2010; Childers et al., 2011, UNEP, 2011, Sutton et al., 2013; Scholz et al., 2014a) have also stressed the need for global P sustainability to achieve global food security.

1.2.2. Dwindling global phosphate rock reserves

1.2.2.1. Status of the global phosphate rock reserves

An analysis of recent global phosphate rock reserves (**Fig. 1.2A)** shows an increase from 11,700 MMT (million metric tons) in 2000 to 17,792 MMT in 2002, and later, a decrease to 15,627 MMT in 2009. After 2009, a massive rise in global phosphate rock reserves was observed. The initial rise of global reserves in 2002 occurred after a significant revision of the estimates of Chinese 'reserves' (resources that are extractable and utilizable under current economic conditions and technological facilities) and 'reserves base' (resources that are not extractable and utilizable under current economic conditions and technological facilities, but could be extracted and utilized under favourable economic conditions and technological facilities) according to new information from official country sources (USGS, 2003). This revision resulted in a substantial increase of the Chinese reserves from 500 MMT in 2000 to 6,600 MMT in 2002. China occupied the highest proportion (approx. 37%) of the global phosphate rock reserves between 2002 and 2007. After 2007, the estimated domestic reserves of China dropped markedly, although this coincided with a nine-fold increase in Moroccan reserves (from 5,700 MMT in 2009 to 50,000 MMT in 2010) which was based on information from the Moroccan producer, and a report by the IFDC (USGS, 2011). The global picture thus remained healthy, increasing from 15,627 MMT in 2009 to 65,000 MMT in 2010. Moreover, in 2010 and 2011 as indicated in **Fig. 1.2A**, a significant reserve of phosphate rock was reported for the first time from Algeria (2,200 MMT) and Iraq (5,800 MMT) respectively. The Algerian reserves data was based on individual company information (USGS, 2011), and that of Iraq was according to a report released jointly by the USGS and the Iraqi Ministry of Industry (USGS, 2012). The identification of these new reserves boosted the estimated global phosphate rock reserves to about 71,000 MMT in 2011.

1.2.2.2. Status of the global phosphate rock production

The analysis of past 13 years (2000-2012) global phosphate rock production data of the USGS (**Fig. 1.2B)** reveals that the global mine production increased at a steady rate (approximately 6 MMT per year) from 139.3 MMT in 2000 to 147.2 MMT in 2005 and 207.5 MMT in 2012. It indicates that the global mine production rate is likely to increase in future. Between 2000 and 2005, the US was the top producer in the world, but its production rate decreased from 38.3 MMT (26% of the global production) in 2005 to 29.2 MMT (14% of the global production) in 2012. China became the number one producer after 2006, with the gradual increase in production rate from 32 MMT (22% of the global production) in 2006 to 55 MMT (35% of the global production) in 2009 and finally, 89 MMT (about 43% of the global production) in 2012. However, if focused on the mine production of Morocco, it is observed that its annual production ranged from 21 to 28 MMT between 2000 and 2012 (**Fig. 1.2B**). Morocco is planning to become one of the dominant producers in near future, and intends to increase its production from a current level of about 30 MMT to approximately 55 MMT per annum by 2020. To achieve this milestone, it has planned a number of initiatives that include increased monetary investments to develop mining infrastructure, initiate several trade agreements with different countries to ensure increased trade and investments within P mining sector, and revise and upgrade traditional mining laws to encourage international investments and to ensure transparency (Wellstead, 2012).

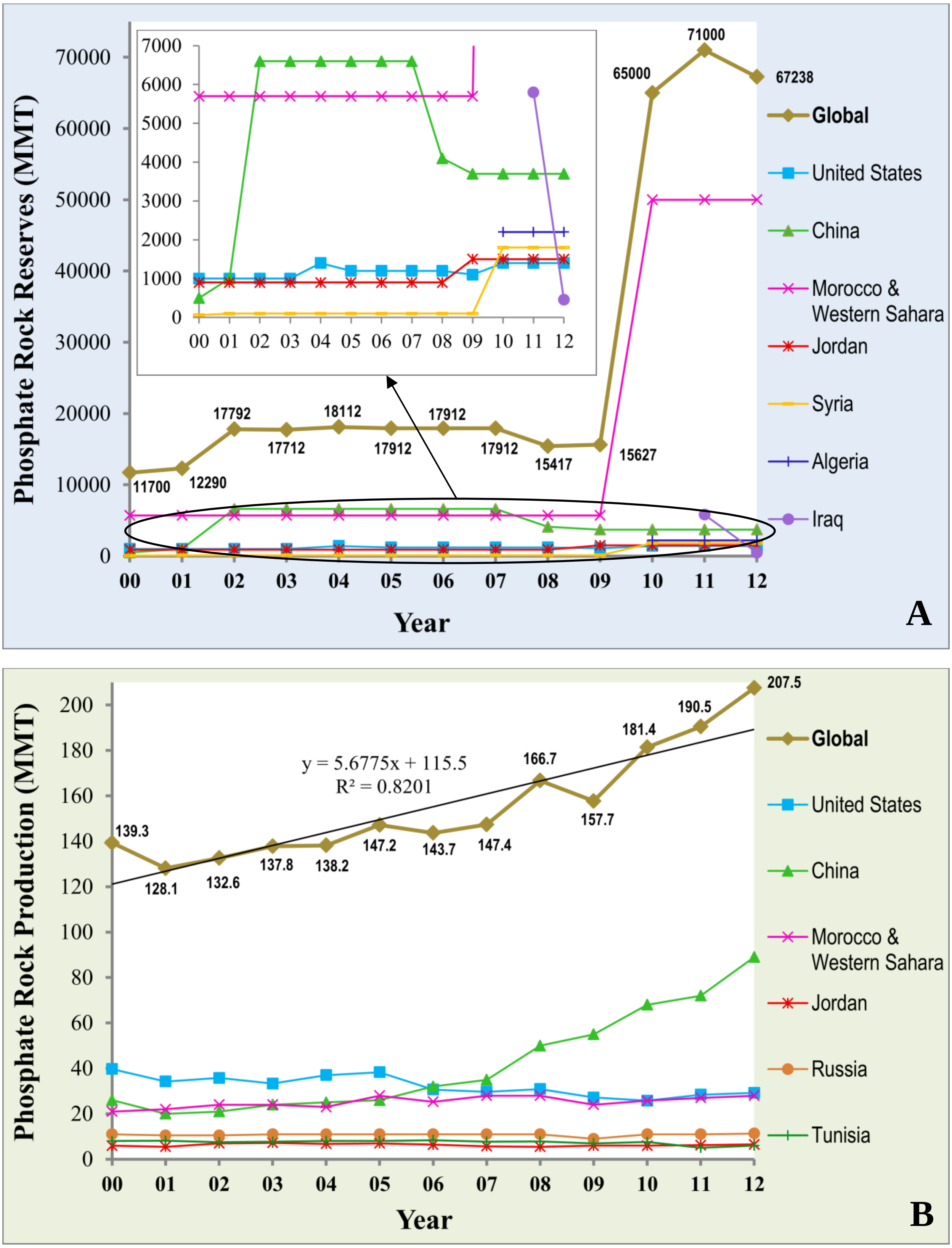


Fig. 1.2 The trends of mine phosphate rock (A) Reserves (in MMT: million metric tons), and (B) Production (in MMT) of the world and the countries with major reserves and production capacity over last thirteen years period (2000-2012). Data Source: USGS (2014).

1.2.2.3. *Phosphate fertilizer production, consumption, export and import by different regions of the world*

Apart from providing an idea about the status of global phosphate rock reserves and production, this study presents a comparative status of the total phosphate fertilizer production, consumption, export and import by different regions of the world between 2002 and 2007 (**Fig. 1.3**). As observed in this figure, East & Southeast Asia (mainly China) occupied the highest proportion (30%) of global phosphate fertilizer production (235 MMT) between 2002 and 2007; while, North America (mainly US) and South Asia (mainly India) accounted respectively 27% and 11% of the global production. Similarly, the majority (35%) of the global phosphate fertilizer consumption (236 MMT) occurred in East & Southeast Asia (mainly in China), and 16% and 15% and 13% occurred in South Asia (mainly in India), North America (mainly in US) and South America (mainly in Brazil) respectively.

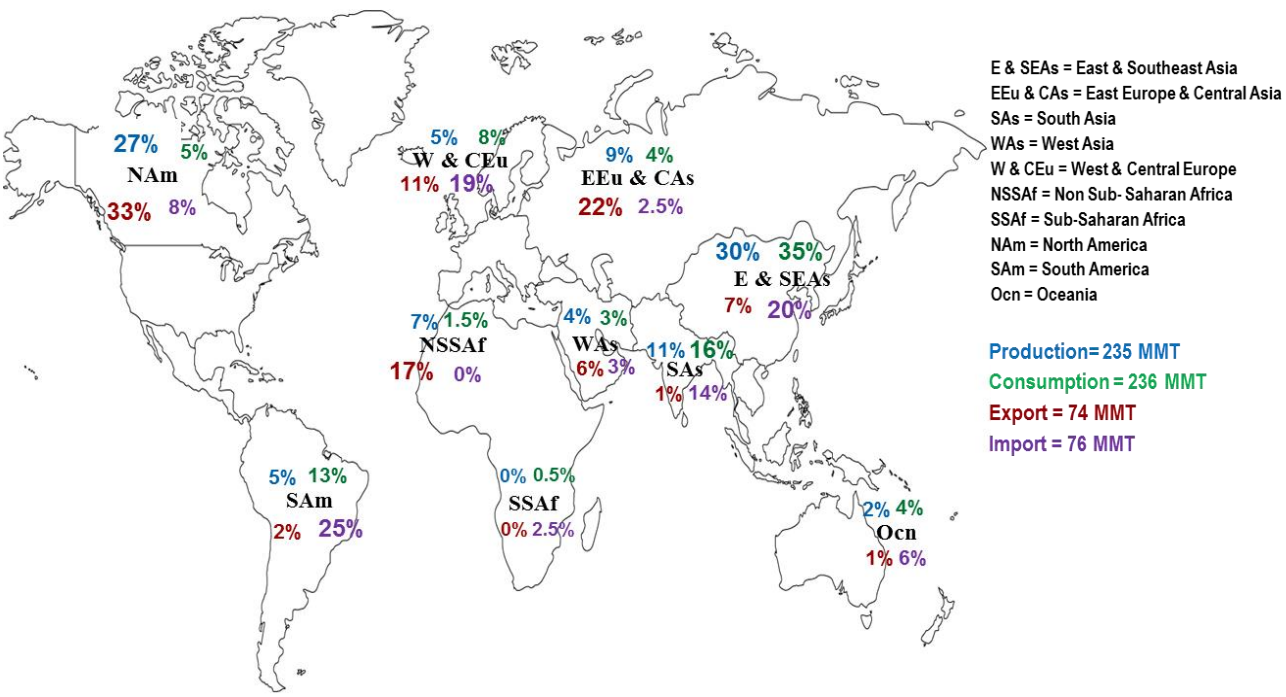


Fig. 1.3 A comparative picture of production, consumption, export and import (in million tonnes) of phosphate fertilizer in different regions of the world between 2002 and 2007. Information placed on map has been systematically adapted from IFPRI (International Food Policy Research Institute) discussion paper by Hernandez and Torero (2011). Map is courtesy of Bruce Jones Design Inc. (2009) and FreeUSandWorldMaps.com (available at; http://www.freeusandworldmaps.com/html/World_Projections/WorldPrint.html).

If focused on the regional export, it is observed that North America (mainly US) accounted the largest proportion (33%) of the total global phosphate fertilizer export (74 MMT); whereas, East Europe & Central Asia (mainly Russia) and Non Sub-Saharan Africa (mainly Morocco and Tunisia) accounted for respectively 22% and 17% of the global export between 2000 and 2007. In contrast, South America was the prime importer of phosphate fertilizer, occupying about 25% of the global import (76 MMT), with East & Southeast Asia, and West & Central Europe accounting respectively 20% and 19% of the global import. Other regions such as Oceania, Sub-Saharan Africa, and West Asia accounted for a small proportion (close to or less than 5%) of global phosphate fertilizer production, consumption, export and import between 2002 and 2007.

1.2.2.4. Global Phosphate rock reserves lifetime and associated uncertainties

According to the global phosphate rock reserves and production ratio of 2011, the lifetime of available global reserves is 370 years (Cooper et al., 2011, Sutton et al., 2013), which is remarkably higher than the 70-100 years as suggested in many earlier studies (Smil, 2000; Fixen, 2009; Smit et al., 2009; Vaccari, 2009). The lifetime of the latest global reserves somewhat matches the IFDC estimate of 300-400 years (Van Kauwenbergh, 2010) that was made prior to the huge rise of estimated global reserves in 2010. The IFDC estimate had been criticized to be too ambitious by some studies. For instance, Vaccari et al., (2011) stated, the IFDC estimate includes inferred reserves that have not been verified by on-site prospecting of the grade or purity, and not yet been independently verified. One point should be noted that if the available global phosphate rock resources (potential future reserves that are recoverable with available technologies and manageable cost) are taken into account, the lifetime of global reserves would be even greater 1000 years or more (Scholz and Wellmer, 2013; Sutton et al., 2013; Van Kauwenbergh, 2013), which would suggest the IFDC estimate of 300-400 years is a conservative one (Van Kauwenbergh, 2010). In this consideration, the world is not going to experience P crisis in the near future. Nevertheless, there could be an emergence of the short or long term global P scarcity in future because the available global phosphate rock reserves are geographically unevenly distributed and many countries lack adequate domestic reserves (USGS, 2013). Owing to this reason, countries those with low reserves and rely on P import from other countries may extensively suffer from any strategic dimension on P export (geopolitical dimension of global P scarcity is discussed in the following section). There are also controversies regarding the available estimates of the global peak production and reserves lifetime of phosphate rocks. For instance, by applying the ‘Hubbert Curve’ principle (Hubbert 1949), Cordell et al. (2009) primarily estimated that global peak in phosphate rock production will be reached by 2033, which was later revised (Cordell et al., 2011) to be 2070. The estimates of peak production of Cordell (2009, 2011) has been criticized with detailed explanations in a number of recent studies (Vaccari and Strigul, 2011; Scholz and Wellmer, 2013; Scholz et al., 2014a; Vaccari et al., 2014). Vaccari and Strigul (2011) showed that Hubbert-type extrapolation is not appropriate for resources without alternatives such as phosphate rock and in a situation where the data are highly incomplete or inconsistent. Scholz and Wellmer (2013) also demonstrated that the prediction of Cordell et al. (2009) lacked adequate incorporation of geological knowledge and other important facts viz. dynamics of exploration, dynamics of technology improvement in P mining and production, changes in demand, or market mechanisms of P pricing.

It has been observed that studies usually estimate phosphate rock reserves lifetime based on the reserves and production ratio of a particular year, which is also known as R/C (resource/ consumption) ratio or static resource lifetime (Vaccari et al., 2014). Although the static lifetime or Hubbert type prediction of peak could act as an ‘early warning indicator’, thus, allowing societies to have adequate time to take mitigating measures; they cannot predict the physical scarcity of resources or actual lifetime, and therefore, may lead to improper reactions by society (Scholz and Wellmer, 2013; Vaccari et al., 2014). In reality, the rate of mine production will not be static every year as it will need to cope with the growing demand of P fertilizer to produce adequate food for increasing global population. Lott et al. (2011) estimated that between 1995 and 2008, the global P fertilizer usage increased 2.4% annually. According to FAO (2011), the global demand of phosphate fertilizer will increase at a growth rate of 1.9% annually from 41.7 MMT in 2011 to 45 MMT in 2015. Therefore, it is anticipated that with the increasing demand and mine extraction rate at every year, the available global phosphate rock reserves will be depleted earlier than expected.

1.2.3. Increasing global P demand

If new sources of good quality, accessible and economically feasible phosphate rock deposits are not discovered, the available global phosphate rock reserves will dwindle with time. Another problem is that with time the global population will increase, which will surely result in growing demand for food. According to the medium variant of the 2010 Revision of World

Population projection, global population will reach to about 9.3 billion in 2050 with a 33% increment (approx.) of the 2011 level (close to 7 billion), which may reach 10.1 billion in 2100 (UN, 2011). To feed 9.3 billion people in 2050, the global food production will need to be increased by 70% of the 2005/2007 level including an additional production of about one billion tonnes of cereals and 200 million tonnes of meats (FAO, 2009a). Tilman et al. (2011) also forecasted, by 2050, global crop demand will increase by 100-110% compared to the level of 2005. Given the crucial role of P in the global production of cereal grains and legume seeds (FAO, 2004; Lott et al., 2011) as well as dairy and meats (Satter et al., 2005; Gourley et al., 2010), in future, there will be an increased demand of phosphate fertilizers to produce enough food for growing global population. Tilman et al. (2001) projected, the global P fertilizer use could be 2.4 times more in 2050 (83.7 MMT) than in 2000 (34.3 MMT); whereas, Bouwman et al. (2011) projected that total P fertilizer consumption in the global agricultural system will increase from a level of 14 MMT yr^{-1} in 2000 to 23 MMT yr^{-1} in 2050. However, an exception from above is the projection (a change in global P fertilizer use from the current amount of about 17.8 MMT yr-1 to about 16.8-20.8 MMT yr-1 in 2050) of Sattari et al. (2012) that considers the influence of residual soil P, and therefore, this is around 50% less than other estimates. Moreover, in future, factors like decreasing inherent soil productivity, increasing energy and water crisis, climate change and increased frequency of natural disasters, increased urbanization and shortage of cultivable lands, and increased biofuel production could render sustainable food production more challenging, which in turn may necessitate increased input of P and other fertilizers to produce more food. An increase in P demand may increase the depletion rate of available reserves, which in turn may increase the P price and reduce the P availability for food production, and may eventually hinder global P security.

1.2.4. Geopolitics regarding P

1.2.4.1. Causes and possible impacts of P geopolitics

The global disparity in phosphate rock reserves has been shown in **Fig 1.4**. More than 90% of the global reserves are geographically restricted to a few countries, with Morocco alone possessing nearly 75% of the global reserves. This non-uniform geographic distribution of the limited global phosphate rock reserves, in a situation of global P scarcity, could lead to restricted access of many countries to P fertilizer. Cooper et al. (2011) estimated that with the current domestic reserve and production ratio, the available domestic reserves of almost all countries other than Morocco will deplete within 100 years, where the reserves of the US and China, the two main producers of phosphate rocks, will deplete within 60 years. This may eventually drive the countries with major reserves and production capacity to initiate strategic decisions regarding their available domestic reserves. A number of studies (Rosemarin, 2004; Gilbert, 2009; Cordell et al., 2009; Schröder et al., 2010; Cordell and White, 2011; Childers et al., 2011; Vaccari, 2011; Elser and Bennett, 2011; Neset and Cordell, 2012; Obersteiner et al., 2013, Scholz and Wellmer, 2013) have addressed the fact of geopolitical challenge of global P management and its probable impact on future P accessibility. Schröder et al. (2010) stated that geopolitical constraints can limit the availability of phosphate fertilizer for food production in many countries in the short or long term. For example China imposed a 135% export tariff during 2008, which sparked the increase in global P fertilizer price and restricted its availability to P importers. Childers et al. (2011) mentioned, financial challenges of high-priced P may unevenly affect food production in countries with no phosphate rock reserves, countries that have political problems with the P exporters, and countries with poor economic and technological capabilities.

1.2.4.2. Signs of P geopolitics

As indicated in **Fig. 1.2A,** the phosphate rock reserves of China which were constant at 6600 MMT between 2002 and 2007, dropped dramatically to 4100 MMT in 2008. Given the annual mine production rate of China of about 50 MMT in 2008 (USGS, 2009), the reduction of 2500 MMT in Chinese reserves within a single year period is questionable. If focused on **Fig. 1.2B**, an increasing trend has been observed in the mine phosphate rock production of China after 2007, where its production increased from 35 MMT in 2007 to 50 MMT in 2008 and finally, 89 MMT in 2012. These types of trends in phosphate rock reserves and production of China appear contradictory and an indication of strategic dimension because generally, if domestic reserves decrease, countries tend to reduce their mine production and export to secure adequate domestic reserves for future availability. **Fig. 1.2B** also indicates that compared to the period from 2000 to 2005, the annual mine production rates of the US were lower between 2005 and 2012, where its production decreased from 38.3 MMT in 2005 to 29.2 MMT in 2012. Probably, anticipating the future global P crisis, the US has decided to decrease P extraction from domestic mines. Elser and Bennett (2011) mentioned earlier that to ensure future access to the sources of vital minerals, P could be considered as a strategic material in the pending US legislation.

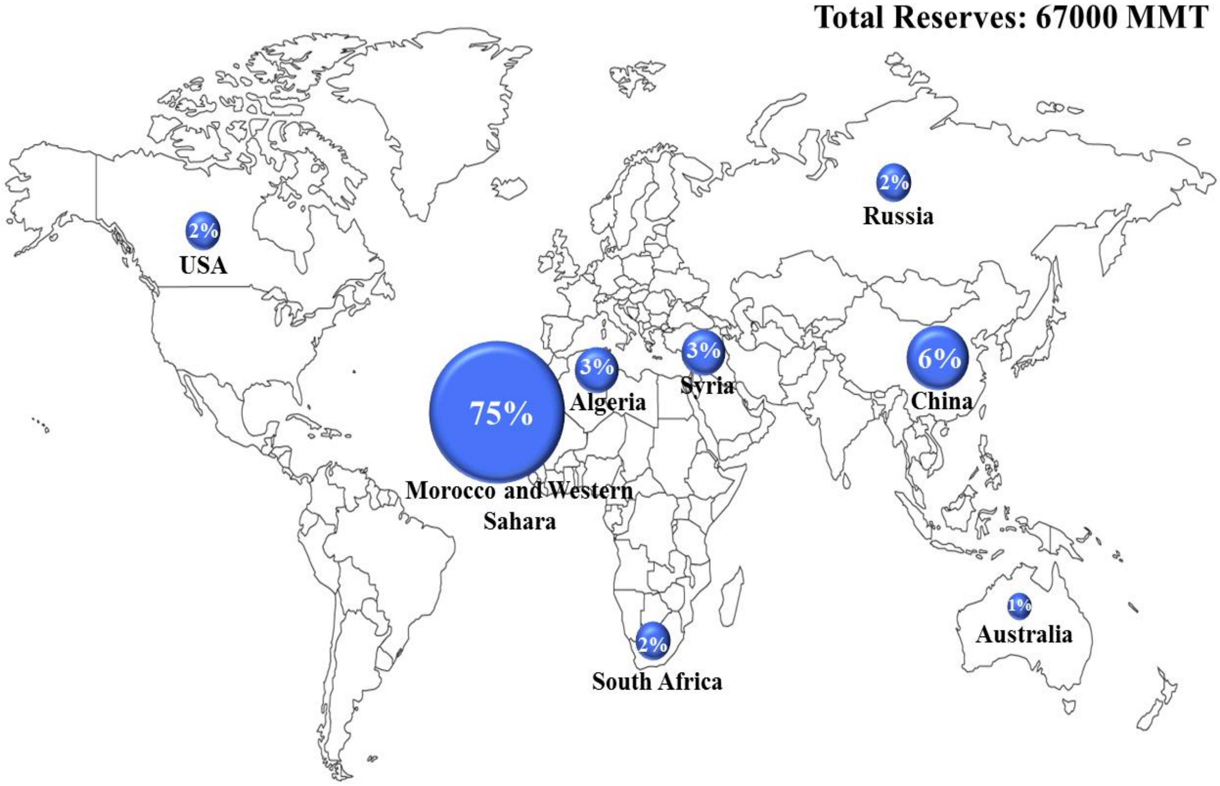


Fig. 1.4 Global phosphate rock reserves by countries as percentage of total global reserves (in million tonnes) in 2013 (USGS, 2014). Map is courtesy of Bruce Jones Design Inc. (2009) and FreeUSandWorldMaps.com.

Moreover, the US has already established a sound strategic partnership (through the provision of Free Trade Agreement, designation as a major non-NATO ally, Millennium Challenge Corporation, and military aid and development assistance) with Morocco, and the issue of global food security and role of P received a significant importance in this strategic relationship (MACP, 2013). All these strategic initiatives could allow the US to have sufficient access to P resource even in a situation of serious global P scarcity. According to a prediction by Cooper et al. (2011), Morocco alone will occupy 40% of the global phosphate rock production by 2050, which may reach up to 80% by 2100. This indicates that after 2100, almost all other countries may need to depend on Morocco for the P import for food production. In such situations, countries that do not maintain a good strategic relationship with Morocco or have not yet planned adequate strategic measures to secure sustainable supply of P resources for future use may suffer severely from any geopolitical constraint set by Morocco.

The present study has utilized the USGS phosphate rock reserves and production data which are widely accepted and used. However, a number of studies (Fixen, 2009; Gilbert, 2009; Schröder et al., 2010; Van Vuuren et al., 2010; Elser and Bennett, 2011; Edixhoven et al., 2013) have questioned the consistency and reliability of these data. The USGS data are usually prepared based on the reports issued from either individual company or official government sources of a particular country (USGS, 2010). With more than 1600 deposits of phosphate rock in the world (Orris and Chernoff, 2002), there is a high likelihood that the assumptions and estimations used for calculating reserves will vary from one country to another and even from one company to another within a country.. Therefore, it is quite apparent that the USGS have almost no control over the quality and reliability of the reported reserves data from different countries. For instance, in the case of Iraq, it is observed that the phosphate rock reserves of this country decreased from 5800 MMT in 2011 (which was reported for the first time) to 460 MMT in 2012, a 92% reduction in just one year (**Fig. 1.2A)**. Scholz et al. (2014a) reported that this high difference was due to the use of two different methods of estimation that is the Russian categorization, and the common US classification in two different years. So, the concern is the absence of an internationally accepted standard for classification, or lacking of a mechanism to address the uncertainty associated with estimates from different methods. These shortcomings could allow countries to mislead the international community by using non-standard methods to estimate reserves data. Edixhoven et al. (2013) emphasized the need for developing appropriate methodologies for estimating extractable phosphate rock deposits and concluded that there is requirement for further research to the quantity of global phosphate rock deposits and their viability for future extraction. Another interesting fact must be noted that up until 2009, the USGS published the phosphate rock 'reserves base' data of different countries along with the reserves data, but after 2009, they stopped reporting the 'reserve base' data. Probably, observing the global P price shock and food crisis in 2007-2008, countries became concerned about the risk of a future global P crisis, and therefore, to secure adequate domestic reserves for future access, countries became reluctant to provide updates on non-reserves component of the information upon which the reserve base data were estimated, which is another notable sign of geopolitical dimension.

1.2.5. Excessive wastage and losses of P

In the traditional P management system, a substantial amount of P wastage and loss occurs from the anthropogenic P cycle. As indicated in **Fig. 1.5**, only 17% (according to Cordell et al. (2009), this is equivalent to 3 million tonnes per annum) of the total amount of elemental P that is mined globally in a year is ultimately consumed as food by humans. Nearly all of the P consumed in human food is excreted as human waste. On the other hand, only half of the 80% of the mined P that is coming in the livestock and crop production systems ends up in crop and livestock products, and the remainder is either stored in soils or lost to downstream. Increased soil P pool may ultimately lead to the increased risk of P loss to water bodies which mainly occurs in four ways viz. erosion of soil attached P, soluble P in runoff water, soluble P leaching, and washed away fertilizer or manure (Osmond, 2005). P lost in these ways may remain in stream or drainage systems as bottom sediments, or could eventually be transported to coastal waters and ocean.

To demonstrate the fact of excessive P wastage and loss, a collation of the information relating to the nature and magnitude of P wastage and loss at different geographical scales as reported in available studies has been presented in **Table 1.1**. If focused on country scale studies, it is observed that in China between 1984 and 2008, a total of about 124,300 kilotonnes (kt) P (which is about 74% of the total P inflow in China in the same period) related to anthropogenic use were wasted to natural water bodies and soils (Ma et al., 2012), which is about three times the global P fertilizer demand in 2008 as reported to be approximately 41,000 kt by FAO (2008a). Suh and Yee (2011) assessed that about 1,671 kt of P were wasted from the US food system in 2007. The analysis of domestic P flow of Japan for 2002 by Matsubae-Yokoyama et al. (2009) revealed that about 93.1 and 91.7 kt P were wasted in steel making slag and landfills respectively. This analysis also identified that about 375.71 kt P were stored in agricultural soils. Lederer et al. (2014) assessed that 70% (that associated with soil, household and infrastructure) of the total anthropogenic P stocks in Austria are not technically extractable, 20% (municipal solid waste landfill) with very low grade P is not practically feasible to recover, and only 10% (sewage sludge incineration ash and incineration bottom ash landfill) is recoverable with a production cost nearly 5-10 times higher than the unit price of commercial P fertilizer. Therefore, these types of unwanted P stock under current cost structures could be regarded as P wastage.

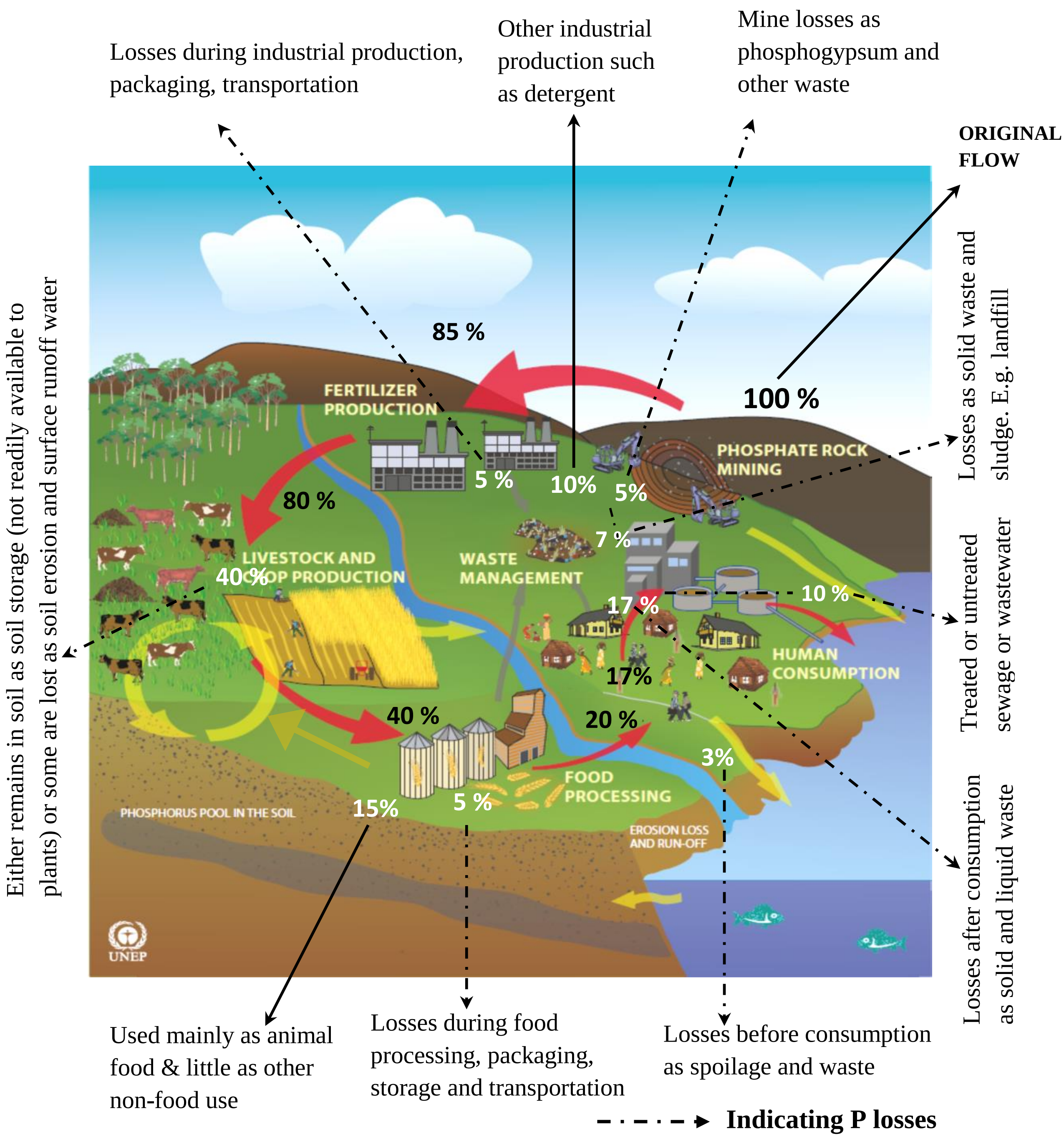


Fig. 1.5 A schematic view of P wastage and loss (as % of total mining of P in a year) at different stages of its journey from mine to human consumption in the traditional global P management system. The image source is UNEP (2011) and the percentages placed on the image are systematically adapted from Cordell et al. (2009).

Table 1.1 Types and quantity of P wastage and loss of at different geographical scales.

Geographic scale	Location	Type of system considered for P flow analysis	Year of flow	[1]Measuring unit	Total inflow of P to the system	[2]Nature and quantity of P wastage and loss	[3]% of total inflow	Reference
Country	USA	Food	2007	kt/a	5616	Waste: 1671 *Soil of CrP: 672*	30 *12*	*Suh and Yee, 2011*
	Netherlands	Agriculture, industrial production and households	2005	kt/a	108	Waste: 27.6 *Soil of AgP: 31.3*	23 *29*	*Smit et al., 2010*
	Finland	Agricultural and food system	1995-1999	kt/a	33.3	ERL: 2.4 Wastewater: 0.7 *Soil of AgP: 23.7*	7 2 *71*	*Antikainen et al., 2005*
	Turkey	Anthropogenic flow	2001	kg/cap/a	4.33	Waste: 2.61 ERL: 1.00	60 23	*Seyhan, 2009*
	UK	Food production and consumption	2009	kt/a	138	Wastewater:41.5 *Soil of AgP:37.5*	30 27	*Cooper and Carliell-Marquet, 2013*
	France	Waste management	2006	kt/a	286	Solid waste:69 Wastewater:19	24 7	*Senthilkumar et al., 2014*
	Australia	Food system	2007	kt/a	214	Soil Erosion: 84 Waste: 79	39 37	*Cordell et al., 2013*
	China	Anthropogenic flow	1984-2008	kt/25y	167300	Waste: 124300 *Soil of AgP: 38300*	74 *23*	*Ma et al., 2012*
	Japan	Domestic flow	2002	kt/a	747	Slag: 93.1 Solid waste: 91.7 ERL: 32.93 *Soil of AgP: 376*	13 12 4 *50*	*Matsubae-Yokoyama et al., 2009*
	South Korea	Domestic flow	2005	kt/a	380	Solid waste: 52 Slag: 35.7 *Soil of AgP: 125*	14 10 33	*Jeong et al., 2009*
Regional	Linkoping, Sweden	Food production and consumption	2000	kg/cap/a	2.09	Waste: 0.43 *Soil of CrP: 0.72*	21 *34*	*Neset et al., 2008*
	Hefei, China	Anthropogenic flow	2008	kt/a	7.81	ERL: 1.00 Solid waste : 0.76 *Soil of CrP: 2*	13 9 *28*	*Li et al., 2010*
	Feixi, China	Socio-economic system	2008	kt/a	19.1	ERL: 5.33 Wastewater: 4.93 *Soil of CrP: 3.66*	28 26 *19*	*Wu et al., 2012*
	Hanam, Vietnam	Rural areas	2008	kt/a	0.12	Waste: 0.048 ERL: 0.014 *Soil of CrP: 0.018*	40 12 *15*	*Do-Thu et al., 2011*
City	Twin cities, US	Urban ecosystem	2000	kt/a	4.07	Solid waste : 1.76 Wastewater: 1.14	43 28	*Baker, 2011*
	Linkoping, Sweden	Food consumption and sanitation	2000	kg/cap/a	0.57	Solid waste: 0.51	89	*Neset et al., 2010*
	Sydney, Australia	Urban ecosystem	2000	kt/a	5.99	Wastewater: 2.66 Solid waste : 0.81 *Soil of AgP: 1.88*	44 14 *31*	*Tangsubkul et al., 2005*
	Beijing, China	Food consumption system	2008	kt/a	6.22	Solid waste: 2.94 Wastewater: 1.72 *Soil of AgP: 1.01*	47 28 *18*	*Qiao et al., 2011*

[1]kt/a: kilotonne (1000 metric tons) per annum; kt/ 25y: kilotonne per 25 years; kg/cap/a: kilogram per capita per annum.

[2]**Waste**: Any type of solid and/or liquid waste originated from any subsystem or process within the system and eventually disposed without P recovery; **Wastewater**: treated or untreated wastewater that is eventually discharged to water bodies or environment; **Solid waste**: solid fraction of waste including sludge from wastewater treatment plant that is eventually landfilled. **CrP**: crop production; **AgP**: agricultural (crop and livestock) production; **ERL**: soil erosion, runoff water, and/or soil leaching

[2, 3]Italic marked text and number represents unwanted P stocks that is not technically extractable and eventually could increase the intensity of P loss as soil erosion, surface runoff of water, and/or leaching. So, this type of P storage could be regarded as P wastage.

A number of other studies also quantified P wastage from different systems in various parts of the world. For instance, Wu et al. (2014) in a regional scale study assessed that the total P loss relevant to the farming system in Anhui Province of China was about 398 kt in 2011, which was more than the amount (329 kt P) applied as chemical fertilizer in the same year. The assessment of the Austrian annual P budget also revealed that the amount of P that belongs to municipal sewage sludge, and meat and bone meal could substitute up to 70% of the total P applied as mineral fertilizer (2 kg per capita per annum) in that country (Egle et al., 2014). Ott and Rechberger (2012) in an analysis of European P flow identified that in the Europe P wastage mainly occurs as net accumulation in agricultural soils (2.9 kg per capita per annum) and disposal of wastes to landfills (1.4 kg per capita per annum). In a global scale study, Liu et al. (2008) estimated that in 2003 approximately 19,300 and 17,200 kt P were lost globally as soil erosion from the cropland and pastureland respectively. Bouwman et al. (2009) also calculated that between 1970 and 2000, annually about 2,000-3,000 kt P were lost as leaching and runoff from the soil of the global agricultural production sector, and about 9,000-13,000 kt P were accumulated in the soil of this sector. According to Villalba et al. (2008), about 98% (18500 kt) of the global mine P production (18,900 kt) in 2004 eventually ended up in the soil. Moreover, Mihelcic et al. (2011) calculated, about 3,400 kt of P were excreted in urine and faeces by the global population in 2009, most of which were eventually wasted.

1.2.6. Excessive P discharge to water bodies and associated harmful consequences to aquatic ecosystems

1.2.6.1. Evidence of high P discharge to water bodies around the world

The majority of the P lost from different systems is eventually discharged to water bodies. For instance, between 2001 and 2006, the estimated annual average waterborne loadings of P in the Baltic Sea were 30.2 kt (HELCOM, 2009). Bi et al. (2013) estimated, in 2008 about 3.55 kt P were discharged to the local water bodies from the socioeconomic system of Wuwei County in China. In another study for Shucheng County in China, Yuan et al. (2011) identified that about 3.88 kt P in wastewater entered into the water bodies in 2008. Ma et al. (2013) also calculated, in China between 2003 and 2008, annually about 900 kt of P related to anthropogenic P use were released to surface water bodies. In France, about 12.2 kt P were discharged to water bodies as treated wastewater from treatment plants in 2006 (Senthilkumar et al., 2014). Estimates also suggest that about 21.68 kt of P was loaded to Chesapeake Bay (USA) in 2011 water year, which is about 12.7 kt more than the estimated average annual loads between 1990 and 2011 (Chesapeake Bay Program, 2012). Between 2006 and 2010, approximately 1.58 kt P were discharged from major wastewater treatment systems in the Upper Pontchartrain Basin in Louisiana to Mississippi River in USA (Roy et al., 2014). According to US EPA (2011), close to 200 kt of total P were loaded to the northern Gulf of Mexico in 2010. Apart from the P loadings to surface water bodies, P leaching to groundwater, and its associated P discharge to streams was also reported (Domagalski and Johnson, 2012).

1.2.6.2. Evidence of the P led eutrophication and other harmful consequences on water bodies

The critical role of P in accelerating algal bloom, hypoxia, and eutrophication (**Fig. 1.6**) in both freshwater and marine ecosystems worldwide is well documented. For instance, excessive discharge of P contributed to the eutrophication in the West Point Lake (USGS, 2013a), and hypoxia and eutrophication in the Chesapeake Bay (Boesch et al., 2001; Kemp et al., 2005; Murphy et al., 2011) in the US; hypoxia and dead zones in the Gulf of Mexico (Rabalais et al., 2007; Scavia and Donnelly, 2007; Boesch et al., 2009); cyanobacterial bloom in Gippsland Lakes (Holland et al., 2010; Holland et al., 2011) and eutrophication in the Great Barrier Reef Lagoon (Brodie et al., 2011) in Australia; cyanobacterial bloom and eutrophication in the Lake Taihu in China (Guo, 2007; Qin et al., 2007; Xu et al., 2010); hypoxia, eutrophication and dead zones in the Baltic sea in Europe (Conley et al., 2009; HELCOM, 2009; Saikku and Asmala, 2010; Conley, 2012; Gustafsson et al., 2012). A 37 year field investigation in Lake-227 at the Experimental Lakes Area of northwestern Ontario, Canada also confirmed that P is a major contributor in the freshwater eutrophication (Schindler et al., 2008). According to Tilman et al. (2001), by 2050, extensive agricultural production could result in a 2.7 fold increment (compared to the level of 2000) in P-driven eutrophication of global freshwater and costal ecosystems. In the last decade, an average of about 60,000 km^2 of the Baltic Sea has been hypoxic in each year (Conley, 2012), where both P and nitrogen (N) contributed significantly in causing the hypoxia (Conley et al., 2009a; Conley, 2012).

Fig. 1.6 Algal bloom and eutrophication of a water body in France caused by excessive nutrients such as phosphorus and nitrogen. (Image source: F. lamiot (own work), available at; http://commons.wikimedia.org/wiki/File:EutrophicationEutrophisationEutrophierung.jpg)

1.2.6.3. Evidence of the adverse consequences of eutrophication, hypoxia, and algal bloom on the aquatic ecosystems and fish production

Smith and Schindler (2009) outlined, eutrophication of freshwater and marine ecosystems can increase fish death, reduce species diversity, diminish biomass of harvestable fish and shellfish, change composition of macrophyte vegetation, hamper coral reef health, and cause depletion of coral reef communities. Eutrophication may also increase parasitic infection of birds, snails, and amphibian larvae eventually causing frequent limb deformities and mortality (Johnson et al., 2007). Extinction of different species of Whitefish in some pre-alpine European lakes has been identified to occur through eutrophication driven speciation reversal and demographic decline (Vonlanthen et al., 2012). Dodds et al., (2009) estimated that in order to prevent eutrophication induced losses of freshwater biodiversity in the US, annually about US$ 44 million is required. In England and Wales, the total damage cost of freshwater eutrophication is estimated to be US$ 105 to 160 million per annum (Pretty et al. 2003).

Hypoxia in water bodies can cause the habitat compression and loss of aquatic fauna ultimately affecting ecosystem energetics and functions because of the death and decomposition of organisms (Diaz and Rosenberg, 2008). Due to hypoxia, benthic eggs of some oyster reef fishes such as blennies, gobies and clingfish in some areas of the Chesapeake Bay experience significant mortality in shallow water (Breitburg, 2002). Similarly, essential ecosystem functions of benthic fauna, biogeochemical processes and biomass production in the Baltic Sea are damaged by hypoxia (Carstensen et al., 2014). The aerial measurements of lost biomass for about 33% of the global dead zones has revealed that hypoxia caused the displacement of approximately 343 to 734 kt of carbon over an area of 245,000 km^2 (Diaz and Rosenberg, 2008). Vaquer-Sunyer and Duarte (2008) stated that fish and crustaceans are the most vulnerable to hypoxia in the costal ecosystem. Because of the hypoxic condition induced by cyanobacterial bloom in summer in the Baltic Sea, the suitable habitat for cod fish in the bottom water is significantly decreased (Conley, 2012). Mackenzie et al. (2011) reported, due to algal bloom, about 200 tonnes of Chinook salmon in a sea-cage farm at Ruakaka Bay, New Zeland died over a six day period in 2010 mid-winter. Carpenter (2008) mentioned that the formation of dead zones in the Gulf of Mexico caused a reduction in the animal production, with acute impacts on finfish and shrimp fisheries. Moreover; algal bloom, hypoxia, and eutrophication have been identified amongst the major causes of the death of more than 383 million fishes in the coastal waters of Texas (US) between 1951 and 2006 (Thronson and Quigg, 2008).

From the above discussions, it is evident that P induced water pollution leads to the reduced production of fishes and other aquatic foods, which may eventually cause the increased market price of these products. Owing to the rise in price, many people around the world particularly the poor people those rely on fishes and seafood as the main source of protein in their diet, may not be able to purchase the required amount of food to satisfy their dietary needs. As a result, people may suffer from hunger and malnutrition which eventually hinder global food security.

1.3. Statement of the problem at the country scale

The sustainability challenges for P at the country scale are linked to the challenges at the global scale. Any form of P scarcity at the global scale is likely to have impact on P management at the country scale because many countries rely on P import from countries with major phosphate rock reserves. Although the status of P management may vary from one country to another, there are some basic sustainability challenges that are relatively common in all countries. In this study, a new approach of viewing the sustainability challenges at the country scale has been presented (**Fig. 1.7**). In this approach, the challenges have been grouped into three categories that include 'the burdens of the past and present' which indicates the inherent or traditional problems related to P management; 'the challenges of the future' which indicates the anticipated future problems related to P management'; and 'questions that must be answered to achieve P sustainability' which means finding appropriate solutions for the burdens of the past and present, and for the challenges of the future to achieve P sustainability .

To briefly explain the sustainability challenges for P at the country scale as indicated in **Fig. 1.7**, the example of Australia has been utilized here;

1.3.1. Burdens of the past and present

- Australia produces approximately 93% of the domestic food supply, and exports nearly 60% of its total agricultural products (PMSEIC, 2010), where it had a $14.2 billion food export surplus over food imports in 2009-10 (DAFF, 2011);
- Approximately 36% (865 kt) of the total phosphate fertilizers (2,403 kt) consumed in this country in 2007 were imported (ACCC, 2008);
- According to USGS (2014), its total domestic phosphate rock reserves is approximately 870,000 kt which accounts for only about 1.30% of the total global phosphate rock reserves;
- Excessive wastage and loss of P from different systems is a key burden for sustainable P management in this country. Cordell et al. (2013) estimated that in 2007, about 87 kt P were lost mainly as soil erosion from its agricultural sector, whereas about 11 kt and 12 kt P were wasted as domestic wastewater and organic waste (mainly food waste) respectively. Test of soil samples from 40 conventional dairy farms in different regions of Australia indicated that 50% of the total 1,768 paddocks sampled had P level 1.5 times the recommended agronomic requirements (20 mg Olsen P/kg soil), whereas 20% had 3 times the required level (Gourley et al., 2010). Application of P fertilizer in such soil may result in P wastage;

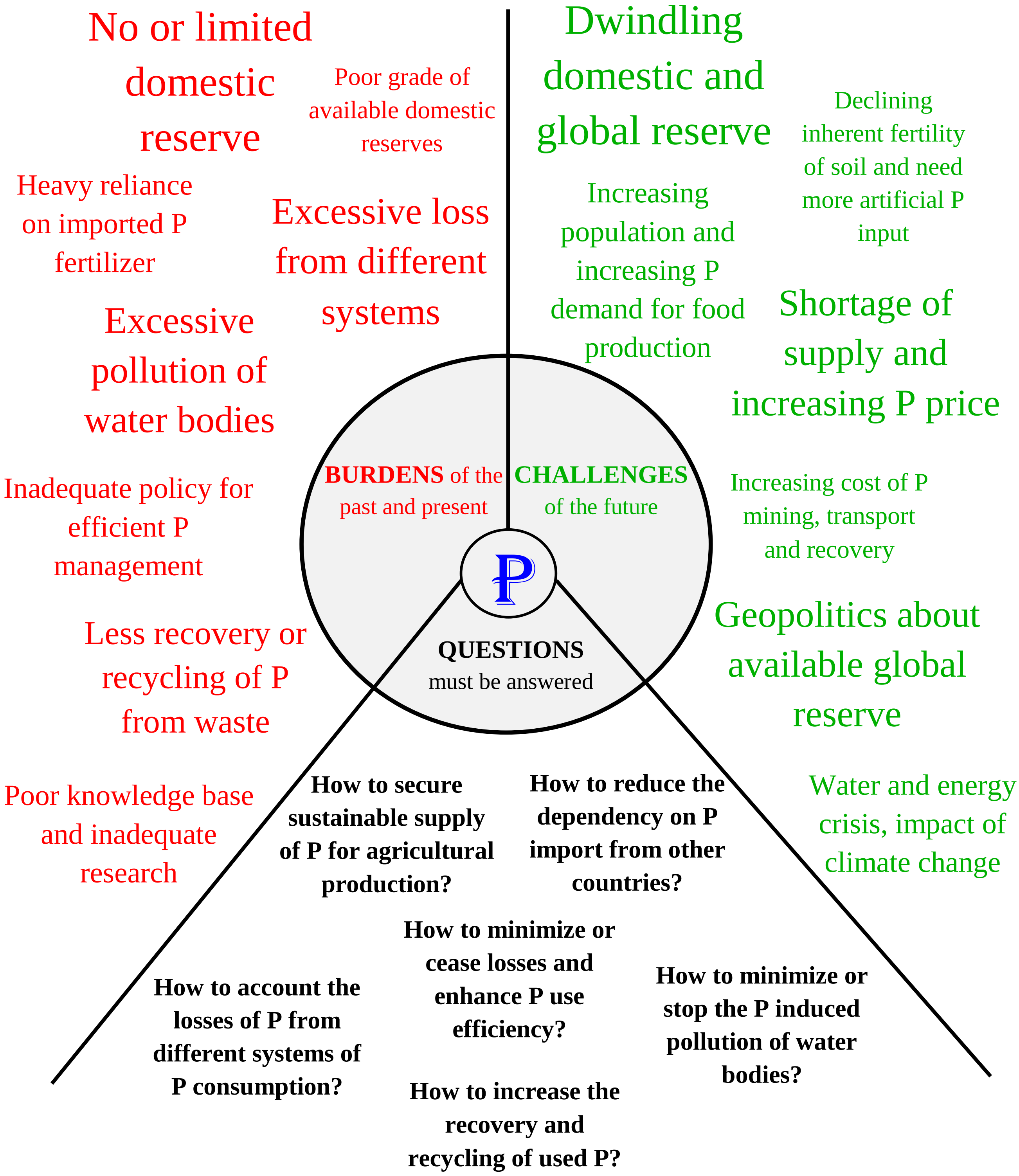


Fig. 1.7 A new approach of viewing the sustainability challenges for P at the country scale.

- Low or no recovery from waste is the main reason for significant P loss as described above. For instance, in 2006-07, approximately 13.6 million tonnes of solid wastes containing about 11 kt P were disposed to landfills without any P recovery (EPHC, 2010); whereas Cordell et al. (2013) estimated that approximately 11 kt P in domestic wastewater were eventually disposed to water bodies or landfills (as sludge) in 2007;

- High P discharge to water bodies and associated pollution and damage cost is also a major concern. For instance, the mean annual river loads of total P to the Great Barrier Lagoon in Queensland increased by 8.9 times to about 16 kt per annum since the European settlement (Kroon et al., 2012). Annually about 0.19 kt P (on an average) were discharged from the surrounding catchment to the Gippsland lakes in Victoria over the 30 years period from 1978 to 2008 (Holland and Cook, 2009). The overall damage cost of freshwater algal bloom in Australia is about AUD 180 to AUD 240 million per year (Atech Group, 2000). The direct economic impact of the 2008 blue green algal bloom of the Gippsland lakes on the Gippsland tourism industry was estimated to be a loss of AUD 18.2 million and the net impact of it on Victorian economy was a loss of AUD 6.7 million (Connolly and Hylands, 2009);
- There are also burdens such as poor knowledge base of P among managers of different systems, lack of research and lack of adequate policy for sustainable P management in Australia.

1.3.2. Challenges of the future

- With the continuous mining of phosphate rocks from domestic mines, the available domestic reserves of Australia will gradually deplete. Given the annual mine production rate of 2,600 kt against a total domestic reserves of 870,000 kt (USGS, 2014), the lifetime of the domestic reserves can be calculated as about 335 years;
- The average grade of domestic phosphate rock reserves of Australia is comparatively poorer than that of the world. The grade of Economic Demonstrated Resources (EDR) of phosphate rocks occurring at different mines in Australia ranges from 8.7% P_2O_5 to 28.4% P_2O_5 with a mean value of 16.8% P_2O_5, but globally the average grade for direct shipping needs to be approximately 30% P_2O_5 (Geoscience Australia, 2013). Moreover, the high-grade phosphate rock resources are declining but the demand is increasing, and companies are increasingly finding ways of mining lower grade phosphate resources and improving grade through beneficiation (Geoscience Australia, 2013);

- Australia imports P fertilizers mainly from Morocco, USA, China, South Africa and Togo (FIFA, 2013), which are likely to be geopolitically sensitive countries in terms of global P management. Therefore, it is vulnerable to anticipated geopolitical constraints set by these countries;
- Increasing population and growing demand of P for food production could be another future challenge to the sustainable management of P in this country. According to the medium scenario (Series B) of ABS (2008) population projection, its population is likely to increase from 21 million in 2007 to 35 million in 2050. Due to such an increase in population, the domestic demand for food will increase and similarly, due to increased global population, the demand for food export will also rise in future. The increased demand for food will eventually lead to the increased demand of P fertilizer for food production;
- Increasing freight cost for shipping P fertilizers and rising P fertilizer price could also be major future challenge. According to ACCC (2008), the average freight costs for shipping fertilizers from the US Gulf to Australia increased from about AUD 35 per tonne in February 2000 to approximately AUD 105 per tonne in March 2008[1]. Keeping pace with the increment in freight cost, the retail price of P fertilizer in Australia also increased over the period;
- Moreover, other factor such as decreasing inherent soil fertility due to over exploitation, energy and water crisis, and adverse impact of climate change and land use change could appear as potential barrier in the way of achieving P sustainability in Australia.

In order to overcome the burdens of the past and present as well as the challenges of the future as described above, Australia needs to find solutions for a number of key questions as highlighted in **Fig. 1.7**.

The detailed assessment of the key sustainability challenges for P at the global and country scales as presented in this study indicates that these challenges, if not properly tackled, could eventually lead to global P scarcity and food crisis. The issue of global P scarcity can be regarded as more crucial than all other existing global issues that tend to threaten human survival and development such as climate change, energy crisis and water crisis. This is

[1] It should be noted that in the ACCC (2008) report, it is not mentioned whether the difference in freight cost between 2000 and 2008 is in constant value dollar or includes the inflation of money over the period. Probably, the price is indicated in the dollar value of the corresponding year.

because the impacts of climate change are somehow adaptable, energy is somewhat renewable and substitutable, and water is also renewable; but P is neither renewable nor substitutable, and the situation when the last unit of global phosphate rock reserves will be depleted is not adaptable. Therefore, necessary research should be undertaken to identify appropriate solutions towards mitigating the sustainability challenges for P. The following section highlights the general research needs in this regard.

1.4. General research needs

In order to provide effective policy and management response to overcome the sustainability challenges for P that have been discussed in this chapter, there is a need for research to identify key information regarding the

- Nature and magnitude of P flow through different systems at different geographical and temporal scales;
- Pathways of P loss in different systems and the magnitude of P loss through these pathways;
- Possible opportunities of minimizing P loss and increasing P recovery in different systems, and also the suitable way of utilizing the recovered P to meet the increasing P demand and therefore, to reduce the rate of phosphate rock mining so that the available phosphate rock reserves could be sustained for a longer time.

This chapter concludes that P is an essential element for sustaining global food production, but there are a number of sustainability challenges for this key element. If adequate and effective measures for mitigation are not taken immediately, these challenges could eventually appear as a potential threat to global P security and food security. So, there is an urgent need for research particularly to understand the nature and magnitude of P flow through different systems so that based on that understanding, effective policy and management response could be provided towards overcoming these challenges and achieving global P sustainability. The next chapter presents an in-depth and critical review of research conducted so far in this regard and highlights the gaps in available knowledge as well as the specific needs for research to fill the knowledge gaps.

Chapter-2

REVIEW OF LITERATURE

Focusing on the general research needs as identified in the previous chapter, this chapter presents a comprehensive review of available literature to assess the nature and magnitude of key P flows through different systems at different geographical scales as well as to identify knowledge gaps to determine specific objectives for the current research. This chapter is divided into six sections viz. *General overview*- which presents a brief introduction of the available P flow analyses at different geographical scales and outlines the aims of this literature review; *Approach used for the review*- which describes the types of studies considered and procedure followed for this review; *Outcomes of the review in terms of assessing key P flows at different geographical scales*- which presents an assessment of the key P inflows, outflows, storage, internal flows and recycling flows at different geographical scales, and identify priority areas for P management, *Knowledge gaps*- which describes the areas of research that received a limited attention in the available studies and highlights the knowledge gaps, *Limitations of this review*- which outlines the shortcomings of this review, and *Specific research objectives*- which highlights the specific research needs based on identified knowledge gaps, and precisely delineates the objectives of the current research. The findings of the literature review as presented in this chapter have been published in a peer reviewed international journal (Chowdhury et al., 2014) which is attached as **Appendix 1**.

2.1. General overview

In the previous chapter, it has been concluded that in order to mitigate the challenges for the global P resource and to secure a sustainable supply of P for global food production, there is an urgent need for policy responses to ensure the sustainable management of this vital resource. Formulation of better policy and management responses in turn requires a better understanding of the nature and magnitude of P flow through different systems at different geographical and temporal scales. A preliminary review of available literature indicates that in the recent times a considerable number of studies have been conducted for the quantitative assessments of P flow through different systems at various geographical scales such as global scale (Liu et al., 2008; Villalba et al., 2008; Bouwman et al., 2009; Van Vuuren et al., 2010), multiple country scale (Ott and Rechberger, 2012), country scale (Antikainen et al., 2005; Saikku et al., 2007; Antikainen et al., 2008; Chen et al., 2008; Fan et al., 2009; Jeong et al., 2009; Matsubae-Yokoyama et al., 2009; Seyhan, 2009; Gourley et al., 2010, 2010; Smit et al., 2010; White et al., 2010; Ghani and Mahmood, 2011; Suh and Yee, 2011; Ma et al., 2012; Senthilkumar et al., 2012; Cooper and Carliell-Marquet, 2013; Cordell et al., 2013), regional scale (Neset et al., 2008; Li et al., 2010; Do-Thu et al., 2011; Yuan et al., 2011a, 2011b; Wu et al., 2012), city scale (Tangsubkul et al., 2005; Neset et al., 2010; Baker, 2011; Fissore et al., 2011; Qiao et al., 2011; Metson et al., 2012), and some studies at smaller geographical scales (Baker et al., 2007; Kupkanchanakul and Kwonpongsagoon, 2011). These studies identified the nature and magnitude of P wastage and loss from the system, and determined the potentials for minimizing P loss and increasing P recovery and reuse. Based on the outcomes of P flow analysis, these studies were also able to suggest better site-specific P management decisions.

Although a considerable number of P flow analyses have been conducted at various geographical scales, there is a lack of any systematic review of the available studies to assess the nature and magnitude of key P flows at different geographical scales. The objective of this chapter is to determine the significant P flows at different geographical scales and identify areas that require attention in future P flow analyses. For this review, a systematic approach as described in the next section has been followed.

2.2. Approach used for the review

Thirty-two recent analyses of P flow were initially selected for this review according to the following criteria:

- Peer-reviewed articles written in English;
- Published between 2005 and 2012;
- Used Substance Flow Analysis (SFA) as a method for the quantitative assessment of P flow through a system;
- Conducted at any of the geographical scales such as global, multiple country, country, regional, city;
- Performed single or multiple years analysis of flow; and
- Considered single or multiple sectors or subsystems within the system.

However, an additional requirement was the publication contained quantitative information regarding key P inflows, outflows, storage, internal flows and recycling flows. Studies unable to meet this requirement were further excluded, and twenty-one studies mainly at the city, regional and country scales were eventually selected for an in-depth review.

The majority of the studies selected for the current review utilized the method of 'SFA' which applies mass balance principles to assess the flows and storage of a substance within a system defined in space and time (Voet, 2002; Brunner and Rechberger, 2004; Brunner, 2010). Although a few of the studies did not denote their method explicitly as SFA, they applied mass balance principles to quantify P flows and storage consistent with this methodology and therefore, have been considered in this review. In most cases, analysis of P flow was limited to a particular year. In the case of multiple-year and historical (more than 100 years) analyses, the average P flow per annum and the most recent year P flow respectively have been considered for this review. In some studies, crop and livestock production sectors were considered together as the agricultural production sector, whilst in others, they were considered separately. In this review, the former categorization of the agricultural production sector has been adopted. In two studies (Ghani and Mahmood, 2011; Senthilkumar et al., 2012), several regions within a country were considered for the analysis of P flow, which in this review, have been categorized as the country scale analysis. Studies that analysed P flow of only one region within a country, have been categorized as the regional scale analysis.

In this review, *P inflow* means, the quantity of P that enters into a particular geographical scale or system in a given time through a particular medium. At the country scale, P flow as phosphate rock mining from geological deposits has also been considered as inflow in this study. *P outflow* means, the amount of P that leaves a particular geographical scale or system in a given time through a particular medium. In this review, P discharge to a water body has been considered as P outflow only in the case of studies where the water body (stream, river, and lake) has been found to extend beyond the boundary of the geographical scale under consideration or ultimately discharge its water outside the boundary of the geographical scale or at least, connected to another water body that extend beyond the boundary. *P storage* means, the amount of P that is stored in a component or sector within a particular geographical scale or system in a given time that is the difference between inflow and outflow; internal flow means, the amount of P that flows from one sector to another through a medium within a particular geographical scale or system in a given time, and *P recycling flow* means, the amount of P that is recovered from waste and is recycled back to any sector within a particular geographical scale or system in a given time. In this review, *sector or subsystem* means a particular type of system that has some unique properties and consists of a set of component or processes working together as parts of a complex process or an interconnecting network. For instance; mining, crop production, waste management, streams and rivers all are different sectors or subsystems.

2.3. Outcomes of the review in terms of assessing key P flows at different geographical scales

This section presents a comprehensive assessment of the key sectors of P flow as well as the key inflows, outflows, storage, internal flows, and recycling flows of P at the city, regional, and country scales.

2.3.1. Key sectors of P flow

The outcome of any P flow analysis depends upon how the system under consideration is defined in terms of geographical scale and key sectors of P flow. As the availability and size of the key sectors for P flow varies from one geographical scale to another, the priority areas of P flow might be different at various geographical scales.

Based on the current review, **Fig. 2.1** presents a holistic view of all the key sectors that are usually considered in P flow analyses at different geographical scales. At the city scale, human consumption and waste management are the two key sectors of P flow. Although the trade and commerce sector is quite important in terms of P flow at the city scale, it was usually omitted in the city scale studies, probably, to reduce the complexity of P flow analysis. Agricultural production is the main sector at the regional scale, and the key difference between the city and regional scale lies in the presence of this sector. However, a small scale agricultural sector is sometimes found in some cities and occasionally considered in the city scale analysis. In contrast, P fertilizer production sector is not usually found at the regional scale and in some cases, at the country scale, except for the countries having high reserves of phosphate rock and/or P fertilizer production such as China and the US. The country scale is spatially far bigger than the city and regional scales, and usually includes P mining and/or fertilizer production sectors, a coastal water sector along with other key sectors that are contained in the city and regional scales (**Fig. 2.1**). The global and multiple country scales consider the sectors available at the country scale along with the sectors that extend beyond the country scale such as river systems, coastal waters, and the ocean.

A complete and contrasting picture of the different geographical scales of P flow analysis along with their relevant sectors and intersectoral interactions has been presented in **Fig. 2.1**, which is so far missing from the available literature. This figure could be utilized as a guideline for choosing the appropriate geographical scale for any P flow analysis. The selection of proper geographical scale is important to ensure the inclusion or exclusion of any vital sector because the outcome of the P flow analysis depends mainly on it. For instance, the selection of city scale may exclude the agricultural production sector which is one of the vital sectors in terms of P flow. But this sector could be covered by selecting the regional scale. Sectors such as coastal waters, P mining and fertilizer production may not be available in some countries, thus, may be excluded in some country scale analyses; but these sectors may become relevant for SFA across multiple countries or global scale. It is apparent that the analysis of P flow only at a particular geographical scale will exclude certain sectors and may not provide the comprehensive information required to make informed policy decisions, which indicates the necessity for cross-scale or multi-scale analysis. A similar conclusion was also reached by Cordell et al. (2012).

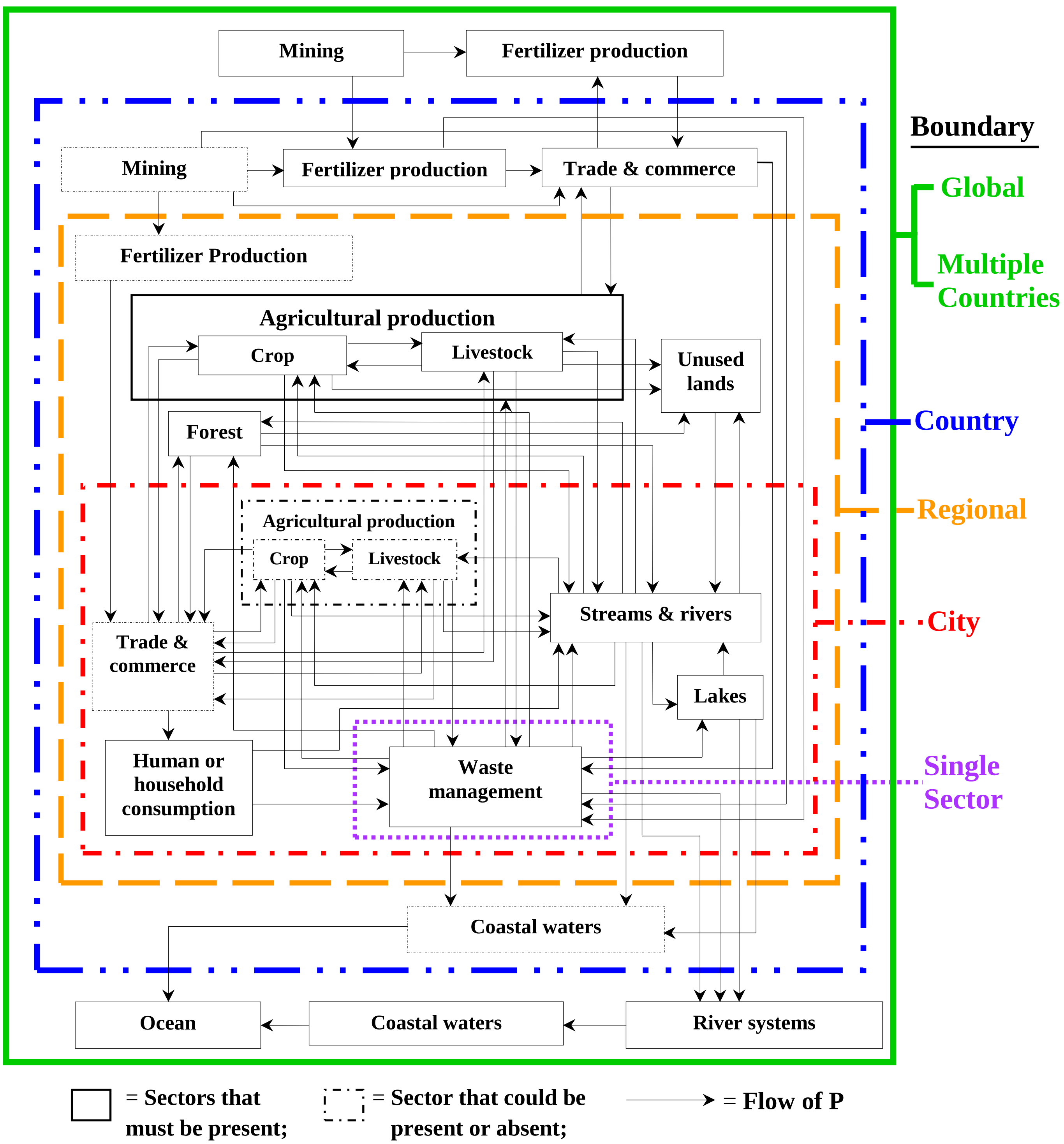


Fig. 2.1 Key sectors of P flow relating to different geographical scales and their interactions in terms of direction of P flow.

2.3.2. Key P inflows and outflows

Understanding the key P inflows and outflows relating to a particular geographical scale is vital to identify the priority areas of P management for that scale. Based on the current review, **Table 2.1** presents an analysis of vital information of the selected P flow studies with regard to the geographical and temporal scale, type of system, total inflow, total outflow, key inflows and outflows, the type of sectors receiving the inflows and releasing the outflows. Here, two typical cases, one of of a city and another of a country scale analysis have been illustrated below (from **Table 2.1**) and further information can be obtained for the remaining studies by the careful use of the list of abbreviations provided at the bottom of the table.

Tangsubkul et al. (2005) presented a city scale study in which P flow through the Urban Ecosystem (UrEc) of Sydney (Australia) has been analysed for the year 2000. The analysis revealed that the total inflow was 5.99 kt (kilotonnes: 1000 metric tons or tonnes) P, with a total outflow of 2.91 kt. The balance of 3.08 kt P was stored in different sectors within the system (P storage will be discussed separately in **Section 2.3.3**). The three key inflows were food (2.09 kt P, 35%), animal feed (1.55 kt P, 26%) and detergent (1.24 kt P, 21%) as imported products from outside of Sydney to the commerce sector. Most of this imported P was consumed at the household sector, which ultimately resulted in a large discharge (2.66 kt P) as treated wastewater to coastal water. Thus, about 91% of the total outflow occurred because P recovery from wastewater was entirely absent in Sydney. This study suggested that better P management in Sydney could be achieved by incorporating P recovery options to wastewater management for the outflows or by using P free detergents for the inflows.

Jeong et al. (2009) conducted a country scale analysis in which the domestic P flow of South Korea has been analysed for the year 2005. The total P inflow in South Korea was about 380 kt; while, the total outflow was about 77 kt. The balance of the P, which is about 303 kt, was stored in various sectors within the system. The key P inflow was the imported mineral ore (179 kt or 47%) to the fertilizer production sector, while the main outflow (72.9 kt or 95%) occurred as P fertilizer export to other countries. The majority (about 80%) of the P that entered in South Korea, remained within the system either as soil storage in the crop and livestock production sector, or as products and by-products of chemical and other industries, or as wastes at landfill and steelmaking slag. This study recommended that P recovery from steel making slag could be a better P management option for South Korea.

2.3.2.1. Key P inflows

As identified in this review, a comparative view of the magnitude of the key P inflows at different geographical scales has been presented in **Fig. 2.2.** This figure shows, the main P inflow at the city scale occurs through imported food to the human consumption sector, and this has been concluded for each of the five city scale analyses. In two city scale studies, one that analysed P flow through the food consumption system in Beijing (China) for 2008 (Qiao et al., 2011) and another that analysed P flow through the food consumption and sanitation system in Linkoping (Sweden) for the year 2000 (Neset et al., 2010), food has been identified to account for nearly 100% of the total P inflow (**Fig. 2.2A**). In some of the city scale studies; either P fertilizer, or animal feed, or detergent has been observed to be one of the key P inflows after food. However, these flows have been identified to account for less than 30% of the total inflow in almost all the reviewed city scale analyses. Thus, P inflow as food should receive attention when forming any city scale P management decision because even though the opportunity for changes such as reducing food spoilage may be limited in percentage terms they can potentially operate on a large base. Presenting the data in this way also highlights the potential for some key inflows, for example detergent, being missed in some studies or indicates that P inflow through detergent is not significant.

At the regional scale, the major P inflow has been identified to occur either as fertilizer, mineral ore, or animal feed (**Fig. 2.2B**). For instance, in another study of Linkoping (Sweden) which considered the food production sector along with the food consumption sector for the analysis of P flow for 2000, about 95% (2 kg per capita (kg/cap)) of the total inflow has been found to occur through P fertilizer import (Neset et al., 2008). Whereas, in the P flow analyses through anthropogenic system by Yuan et al. (2011a) and Yuan et al. (2011b) in two different regions of China, P inflow as mineral ore import has been observed to account respectively about 69% (5.7 kt) and 56% (4.75 kt) of the total inflow in 2008. In another regional scale study by Wu et al. (2012) that analysed P flow through the socio-economic system in Feixi County (China), animal feed has been identified as the main inflow, where it accounts for about 70% (13.31 kt P) of the total inflow in 2008. It can be concluded that in absence of P fertilizer production industry, the major P inflow in the regional scale occurs either through the import of P fertilizer or animal feed, and with its presence, the main P inflow can occur as mineral ore import.

Table 2.1 Nature and magnitude of the key P inflows and outflows through different systems at different geographical scales.

Geographical scale						**Inflow**			**Outflow**		
[1]Studies	[2]Extent	Location	[3]Type of system	Year of flow	[4]Measuring unit	**Total inflow**	[5]Key flows (From - to)	**% of total inflow**	**Total outflow**	[6]Key flows (From - to)	**[7]% of total outflow**
Qi	Ci	Beijing, China	FoC	2008	kt / a	6.22	Fo (FoP - UrC): 5.37 Fo (FoP - RuC): 0.85	86 14	1.72	*UWw (UrC - Aq): 1* *TWw (STP - Aq): 0.39* *UWw (RuC-Aq): 0.33*	*58* *23* *19*
		Tianjin, China				4.18	Fo (FoP - UrC): 3.18 Fo (FoP - RuC): 0.99	76 24	1.51	*UWw (UrC - Aq): 0.63* *UWw (RuC - Aq): 0.45* *TWw (STP - Aq): 0.44*	*41* *30* *29*
Ba	Ci	Twin cities, US	UrEc	2000	kt / a	4.07	Fo (IFo - C): 1.67 De (IDe - C): 1.37 Fe (IFe - Pets, LiP): 0.59	41 34 15	1.43	*Ww (Wm - O): 1.14*	*80*
Ne10	Ci	Linkoping, Sweden	FoC & San	2000	kg / cap/a	0.57	Fo (FoP - C): 0.57	100	0.562	*Waste (SlH - O): 0.512*	*92*
Me	Ci	Phoenix, Arizona, USA	UrEc	2005	kt / a	7.98	Fo (IFo - C): 3.83 Fr (FrP - CrP, ReS): 1.9	48 24	0.056	No significant outflow reported	-
Ta	Ci	Sydney, Australia	UrEc	2000	kt / a	5.99	Fo (IFo - ITC): 2.09 Fe (IFe - ITC): 1.55 De (IDe - ITC): 1.24	35 26 21	2.91	*TWw (STP - CoW): 2.66*	*91*
Li	Re	Hefei City, China	An	2008	kt / a	7.81	Mo & Cr (IMo, ICr - InP, FdP): 3.7 Fr (IFr - CrP): 3.1	47 40	4.16	Fr (FrP - O): 2.4 *ErL (CrP - Aq): 1*	58 *24*
Yu-a	Re	Lujiang County, China	An	2008	kt / a	8.31	Mo (IMo - FrP): 5.7 Fe (IFe - LiP): 2.23	69 27	5.67	CrPr (CrP - O) : 3.7 *Ww (LiP - Aq): 1.66*	65 *30*
Yu-b	Re	Chaohu City, China	An	2008	kt / a	8.52	Mo (IMo - FrP): 4.75 Fe (IFe - LiP): 1.81 Fr (IFr - CrP): 1.68	56 21 20	5.26	Fr (FrP - O): 3.34 CrPr & LiPr (CrP, LiP - O): 1.38	64 26
Wu	Re	Feixi, China	SoEc	2008	kt / a	19.15	Fe (IFe - LiP): 13.31 Fr (IFr - CrP): 3.75 Mo (IMo - InP): 1.9	70 20 10	15.6	*ErL (CrP - Aq): 5.33* *UWw (LiP - Aq): 4.93* Fo (LiP - O): 3.10	*34* *32* 20
Ne08	Re	Linkoping, Sweden	FoP & C	2000	kg / cap/a	2.095	Fr (IFr - CrP): 2.0	95	1.345	LiPr (LiP - O): 0.69 *Waste (Wm - O): 0.43*	51 *41*
Do	Re	Hanam, Vietnam	RuA	2008	kt / a	0.12	Fo & Fr (IFo, IFr - ITC): 0.109	91	0.065	Cr, LiPr (ITC - O): 0.024 *ErL(CrP - Soil/G): 0.014* *Ww (Wm - Aq): 0.014* *Waste (AqC- Soil): 0.013*	37 *21* *21* *20*
Ma	Co	China	An	1984 - 2008	kt / 25y	167300	Mo (N - MiP): 154500	92	129000	*Waste (Wm - Aq, Soil): 124300*	*96*
Su	Co	US	Fo	2007	kt / a	5616	Mo (N - MiP): 3773 Fe (Grazing - LiP): 748	67 13	4001	*Waste: 1671* Fr (InP - O): 1291 CrPr & LiPr (CrP, LiP - O): 435	*42* 32 11

Sm	Co	Netherlands	Ag, IP & Ho	2005	kt / a	108	Fe (IFe - FeP): 50.4 Fo (IFo - FoP): 28 Fr (IFr - CrP): 21	47 26 19	48	Fo (InP - O): 37.5 ExM (LiP - O): 7	78 15
Gh	Co	Malaysia	An	2007	kt / a	218	Mo (IMo - FrP): 162	75	254	*ErL (AgP - Env): 132* Fr (InP - O) : 40 *Ww (Wm - Aq): 31*	*52* 16 *12*
Se	Co	Turkey	An	2001	kg / cap/a	4.33	Mo & Fr (IMo, IFr - ITC): 3.75	86	4.05	*Waste (La - Env): 1.33* *UWw (HoC - Env): 1.07* *ErL (AgP - Aq & Soil): 1*	*33* *26* *25*
Je	Co	South Korea	Dom	2005	kt / a	380	Mo (IMo - FrP): 179 Fr (IFr - AgP): 68.9 OMi (IMo - InP): 58.1	47 18 15	77	Fr (FrP - O): 72.9	95
Mat	Co	Japan	Dom	2002	kt / a	747.8	Fo (IFo - HuC): 173.52 OMi (IMo - InP): 156.50 ChS (ICh - InP): 155.92 Fr (IFr - FrP): 151.32 Mo (IMo - InP): 110.56	23 21 21 20 15	55.67	*ErL (AgP - Aq): 32.93* *Ww (HuC - Aq): 16.12*	*59* *29*
Ant	Co	Finland	Ag & Fo	1995 - 1999	kt / a	33.3	Fr (FrP - CrP, LiP): 29.5	89	6.2	Fo & Fe (Fo, FdP - O): 2.9 *ErL (CrP, LiP - Aq): 2.4* *TWw (STP- Aq): 0.7*	47 *39* *11*
Sh	Co	Centre, France	Ag	2002 -2006	kg / ha/a	17.1	Fr (IFr - Soil): 12.9	75	16.2	CrPr (CrP - O): 13.4	83
		Brittany, France				38.8	Fe (IFe - LiP): 28.9	75	21.1	LiPr (LiP - O): 12.3	58
Ot	MCo	EU	An	2006 - 2008	kg / cap/a	5.3	Mo & Fr (IMo, IFr - ITC): 4.1	77	1.433	Fr (ITC - O): 0.43 Fo & Fd (ITC - O): 0.33	30 23

1 Ant: Antikainen et al., 2005; Ba: Baker, 2011; Do: Do-Thu et al., 2011; Gh: Ghani and Mahmood, 2011; Je: Jeong et al., 2009; Li: Li et al., 2010; Ma: Ma et al., 2012; Mat: Matsubae-Yokoyama et al., 2009; Me: Metson et al., 2012; Ne08: Neset et al., 2008; Ne10: Neset et al., 2010; Ot: Ott and Rechberger, 2012; Qi: Qiao et al., 2011; Se: Seyhan, 2009; Sh: Senthilkumar et al., 2012; Sm: Smit et al., 2010; Su: Suh and Yee, 2011; Ta: Tangsubkul et al., 2005; Wu: Wu et al., 2012; Yu-a: Yuan et al., 2011a ; Yu-b: Yuan et al., 2011b.

2 Ci: City; Co: Country; MCo: Multiple country; Re: Regional.

3 Ag: Agricultural; Ag & Fo: Agricultural and food; Ag, IP & Ho: Agricultural, industrial production and household; An: Anthropogenic; Dom: Domestic; FoC: Food consumption; FoC & San: Food consumption and sanitation; FoP & C: Food production and consumption; Fo: Food; RuA: Rural area; SoEc: Socio-economic; UrEc: Urban ecosystem.

4 kt/a: kilotonne (1000 metric tons) per annum; kt/ 25y: kilotonne per 25 years; kg/cap/a: kilogram per capita per annum; kg/ha/a: kilogram per hectare per annum.

5, 6 Flows less than 10% of the total inflow or outflow are not presented here.

AgP: Agricultural (crop and livestock) production; Aq: Aquatic system; AqC: Aqua-culture; C: Consumption; ChS: Chemical substance; CoW: Coastal waters; Cr: Crop; CrP: Crop production; CrPr: Crop products; De: Detergent; Env: Environment; ExM: Exported manure; Fd: Fodder; FdP: Fodder production; Fe: Feed (pets or livestock); FeP: Feed production; Fo: Food; FoP: Food production; Fr: Fertilizer; FrP: Fertilizer production; G: Groundwater; HoC: Household consumption; HuC: Human consumption; ICh: Imported chemical; ICr: Imported crop; IDe: Imported detergent; IFe: Imported feed; IFo: Imported food; IFr: Imported fertilizer; IMo: Imported mineral ore; InP: Industrial production; ITC: Industry, trade and commerce; La: Landfill; LiP: Livestock production; LiPr: Livestock products; MiP: Mine production; Mo: Mineral ore; N: Nature (Mine); O: Outside the system; OMi: Other minerals; ReS: Residential soil; RuC: Rural consumption; SlH: Sludge handling; SoL: Soil losses (erosion, runoff and/or leaching); STP: Sewage treatment plant; TWw: Treated wastewater; UrC: Urban consumption; UWw: Untreated wastewater; Waste: Solid and liquid waste; Wm: Waste management; Ww: Wastewater.

6, 7 Italic marked texts and numbers indicate various types of unproductive outflows of P.

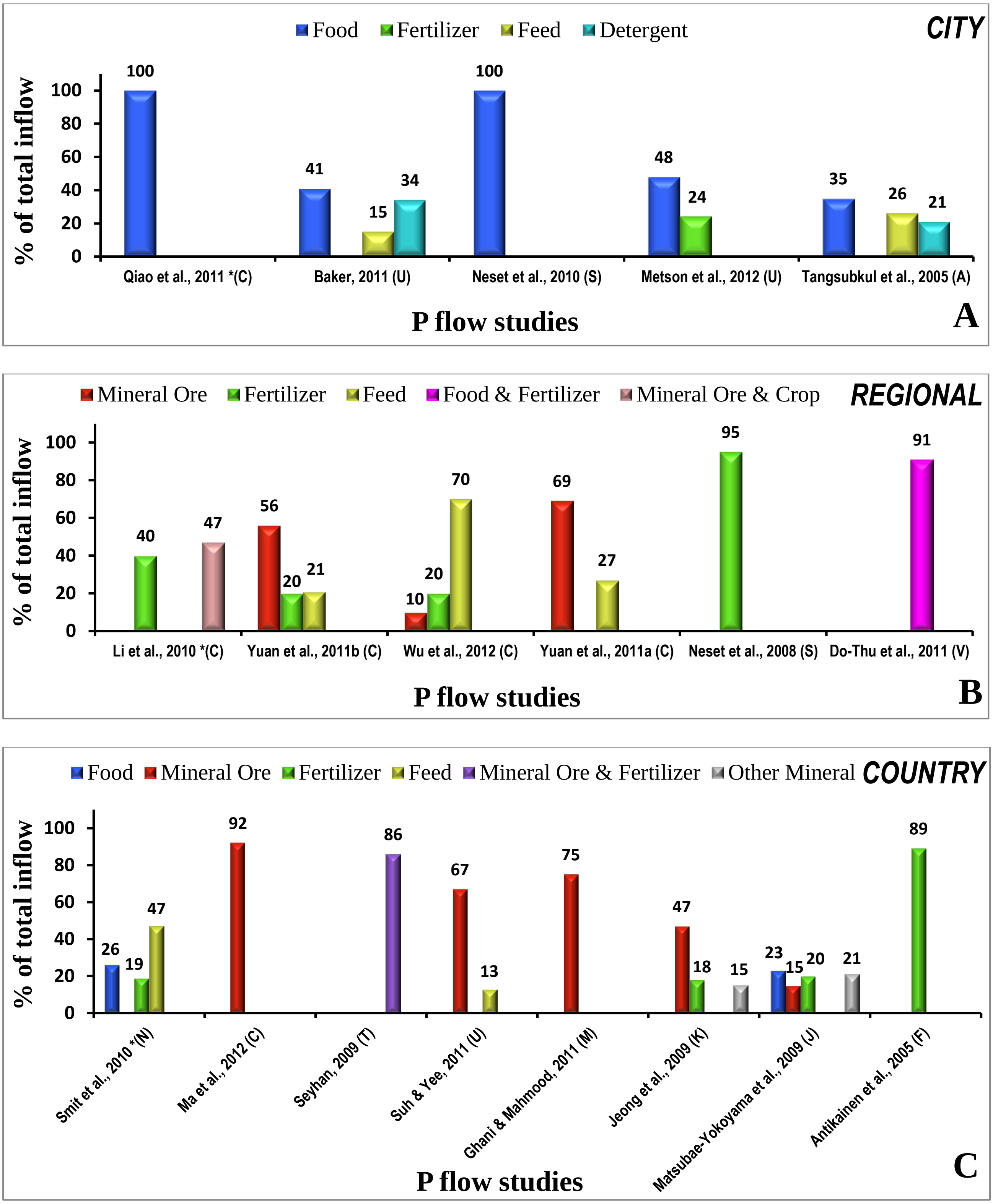


Fig. 2.2 Key inflows of P at the (A) city, (B) regional, and (C) country scales. Flows less than 10% of the total inflow are not presented here. Details of the studies are presented in **Table 2.1**. *( ): country of study indicated by the letter within the brackets in the horizontal axis - A: Australia; C: China; F: Finland; J: Japan; K: South Korea; M: Malaysia; N: Netherlands; S: Sweden; T: Turkey; U: US; V: Vietnam.

In most of the country scale studies as presented in **Fig. 2.2C**, either mineral ore or fertilizer import has been observed to be the key P inflow. In the analyses of P flow through the anthropogenic system of China for 1984-2008 (Ma et al., 2012), of Malaysia for 2007 (Ghani and Mahmood, 2011), and through the food system of USA for 2007 (Suh and Yee, 2011) and domestic system of Korea for 2005 (Jeong et al., 2009); P mineral ore has been identified to account for respectively about 92% (154500 kt/25 years), 75% (162 kt), 67% (3773 kt), and 47% (179 kt) of the total P inflow. Import of P as chemical fertilizer is another main inflow at the country scale particularly in the countries with low reserves of phosphate rock. For instance, in the study by Antikainen et al. (2005) regarding the analysis of P flow through agriculture and food system in Finland, P import as chemical fertilizer has been identified to account for approximately 89% (29.5 kt) of the total annual P inflow between 1995 and 1999, while the case study by Seyhan (2009) identified, in Turkey, P mineral ore and chemical fertilizer together accounts for about 86% (3.75 kg/cap) of the total inflow in 2001. Both these countries lack adequate phosphate rock reserves to meet their domestic P demand and thus, rely on P import as chemical fertilizer from other countries. Apart from mineral ore and fertilizer import, significant P inflow in the country scale can also occur either through animal feed which has been identified to be 47% (50.4 kt) of the total inflow in the Netherlands in 2005 (Smit et al., 2010) or through food which accounts for about 23% (173.52 kt) of the total inflow in 2002 in Japan (Matsubae Yokoyama et al., 2009).

2.3.2.2. Key P outflows

As portrayed in **Fig. 2.3**, here, a comparative picture of the magnitude of the key P outflows at different geographical scales has been provided. In three of the four city scale analyses as presented in **Fig. 2.3A**, wastewater has been observed to account for nearly or more than 80% of the total P outflow. Wastewater has been found to occupy about 100% (1.72 kt or 28% of the total inflow), 91% (2.66 kt or 44% of the total inflow), and 80% (1.14 kt or 28% of the total inflow) of the total outflow respectively in Beijing, China in 2008 (Qiao et al., 2011), Sydney, Australia in 2005 (Tangsubkul et al., 2005), and Twin Cities, US in 2000 (Baker, 2011). P outflow as wastewater to water body is an unproductive outflow because it does not bring any benefit to the producers of agricultural commodities or the end users. So, it is apparent that the wastewater sector is very important in terms of P outflow at the city scale and to achieve better P management at the city scale, greater emphasis should be given on the management of wastewater.

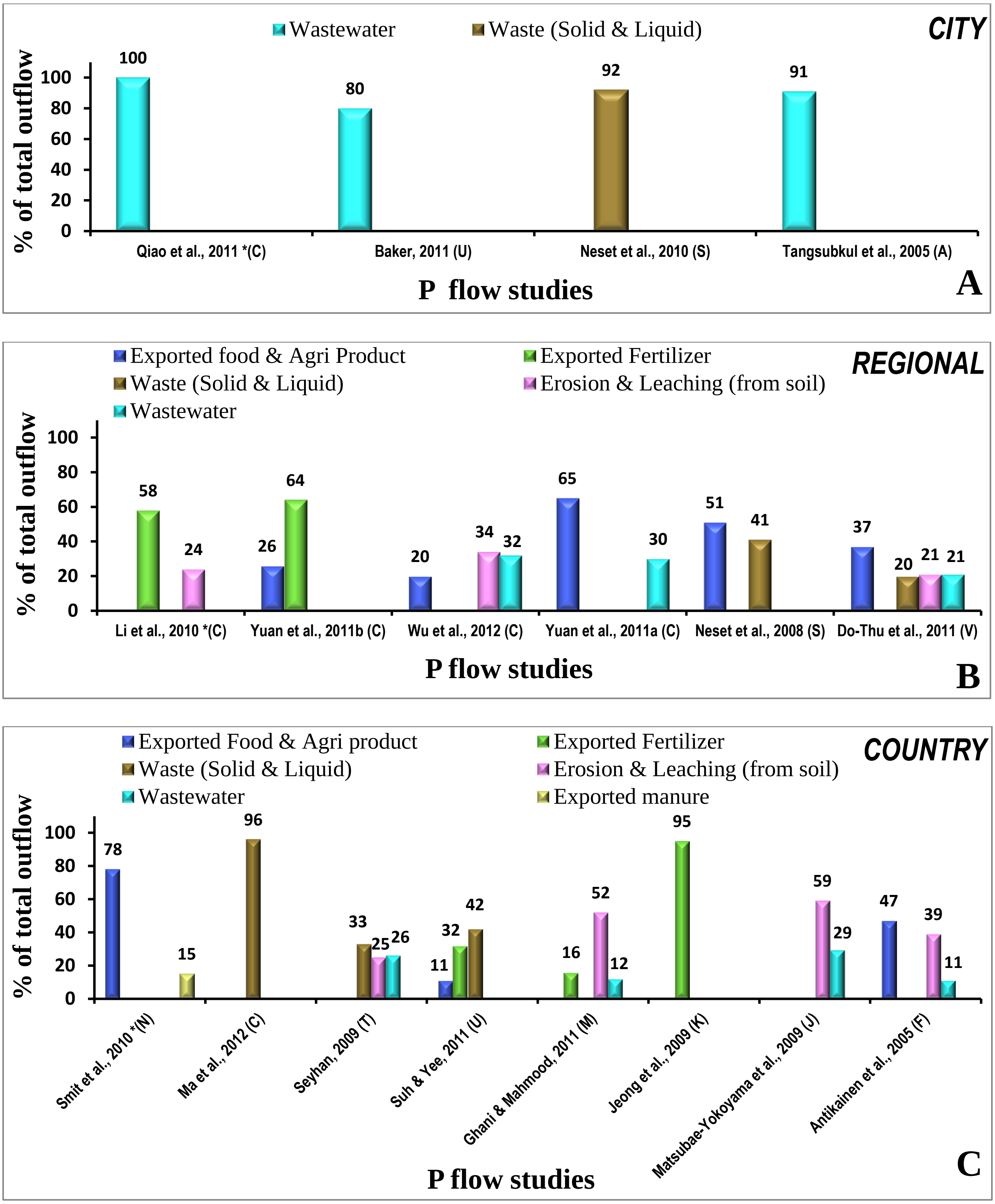


Fig. 2.3 Key outflows of P at the (A) city, (B) regional, and (C) country scales. Flows less than 10% of the total outflow are not presented here. Details of the studies are presented in **Table 2.1**. *( ): country of study indicated by the letter within the brackets in the horizontal axis - A: Australia; C: China; F: Finland; J: Japan; K: South Korea; M: Malaysia; N: Netherlands; S: Sweden; T: Turkey; U: US; V: Vietnam.

At the regional scale, the main outflow of P has been observed to occur either through exported fertilizer or as exported food and agricultural products (**Fig. 2.3B**). Key outflow as exported fertilizer occurs in regions that have P fertilizer production sectors. Such a region is usually found in the countries having high reserves of phosphate rocks such as China. Probably, owing this reason, fertilizer export has been found to be the main P outflow in the two regional scale studies (Li et al., 2010; Yuan et al., 2011b) of China, where it accounts for more than 50% of the total outflow in both cases. But in most other countries, P outflow at the regional scale occurs through the export of food and agricultural products, where it has been identified to occupy about 65% (3.7 kt or 45% of the total inflow) and 51% (0.69 kg/cap or 33% of the total inflow) of the total outflow respectively in Lujiang County, China in 2008 (Yuan et al., 2011a) and in Lingkoping, Sweden in 2000 (Neset et al., 2008). Among the other outflows at the regional scale either waste (both solid and liquid), or wastewater, or erosion and leaching has been identified to be quite significant in terms of P outflow. Most of these outflows are unproductive and harmful to the environment. Erosion and leaching has been found to be the main outflow in the case of Feixi County (China), where it accounts for about 34% of the total outflow (5.33 kt or 28% of the total inflow) in 2008 (Wu et al., 2012).In contrast, waste has been identified to be the second main outflow in Linkoping (Sweden) in 2000, where it accounts for about 41% (0.43 kg/cap or 21% of the total inflow) of the total outflow (Neset et al., 2008). Therefore, it could be suggested that P management decision at the regional scale should put more emphasis on minimizing the key unproductive outflows that have been identified in this review.

At the country scale, the nature and magnitude of key P outflows have been observed to vary from one country to another. In three of the eight reviewed country scale analyses, waste (both solid and liquid) has been found to be the main outflow. For instance, waste accounts for about 96% (124300 kt/25 years, or 74% of the total inflow) and 42% (1671 kt or 30% of the total inflow) of the total P outflow in the analysis by Ma et al. (2012) of China for 1984-2008 and Suh and Yee (2011) of US for 2007 (**Fig. 2.3C**). In some studies, exported food and agricultural products has been identified to be the main P outflow, where it accounts for about 78% (37.5 kt or 35% of the total inflow) and 47% (2.9 kt or 9% of the total inflow) of the total annual outflow respectively in the Netherlands in 2005 (Smit et al., 2010) and in Finland between 1995 and 1999 (Antikainen et al., 2005). In another country scale study by Jeong et al. (2009) that analysed domestic P flow in South Korea for the year 2005, exported fertilizer has been observed to occupy about 95% (72.9 kt or 19% of the total inflow) of the total outflow. However, in some studies at this scale, P outflow as soil erosion and leaching has been found to be quite significant, where it accounts for about 59% (32.93 kt or only 4% of the total inflow), 52% (132 kt or 61% of the total inflow) and 39% (2.4 kt or 7% of the total inflow) of the total annual outflow respectively in Japan in 2002 (Matsubae Yokoyama et al., 2009), in Malaysia in 2007 (Ghani and Mahmood, 2011) and in Finland between 1995 and 1999 (Antikainen et al., 2005). Thus, it is evident that major P outflows at the country scale can be of diverse types and differ from one country to another depending upon the availability of potential sectors of P flow.

Assessment of the key P outflows at different geographical scales as presented in **Table 2.1** and **Fig. 2.3** revealed that a significant quantity of P leaves the system as unproductive outflows, which is as wastewater at the city scale, and as erosion and leaching, or waste, or wastewater at the regional and country scales. The majority of these outflows ultimately find their way to surface water bodies, and cause problems like algal blooms, hypoxia, and eutrophication as described in **Section 1.2.6**.

2.3.3. Key P storage, internal flows, and recycling flows

Based on the current review, an analysis of key P storage, internal flows and recycling flows at various geographical scales has been presented in **Table 2.2**. To illustrate the information in **Table 2.2**, the details of three studies at three different scales are presented here:

Qiao et al. (2011) reported a city scale study that analysed P flow through the food consumption system in two major cities (Beijing and Tianjin) of China for the year 2008. The analysis revealed, in Beijing, about 72% (4.5 kt) of the total inflow of P was stored within the system, where the majority of the P (2.94 kt or 47% of the total inflow) stored in landfills. Phosphorus flow as wastewater (3.86 kt or 62% of the total inflow) from the urban consumption sector to the sewage treatment plant was the main internal flow of P in that city. The study also identified that a significant amount of about 1.01 kt P (16% of the total inflow) were recycled as organic fertilizer from the waste management sector to the agricultural (food) production sector in Beijing.

Wu et al. (2012) analysed P flow through the socio-economic system of Feixi County in China for 2008. They identified, about 19% (3.70 kt) of the total amount of P that entered in Feixi in 2008 was stored within the system, particularly, in the soil of the crop production sector. P flow as livestock excreta (5.25 kt or 27% of the total inflow) to the crop production sector was the main internal flow. Again, 6 kt P which is about 31% of the total inflow were recycled as manure from the livestock to the crop production sector, while a small amount of about 0.54 kt P (only 3% of the total inflow) were recycled as organic fertilizer (mainly human excreta) from the rural consumption to the crop production sector.

Antikainen et al. (2005) reported a country scale study in which annual P flow through Finnish agricultural and food system was analysed for the period of 1995-1999. This study revealed that about 81% (27.1 kt) of the total annual inflow of P was stored within the system, and the majority of this (about 23.7 kt) was retained in the soil of the agricultural production sector. About 15.9 kt P (48% of the total annual inflow) and 6.2 kt P (19% of the total annual inflow) were recycled back to the food and agricultural system respectively as manure from the livestock production to the crop production sector and as recycled feed from the food processing sector to the livestock production sector.

Similar illustrations can be given for the key findings of all other P flow analyses presented in **Table 2.2**.

2.3.3.1. Key P storage

This review has revealed, at all the three scales (city, regional and country), a substantial proportion of the total quantity of P that enters into the system, is retained within the system as storage (**Fig. 2.4**). In all the city scale analyses as shown in **Fig. 2.4A**, more than 50% of the total inflow of P has been found to be stored within the system. Landfill has been identified to be the key place of P storage at this scale, where it accounts for the storage of about 47% (2.94 kt), 43% (1.76 kt) and 14% (0.81 kt) of the total inflow of P respectively in Beijing, China in 2008 (Qiao et al., 2011), in Twin cities, US in 2000 (Baker, 2011) and in Sydney, Australia in 2000 (Tangsubkul et al., 2005). However, in the case of Sydney, about 31% (1.88 kt P) of the total inflow of P has been found to be stored within the soil of the agricultural production sector. This exception is because this city scale study included the agricultural sector within the system boundary, which is usually overlooked in the studies at this scale.

In all the reviewed regional scale studies, a considerable proportion (about one third) of the total inflow of P has been observed to be retained within the system (**Fig. 2.4B**). In majority of the studies at this scale, the soil of the crop production sector has been found to be the main place of P storage. For instance, in 2008, about 19% (3.66 kt) and 31% (2.60 kt) of the total inflow of P respectively in Feixi (Wu et al., 2012) and Lujiang County (Yuan et al., 2011a) of China was stored within the soil of the crop production sector. Thus, it is evident that the soil of the crop production sector is very important in terms of P storage at the regional scale.

In three of the seven reviewed country scale analyses as presented in **Fig. 2.4C**, almost 80% of the total inflow of P has been found to be retained within the system. The current assessment has revealed that the soil of the agricultural production sector stores a great proportion of the total P inflow at the country scale. For instance, about 71% (23.7 kt), 54% (376 kt) and 33% (125 kt) of the total annual inflow of P were eventually retained within the soil of the agricultural production sector respectively in Finland between 1995 and 1999 (Antikainen et al., 2005), in Japan in 2002 (Matsubae-Yokoyama et al., 2009) and in Korea in 2005 (Jeong et al., 2009). In most other country scale studies too, the soil of the agricultural production has been found to be the key place of P storage within the system.

Table 2.2 Nature and magnitude of the key P storage, internal flows and recycling flows through different systems at different geographical scales.

Geographical scale							Storage				[6]Major internal flow	Recycling flow	
[1]Studies	[2]Extent	Location	[3]Type of system	Year of flow	[4]Measuring unit	**Total inflow**	**Sum of all storage**	**% of total inflow**	[5]Key storage	**% of total inflow**	(From - to)	[7]Key flow (From - To)	**% of total inflow**
Qi	Ci	Beijing, China	FoC	2008	kt / a	6.22	4.50	72	La: 2.94 AgP (soil): 1.01	47 16	Ww (UrC - STP): 3.86	OFr (Wm - AgP): 1.01 ReW (Wm- UrL): 0.54	16 9
		Tianjin, China				4.18	2.67	64	La: 1.8 AgP (soil): 0.86	43 21	Ww (UrC - STP): 2.24	OFr (Wm - AgP): 0.86	21
Ba	Ci	Twin cities, US	UrEc	2000	kt / a	4.07	2.64	65	La : 1.76 EcoStor (Soil): 0.66	43 16	Sl (UrC - Wm): 1.46	Fe (Wm - LiP): 0.03 OFr (Wm - AgP): 0.02	0.7 0.5
Ne10	Ci	Linkoping, Sweden	FoC & San	2000	kg/ cap / a	0.57	0.008	1.5	SeTP: 0.003	0.5	Sl (SeTP - SH): 0.55	OFr (Wm - AgP): 0.033	6
Ta	Ci	Sydney, Australia	UrEc	2000	kt / a	5.99	3.08	51	AgP (Soil): 1.88 La : 0.81	31 14	Ww (HoC - STP): 3.45	OFr (Wm - AgP): 1.33 Man (AgP- AgP): 1.08	23 18
Li	Re	Hefei City, China	An	2008	kt / a	7.81	3.66	47	CrP (Soil): 2 La : 0.7	26 9	Fe & Fr (InP - LiP): 1.2	Man (LiP - CrP): 0.5 OFr (RuC - CrP): 0.21	6 3
Yu -a	Re	Lujiang County, China	An	2008	kt / a	8.31	2.65	32	CrP (Soil): 2.6	31	Fr (InP - CrP): 5.6	Man (LiP - CrP): 2.3 RSt (CrP - CrP): 1.07 OFr (RuC - CrP): 0.73	28 13 9

Yu -b	Re	Chaohu City, China	An	2008	kt / a	8.52	3.25	38	AgP (Soil): 2.48	29	Fr (InP - CrP): 1.35	Man (LiP - CrP): 1.05 OFr (RuC - CrP): 0.44	12 5
Wu	Re	Feixi, China	SoEc	2008	kt / a	19.15	3.70	19	CrP (Soil): 3.66	19	LiEx (LiP - CrP): 5.25	Man (LiP - CrP): 6.01 OFr (RuC - CrP): 0.54	31 3
Ne08	Re	Linkoping, Sweden	FoP & C	2000	kg / cap /a	2.095	0.75	36	CrP (Soil): 0.72	34	Fe (CrP - LiP): 3	Man (LiP-CrP): 1.8 OFr (Wm-CrP): 0.12	86 6
Do	Re	Hanam, Vietnam	RuA	2008	kt / a	0.12	0.055	46	La : 0.021 CrP (Soil): 0.018	17 15	Fe (ITC - LiP): 0.044	Man (LiP - CrP): 0.011	9
Ma	Co	China	An	1984-2008	kt / 25 y	167300	43000	26	AgP (Soil): 38300	23	Waste (C - Wm): 138300	OFr (Wm - AgP): 78700	47
Su	Co	US	Fo	2007	kt / a	5616	1615	29	LiP (Pasture): 943 CrP (Soil): 672	17 12	Mo (MiP - InP): 3771	Man (LiP - CrP): 422 Fe (FoPr - LiP): 121	8 2
Sm	Co	Netherlands	Ag, Ip & Ho	2005	kt / a	108	60	56	AgP (Soil): 31.4	29	Fe (InP - LiP): 44.4	Man (LiP - CrP): 54.8	51
Gh	Co	Malaysia	An	2007	kt / a	218	-	-	-	-	De (InP - HoC): 129	No recycling reported	-
Se	Co	Turkey	An	2001	kg / cap / a	4.33	0.28	7	La: 0.21	5	CrPr (AgP - ITC): 1.8	No recycling reported	-
Je	Co	South Korea	Dom	2005	kt / a	380	303	80	AgP (Soil): 125 Pr/by-Pr: 70.2 Sw (La): 52 Slag : 35.7	33 23 14 9	Fr (InP - AgP): 163	Man (LiP - CrP) : 36 OFr (Wm - AgP): 8.5	9 2
Mat	Co	Japan	Dom	2002	kt / a	747.8	692.1	93	AgP (Soil): 376 Slag: 93.1 La: 91.7	54 14 13	Fr (InP - AgP): 400.5	Man (LiP - CrP): 145.2	19
Ant	Co	Finland	Ag & Fo	1995-1999	kt / a	33.3	27.1	81	AgP (Soil): 23.7	71	Fr (InP - AgP): 29.5	Man (LiP - CrP): 15.9 Fe (FoPr - LiP): 6.2	48 19
Sh	Co	Centre, France	Ag	2002-2006	kg / ha /a	17.1	0.9	5	CrP (Soil): 0.9	5	P uptake (Soil - Crop): 20.2	RSt (CrP - Soil): 4 Man (Li - Soil): 4.2	23 25
		Brittany, France				38.8	17.7	46	LiP (Soil): 17.1	44	LiEx (LiP - Soil): 29.1	Man (Li - Soil): 29.1	75
Ot	MCo	EU	An	2006-2008	kg / cap /a	5.3	4.13	73	AgP (Soil): 2.9 Wm : 1.4	55 26	Fr (ITC - AgP): 2.7	OFr (Wm - AgP): 0.76	14

[1, 2, 3, 4] Details are same as stated for **Table 2.1.**

[5, 6, 7] AgP: Agricultural (crop and livestock) production; C: Consumption; CrP: Crop production; CrPr: Crop products; De: Detergent; Fe: Feed (livestock); FoPr: Food processing; Fr: Fertilizer; EcoStor: Ecosystem storage; HoC: Household consumption; InP: Industrial production; ITC: Industry, trade and commerce; La: Landfill; Li: Livestock; LiEx: Livestock excreta; LiP: Livestock production; Man: Manure; MiP: Mine production; Mo: Mineral ore; OFr: Organic fertilizer; Pr/by-Pr: Products/by-products; ReW: Reclaimed water; RSt: Recycled straw; RuC: Rural consumption; SeTP: Secondary treatment plant; SH: Sludge handling; Slag: Steelmaking slag; Sl: Sluge; STP: Sewage treatment plant; Sw: Solid waste; UrC: Urban consumption; UrL: Urban Landscape; Waste: (solid and liquid); Wm: Waste management; Ww: Wastewater.

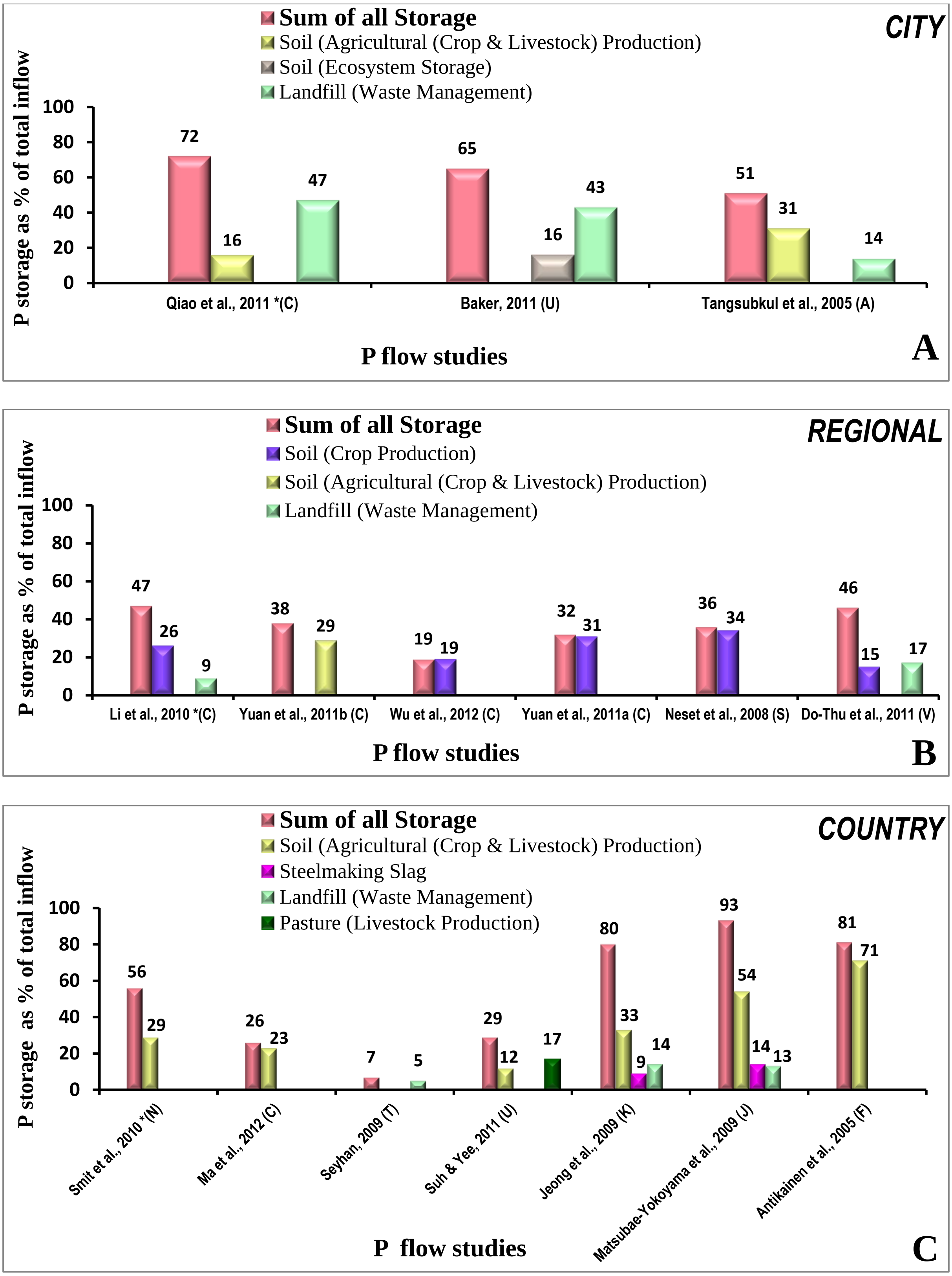


Fig. 2.4 Key places or components of P storage at the (A) city, (B) regional, and (C) country scales. Details of the studies are available in **Table 2.2**. *( ): country of study indicated by the letter within the brackets in the horizontal axis - A: Australia; C: China; F: Finland; J: Japan; K: South Korea; N: Netherlands; S: Sweden; T: Turkey; U: US; V: Vietnam.

2.3.3.2. Key P recycling flows

The assessment of the key P recycling flows at different geographical scales as presented in **Fig. 2.5** has revealed that in most of the reviewed studies, recycling flows have been identified to account for only a small proportion of the total P inflow, and even in some cases, P recycling was entirely absent. In only one (Tangsubkul et al., 2005) of the four reviewed city scale analyses (**Fig. 2.5A**), total P recycling has been identified to account for close to 50% of the total inflow, while it accounts for only 1% (0.05 kt P), 6% (0.033 kt P) and 25% (1.55 kt P) of the total inflow respectively in the studies of Baker (2011), Neset et al. (2010) and Qiao et al. (2011). Organic fertilizer from the waste management to the agricultural production sector has been identified to be the main P recycling flow in almost all the studies at this scale, where it has been observed to occupy about 23% (1.33 kt) and 16% (1.01 kt) of the total P inflow respectively in the analysis by Tangsubkul et al. (2005) of Sydney for 2000 and Qiao et al, (2011) of Beijing for 2008.

The majority of the P recycling at the regional scale has been identified to occur as manure from the livestock production to the crop production sector, where it accounts for about 86% (1.8 kg/cap), 31% (6 kt) and 28% (2.3 kt) of the total inflow of P respectively in Linkoping, Sweden in 2000 (Neset et al., 2008), in Feixi, China in 2008 (Wu et al., 2012) and in Lujiang county, China in 2008 (Yuan et al., 2011a). In other reviewed studies (Li et al., 2010; Yuan et al., 2011b; Do-Thu et al., 2011) at this scale, total recycling of P has been found to occupy less than 20% of the total inflow. P recycling as organic fertilizer from the waste management to agricultural production sector has been identified to be the second main recycling flow at this scale, where it accounts for less than 10% of the total inflow in all the studies (**Fig. 2.5B**).

In five of the eight reviewed country scale analyses as presented in **Fig. 2.5C**, total recycling of P has been observed to account for less than 20% of the total inflow, where recycling of P has been found to be entirely absent in the P flow analyses by Seyhan (2009) of Turkey for the year 2001 and by Ghani and Mahmood (2011) of Malaysia for 2007. In three other studies (Smit et al., 2010; Ma et al., 2012; Antikainen et al., 2005), total recycling of P has been found to be nearly or more than 50% of the total inflow. Manure from the livestock production to the crop production sector has been identified to be the key recycling flow in two studies, where it accounts for about 51% (54.8 kt) and 48% (15.9 kt) of the total annual inflow respectively in the Netherlands in 2005 (Smit et al., 2010) and in Finland between 1995-1999 (Antikainen et al., 2005).

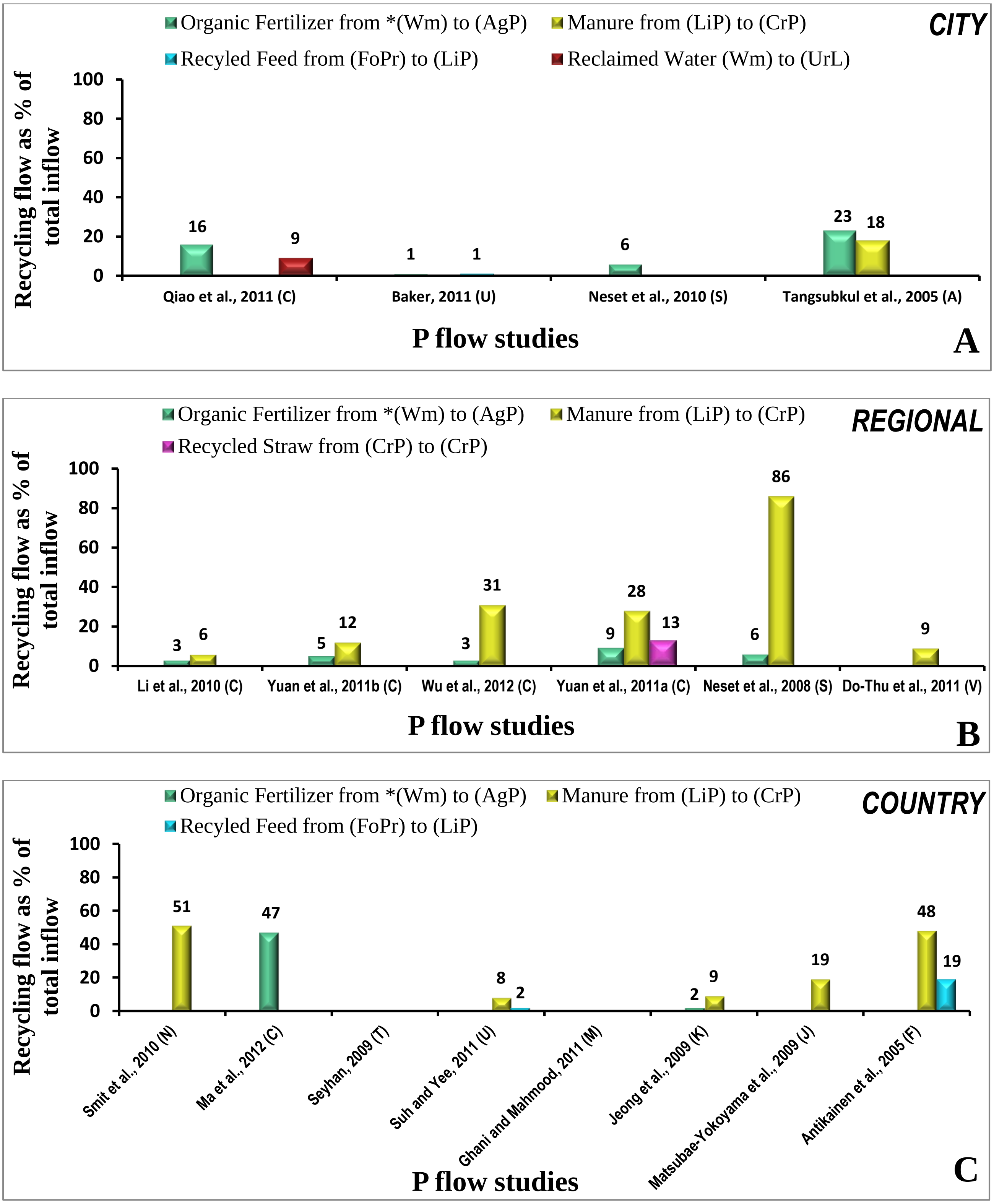


Fig. 2.5 Key P recycling flows at the (A) city, (B) regional, and (C) country scales. Details of the studies are available in **Table 2.2**. *( ): sector indicated by the abbreviation within the brackets in the legend - AgP: Agricultural (Crop and Livestock) Production; CrP: Crop Production; FoPr: Food Processing; LiP: Livestock Production; UrL: Urban Landscape; Wm: Waste Management.

2.4. Knowledge gaps

Along with the identification of priority areas of P flow at different geographical scales, this review has identified the knowledge gaps in the available analyses of P flow. Among all the geographical scales, the regional and the multiple country scales have been found to receive a limited attention in the available studies. The regional scale is much more important in terms of P flow as it considers the agricultural (both crop and livestock) production sector. Generally, the majority of the P that enters as mineral ore or chemical fertilizer into a country is utilized in the agricultural sector. Moreover, most of the P storage resides in the soil of this sector, and the majority of the P outflow occurs either as food and agricultural products, or as erosion and leaching from this sector. It is recommended that the regional scale should receive more attention in the future analysis of P flow.

This review has also revealed that in most of the studies at different geographical scales, there have been a limited number of multiple year P flow analyses particularly at the city and regional scales (**Fig. 2.6**). It is evident that there is a gap of knowledge about the fate and magnitude of P flow over multiple years at the city and regional scales, and the temporal impact of natural processes such as acute erosion, floods, droughts, and bush fire limit the wider interpretation of this information. In addition; socioeconomic, political, and technological decisions may take many years to become apparent. For instance, Ma et al. (2012) in a country scale analysis of P flow over 25 years (1984-2008) in China identified that different socioeconomic variables such as urbanization, improved living standards and growth of population were responsible for increasing the magnitude of the P flows related to ore extraction, use and waste generation, and decreasing the recycling ratio of P in wastes. They recognized, financial and policy support along with technological advancement greatly promoted the progress of P fertilizer industry in China which ultimately transformed the country from a net P importer into a net P exporter after 2000. Another important finding of their study was the identification of anthropogenic P storage in China between 1984-2008, which include respectively 38,300, 19,000 and 105,300 kt P in agricultural soil, natural water and natural soil. Again, Neset et al. (2010) in a city scale analysis of historical P flow of Linkoping, Sweden for the period 1870-2000 identified that changes in sanitation arrangements significantly influenced P flow. They observed, the rate of productive reuse of P varied markedly over the period from a very high level up until the 1920s to almost nil around 1950, and then resuming after the introduction of a P removal unit at the wastewater treatment plants and sludge use in agriculture from the 1970s, followed by a sharp decline at the end of the 20th century due to the rejection of sludge use by Swedish Farmers Union. Therefore, it is evident that knowledge of long-term fate and magnitude of P flow through system is essential for making better P management decisions.

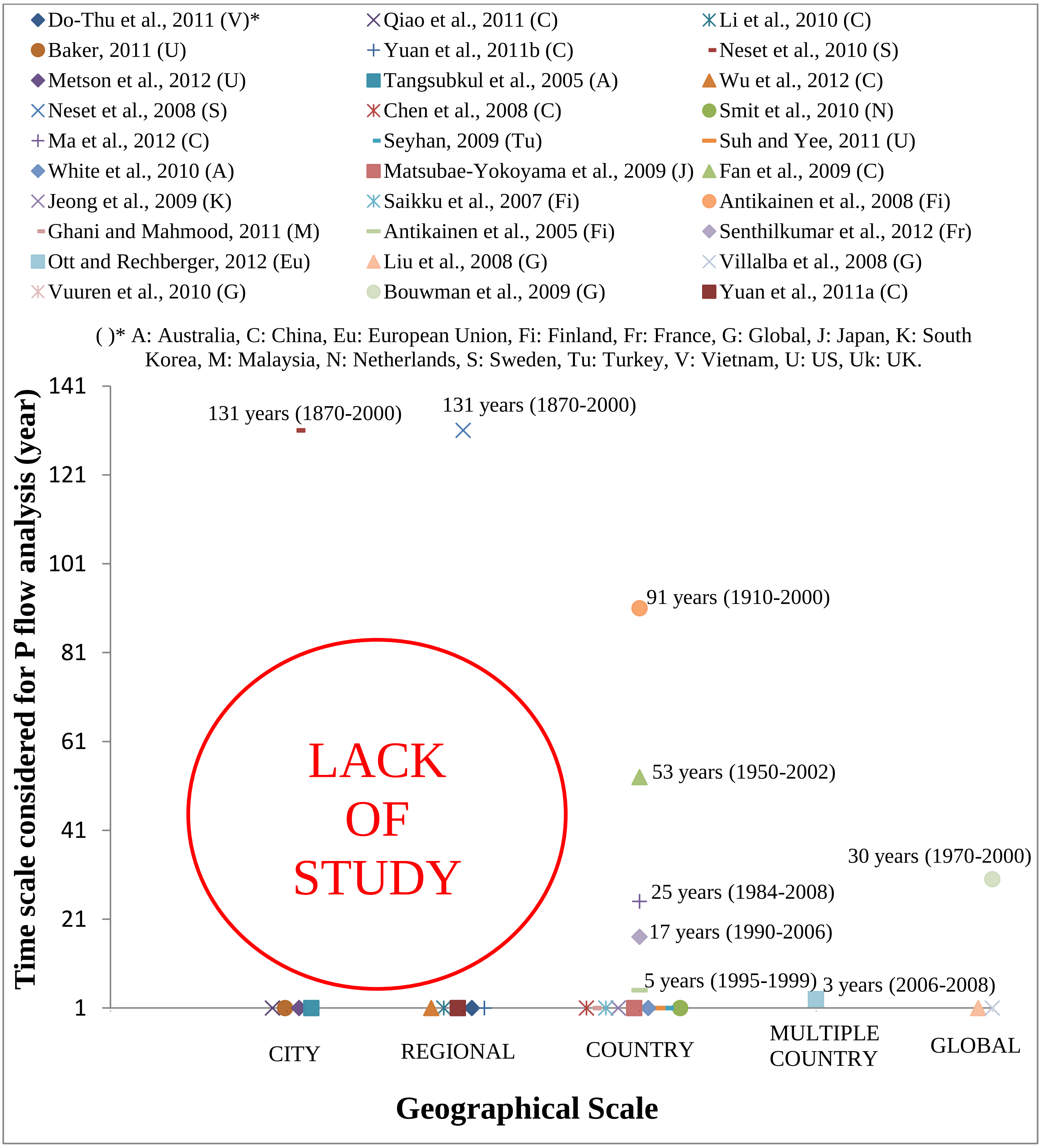


Fig. 2.6 Spatial and temporal distribution of reviewed P flow analyses.

2.5. Limitations of this review

This review has considered the major P flows and storage, and minor flows and storage have been omitted in most cases. Clearly some minor inflows, outflows, and storage could also play significant role in polluting the environment and causing resource scarcity, if considered over longer periods and viewed from strict environmental policy and resource management perspective. Thus, as identified in different analyses, some minor P inflows such as asphalt, concrete, paper and cardboard (Metson et al., 2012), atmospheric deposition (Yuan et al., 2011a; Ott and Rechberger, 2012; Metson et al., 2012; Wu et al., 2012), coal (Matsubae-Yokoyama et al., 2009; Jeong et al., 2009; Yuan et al., 2011a; Wu et al., 2012), iron ore (Matsubae-Yokoyama et al., 2009; Jeong et al., 2009), pet food (Baker, 2011), pesticides and seeds (Yuan et al., 2011a, 2011b; Wu et al., 2012); minor P storage as stored in urban non-residential soil, pets (Metson et al., 2012), septic tanks (Baker, 2011); minor P outflows as leaching from soil to groundwater (Metson et al., 2012), leaching from landfill (Ott and Rechberger, 2012), straw or crop waste (Yuan et al., 2011b; Wu et al., 2012), steel (Matsubae-Yokoyama et al., 2009; Jeong et al., 2009) along with their spatial distribution should also receive better attention for future P management decisions. Additionally, the SFA information that have been used from different studies were originally collected and calculated from a diverse range of data sources which undoubtedly contain a range of assumptions and procedure while collecting and preparing data. Thus, there are likely to be range of uncertainties around the data utilized and the current review has not attempted to assess the impact of this variability.

2.6. Specific research objectives

This review has revealed that the regional scale (a key geographical scale in terms of the magnitude of P flow) has received a limited attention in the available P flow analyses, and there is also lack of multiple year analysis of P flow at this scale. Therefore, the current research will focus on the quantitative analysis of P flow over multiple years at the regional scale. The specific objectives of this research include:

a) Develop a generic regional scale P flow model that can be utilized to

- Analyse the nature and magnitude of P flows and storage relating to all potential systems and subsystems of P use at the regional scale;
- Analyse P flows and storage over multiple years at the regional scale.

b) Utilize the model for the analysis of P flow in a particular case to

- Assess the nature and magnitude of P flows and storage over multiple years in all the potential systems and subsystems of P use;
- Suggest effective P management decisions towards achieving P sustainability.

This chapter concludes that in order to obtain essential information for making better P management decisions towards achieving global P sustainability, there is an urgent need for research to assess the nature and magnitude of P flow over multiple years at the regional scale. The next chapter describes the procedures that have been followed to perform the quantitative modelling of multi-year P flow at the regional scale.

Chapter-3

METHODS OF ANALYSIS

This chapter presents a detailed description of the methods utilized in this study for the quantitative modelling of multi-year P flow at the regional scale. It consists of two main sections viz. *method used for the quantitative modelling of multi-year P flow at the regional scale*- which briefly describes the method 'substance flow analysis (SFA)' that is commonly used for the quantitative modelling of flows and storage of substance in a system, and *Application of the SFA method in this research*-which provides a detailed description of how the SFA method has been applied in the current research to carry out the quantitative modelling of P flow over multiple years at the regional scale. This section includes defining the system and system boundaries, selecting the key subsystems, processes and materials of P flow and developing conceptual framework for the model, explaining the software tool selected for modelling and the procedure of model construction in that software platform, describing the case study area, explaining the criteria used for collecting and defining the reliability of data, presenting the data along with defined reliability, and explaining the approach utilized to get accurate and reliable results from the modelling.

3.1. Method used for the quantitative modelling of multi-year P flow at the regional scale

In order to perform the quantitative modelling of the multi-year P flow at the regional scale, the method of SFA has been utilized in this study. As mentioned earlier in **Section 2.2.**, SFA applies the mass-balance principle for a systematic quantitative analysis of flows and storage of a material within a system defined in space and time, and therefore, it helps to identify useful information for making effective resource management decisions (Brunner and Rechberger, 2004). SFA can be applied as a basic tool for quantitative analysis in diverse fields such as environmental management and engineering, industrial ecology, resource management, and waste management. As an effective decision support tool for P management (Brunner, 2010), in the recent times, numerous studies from around the world have adopted SFA for the quantitative analysis of P flow in different systems. The procedure of SFA has been described in several literature, and there is no hard and fast rule about the procedure of SFA except the application of the mass-balance principle. In this study, a brief and 'classical' explanation of the SFA method has been provided according to the "Practical Handbook of Material Flow Analysis" by Brunner and Rechberger (2004) as follows:

3.1.1. Terminology of SFA

In order to generate reproducible and transparent results, and to ensure effective communication; it is necessary to define the key 'terms' of SFA. The key relevant 'terms' as used in the study have been explained as follows:

3.1.1.1. Substance

Any chemical element or compound that is made up of uniform units and can be characterized by a unique and identical constitution is termed as a substance. For instance; phosphorus, carbon are substances.

3.1.1.2. Material

A material is composed of different substances. An example of this is wood. Wood is composed a number of substances such as cellulose, carbon, hydrogen, oxygen, and many others. Food, soil, and wastewater are other examples of material.

3.1.1.3. Process

The means of transformation, transport, or storage of materials or substances can be termed as a process. For instance; plant photosynthesis, transpiration, rainfall runoff, soil erosion, decomposition of organic matter in soil are different processes. Generally in the SFA literature, processes are regarded as ‘black box’ indicating sub-processes are not taken into account and only the inflows and the outflows are of interest. If this is not the case, then the process should be disaggregated into sub-processes, which allows the analysis of the functions of the overall process in more detail (**Fig. 3.1**). An exception to the ‘black box’ approach is a type of process that is used to explain the quantity of substances within a process. For explaining such quantity, both the total amount of substances stored in the process that is the ‘stock of substances’ and the rate of stock change over unit time that is the ‘accumulation or depletion of substances’ are essential parameters. The process in which the substances have very long residence times (in an anthropogenic sense, more than 1000 years) could be termed as a ‘final sink’.

3.1.1.4. Flow

A flow is the mass movement of a substance per unit time across a system boundary. For each flow, it is necessary to define a ‘process of origin’ and a ‘process of destination’. Flow that enters in a system is called inflow and the associated process is called import process, and flow that leaves the system is called outflow and the associated process is called export process (**Fig. 3.2, Fig. 3.3**). For instance, food intake by which a substance (e.g. phosphorus) enters the human body is import process (inflow) and excretion by which that substance (e.g. phosphorus) leaves the human body is export process (outflow).

3.1.1.5. System and system boundaries

A system can be defined by a group of physical components, their interactions and the boundaries between these and other components in space and time. In SFA, the physical components are termed as processes and the interactions among processes can be expressed by flows. A system can be represented with a single process or a combination of various processes. Proper definition of the system is important in SFA because inappropriate system definition can give inaccurate results.

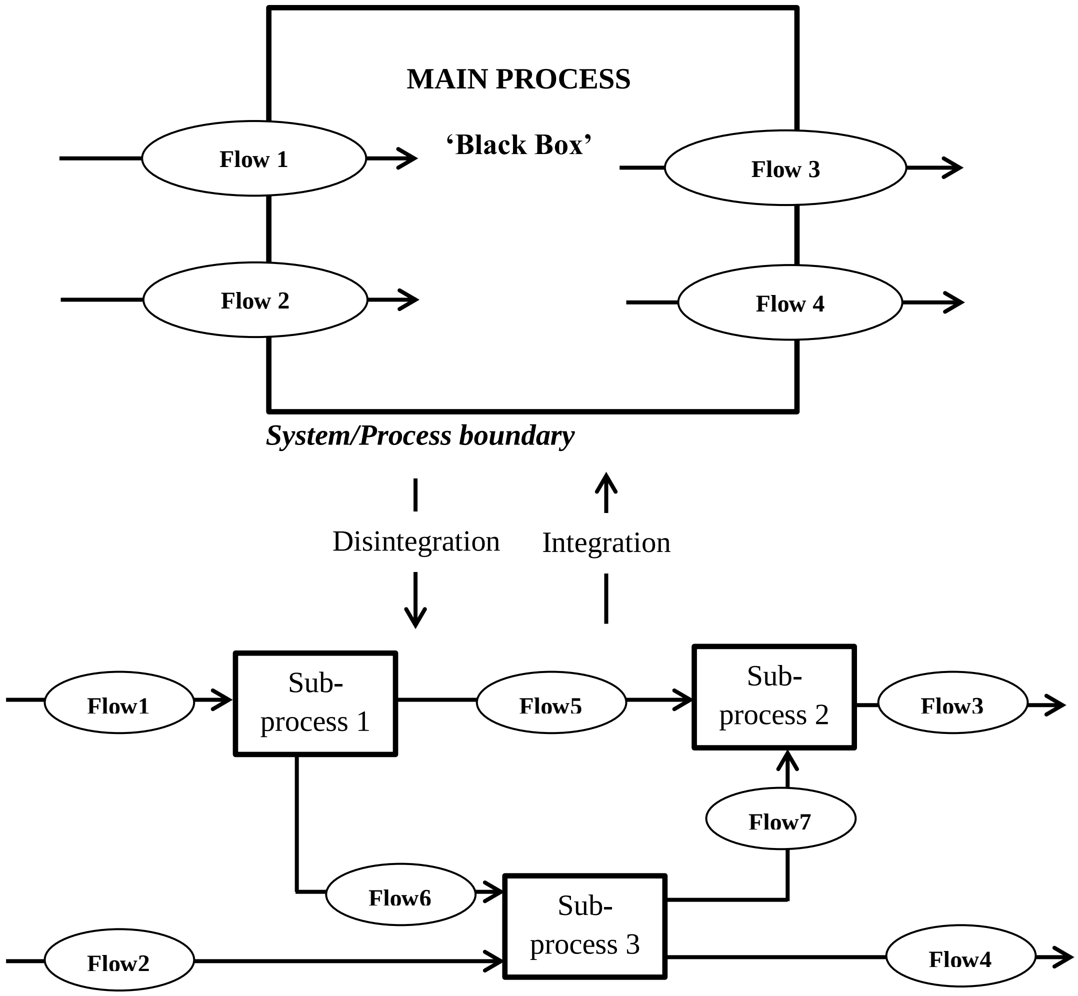


Fig. 3.1 Opening up a 'Black Box' by disintegrating a single process into a number of sub-processes which gives additional information about the black box (adapted from Brunner and Rechberger (2004)).

Temporal and spatial scales are used to define the system boundary. The selection of the temporal and spatial scale for defining the system boundary depends on the type of system considered and the purpose of the analysis. Temporal boundary is the time period over which the flows and storage of a substance within a system are analysed and balanced. In case of anthropogenic systems like an industry, city, region, or a country, one year period is usually chosen for better data availability because financial accounting and other reporting of government and non-government institutions are normally done on an annual basis. The spatial boundary of a system is generally determined on the basis of the geographical area in which the processes of a system are situated. For instance, a spatial boundary of a system can be the geographical or political boundary of a town, region, country, continent, or the Earth. Defining spatial boundary vertically is also essential for many studies. Generally, the first 500 m of atmosphere above the Earth's surface is considered as vertical spatial boundary because the main exchange of air (containing atmospheric pollutants) between regions occur within this layer.

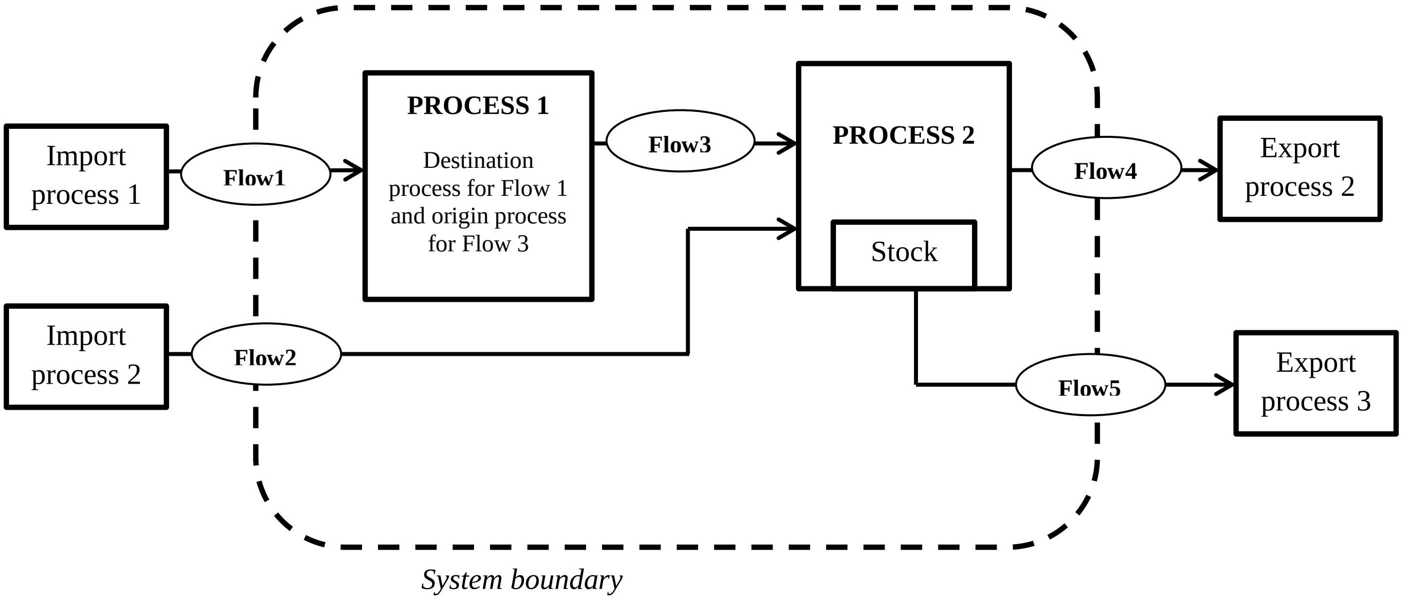


Fig. 3.2 A schematic representation of process, import process, export process and system boundary (adapted from Brunner and Rechberger (2004)).

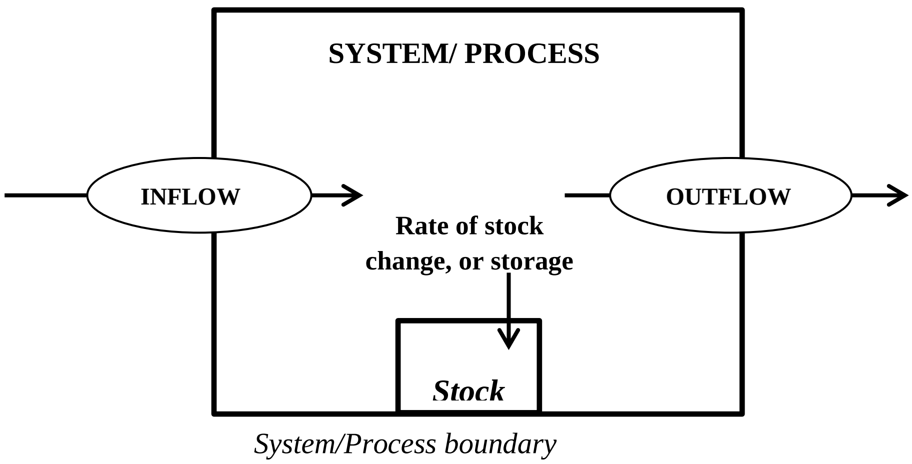


Fig. 3.3 A schematic representation of inflow, outflow and stock related to a system/process.

3.1.2. Procedure of SFA

SFA is carried out in a number of steps as presented in **Fig. 3.4**. It is not required to follow these steps in a strictly consecutive manner. There is a need for continuous revisions of selections and provisions that are made during the course of SFA. Sometimes, going back to the previous steps or repetition of the steps may be required to get better outcomes. One can start with rough estimates and provisional data, and then need to continually revise and improve the system and data to obtain better results. The key steps of SFA are briefly described as follows:

3.1.2.1. Definition of the problem, setting of goals, and selection of substance

SFA aims to produce useful information for making appropriate decisions to solve resource management problems. The problems to be managed need to be specified at the beginning along with the goals to be achieved. Substances that are of high economic and environmental importance and faces greater resource management problems are usually considered for SFA.

3.1.2.2. Definition of system in space and time

The system and system boundary for SFA should be selected to be as small and concise as possible but in a way that warrants the inclusion of all essential subsystems, processes as well as significant flows of the substance under consideration. The spatial boundary of the system is generally determined on the basis of the scope of the project. Usually, the politically defined area (for instance, administrative area) or an area that is defined on hydrological features (for instance, a catchment area of a river) is chosen for selecting spatial boundary. However, the advantage of defining system boundaries as administrative areas such as countries, states, cities, is that on these scales, the required data for SFA can be collected systematically. Another key benefit of selecting administrative areas as system boundary is that the political and administrative stakeholders often reside within such boundary, which eventually allows the outcomes of SFA to be implemented more easily in such areas.

Temporal boundaries should be determined at a time scale on which the key flows and stocks (in terms of quantity) of the substance under consideration become effective and meaningful, and the actual picture of the nature and magnitude of substance flow in a system is identified. Depending upon the purpose of the analysis as well as on the type of substance, the temporal boundary could be shorter or longer. Consideration of longer time scale may allow overcoming the short term changes and unsteadiness of the system, whereas shorter time scale may allow identifying the short-term anomalies and non-linear flows.

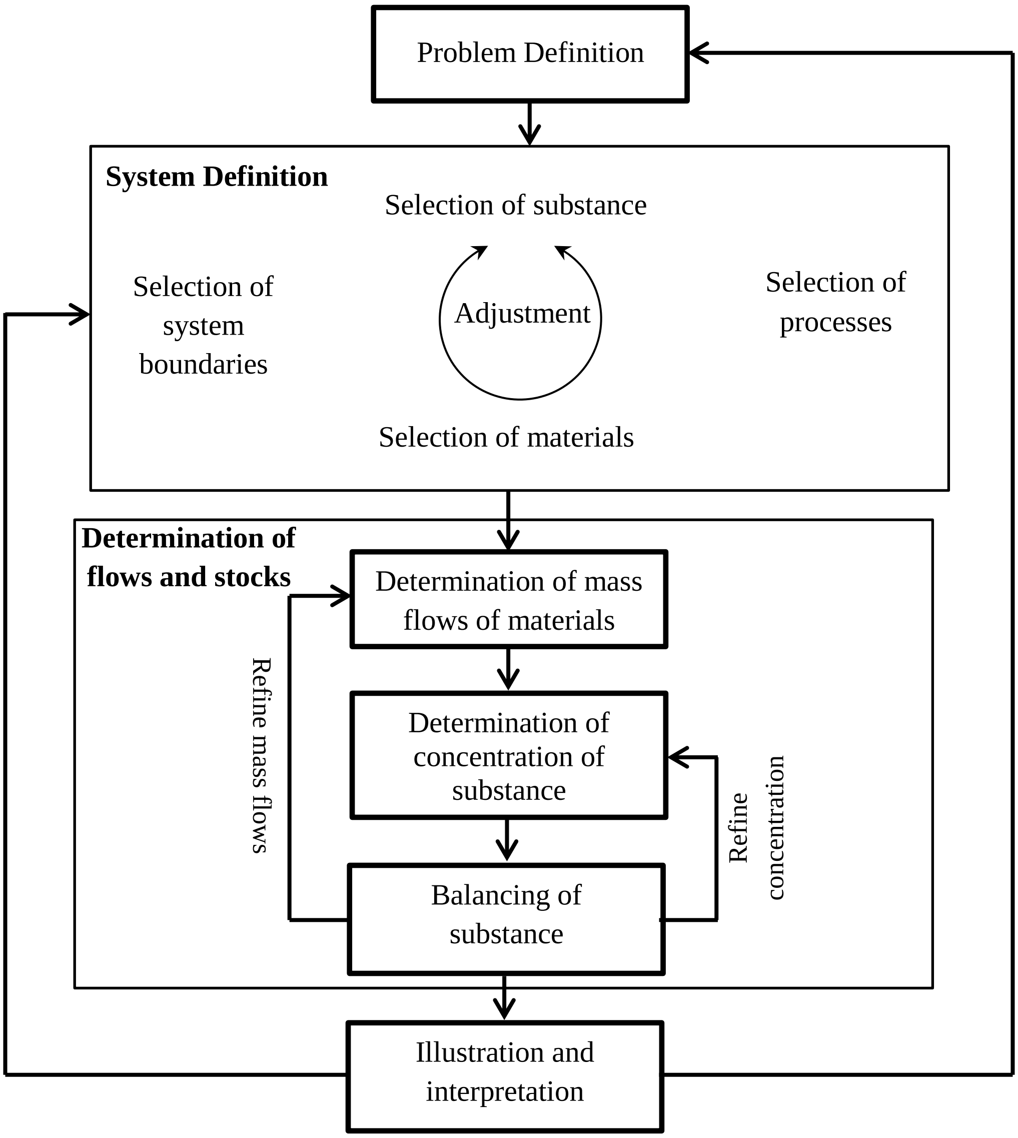


Fig. 3.4 A schematic representation of procedure of SFA (adapted from Brunner and Rechberger (2004)).

3.1.2.3. Identification of relevant flows, stocks, and processes

After the selection substance and system and system boundaries, the next step is to identify the relevant flows, stocks, and processes. Information regarding these can be found from relevant academic literature. Contacting experts in the relevant field, resource managers, or visiting government organizations can also help to identify relevant flows, stocks, and processes for SFA study. Usually, the number of processes required to explain the system depends on the purpose of analysis as well as on the complexity of the system. Processes can be subdivided into subprocesses, and a number of processes can be integrated into a single process. While selecting processes, it should be kept in mind that the purpose of SFA is to build simple and reliable models to portrait the reality. To mathematically explain; suppose, $\dot{S}$ is the mass flow of substance in a particular flow and k is the number of flows in a system or process. According to the principle of mass balance, the total mass of all input flows of substance into a system/process equals the mass of all output flows of substance of that system/process plus the mass of the net storage of substance that considers either accumulation or depletion of substance in that system/process in a given time period. Therefore, this principle could be mathematically expressed as follows:

$$\sum_{k_i} \dot{S}_{input} = \sum_{k_o} \dot{S}_{output} + \dot{S}_{storage} \qquad \text{(Equation: 3.1)}$$

However, it should be noted that if the mass of inputs, outputs, and storage of a substance do not balance according to the **Equation 3.1**, then there must be some uncertainties associated with the results that originates from either missing flows or inaccurate calculations. Usually, net storage of substance within a system or process is determined by the difference between inputs and outputs in a given time.

3.1.2.4. Determination of mass flows, stocks, and concentrations

Information regarding mass flow of materials is generally collected from available databases or direct field measurements. International, national, and regional administrative authorities for instance; bureaus of statistics, other government and non-government organizations, industrial associations, professional networks and consumer association can be good sources of collecting mass flow data of materials. Data on emission of pollutants, concentration of substance in soil, water, air and other materials can be collected from international and national environmental protection agencies. Some data of this kind can also be collected from scientific journals, magazines, books, proceedings and other academic reports. The search for data and the collection, processing, and evaluation are fundamental tasks of SFA. Sometimes, in case of missing site specific data, mass flow data of materials can be assessed on the basis of assumptions, cross comparisons between similar systems, or proxy data that means data of one site is used as a proxy for another site. However, it is important to evaluate whether a proxy is suitable to be transferred from one site to another.

Depending upon the availability of time and financial resource and facilities for performing an SFA, mass flow of materials and concentration of substance can be actually measured by field investigation and laboratory analysis. However, if the system considered is too large and complex, and data needs to be collected for extended time period; such investigation becomes expensive and impractical.

3.1.2.5. Assessment of total substance flows and stocks

Mass flow (both inflow and outflow) of substance can be calculated through directly multiplying the mass flow of materials by the concentration of substance in these materials. To mathematically describe, let consider $\dot{S}$ is the mass flow of substance in a material, $\dot{m}$ is the mass flow of that material, and c is the concentration of the substance in that material, therefore mass flow of substance can be calculated by the flowing equation:

$$\dot{S}_i = \dot{m}_i \times c_i \quad \text{(Equation: 3.2)}$$

Where,

i = 1,…, k as the index for materials and

Stocks of substance within a system or process can be determined in two ways. In the first approach, the total mass of substance stock can be estimated either by direct measurement of the mass or by assessing the volume and the density of the stock. This method is usually applied to assess the stocks that do not change substantially for longer time period. In the second approach that is commonly used for the stock that changes quickly, the total mass of the substance stock can be calculated from the difference between the total mass of input flows and the total mass of output flows over an appropriate time span, and the known initial mass of stock at the beginning of the time. Suppose, $\dot{S}_{input}$ is the total mass inflow of a substance and $\dot{S}_{output}$ is the total mass outflow of that substance in a system in a time span of (t_0 to t); when the mass of stock (S_{stock}) of that substance in that system at the initial time t_0 is known, then total mass of stock at time t can be calculated from the following equation:

$$S_{stock}(t) = \int_{t_0}^{t} \dot{S}_{input}(\tau)d\tau - \int_{t_0}^{t} \dot{S}_{output}(\tau)d\tau + S_{stock}(t_0) \quad \text{(Equation: 3.3)}$$

However, due to a number of reasons such as the variability in data collected from various sources, missing data, and use of assumptions or proxy data, and errors in calculations; there could be a certain degree of uncertainty associated with the outcomes of SFA. While performing the analysis, careful attention should be paid to minimize these shortcomings.

3.2. Application of the SFA method in this research

The procedure of SFA method as described in **Section 3.1.2** has been systematically applied in the current research. An explanation of the way in which the SFA method has been utilized in this research has been presented as follows:

3.2.1. Defining problem, goals and substance for analysis

In Chapters 1 and 2, the key problems associated with the traditional P management system were identified as increasing demand and dwindling available fossil P reserves, excessive wastage of P from different systems, and high discharge of P to water bodies and associated harmful consequences such as algal bloom and eutrophication. Therefore the goal of this SFA is to analyse the nature and magnitude of P flows and storage relating to all potential systems and subsystems of P use over multiple years at the regional scale to generate essential information for making effective P management decisions to overcome these problems and contribute towards P sustainability.

3.2.2. Defining system and system boundary

The P flow system in a region (mainly agricultural) within a country that includes the key subsystems in a regional scale as indicated in **Fig. 2.1** in the previous chapter has been considered as the system for the current modelling. As mentioned earlier, the administrative boundaries are commonly chosen as system boundaries for SFA because of better data availability. Somewhat unusually in global terms, the administrative boundary largely coincides with physical geographic boundaries of coasts and watersheds. However, the choice of boundary for P flow system may vary from one region to another depending upon the geographical location, administrative system, and political condition. The boundaries for P flow system should be chosen in a way that includes the key subsystems of P flow and key pathways of P inflows and outflows in a particular geographical scale to represent the real situation of P flow. As the current study focuses on developing a generic regional scale P flow model, it selects the system boundaries in a manner that better represents the typical P flow system in a regional scale as indicated in **Fig. 2.1** based on the review of available regional scale P flow analyses. However, the current model will be developed in a way that allows greater flexibility to modify the system boundaries according to purpose and needs of any case study. The temporal boundary in the model will be considered in a manner that in an annual time step, allows performing the analysis of P flow for as many as years required depending upon the purpose of the case study and data availability.

3.2.3. Identifications of key subsystems, flows and stocks

The key subsystems, processes (related to the main systems and different subsystems), and materials that account for a significant mass flow and storage of P, have been selected on the basis of the extensive review of available P flow analyses at the regional scale as presented in **Chapter 2**. The P inflows and outflows related to the main system and all various subsystems, as well as the interaction among subsystems in terms of P flow has been presented in **Fig. 3.5**. An example of a typical P flow pathway (through which P enters into the system, travels different subsystems within the system and finally leaves the system) has been presented in **Fig. 3.6**.

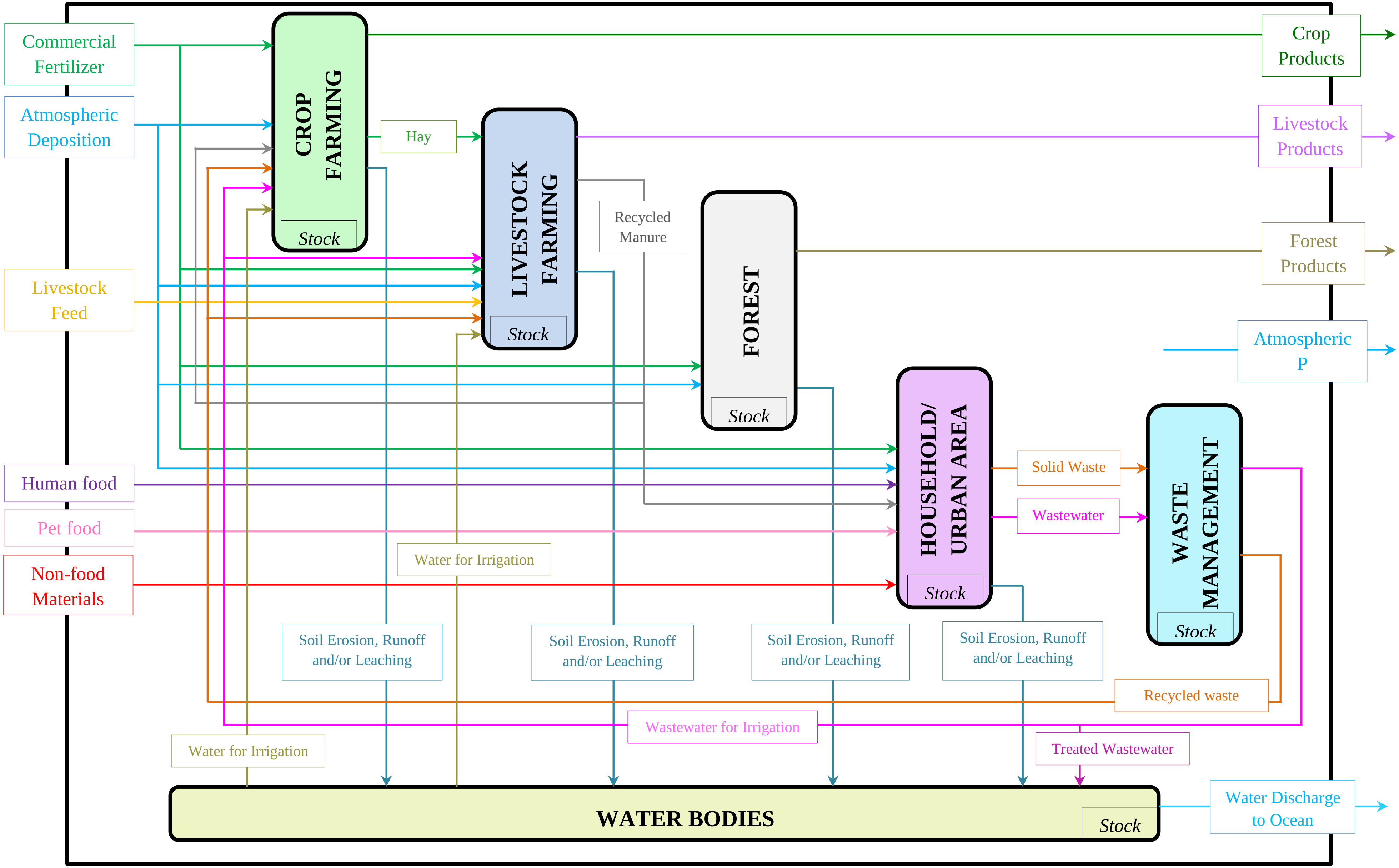


Fig. 3.5 Conceptual framework of P inflows and outflows of the main system and the interaction among subsystems in terms of P flow in a regional scale.

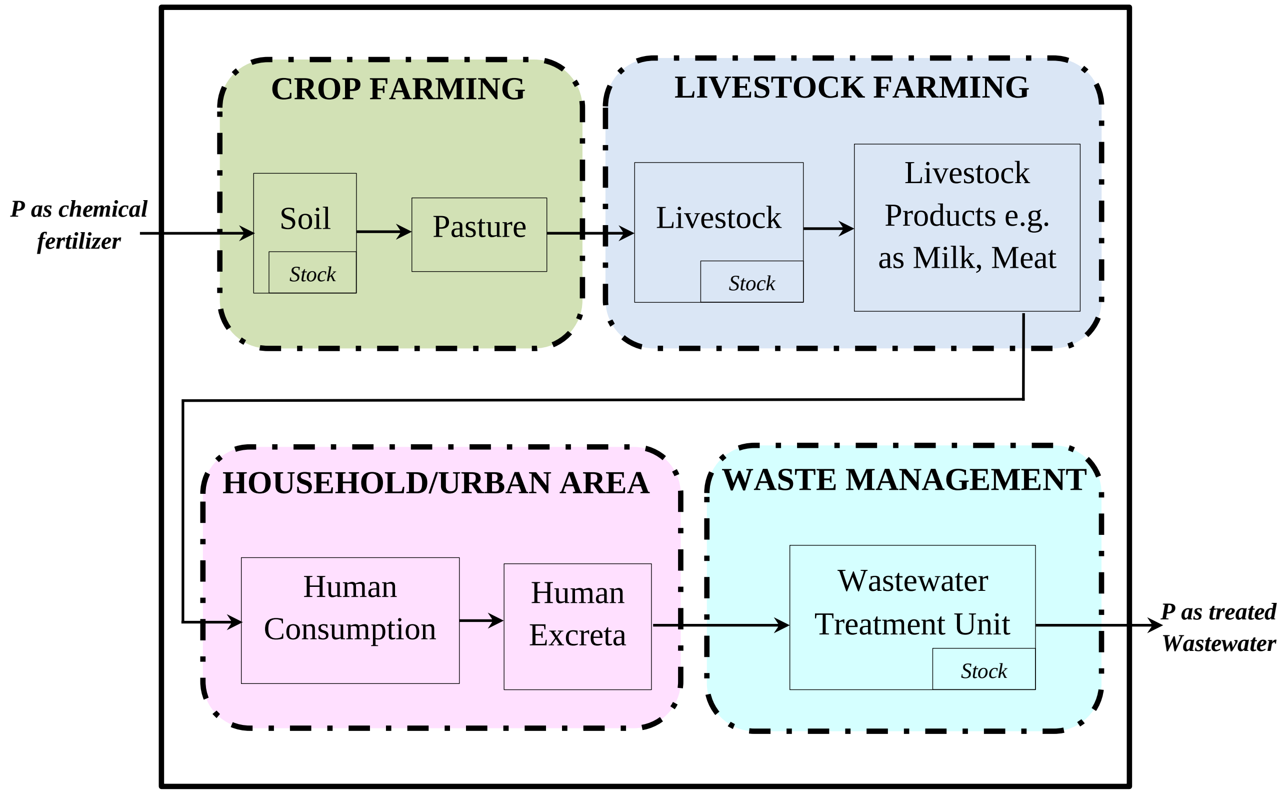


Fig. 3.6 Conceptual framework of a typical pathway of P flow through which P enters into the system, travels different subsystems within the system, and finally leaves the system in a regional scale. The main system consists of a number of such pathways of P flow.

The subsystems that have been considered for the current analysis include; crop farming, livestock farming, forest, urban and household, waste management, and water bodies. The key materials and processes in terms of P mass flow (inflow, outflow and storage) relating to different subsystems that are considered in this analysis, have been schematically presented in **Fig. 3.7** to **Fig.3.12**. The geographic boundary of each of the subsystems has been defined based on the general land uses and activities relevant to each of the subsystems. A brief description of these subsystems has been provided as follows:

3.2.3.1. Crop Farming

This subsystem includes the crop farming or planting areas dedicated to the production of cereal and non-cereal crops, pastures, and fruits and vegetables, as well as associated activities, processes, and flow of materials.

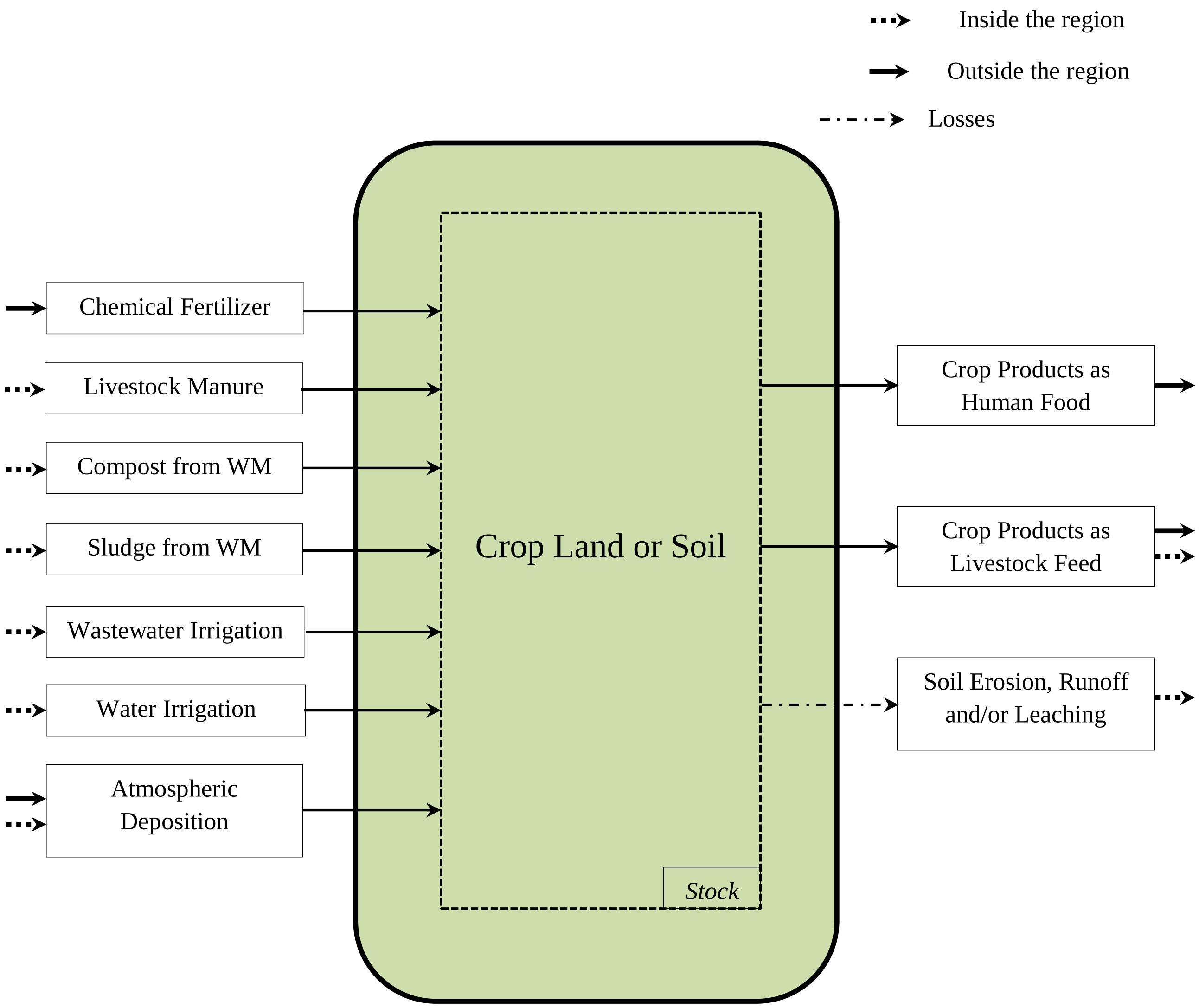


Fig. 3.7 Conceptual framework of P flows and storage of the crop farming system.

3.2.3.2. Livestock Farming

This subsystem includes the livestock farming areas dedicated to the farming of dairy cattle, meat cattle, sheep, pig, and chicken as well as associated activities, processes and flow of materials.

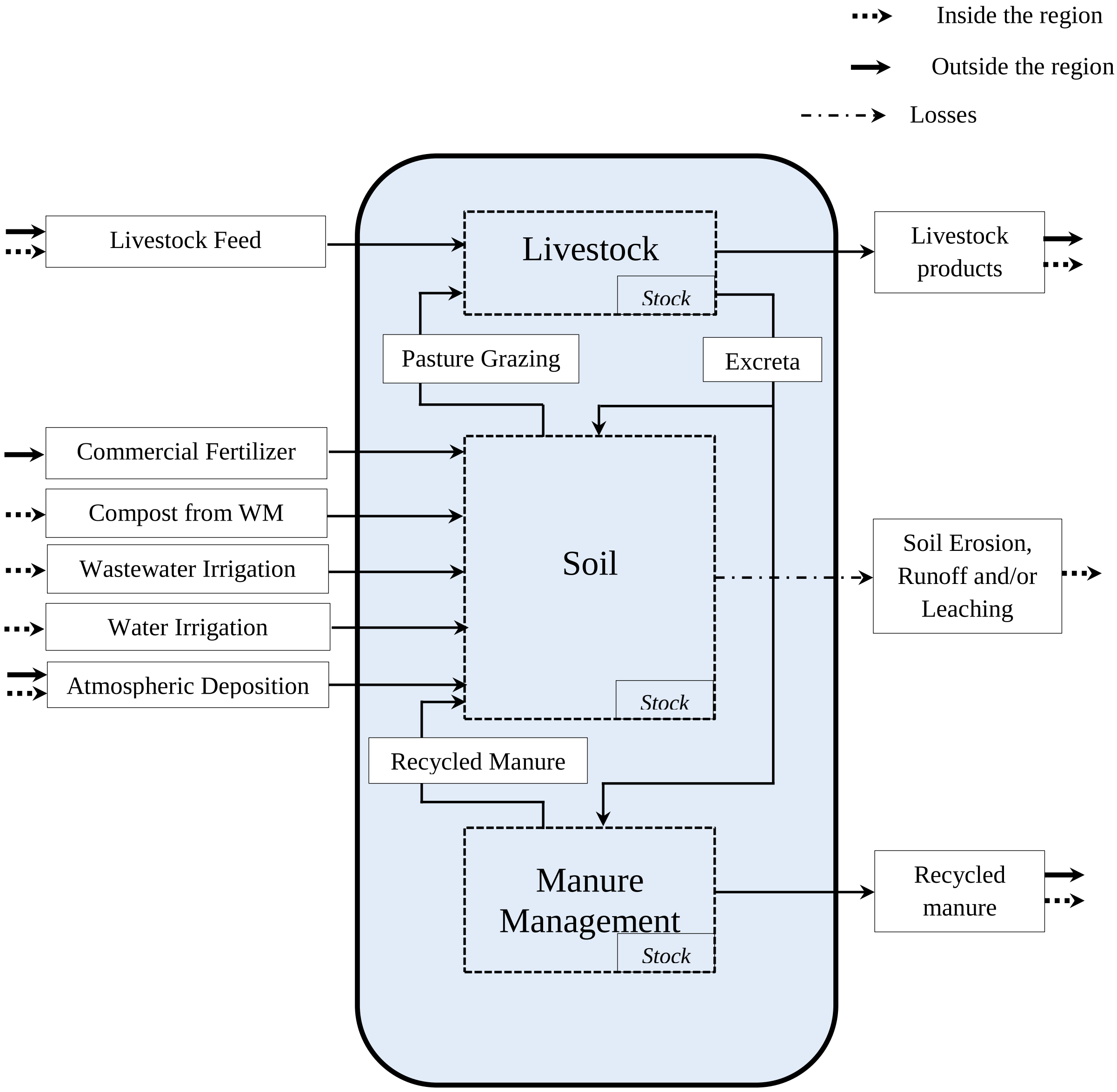


Fig. 3.8 Conceptual framework of P flows and storage of the livestock farming system.

3.2.3.3. Forest

This subsystem includes forest reserves, national parks, conservation areas, and timber plantation areas as well as associated processes and flow of materials.

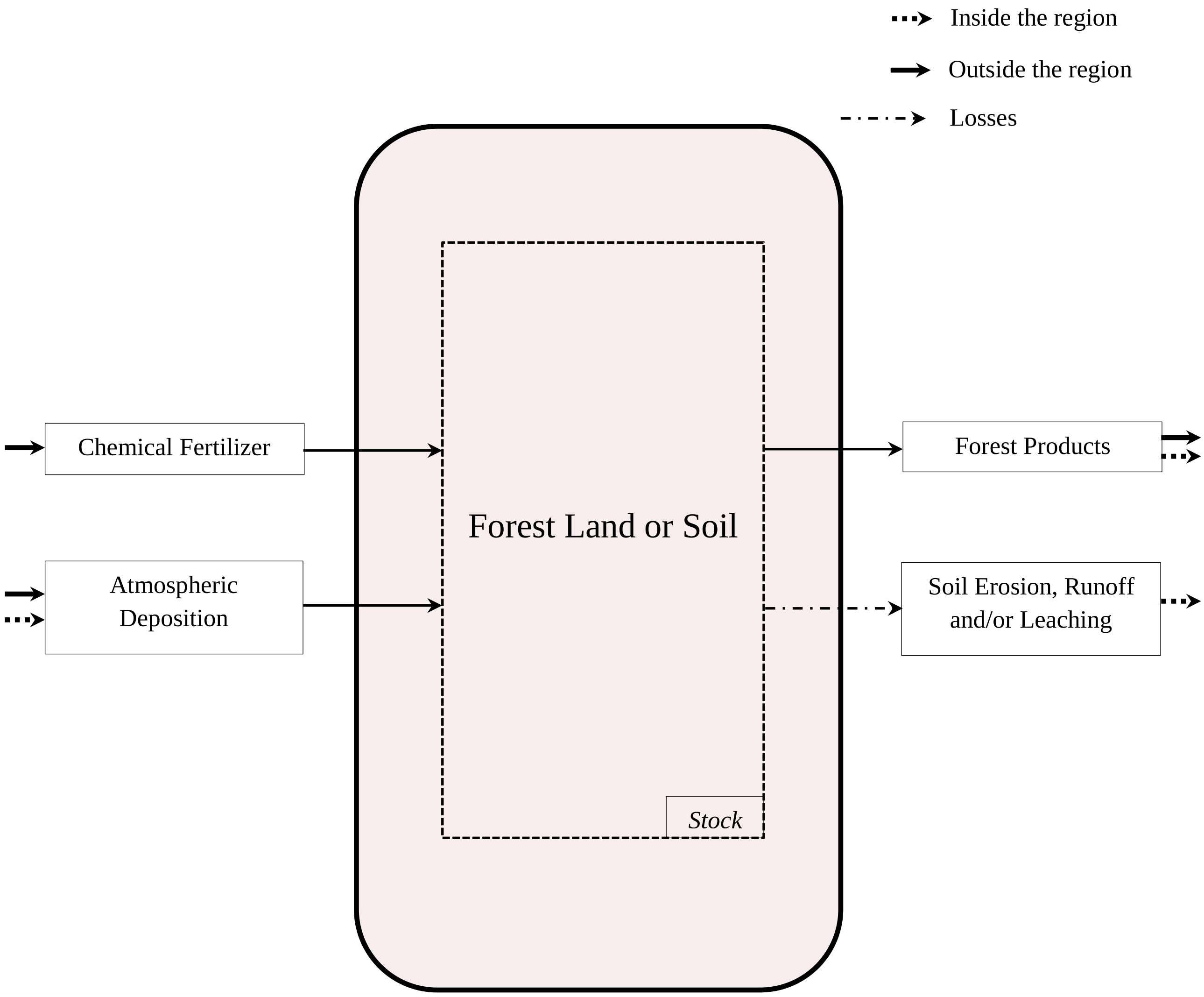


Fig. 3.9 Conceptual framework of P flows and storage of the forest system.

3.2.3.4. Household and urban

This subsystem includes all residential, commercial and industrial areas within urban landscape, as well as associated activities, processes and flow of materials.

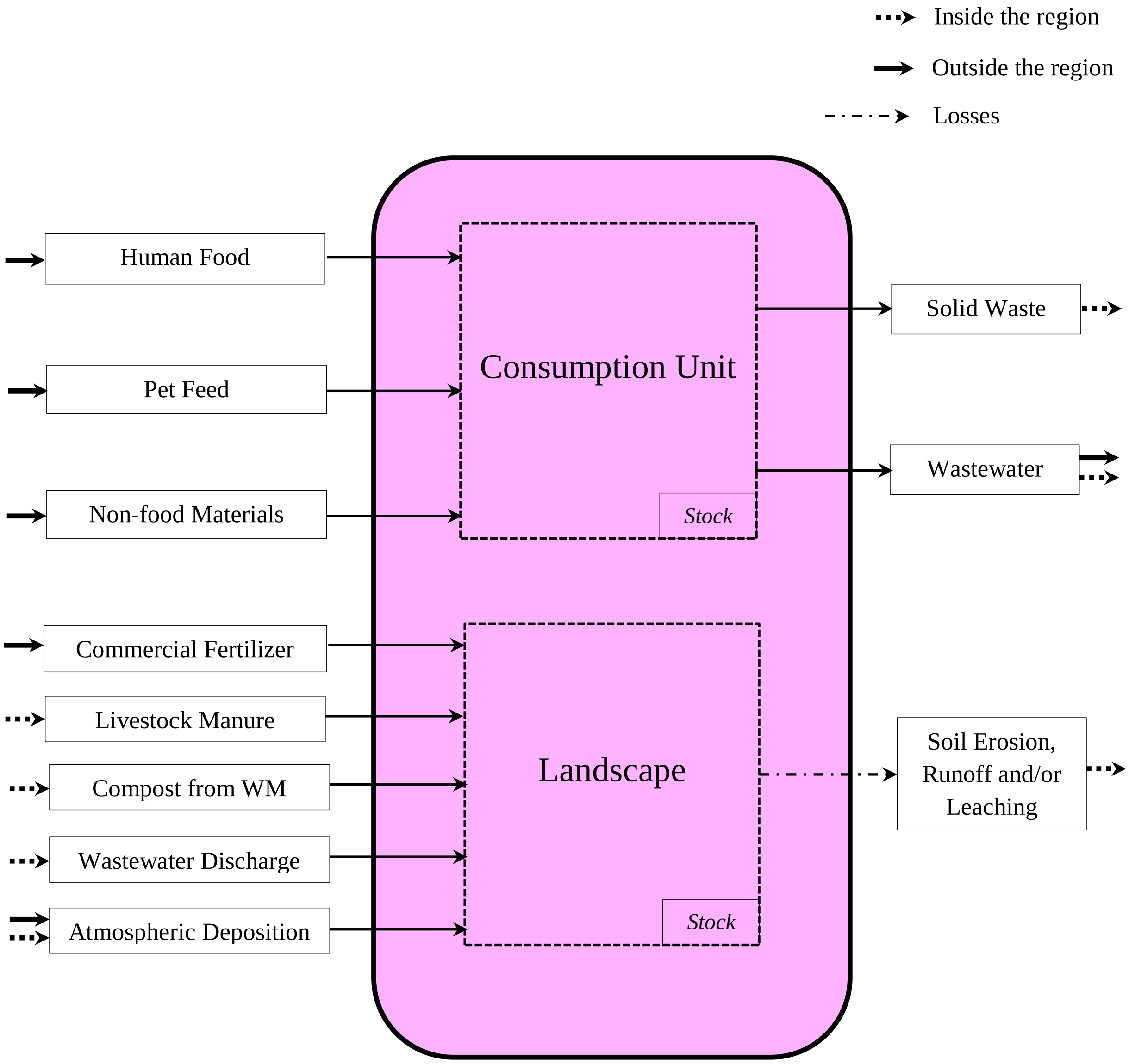


Fig. 3.10 Conceptual framework of P flows and storage of the household and urban system.

3.2.3.5. Waste Management

This subsystem includes waste management facilities for instance solid waste collection, wastewater treatment plants, landfills particularly related to urban waste management system, as well as associated activities, processes and flow of materials.

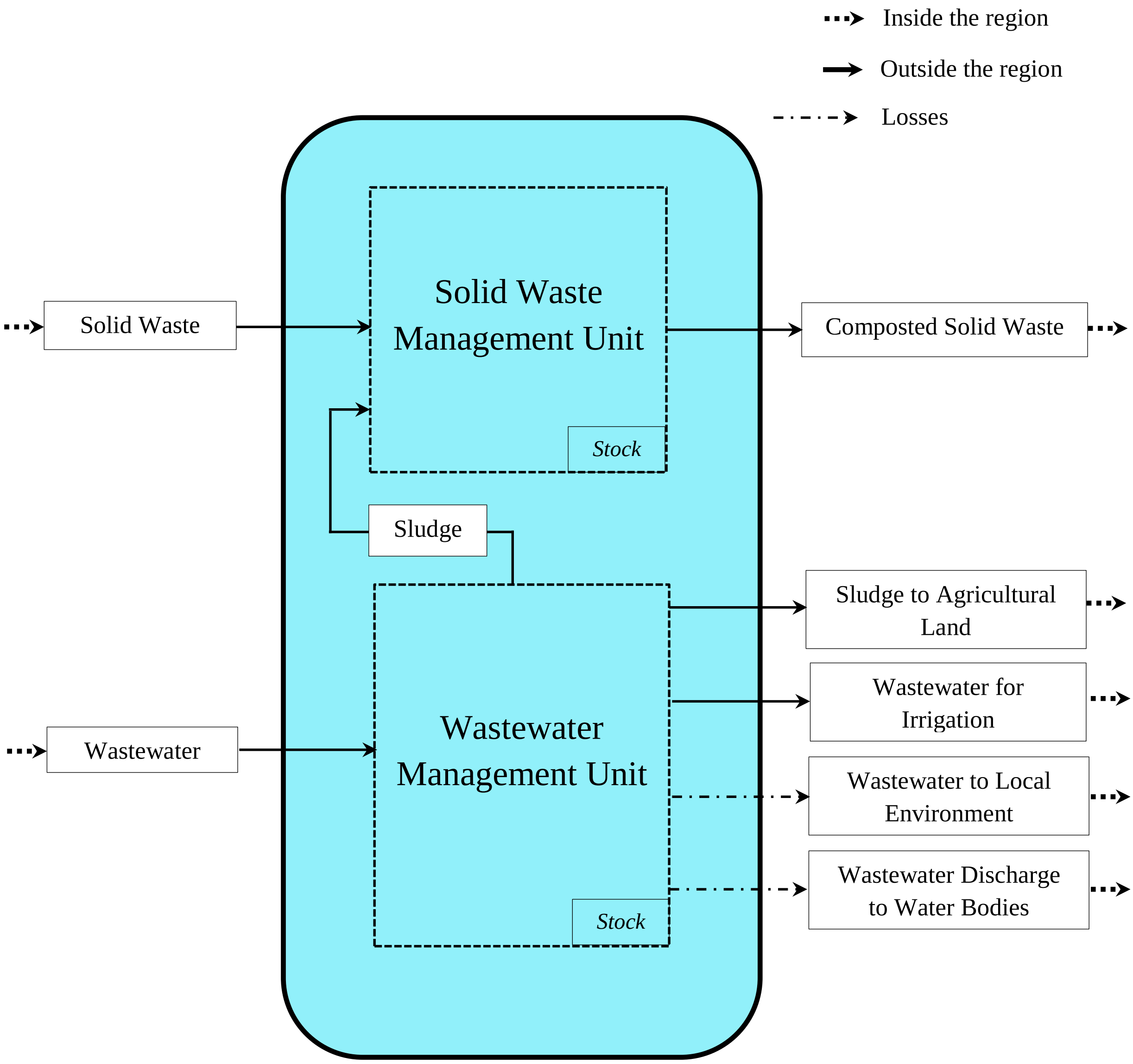


Fig. 3.11 Conceptual framework of P flows and storage of the waste management system.

3.2.3.6. Water bodies

This subsystem includes all fresh surface water bodies including streams, lakes and rivers and associated processes and flow of materials.

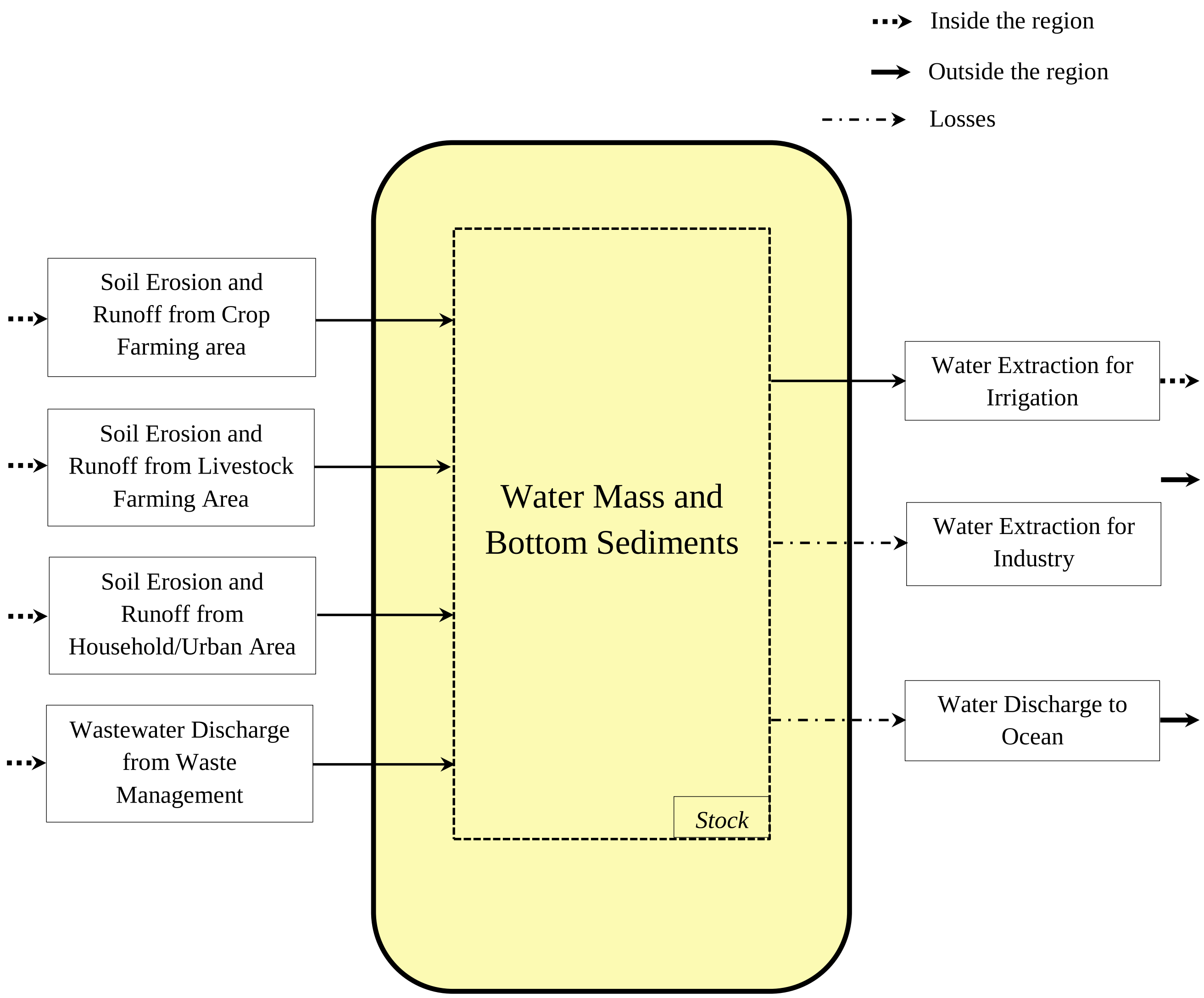


Fig. 3.12 Conceptual framework of P flows and storage of the water system.

3.2.4. Development of the regional scale P flow model

After the selection of the system, system boundaries, key subsystems, key processes and materials in terms of P mass flow and storage, and the development of the conceptual framework; the next step is to construct the P mass flow model. This step includes first, the selection of appropriate software platform for constructing and operating the model, and second, the construction of the model in the software platform based on mass flow and mass balance equations using appropriate modelling techniques.

3.2.4.1. Selection of appropriate software platform for modelling

For the quantitative modelling of material/substance flow in a complex and dynamic system, there are a number of techniques available in the mathematical and statistical arena. To assist in the successful implementation of such mathematical and statistical techniques, a number of software tools have been developed so far, which can be utilized for the quantitative modelling of material/substance flow in complex systems. Based on given instructions, these software tools are capable to process and analyse data, simulate the dynamic behaviour and function of complex systems, analyse uncertainty, calculate performance indicators, analyse scenarios, link to other types of models and make visual representation of complex system (Elshkaki, 2007).

Some of the software packages that are commonly used for the quantitative modelling of environmental systems include STELLA (Isee systems, Inc., 2014), POWERSIM (Powersim Software AS, 2014), VENSIM (Ventana Systems, Inc., 2014), STAN (Vienna University of Technology, 2012) and MATLAB/Simulink® (The MathWorks, Inc., 2014). These software tools have been successfully utilized in a number of recent studies for instance, STELLA in Ouyang et al. (2011), Fernández et al. (2013), Feng et al. (2013) and Bala et al. (2014); POWERSIM in Weber et al. (2010), Chlot et al. (2011), Georgiadis (2013) and Dace et al. (2014); VENSIM in Zhao et al. (2011), Parsons et al. (2011), Li et al. (2012) and Akhtar et al. (2013); STAN in Ott and Rechberger (2012), Egle et al. (2013), Arena and Gregorio (2013) and Gsodam et al. (2014), and MATLAB/Simulink® in Fagan et al. (2010), Elshkaki (2013), Moazzem et al. (2013) and Prando et al. (2014). Although all of these software tools are more or less effective in the quantitative modelling, the selection of a particular software tool may depend upon a number of factors such as nature and purpose of the analysis, availability and price, accessibility to adequate facilities to use and maintain it, stability and reliability, strength in handling complexity, user friendliness and expertise of the user, and on personal choice. In this study, two software packages viz. STAN and MATLAB/Simulink® were initially considered for the quantitative modelling of P flow. However, a deeper evaluation of these two tools revealed that MATLAB/Simulink® is superior to STAN on some aspects, and therefore, was finally selected for the current modelling. For instance, STAN is not as flexible as MATLAB/Simulink® because it is mainly suitable for SFA, whereas MATLAB/Simulink® is suitable for simulating any kind of complex and dynamic systems, as well as performing any kind of complex and robust analysis including SFA. In addition, the modelling in STAN can only be performed based on built-in features, it does not allow coding or building new features, or the inclusion of any new feature necessary for complex modelling; while MATLAB/Simulink® if free from such limitations. Moreover, STAN can perform the analysis of substance flow only for a particular year at a time, whereas MATLAB/Simulink® allows performing multi-year analysis of substance flow at a time. Simulink is basically an advanced extension of MATLAB software that allows modelling, simulating, and analysing complex and dynamic systems. The MATLAB/Simulink® software platform has been found suitable mainly for the following reasons:

- It is a widely used and freely available software tool for the students of the University of Melbourne;
- It allows the modelling of linear and non-linear systems in continuous and sampled time or an amalgamation of the both;
- It has a number of features such as block libraries, hierarchical modelling, signal labelling, and subsystem masking which render it as a powerful tool for simulating dynamic systems;
- It provides a large collection of blocks with common mathematical expressions and functions used in building process equations and these blocks are grouped in block libraries on the basis of their functionality in a system. These blocks can be used for the rapid and instant construction of the model;
- It has a GUI (graphical user interface) for building models by using block diagrams, using click and drag mouse operations. The visual block diagram interface in Simulink also provides a simple and quick way for building, modifying and maintaining complex system models;
- It also allows keeping records of the detailed description of each and every input data in the model;
- It also allows the visual representation of the overall systems, each and every subsystems, sub-subsystems and processes within the system and associated interactions of each and every components of the system.

Overall, Simulink is an appropriate tool for the quantitative modelling of complex and dynamic system. Although as mentioned before, this tool has been utilized in a number of studies for the quantitative modelling of complex and dynamic systems, so far, no available studies have utilized this software tool for the quantitative modelling of P flow in a system. However, given the nature and complexity of the analysis that this study needs to deal with, it is believed that Simulink will be an effective tool for the current quantitative modelling of P flow over multiple years at the regional scale.

3.2.4.2. Construction of the model using appropriate mathematical equations

The regional scale P flow model has been developed using a number of basic mass flow and mass balance equations which are presented as follows:

Mass flow equation:

$$\dot{P}_i = \dot{m}_i \times c_i \qquad \text{(Equation: 3.4)}$$

Where,

$\dot{P}$ is the mass flow of phosphorus in a particular material;

$\dot{m}$ is the mass flow of that material;

c is the concentration of phosphorus in that material;

i = 1,…, n as the index for materials.

Mass balance equation:

$$\sum_{k_i} \dot{P}_{input} = \sum_{k_o} \dot{P}_{output} + \dot{P}_{storage}$$

$$\dot{P}_{storage} = \sum_{k_i} \dot{P}_{input} - \sum_{k_o} \dot{P}_{output} \qquad \text{(Equation: 3.5)}$$

Where,

$\dot{P}_{input}$ is the mass flow of phosphorus in a particular input flow into a system;

$\dot{P}_{output}$ is the mass flow of phosphorus in a particular output flow from that system;

$\dot{P}_{storage}$ is the mass of phosphorus storage within that system;

k_i is the total number of input flows into that system;

k_o is the total number of output flows from that system.

Mass stock Equation:

$$P_{stock}(t) = \int_{t_0}^{t} \dot{P}_{input}(\tau)d\tau - \int_{t_0}^{t} \dot{P}_{output}(\tau)d\tau + P_{stock}(t_0) \quad \text{(Equation: 3.6)}$$

Where,

$\dot{P}_{input}$ is the total mass inflow of phosphorus into a system;

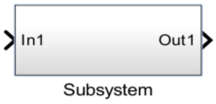
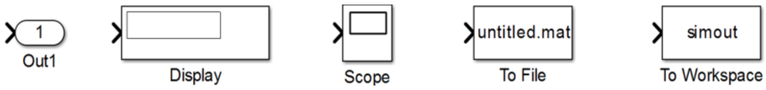
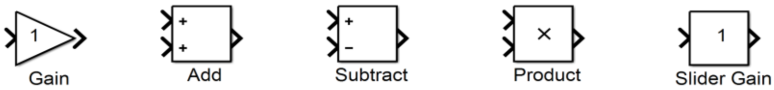
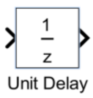
$\dot{P}_{output}$ is the total mass outflow of phosphorus from that system;

(t_0 to t) is the time span for all phosphorus inflows and outflows to be occurred, where t_0 is the initial time, and t is the final time;

$\dot{P}_{stock}$ is the mass of total phosphorus reserves within that system.

The P flow model that includes the main system, the subsystems, the sub-subsystems and processes, the mass flow of phosphorus into and out of the system, and the associated interactions among different subsystems in terms of P flow as conceptualized earlier in this study have been constructed on the MATLAB/Simulink® software platform using the basic mass flow and mass balance equations explained above. A number of readily available blocks from Simulink block libraries as presented in **Table 3.1** have been systematically connected (using a connecting line with an arrow that showing the direction of the signal flow) to express these mathematical equations for constructing the P flow model. Once the basic structure of the P flow model has been constructed in Simulink, then each and every components of the model is checked with using random numerical values as data input to test that the model is accurately representing the mass balance principles. Once it is confirmed that each component of the model is correctly following the mass balance principle, the model is then considered ready to be utilized for analysing multi-year P flow relating to a particular case at the regional scale. In the present study, the model has been applied in the case of Gippsland region in Australia.

Table 3.1 Blocks selected for constructing the regional scale P flow model in Simulink (The MathWorks, Inc., 2014).

Block Types	***Block Diagram and Block Name***
Port & Subsystem	 Subsystem
Sources	 In1; Constant; Repeating Sequence Interpolated
Sinks	 Out1; Display; Scope; To File; To Workspace
Math Operations	 Gain; Add; Subtract; Product; Slider Gain
Discrete	 Unit Delay
Signal Routing	 Mux; Demux

3.2.5. Assessment of P flows and storage: The case of Gippsland, Australia

3.2.5.1. A brief description of the study area

Geographically, the Gippsland region stretches from the edge of metropolitan Melbourne in the west to the most easterly point of Victoria, while bordering New South Wales and the Hume region in the north, and Victorian coastline in the south (**Fig. 3.13**). It covers a total area of about 41,557 square kilometres, which represents 18 per cent of Victoria's total area (ABS, 2014). This region comprises the local government administrative areas of Bass Coast, Baw Baw, East Gippsland, Latrobe, South Gippsland, and Wellington. It had an estimated resident population of about 263,858 in 2013 (ABS, 2014), which has been projected to be 386,000 in 2041 with an average annual population growth of 1.19% (DPCD, 2013). Gippsland's economy is mainly based on natural resources and commodities, with main industry sectors comprising agriculture, dairy and meat industries, forestry, fishing, and coal mining for electricity production, oil and gas extraction and processing. About 28 % (11,550 sq. km.) of the total area of the Gippsland region is occupied by agricultural lands, whereas about 33% (13,580 sq. km.) by production forestry, and approximately 28% by conservation and natural environment (ABARES, 2014). A typical land use map of this region has been presented in **Fig. 3.14**. The natural environment and climate of the Gippsland region are very favourable to natural resource based industries, in particular agriculture, forestry and energy production. This region contributes about 60% of Melbourne's water demand, about 90% of Victoria's electricity needs, 97% of the of the Victoria's natural gas extraction and approximately 29% of Victoria's agriculture, forestry and fishing exports (DPCD, 2013).

Rationale for selecting the Gippsland region for the analysis of P flow:

- ➢ Gippsland is a net food producing region in Australia. The agribusiness sector is a major employer in this region, with more than 37% of its business involved in agriculture and fishing, and an additional 15% engaged in upstream processing operations (DPCD, 2013). This region comprises more than 1500 dairy farms that produce about 2.1 billion litres of milk annually, accounting for nearly 23% of Australia's milk production (GippsDairy, 2014). This region also produces about 25% of the Victoria's beef production and 14% of Victoria's fruits and vegetable production. As a whole, 29% of the Victoria's agricultural forestry and fishing exports are contributed by this region (DPCD, 2013). There are more than 6500 farms in Gippsland, together produces about AUD 1.3 billion worth of agricultural products each year (DEPI, 2014). As a key agricultural region of Australia, there is a necessity for sustainable P management in Gippsland. Moreover, so far, no geological deposits of phosphate rock have been reported to found in this region, and all chemical P fertilizers used in this region are sourced from outside;

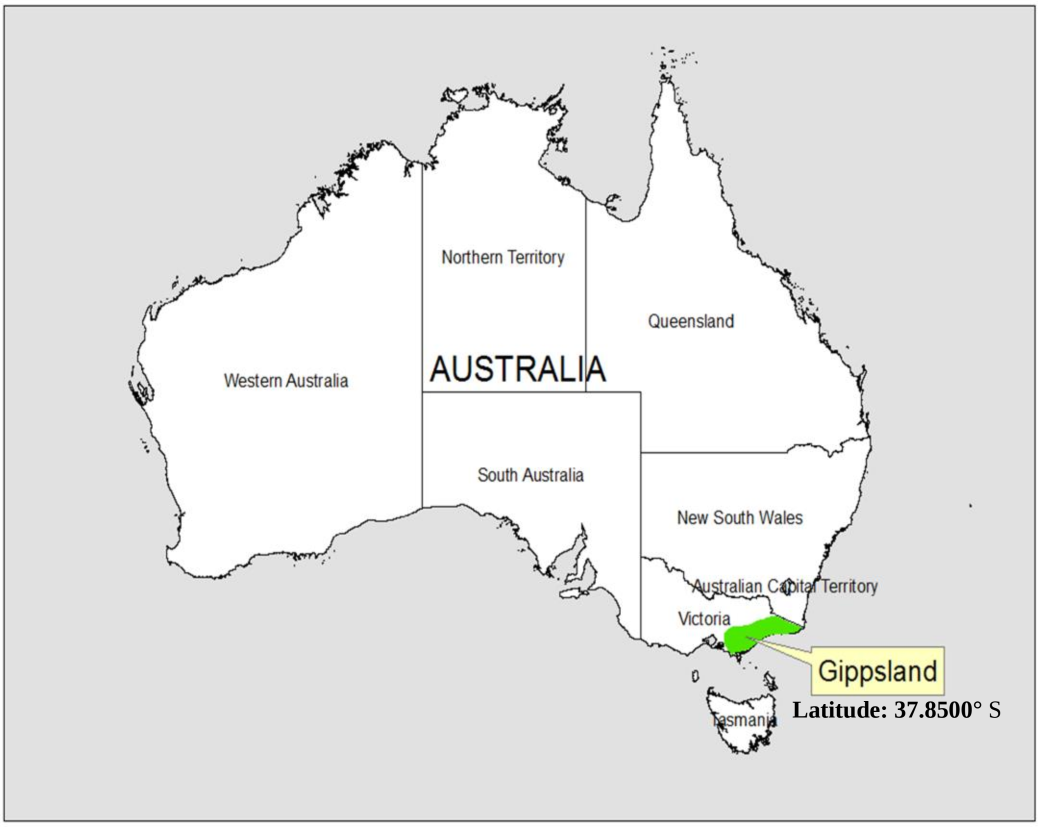


Fig. 3.13 Map showing the location and boundary (green coloured portion) of the case study area, the Gippsland region in Victoria, Australia. The enlarged Gippsland map (showing major land uses) is presented in **Fig. 3.14**. Map is the courtesy of Mr. Keirnan James Andrew Fowler, PhD student, Department of Infrastructure Engineering, the University of Melbourne.

- The lakes and adjacent wetlands in Gippsland constitute about 600 sq. km. in a catchment, which are of intrinsic ecological value and help to sustain the region's economy and community by generating benefits through recreational activities, tourism and fishing (GLMAC, 2013). The lakes in this region have been reported to significantly suffer from P induced pollution. Holland and Cook (2009) reported that over the last 30 years period from 1978 to 2008, annually about 190 tonnes of P were discharged to Gippsland Lakes. Due to excessive discharge of phosphorus and other nutrient elements from surrounding agricultural areas, the Gippsland Lakes have been found to suffer from algal bloom and other associated problems (Ladson and Tilleard, 2006; Holland and Cook, 2009;

Cottingham et al., 2006). Connolly and Hylands (2009) estimated that the direct economic impact of the 2008 blue green algal bloom of Gippsland Lake on the Gippsland tourism industry was a loss of AUD 18.2 million and the net impact of it on Victorian economy was a loss of AUD 6.7 million. Therefore, there is potential for significant economic and environmental outcomes of improved P management in the Gippsland region;

- Moreover, Gippsland is a perfect match for the P flow system at the regional scale. This region encompasses a unique combination of well-defined land use systems such as crop farming, livestock farming, forest area, household and urban area, waste management, and water bodies that make this region highly competent for the regional scale P flow analysis.

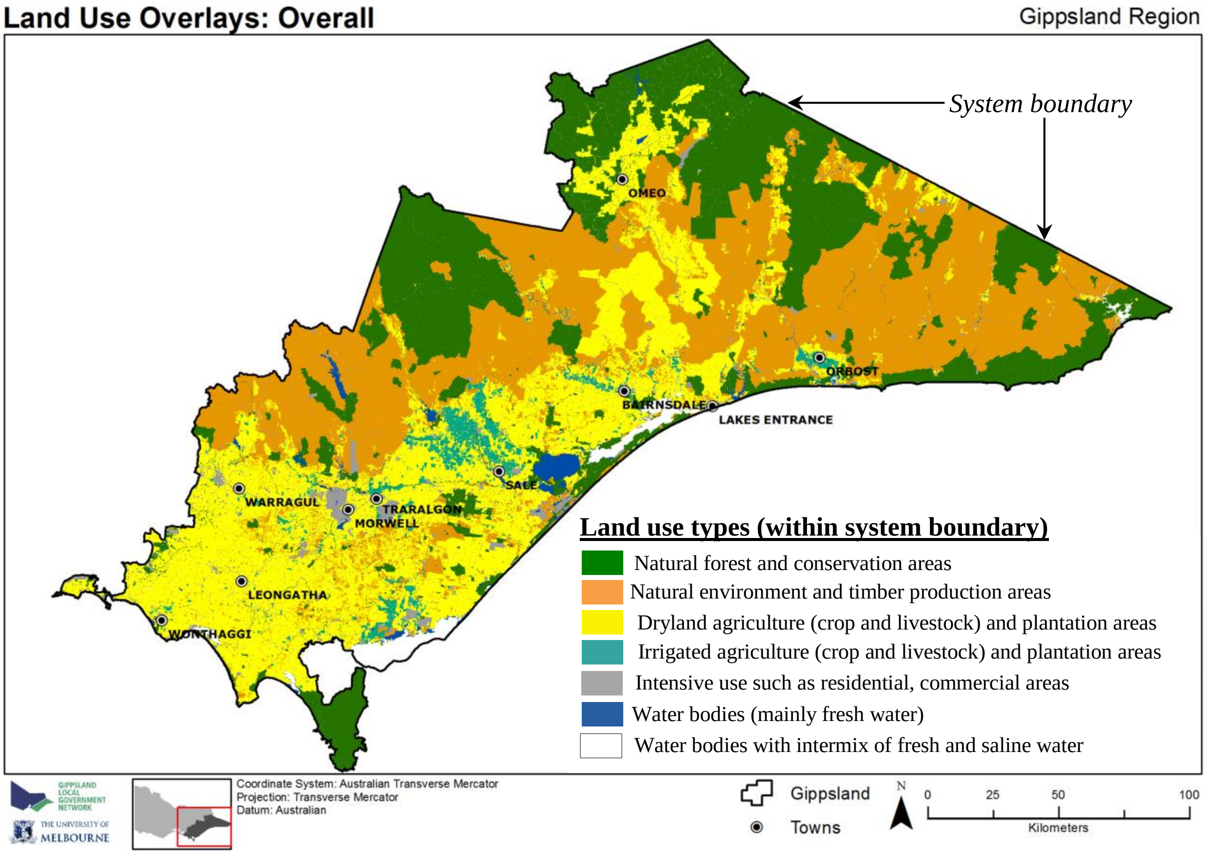


Fig. 3.14 Map showing typical major land uses of the Gippsland region. Map is the courtesy of Harmen Romeijn, Masters student, Department of Infrastructure Engineering, the University of Melbourne.

3.2.5.2. Procedure of data collection for analysis of P flow in the Gippsland region

In order to carry out an effective SFA of P, therefore to generate accurate and reliable information regarding the nature and magnitude P flows and storage, there is a need for adequate, reliable and good quality data. In most of the available SFA of P, the lack of sufficient, reliable, site specific and high quality data had been found to be a big obstacle which eventually affected the accuracy and reliability of the outcomes of SFA (Cordell et al., 2012). Therefore, in this analysis, special attention has been paid on the aspect of data availability and data quality.

3.2.5.2.1. Criteria for selecting temporal scale

For the current analysis of P flow in the Gippsland region, a six years period from 2008 to 2013 has been selected as the temporal scale. The reason for selecting this time scale is that these are the most recent years for which nearly a complete set of good quality data is freely available. However, this study has initially attempted to collect data of years prior to 2008, but in most cases, it has been found that the types of data that are required to assess the nature and magnitude of P flows in Gippsland are either not available or if available, these are neither complete nor of good quality. Using such data in this analysis may generate outcomes that consist of a huge uncertainty, and therefore, may not represent the actual case of P flow in the Gippsland region. A review of the available SFA studies of P indicates that in many studies (Wu et al., 2014; Cordell et al., 2013; Cooper and Carliell-Marquet, 2013; Qiao et al., 2011; Baker, 2011; Suh and Yee, 2011) only a single year was considered for the analysis of P flow mainly due to the lack of sufficient and good quality data over several years. Most of these studies mentioned that they have selected that particular year because that is the latest year for which there was the highest availability of required data. The time step that has been chosen for the current analysis is annual. Generally, P flows are analysed in a yearly time step because this is an effective time step to express the majority of P flows in a system, and most of the materials flow data are usually collected on an annual basis.

3.2.5.2.2. A brief review of the data collection criteria used by available studies

In order to have a better knowledge to define effective criteria for collecting the appropriate data, this study has conducted a review of the data selection and quality assessment criteria considered by available SFA studies of phosphorus. The criteria utilized in some of the studies have been discussed here:

In an SFA of P in the US food system for 2007, Suh and Yee (2011) used the following criteria to assess the quality of data from different sources:

a) Existence of multiple data sources for cross-check;
b) Fitness of the data used in terms of its average base year;
c) Fitness of the data used in terms of its geographical coverage; and
d) Method of original data compilation.

In another SFA analysis of the anthropogenic P flow of Lujiang County of China for 2008, Yuan et al. (2011a) used the following criteria to assess the reliability of the data:

a) High reliability: collected from local accounting systems and field surveys recently;
b) Moderate reliability: field investigation data known to be uncertain, and data of other places of China of the last ten years collected from literatures; and
c) Low reliability: investigation data from their field study which showed relatively high uncertainty, and data obtained from general literature of many different parts of China or around the world that needed some adjustment to utilize in their analysis.

Yuan et al. (2011a) mentioned that of the total data they utilized, 62.3% was highly reliable, 27.9% was moderately reliable and only 9.8% had low reliability. However, Cordell et al. (2013) in their analysis of P flow through Australian food system for 2009 have utilized slightly different approach to categorize the data according to different level of quality, which can be stated as follows:

a) Sufficient: recent data of high or reasonable quality particularly those collected from reliable Australian government official sources;
b) Poor/questionable data: international data used as an alternative for the Australian data, or data that are 10-15 years old; and
c) Absent data: where assumption was used for unavailable data.

While discussing the uncertainties related to data used in the analysis of anthropogenic P metabolism of China, Ma et al. (2012) mentioned that government surveys of special topics are the reliable source of valid data. They also mentioned, data derived from research papers and website always has high inconsistencies in recent decades, where the mean values need to be used eventually introducing uncertainty in the results. Hedbrant and Sorme (2001) in their study titled 'Data vagueness and uncertainties in urban heavy-metal data collection' have used an interesting approach to define the uncertainty level of data collected from different sources. According to their criteria, official statistics on local level fall in the low uncertainty level, official statistics on regional and national levels fall in the moderate uncertainty level, and official statistics on national level downscaled to local level fall in the high uncertainty level. Hedbrant and Sorme (2001) have also developed a method for the analysis of uncertainties associated with data collected from sources of different uncertainty levels. Their method have been referred in several SFAs of P (Bi et al., 2013; Egle et al., 2014; Cooper and Carliell-Marquet, 2013; Li et al., 2010).

3.2.5.2.3. The criteria used for data collection in the current study

This study aimed at collecting the mass flow data of materials relating to different subsystems or processes as defined earlier, and the P concentration data of these materials. In case of the mass flow data of materials, this study has primarily focused on collecting data from the original or the most reliable sources (mainly the local government official sources, or the relevant government departments or research organization which collect primary data, or the Australian national statistical organization). In this perspective, data relating to the Gippsland region that are originated through the local monitoring systems or routine field investigations of the recent years have been given the top priority. In some cases, material mass flow data for the Gippsland region were not available, however, such data were available for Victoria (the state where the Gippsland region belongs to), or for Australia. In such cases, the per capita material mass flow data of Victoria or Australia have been systematically utilized to produce the total material mass flow data for Gippsland. When material mass flow data and P concentration data for a particular type of material is available from a number of sources, then, the most reliable data have been selected based on the following criteria:

a) Location of the samples collected (preference given to locations within or near Gippsland);
b) Date of the samples or data collected (preference given to more recent data);
c) The methods utilized for collecting samples or data, and for the analysis of samples or data (preference given to more scientifically and statistically accurate methods);
d) The description of the accuracy and reliability of the reported data (preference given to that presented with standard deviation and co-efficient of variation);
e) The reputation of the organization that collected the samples or data (preference given to the organizations that perform high quality research and are commonly used sources for data);
f) The reputation of the organization or the journal that published the data (preference given to journals with high impact factor).

However, in order to express the magnitude of reliability of the collected material mass flow and P concentration data, five reliability levels have been defined in this study, viz. high, high to moderate, moderate, moderate to low, and low. The level of reliability of a particular data has been determined by comparing the data against the criteria selected for defining reliability as presented in **Table 3.2**. According to **Table 3.2**, for instance, the reliability of a data is defined as ‘high’ if the samples of that data were collected directly from Gippsland, in the recent times (after 2000), using standard sampling procedure, analysed with standard method, described with the associated uncertainty range (standard deviation), collected by a reputed organization, and published in a reputed source. Any data for which the sample was collected outside Australia, but it met all other criteria such as collected in the recent times, followed standard sampling produce and method of analysis, described associated uncertainty range, collected by reputed organization and published in a reputed journal or by renowned organization, then the reliability of such data is 'moderate'. In the similar way, the data of other reliability levels can be determined using **Table 3.2**. However, if all data sources for a particular type of material are more or less equally reliable, then the average or median value of the data from different sources have been considered depending upon the divergence of data.

Table 3.2 Criteria used for defining the reliability of collected data. (√ (tick) mark indicates that a particular criterion is met).

Reliability	**Criteria for defining reliability of collected data**									
	Location of sample or data collection				Time	Method of sampling and analysis		Uncertainty	Source	
	Gippsland	**Victoria (where Gippsland may fall or not fall)**	**Australia (outside Victoria)**	**Outside Australia (mainly Europe, USA, New Zealand)**	**Recent (after 2000)**	**Standard Sampling procedure**	**Standard method of analysis**	**Uncertainty range described (range or standard deviation)**	**Sample or data collected by reputed organization**	**Published by reputed organization or in reputed journal**
High	√				√	√	√	√	√	√
High to moderate	√					√	√	√	√	√
		√			√	√	√	√	√	√
Moderate	√				√			√	√	√
		√				√	√		√	√
			√		√	√	√	√	√	√
Moderate to low	√								√	√
		√			√				√	√
			√			√	√		√	√
				√	√	√	√	√	√	√
Low	√									
		√								
			√						√	√
				√		√	√		√	√

Using the mass flow and P concentration data of materials, it is possible to calculate most of the P flows in Gippsland. However, for the calculation of P storage and some important P flows that are not possible to directly calculate due to data unavailability, this study has applied the mass balance principle, which is the core idea of SFA analysis and one of the greatest advantages. A number of SFA studies of P (Wu et al., 2014; Cordell et al., 2013; Cooper and Carliell-Marquet, 2013; Ott and Rechberger, 2012; Yuan et al., 2011a; Suh and Yee, 2011), in a situation where mass flow and P concentration data of materials to calculate a particular type of P flow were not available, applied the mass balance principle to determine such flows.

3.2.5.3. Preparation of data and assumptions considered for the quantitative modelling of P flow in the Gippsland region

Based on the criteria developed, the level of reliability for each of the material mass flow and associated P concentration data that considered for the analysis of P flow relating to the Gippsland region have been defined. The material mass flow data along with their assigned reliability levels and sources have been presented in **Appendix 2**. Phosphorus concentration data relating to different materials and process along with their reliability levels and sources have been presented in **Appendix 3**. These data can be readily utilized in the regional scale P flow model as developed in the Simulink platform for performing the quantitative analysis of the multi-years P flow in the Gippsland region.

In case of missing material mass flow data and P concentration data of materials and processes relating to the Gippsland region, a number of assumptions have been made on the basis of relevant information available through the reports and website of different organizations, author's basic understandings about the facts, systematic mathematical and mass balance calculation, and in some cases, based on educated guess and expert's advice. The basis for various assumptions relating to the main system and all different subsystems as considered for the current analysis have been presented in **Table 3.3**.

Table 3.3 Assumptions used in case of limitations of data and information necessary for the quantitative modelling of P flow in the Gippsland region. The considerations and assumptions relating to the Gippsland region as a whole and all different subsystems within this region have been distinctly presented with different background colours. As presented in the table below, these considerations and assumptions begins for the Gippsland region at page: 85, Crop Farming at page: 87, Livestock Farming at page: 89, Household and Urban at page: 92, Waste Management at page: 92, and Water subsystem at page: 96.

System	Flow	Assumption used
GIPPSLAND	*Commercial fertilizer import*	Data on commercial fertilizer import in Gippsland is available for 2008, 2010, 2012 and 2013 (ABS, 2009, 2011, 2013, 2014a), but unavailable for 2009 and 2011. Therefore, for 2009 and 2011, the average of the data of previous year and subsequent year has been considered. For instance, 2009 value is the average of 2008 and 2010 data.
	Other manufactured fertilizers import	There is no specific information available regarding the proportion of P based fertilizers in all other manufactured fertilizers used in Gippsland, and the types of different P based fertilizers fall in this category. According to ABS (2013), this is a significant amount (approximately 32,000 tonnes) of fertilizer. Based on the information available through the website of fertilizer suppliers in Gippsland as well as on relevant literature survey; this study has identified different types of manufactured P fertilizers (other than the main commercial P fertilizer such as TSP, SSP, MAP, DAP) that are supplied in Gippsland and Victoria (DEPI, 2010; E.E. Muir and Sons, 2012; Gippsland Bulk Spreaders Pty Ltd, 2011). It has been observed that P based fertilizer accounts for a significant proportion of the different types of other manufactured fertilizer supplied in Gippsland. This study uses the assumption that 70% of other manufactured fertilizer used in Gippsland is P based fertilizer. To calculate the total P flow in other manufactured fertilizers, a list of all other P based manufactured fertilizers used in Gippsland has been prepared. This study assumes that an equal amount of all these different P based fertilizers are used in Gippsland and the calculation has been done accordingly.
	Dairy cattle feed import	According to Gourley et al. (2010), on an average, about 30% of the total dairy feed in Gippsland is imported to farms which include grains and concentrates, and hay and silage, and the rest 70% comes from pasture grazing. According to Spragg (2014), although Gippsland have a large feed demand, there remains a small quantity of grain produced in this region, and the region remains with a 1.3 MMT supply deficit and the gap is usually filled by grain moving from Victorian cropping areas and southern NSW and SA. So, this study considers that grain and concentrate used as livestock feed are imported from outside Gippsland, and hay and silage are sourced from inside Gippsland (According to ABS (2014b), Gippsland produces a significant amount of pasture hay and silage). Based on the proportion of grain in total dairy feed as reported in the study of

	Powell et al. (2012) that include the survey of a number of dairy farms in Gippsland, the current study assumes that approximately 20% of the total dairy feed is imported as grains from outside Gippsland, and the calculation has been done accordingly.
Meat cattle feed import	According to DEPI (2013), most of the Victoria's cattle are kept on managed pastures, and around 10% of the beef cattle herd is grown out in feedlots. The present study takes this fact into consideration for Gippsland, and assumes that 90% of the total beef cattle feed comes from grazing pasture and only 10% of the beef cattle feed is imported from outside Gippsland.
Poultry feed import	Given the types of feed (grain and enzyme based) used in poultry farm (Roberts, 2003); the current study considers that nearly 100% of poultry feeds are imported from outside Gippsland.
Sheep/lamb feed import	Lamb/sheep farms in Gippsland are generally grazing based (Barson, 2013). However, during some special circumstances, occasionally, there is a requirement of supplementary feed (DAF, 2007; DEPI, 2014a) which are imported. The present study assumes that only 10% of the total sheep feed is imported from outside Gippsland and 90% comes through grazing pastures.
Pig feed import	Pig feed is mainly made up of various types of grain such as wheat, barley and sorghum, vitamins and minerals (APL, 2014; Sopade et al., 2013). Based on the nature of pig feed, it can be assumed that almost all pig feed is imported from outside Gippsland.
Atmospheric Deposition	The rate of atmospheric deposition of P could vary from one land use type to another (Redfield, 2002). Gippsland have different types of land use. To find out the rate of atmospheric P deposition for Gippsland, this study considers the average of atmospheric P deposition (dry + wet) rate as reported for different types of land uses by different studies in mainly Australia, US and Europe (Ahn and James, 2001; Anderson and Downing, 2006; Gourley et al., 2010; Redfield, 2002; Winter et al., 2002) and calculates the total atmospheric P deposition for Gippsland accordingly. Due to the lack of Australian atmospheric P deposition rate data for different types of land uses, this study considers data of other countries (necessary explanations have been given in this regard in **Section 3.2.5.2.3**). However, Das et al. (2013) estimated that, the long distance dust transport could contribute to about 25% of the total atmospheric deposition and the rest (75%) is contributed from local sources. The current study uses the same ratio for Gippsland, and considers that 25% of the atmospheric P deposition originated from outside Gippsland. As observed in the Gippsland land use map in **Fig. 3.15,** the region is mostly dominated by vegetation cover. Owing to this reason, the present study assumes that the atmospheric P generated in this region is eventually deposited within this region. Therefore, it can be assumed that the mass of atmospheric P outflow from the Gippsland region is insignificant, and as a result, is not considered in the current analysis.

CROP FARMING	*System considerations*	In the crop farming subsystem of the Gippsland region, this study considers all plant based production such as crop (cereal and non-cereal), pastures, and vegetables and fruits production. It does not include the mixed farming areas. This is to mention that in this analysis, the areas of commercial/intensive pasture production were systematically considered under the crop farming system, and the pasture areas that are used for mainly grazing purpose were considered under the livestock farming system. Data on annual commercial hay and silage production in Gippsland and the land areas dedicated to that are available thorough ABS statistics. Based on that data pasture areas were systematically separated between crop and livestock farming systems.
	P inflow as commercial (mainly chemical) fertilizer	Commercial crops, vegetables and fruits, and pasture and silage production lands are extensive agriculture production areas where a substantial amount of commercial fertilizer is applied. According to Weaver and Wong (2011), average P input in the crop farming area is about 11.75 kg/ha/yr and in the dairy and meat cattle farming area is approximately 17.55 kg/ha/yr (average value of P input in dairy and beef cattle farming area). Although pasture and silage are more likely to grow in the dairy and meat cattle farming area, for the sake of keeping all plant based production in the same subsystem, the present study considers the commercial/extensive pasture and hay production areas under the crop farming system. Therefore, for the crop farming areas in the current analysis, the average of the P input rate of the crop farming, and the dairy and beef farming areas that is (11.75+17.55)/2 or 14.65 kg/ha/yr has been considered. Multiplication of this rate with the total crop farming areas gives a value of about 2003.75 tonnes. Given the extensive fertilizer application in the crop and pasture production areas, the current study considers that about 90 % (1802 tonnes) of the total P input in the crop farming system is sourced from commercial fertilizers, which is on the other hand about 25% of the total imported commercial fertilizers in Gippsland. Based on this calculation, this study considers that about 25% of the total imported commercial fertilizers in Gippsland is dedicated to crop farming areas. This study considers that other than commercial P fertilizers, the remainder 10% of the total P input in the crop farming system is sourced from recycled manures from the livestock farming system, and compost products and treated wastewater from the waste management system.
	P inflow as atmospheric deposition	Based on ABS (2013a) and ABS (2013b), the current study has calculated that the crop farming area is about 3.57% of the total area of Gippsland. Therefore, this study assumes that atmospheric P deposition in the crop farming areas is approximately 3.57% of the total atmospheric P deposition in Gippsland.

P inflow as irrigation	Water for irrigation in Gippsland is mainly sourced from irrigation channels, rivers, bores (Gourley et al., 2010). However, treated municipal wastewater is also used for irrigation in Gippsland (CGRWC, 2009). As approximately 92% of the total water that can be extracted from different sources to use in Gippsland is surface water (DSE, 2011), the present study considers that irrigation water is mainly sourced from surface water. According to DSE (2011), the bulk entitlements of surface water for irrigation in the Gippsland region is about 1,368,280 ML per year. Therefore, the current study assumes that the total amount of water used for irrigation in Gippsland is equal to the bulk entitlements of surface water for irrigation. Irrigation water is mainly used for agricultural production purpose in the crop farming and livestock farming areas. Therefore, in order to calculate P flow as irrigation water in the crop farming areas, this study has first calculated what proportion of the total agricultural areas (crop + livestock and mixed grazing) in Gippsland is crop farming areas and found that 11% of the total agricultural areas in Gippsland is crop farming areas. The present study considers that the same proportion (11% or 150,510.8 ML) of the total irrigation water use in Gippsland is dedicated to crop farming areas. According to CGRWC (2010) and EGRWC (2010), total amount of treated wastewater reused mainly for irrigation to pastures in Gippsland is (1,171+2,152) ML or 3,323 ML. Again, the current study considers that the same proportion (11% or 365.53 ML) of the total treated wastewater reused in Gippsland is dedicated to crop farming areas. According to Gourley et al. (2010), mean P content in irrigation water used (sourced from irrigation channels and bores) in dairy farming areas in Gippsland is 0.04 mg/L. According to Pescod (1992) and MAV and DSE (2006), typical P content in treated domestic wastewater for irrigation is 10 mg/L. Therefore, total P flow as irrigation in the crop farming system in Gippsland is [{(150,510.8*1,000,000*0.04) + (365.53*1,000,000*10)}/1,000,000,000] tonnes or 9.68 tonnes. In the similar way, this study calculates the P flow as irrigation water in the livestock farming areas.
P outflow as crop products	This study mainly considers cereal and non-cereal crops (), and pasture and silage to calculate the P outflow in crop products from Gippsland because there is a substantial production of these crops in Gippsland (ABS, 2014b). In the present study, a preliminary calculation indicates that total annual P flow as vegetable and fruit products from Gippsland is not significant, which is less than 1 tonne. Therefore, for the simplicity of the analysis, this study do not consider P outflow as vegetable and fruit products from Gippsland.

	P outflow as soil erosion and runoff	In order to calculate P outflow in soil erosion and runoff from the crop farming areas, the present study has used the estimate of Hancock et al. (2007) for annual catchment contribution of P to the Gippsland lakes. Hancock et al. (2007) estimated that the main pathways/medium of P transport to Gippsland lakes are channel/river bank erosion (44%), dissolved surface and subsurface runoff (34%), hillslope erosion (15%), and gully and tunnelling erosion (3%). Based on Hancock et al. (2007) data, the current study calculates the rate of P transport (kg/ha/yr) through each of the pathways. For the calculation of P outflow as soil erosion, the present study considers the rate of P flow as channel/river bank erosion, hillslope erosion, and gully and tunnelling erosion; and in order to calculate P outflow as runoff, this study considers the rate of P flow as dissolved surface and subsurface runoff. The same rates have been used for calculating P outflow as soil erosion and runoff from the livestock farming areas.
LIVESTOCK FARMING	*System considerations*	Under the livestock farming subsystem, this study mainly considers extensive livestock farming and mixed farming areas. Mixed farming has been included here because disaggregating data not possible, and principle crops of hay and silage is used on farm.
	P inflow as commercial (mainly chemical) fertilizer	In Gippsland, given the nature of the land use, commercial fertilizers are mainly used in the crop farming, and the livestock farming or mixed farming areas. However, some commercial fertilizer could also be used in the urban landscapes. As it has been estimated earlier in this study that about 25% of the imported commercial fertilizers in Gippsland are used in the crop farming areas, the reminder (75%) should be allocated for the livestock farming and mixed farming areas as well as for the urban landscapes. However, the livestock farming areas as considered in the current analysis is nearly 6 times bigger than the urban and residential areas in Gippsland. Moreover, a considerable proportion of the total urban landscape is paved, which does not require fertilizer application. Considering all these facts, the present study assumes that about 70% of the total imported commercial fertilizers in Gippsland is used in the livestock and mixed farming areas, and only 5% is used in the urban landscapes.
	P inflow as atmospheric deposition	Based on ABS (2013b) data, it can be calculated that the livestock farming area is approximately 29.7% of the total area of Gippsland. Therefore, the present study assumes that atmospheric deposition in the livestock farming system is approximately 29.7% of the overall atmospheric P deposition in Gippsland.

P inflow as purchased or imported pasture or silage (as dairy cattle feed)	According to Gourley et al. (2010), on an average, about 30% of the total dairy feed in Gippsland is imported which include grains and concentrates, and hay and silage. As mentioned earlier, this study considers that grain and concentrate is imported from outside Gippsland, and hay and silage is sourced from inside Gippsland. Based on the proportion of grain in total dairy feed as reported in the study of Powell et al. (2012) that includes the survey of dairy farms in Gippsland, the present analysis considers that approximately 20% of the total dairy feed is imported grain and concentrates. Therefore, the rest of the total imported feed which is approximately 10 % of the total feed intake is purchased or imported pasture and silage from inside Gippsland. As considered earlier in this study, hay and silage is produced in the crop farming system and therefore, the purchased or imported hay and silage to the livestock farming system are needed to be sourced from the crop farming system. This study assumes that the total amount of pasture and silage harvested in the crop farming areas in Gippsland is ultimately utilized as dairy cattle feed in the livestock farming system. This is to mention that in the current analysis, hay and silage have been considered as the only inputs from the crop farming system to the livestock farming system. In Gippsland, there might be the presence of some mixed farms where home-grown grain is fed directly to cattle; however, due to the unavailability of data on that level of details, the current study has not separately accounted for P flow associated with home-grown grain feed.
P outflow flow as livestock products	In the current analysis, mainly milk, meats, bones, and eggs have been considered as the livestock products. This study does not consider any P outflow in live animals rather it considers P outflow in dressed carcases mainly as bones, meats and fats because the majority of the P in animal body is found in bones, meats and fats. About 80% of these P is in bones and the remainder is in soft tissues (Harris et al., 2003; IFP, 2006; Jackson, 2012). The data for total meat cattle number in Gippsland is available in ABS (2013b), but there is not any data available regarding the proportion of the total meat cattle in Gippsland that are slaughtered annually. However, data regarding both the total meat cattle number and the total number of meat cattle slaughtered is available in a country scale for Australia (ABS, 2014c). Based these data, the present study calculates the proportion of the total meat cattle that is slaughtered annually in Australia, which is about 60%. The same proportion has been used for Gippsland and calculated accordingly.
P excreted by dairy cow going to the soil	In Gippsland dairy farms, cows spend nearly 80% of the times in a day in paddocks (Gourley et al., 2010). On this basis of this information, the present study considers that about 80% of the daily excreted P by dairy cows goes to the soil, and the rest (20%) is excreted in dairy sheds which eventually finds its way to manure management.

P excreted by meat cattle going to the soil	As mentioned earlier, most of the Victoria's meat cattle are kept on managed pastures and approximately 10 % of the meat cattle herd is grown in feedlots (DEPI, 2013). This fact has been taken into consideration for Gippsland, and accordingly, it has been assumed that meat cattle spent about 90% of the time in the grazing field. Therefore, the present study considers that about 90% of the P excreted by meat cattle is going to the soil and only 10% is going to the manure management.
P excreted by sheep going to the soil	All the sheep farms in Gippsland are grazing based (Barson, 2013). Therefore, this study considers that all of the P excreted by sheep is going to the soil and no P is going to the manure management.
P excreted by chicken to soil	This study considers that nearly all manure excreted by chicken is collected by manure management systems. However, due to the presence of a number free range chicken farm, it has been assumed that about 10% of P excreted by chicken is going to the soil. However, chicken manure contributes only a small proportion of overall P excreted by livestock in Gippsland.
P going to the dairy cattle manure management	The present study considers that the subsystem ‘dairy manure management’ is mainly consists of manure effluent pond and manure composting system. According to Gourley et al. (2010), none of the 10 surveyed Gippsland farm export any manure to outside the farm. All the manure collected in the effluent pond is eventually applied to the land within the farm. Therefore, this study assumes that all of the 20% (that is excreted in dairy sheds) of the total P in dairy cattle excreta in Gippsland is collected in the effluent pond and then applied to the land.
P going to the meat cattle manure management	Similar to dairy cattle farming, this study considers that about 10% of the P in total meat cattle excreta in Gippsland that is excreted mainly in the feedlot shed is collected in the manure pond and then applied to land.
P going to the poultry manure management	This study considers that all of the P in poultry manure is eventually going to the poultry manure management system.
P going to the pork manure management	According to Kruger et al. (2013), about 71% of the pig waste management system in Victoria is anaerobic lagoon system and 27% is daily spread to land system. The current study considers the same proportion for Gippsland, which means about 27% of the total P excreted by pigs in the Gippsland region are directly going to the soil. According to APL (2011), in Australia, about 71% and 62% of pork producers dispose of treated solid and liquid waste respectively by spreading on land as fertilizer. Considering the same proportion for Gippsland, the present study assumes that about 71% of the total pork manure P in anaerobic lagoon is eventually applied to land and the rest (29%) is composted and exported outside the farm.

HOUSEHOLD AND URBAN	*System considerations*	The urban system in the Gippsland region mainly includes residential, commercial and institutional areas within the urban landscapes. It also includes small scale industries located within or near urban landscape.
	P inflow as non-food materials	This study considers mainly laundry detergent, and paper and paper based products in this category. There is not any data available regarding the quantity of paper and paper based product imported in household. However, there is the availability of data regarding the quantity of paper and paper based products going out from households as solid waste. This study considers all the paper and paper based products imported in Gippsland are eventually ended up in solid wastes, and calculates the P inflow as paper and paper based products accordingly.
	P inflow as fertilizer in urban landscape	Based on the careful observation of urban areas of the Gippsland region in the 'Earth' view of google maps, it is assumed that approximately 35-40% of the total urban area of the Gippsland region is unpaved land where P input is required. Because of the unavailability of data relating to P input rate in the urban areas of Gippsland, this study has systematically adapted the findings of urban nutrient inputs survey of Kelsey et al. (2010) in Western Australia, where the median rate of P input in urban residential area was identified to be 19.7 kg/ha/yr. Generally, the soils in Western Australia are sandy which are deficient in organic matter and have a low ability to retain water and nutrients (CSBP, 2012) and therefore, require higher rate of fertilizer application compared to the Gippsland region. Based on these understandings as well as expert's advice, this study assumes that the rate of P input in the urban areas (including residential and other landscape) of the Gippsland region is approximately 50% of the rate of P input in urban residential areas of Western Australia as estimated by Kelsey et al. (2010). However, according to Kelsey et al. (2010), the majority (more than 93%) of the P input in urban areas is occurred as fertilizer application, where 75% of the P input as fertilizer in urban area occurred as organic fertilizers mainly manure based and 25% occurs as chemical fertilizers. The same proportion has been considered for Gippsland.
WASTE MANAGEMENT	*System considerations*	The waste management subsystem mainly includes urban waste management facilities for instance; solid waste collection, wastewater treatment plants, landfills system, as well as associated activities, processes and flow of materials. It does not include any solid waste or wastewater management facilities that associated with the livestock farming system and major industries.
	P flow as solid waste (green organics)	According to GRWMG (2010), approximately 100% of the total green waste collected in 2008-2009 was processed. Therefore, the present study considers that all the collected green wastes have been taken to composting plants and processed to produce compost. In 2012, Gippsland Water's (GW) Soil and Organics Recycling Facility (SORF) recycled approximately 5.5 million tonnes of organic materials, of which about 2 million tonnes was green waste collected by the local government (Clark, 2014). Based on the diversion

	rate (which remain almost same over the years) of solid waste as reported in Victoria Local Government annual survey (2008-2009, 2009-10, 2010-11) (Sustainability Victoria, 2010, 2011, 2013), it can be assumed that in the later years too, nearly all the green wastes collected were processed for composting.
P flow as solid waste (garbage)	In the garbage, the majority proportion (nearly 70% by weight) is food waste, paper and some garden waste which may have significant P content. Therefore, in order to calculate P flow in garbage, only the abovementioned categories of wastes have been considered. According to GRWMG (2010), there was no diversion of wastes from the garbage collected in 2008-2009. This indicates that all the garbage collected in 2008-2009 was eventually disposed in landfill without P recovery. However, the diversion rate of solid wastes according to the Victoria Local Government annual survey of 2008-09, 2009-10, and 2010-11 (Sustainability Victoria, 2010, 2011, 2013) indicates that the situation remained same over the years.
P flow as solid waste (recyclables)	According to GRWMG (2010), about 85% of the recyclables (paper. Glass, plastic, iron) collected in 2008-2009 was recycled. However, these wastes contain a very small amount of P, and calculation indicates that the total amount of P flow in this category of solid wastes is not significant. Moreover, P recovery from these wastes is not practical. Therefore, the current study does not focus much on these categories of waste.
P flow as domestic wastewater and sludge	According to EGRWC (2010), in 2009-2010, about 2,674 ML wastewater were collected and 2,152 ML wastewater were treated. All (100%) of the treated wastewater were reused. According to CGRWC (2010), in 2009-2010, about 1,171 ML of treated wastewater were reused and 3,644 ML treated wastewater were discharged to water bodies. These are non-saline water and mainly of household origin. Thus, total wastewater treated in 2009-2010 was (1,171+3,644) ML or 4,815 ML. Using the same ratio of collected and treated wastewater according to EGRWC (2010), it can be calculated that the total collected wastewater for Central Gippsland Regional Water Corporation (CGRWC) in 2009-2010 was 5,983 ML. According to South Gippsland Water (2010), about 3,811 ML wastewater were collected and treated in 2009-2010 in South Gippsland treatment facilities. Given the total number of population served by South Gippsland water in 2009-2010, it can be calculated that of the total wastewater collected and treated (3,811 ML), about 1,313 ML wastewater were originated from the household/residential areas. CGRWC, EGRWC and SGW are the three main corporations that are formally treating wastewater in Gippsland. If added up the quantity of wastewater treated by these three corporations, it is found that a total of about (4,815+2,152+1,313) or 8,280 ML wastewater were treated in Gippsland, where total amount of wastewater collected by these there corporations were (2,674+5,983+1,313) or 9,970 ML. The calculation of the total domestic wastewater generation in Gippsland based on the rate of per capita wastewater generation per day (135 L according to RMIT Handbook (2008)) gives a

value of 12,924 ML raw wastewater. Therefore, it can be estimated that about (9,970*100/12,924) % or 77% of the wastewater generated in Gippsland was collected for treatment by the formal central treatment facilities. The remaining 23% may be locally treated or managed. Based on a P content of 13.5 mg/L in raw sewage (Melbourne Water, 2005), it can be calculated that the total P content in raw domestic wastewater generated in Gippsland was 174.5 tonnes. As 77% of the domestic wastewater is collected by central treatment facilities, it can be assumed that about 134.34 tonnes P in wastewater came to the central treatment facilities.

According to CGRWC (2010), EGRWC (2010) and DSE (2009);the total amount of treated wastewater reused (mainly for irrigation to pasture) in Gippsland was (1,171+2,152+144) ML or 3,467 ML, and the total treated wastewater discharged to water bodies was (8,280-3,467) 4,813 ML. According to Pescod (1992) and MAV and DSE (2006), typical P content in treated domestic wastewater for irrigation is 10 mg/L. The water quality monitoring results for irrigation sites that use recycled wastewater from CGRWC treatment plants indicate that a median value of 9.7 mg/L wasrecorded in samples collected in some irrigation sites (CGRWC, 2012), which is close to the typical value of 10mg/L. However, the present study considers this typical value (10 mg/L) and calculates that in Gippsland, about {(3,467*1,000,000*10/1,000,000,000)} or 34.47 tonnes P in treated wastewater was used for irrigation. According to EPA Victoria (2009), the typical recommended level of total P in treated wastewater discharged to water bodies should be 0.5 mg/L. According to CGRWC Annual Performance Statement for 2011-12 financial year (CGRWC, 2012), CGRWC well maintained the EPA criteria and discharged less P (ranging from 0.08-0.33 mg/L) than the recommended level (0.5 mg/L). However, the current study considers the maximum level of P (0.33 mg/L) in treated wastewater discharged to water bodies by CGRWC, and calculates that P flow as treated wastewater discharge to water bodies was {(4,813*1,000,000*0.33)/1,000,000,000} or 1.58 tonnes in 2009-2010. Therefore, (34.67+1.58) or 36.25 tonnes P came out in treated wastewater, and the remainder (134.34-36.25) or 98.09 tonnes P should be contained in sludge.

Again, if taken another approach to calculate P content in sludge that is the typical quantity of raw sludge (biosolids) generated in a wastewater treatment plant is approximately 2% of wastewater inflow to plant, and given that about 9,970 ML of wastewater collected for treatment in two main for treatment facilities in Gippsland, the raw sludge production can be calculated as 199.4 ML. With typical TS content of 5% in untreated primary sludge (Metcalf and Eddy, Inc., 1991), the total solid could be calculated as 9,970 tonnes. As P_2O_5 content is 1.6% of TS (Metcalf and Eddy, Inc., 1991), it can be estimated that about 69 tonnes of elemental P contained in sludge produced in three central treatment facilities.

According to CGRWC (2009), as most of the wastewater treatment plants stabilise sewage sludge in dedicated treatment lagoons, biosolids are only produced when the lagoons require sludge removal which is expected to occur at every 10 to 20 years.

Exceptions to this are the Neerim South and the Rawson wastewater treatment plants. The sludge from the Rawson Wastewater Treatment Plant is disposed of in the Morwell sludge lagoon where it is combined with the sludge produced at Morwell. Sludge generated from the Neerim South Wastewater Treatment Plant is transported to the Warragul Wastewater Treatment Plant and then mixed with its sludge, prior to partial dewatering and transportation to the Soil and Organic Recyling Facility (SORF) at Dutson Downs for further processing. Biosolids can be utilized as a valuable resource for soil reconditioning, fertilizer or energy production. The biosolids transported to the SORF are stabilised through either in-vessel or windrow composting technology, and are beneficially used at Dutson Downs as a soil reconditioner in agribusiness activities of Gippsland Water. During the reporting period, 2,945 tonnes of dewatered sludge (equivalent to approximately 453 dry tonnes) from the two wastewater treatment plants were transported to Dutson Downs and eventually stabilised for reuse.

According to ANZBP (2009), dried biosolids (sludge) have 0.9% of P content, thus, based on CGRWC (2009) data of 453 dry tonnes of biosolids taken to composting facilities, it can be calculated that about 4.077 tonnes of P in biosolids ended up in compositing facilities which was eventually transported to farm as compost. Therefore, the rest (98.09 - 4.077) or 94 tonnes P was either disposed of in landfill areas or applied to agricultural lands.

Another paper (Gokhale et al. (year unknown)) indicates that the Gippsland Water Factory (GWF) is now producing approximately 30,000 wet tonnes/year of biosolids from wastewater (both domestic and industrial) that are being received at Gippsland Water's (GW) Soil and Organics Recycling Facility (SORF). Using the ratio of dewatered sludge to dry tonnes as calculated by CGRWC (2009), this 30,000 wet tonnes could be calculated as equivalent to 4,614 dry tonnes. Given that the domestic wastewater accounts for about 30 % of the of the total wastewater coming to treatment facilities (calculated based on the ratio of total wastewater treated vs domestic wastewater), biosolids originated from domestic wastewater taken to the recycling plants can be calculated as (4,614*30/100) or 1,384 dry tonnes which may have a total P content of about 12.46 tonnes. The rest of the P (98.09-12.46) or 85.63 tonnes of P in biosolids generated from domestic wastewater was either disposed of in landfill areas or applied to agricultural lands.

There is not any information available regarding which proportion of biosoilds from Gippsland wastewater facilities is actually disposed of in landfill areas and what proportion is applied to agricultural lands. However, according to ANZBP (2009), Australia currently produces approximately 300,000 dry tonnes of biosolids annually. Approximately 55% of that is applied to agricultural lands and around 30% is disposed of in landfill sites or stockpiled. The remaining 15% is used in composting, forestry, and land rehabilitation or incinerated. Considering the same proportion for Gippsland, it can be calculate that about (98.09*55/100) tonnes or 54 tonnes P in biosolids was applied to agricultural land and (89.49*30/100) tonnes or 29.43 tonnes P in biosolids was disposed of in landfill areas.

As calculated earlier in this section that about 77% (9,970 ML) of the total domestic wastewater generated in Gippsland was collected by three major centralized wastewater treatment facilities, the rest 23% or (12,924 ML-9,970 ML) or 2,954 ML should be managed locally. Information related to domestic wastewater management in Gippsland available through the website of relevant organization (East Gippsland Shire Council, 2014; Gippsland Water, 2013; South Gippsland Shire Council, 2014) indicate that septic tank system is commonly used in Gippsland particularly in the un-sewered area. Therefore, the current study considers that about 23% (2,954 ML) of the domestic wastewater in Gippsland is managed by septic tank system. That means about (174.5-134.34) or 40.16 tonnes of P in domestic wastewater found its way to the septic tank system. From the septic tank, some P go out as effluent to the local environment and the rest is remained in sludge. According to South Gippsland Shire Council (2014), septic tanks do not remove nutrients or disinfect the effluent, and the effluent is highly infectious and it must be applied to land below ground level. Therefore, after leaving the septic tank, the effluent is then passed into a series of trenches. If the tank is not operated and maintained properly, excessive solids will pass to the effluent dispersal system. This will quickly clog up, cause health hazards, and cause a need for expensive reinstallation of the dispersal area. Sludge removal from the septic tank is required every 3-5 years depending on use. According to NZWWA (2003), raw septic tank sludge could be considered as biosolids only after it receives appropriate treatment. So, septic tank sludge not receiving any treatment should be disposed of in landfill. Using the same method of calculation that has been used for calculating P content in sludge generated by centralized wastewater treatment facilities, it can be estimated that in Gippsland annually about 20.51 tonnes of P in sludge was removed from septic tanks. Therefore, the rest (40.16-20.51) or 19.65 tonnes P was discharged annually as septic tank effluent to local environment. However, there is not any information available regarding the fate of sludge that is removed from septic tanks. This study assumes that about 50% (that contains 10.26 tonnes P) of the sludge removed from septic tanks was disposed of in landfill and the rest (50%) that contains 10.26 tonnes P was taken to recycling plants or eventually recycled. The same methods of calculation are applicable for other years too.

WATER BODIES	*System Considerations*	In the current analysis of the Gippsland region, the water system mainly includes all fresh surface water bodies such as streams, lakes and rivers, and the associated processes and flows of materials. While accounting for P outflow as water extraction for beneficial purposes from this system, the current study only considers the water flow that is dedicated to irrigation purposes in the agricultural (crop and livestock) systems. This analysis does not consider the water that is extracted for industrial and domestic uses with the assumption that P flows associated with these water uses are less significant.

P discharged from water bodies (streams and rivers) to costal water and ocean	According to DSE (2011), average water flows at basin (South Gippsland, Latrobe, Thomson, Macalister, Avon, Mitchell, Tambo and Nicholson, Snowy, East Gippsland excluding Snowy) outlets in Gippsland is 4,925,100 ML/yr. The current study considers that the same amount of water is discharged from fresh water bodies (streams and rivers) to costal water and ocean. According to Gourley et al. (2010), the mean P content in water sampled (57 sample) from irrigation channels, rivers and bores in Gippsland is .04 mg/L. Therefore, it can be calculated that about {(4,925,100*1,000,000*0.04)/1,000,000,000} tonnes or 197 tonnes P discharged annually from streams and rivers in Gippsland to coastal water and ocean. As these information are not available on an annual basis, the present study considers the same situation for each year of the study period.

3.2.5.4. Approach for modelling P flow and reliability assessment

As explained earlier, the model has been carefully constructed in the MATLAB/Simulink® software platform following the appropriate procedure. The initial trial using random numbers also has also indicated that the model is accurately representing the mass balance principle. Therefore, it is believed that the model will perform well. However, in order to investigate how well the model performs, it has been utilized for the analysis of multiple years P flow in the case of the Gippsland region. By nature, the accuracy of the outcomes from the SFA model greatly depends upon the quality of the input data. Keeping this fact in mind, as described earlier, this study has made it utmost attempt to the collect the best set of reliable data relating to the Gippsland region as well as to make the best assumptions in case of missing data or information. Therefore, it is anticipated that utilizing this best set of reliable data in the model, the best set of reliable results relating to the nature and magnitude of P flow in the Gippsland region can be produced. However, in order to attain a further understanding of the accuracy and reliability of the model outcomes, this study has performed a 'reality check' particularly for some significant P flows and storage. This reality check includes comparing the model results with the findings from either actual field based study, independent literature data, or alternative calculations. For instance, the model calculates soil P storage and accumulation in a subsystem based on the given material mass flow and P concentration data input for the inflows and the outflows that associated with soils of that subsystem. By contrast, in an actual field experiment based study, soil P storage in a particular system (e.g. crop, livestock farming) is usually measured based on collecting soil samples and then subsequent chemical analysis of P in the laboratory. Soil P storage data produced in this manner are generally considered to be more accurate and therefore, provide a basis for comparison, however the accuracy is much dependent on appropriate sampling and is sensitive to spatial heterogeneity of P distribution across the landscape. In terms of the alternative calculation, the procedure is to manually calculate the mass of P relating to a particular type of flow by a method different to that has been utilized in the model and then, compare the model outcome for that flow. For instance, P inflow as feed intake in the livestock body in the current model has been analysed just by multiplying the total livestock number with the daily amount of P intake in feed per animal and then multiplying the product with number of days in a year. In an alternative method, P inflow as feed intake in the livestock body can be calculated as multiplying the total livestock number by the daily intake of dry matter in different types of feed (e.g. pasture, grain, concentrate etc.) per animal separately, and then multiplying the product by P concentration in each type of feed and total number of days in a year, and finally, adding up total P intake in each type of feed. If the model results relating to the magnitude of P for a particular type of flow fall within a range of ±40% of the value that identified through any of the approaches considered in the reality check, then the model result for that particular flow is accepted as a reliable result. If the model results relating to the magnitude of any significant P flow or storage do not fall within the defined range of the reality check, then it is brought under further investigations. If required, necessary modifications in the model parameters, structures as well as checking of the collected data and assumptions are performed to get the best reliable outcomes from the model.

This chapter has presented a thorough description of the SFA as well as the procedure in which this method has been applied to perform the quantitative modelling P flow over multiple years at the regional scale. The next chapter presents and discusses the key outcomes of this modelling with special focus on the case of the Gippsland region in Australia.

Chapter-4

RESULTS AND DISCUSSIONS

This chapter presents a detailed assessment of the regional scale P flow model developed in this study, findings of the model application in the case of Gippsland region, Australia, and necessary recommendations for improving P management in this region. It consists of three main sections:

Assessment of the regional scale P flow model developed in this study - which describes the structural and operational aspects of the model, the unique qualities that make it superior to available SFA models, and its reliability.

An analysis of the nature and magnitude of P flow and storage over multiple years in the Gippsland region - which comprehensively illustrates the nature and magnitude of P flow and storage relating to the Gippsland region as a whole and all subsystems within this region for a six year period (2008-2013) to identify the priority areas for improving P management; and

Recommendations for making better P management decisions to achieve P sustainability in the Gippsland region - which provides a wide-range system specific improved P management decisions that might be utilized for securing sustainable management of P in the Gippsland region.

4.1. Assessment of the regional scale P flow model developed in this study

4.1.1. Operational aspects and efficacy of the model

The model developed in this study has taken into account, both structurally and operationally, all the relevant P flows and storage associated with all key systems, subsystems, processes or components, and associated interactions of P flow to represent a typical P flow system at the regional scale. This is a SFA model, and based on the input of known material mass data and associated P concentration data for both inflows (for instance, commercial fertilizer) and outflows (for instance, crop products) at system or subsystem boundaries, the model allocates P mass to flow paths and storage within the system to ensure that mass balance principles are achieved. In this way, the model allows analysing the mass flow (both inflow and outflow) and mass storage of P relating to any system or subsystem (**Fig. 4.1**; **Fig. 4.2**). The model also allows analysing the cumulative storage or accumulation of P over years in a system or subsystem (**Fig. 4.2**). Moreover, it has the ability to account for the actual P stock (that is the sum of the initial reserves at the beginning of a given time and the net storage in that given time) in a system or subsystem for a case where initial P pool or reserves data are available. In addition, the model allows calculating the mean value (along with standard deviation) of P flow over many years. The majority of the available P flow models as developed in SFA studies at the regional scale (Li et al., 2010; Yuan et al., 2011a, 2011b; Do-Thu et al., 2011; Wu et al., 2012) are static and can analyse P flow only for a particular year at a time and therefore, cannot assess the trends or changes in P flow over several years. In contrast, the SFA model, as developed in this study, is capable to analyse the trends or dynamic changes in P flow over many years at an annual time step. Due to data limitations in the case of Gippsland region, the model currently deals with six years, but it can be used for as many years as required depending upon the case with adequate data availability. Although the model currently does not take into account any time step smaller than a year, it allows incorporation of any smaller time step when required and produce results at any desired time steps.

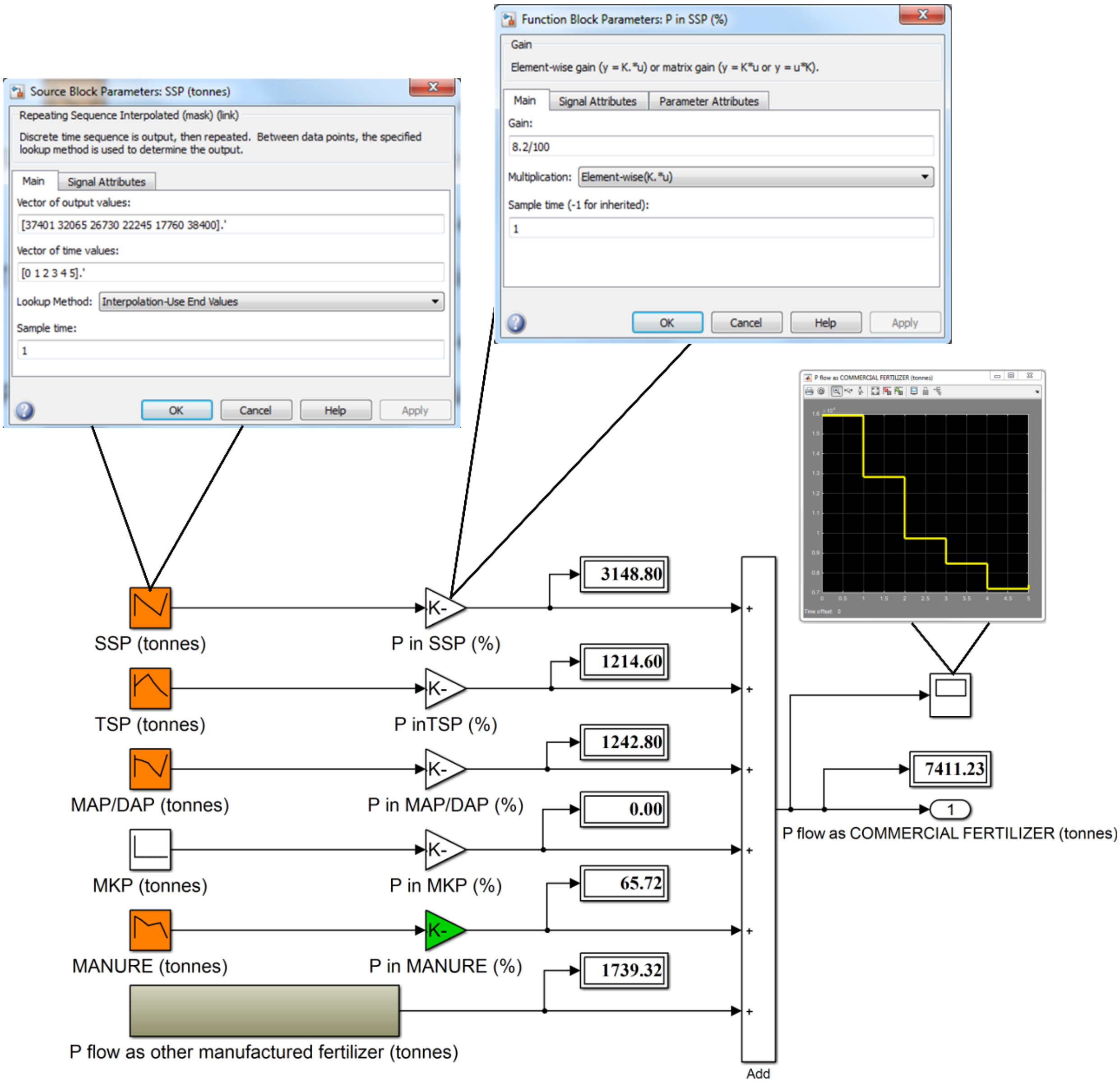


Fig. 4.1 A typical method of analysing P inflow and outflow in a system by the model. The example of analysing P inflow as commercial fertilizer has been presented here. The *Repeated Sequence Interpolated (RSI)* blocks in the far left that are denoted with fertilizer names (for instance SSP) receives material mass data for each corresponding years of the study period (as indicated for six years above), and the *Gain* blocks in the middle that denote the P concentration in fertilizers (for instance P in SSP). If RSI block is connected (here indicated with arrow) to the gain block, when the model is run, a multiplication between the P content data and the material mass flow data occurs, and then the arrow going out of the gain block carries P mass flow. The *Display* blocks (next to Gain blocks) show P mass flow for the latest year. The *Add* block in the right sum up the P mass flows in each type of fertilizers, and the *Scope* block along with the graph in the far right indicates the total P mass flow as commercial fertilizer for the each corresponding years of the study period.

In this model, it is not required to give data input for each and every inflow or outflow relating to the various subsystems. The model utilizes feedback within the system to close the loop where output flow from one subsystem is the input flow for other subsystems. For instance, in the model, P outflow as soil erosion and runoff from the livestock system is an inflow for the water system, and P outflow as compost generated in the waste management system is an input for both the crop production and the household and urban system. The model allows capturing numerous such interactions of P flow among various subsystems and different components within subsystems and sub-subsystems, and therefore, allows addressing the necessary complexity of a P flow system at the regional scale.

This unique ability of the model to comprehensively analyse various P flows and storage in a system while accounting for all the interactions of P flow within the system and subsystem is a significant contribution of this study. For instance, if focused on the case of the livestock farming subsystem, this model is capable not only to analyse P inflow, outflow and storage associated with this system as a whole, but also analyse P inflow, outflow and storage associated with various sub-subsystem within this system such as the livestock body, soil, and manure management system, and even of that associated with different components within these sub-subsystems (**Fig. 4.3**). Similarly, the model has the ability to perform a detailed analysis of other subsystems. A detailed picture of the model in MATLAB/Simulink® software platform has been presented in **Appendix 4**.

The model also allows storing necessary details (for instance, source, quality of data, or any assumptions) regarding each and every data as well as any other necessary descriptions in each block at any point and thus, provides a useful reference for future analysis. It also allows exporting simulation data which involves saving signal values to the MATLAB® workspace or to a MAT-file during simulation for future retrieval and further processing. Another key aspect of this model is that the results or outputs relating to the magnitude of P flow can be instantly viewed at any point in the model. Moreover, the model offers greater flexibility and allows necessary modifications in the model structure, and updating at any point at any time. This implies that by making necessary adjustments for instance, inclusion or exclusion of any subsystem, any flow or storage, and/or making any other required changes in model structure or data, it is possible to utilize this model for the quantitative analysis of regional scale P flow over multiple years for any case where sufficient input data are available. As the model has already been utilized in the case of the Gippsland region, it currently contains input data on material mass flow and P concentration. Generally, P concentration data of materials do not show high variation like material mass flow data in different regions of the world. This implies that the P

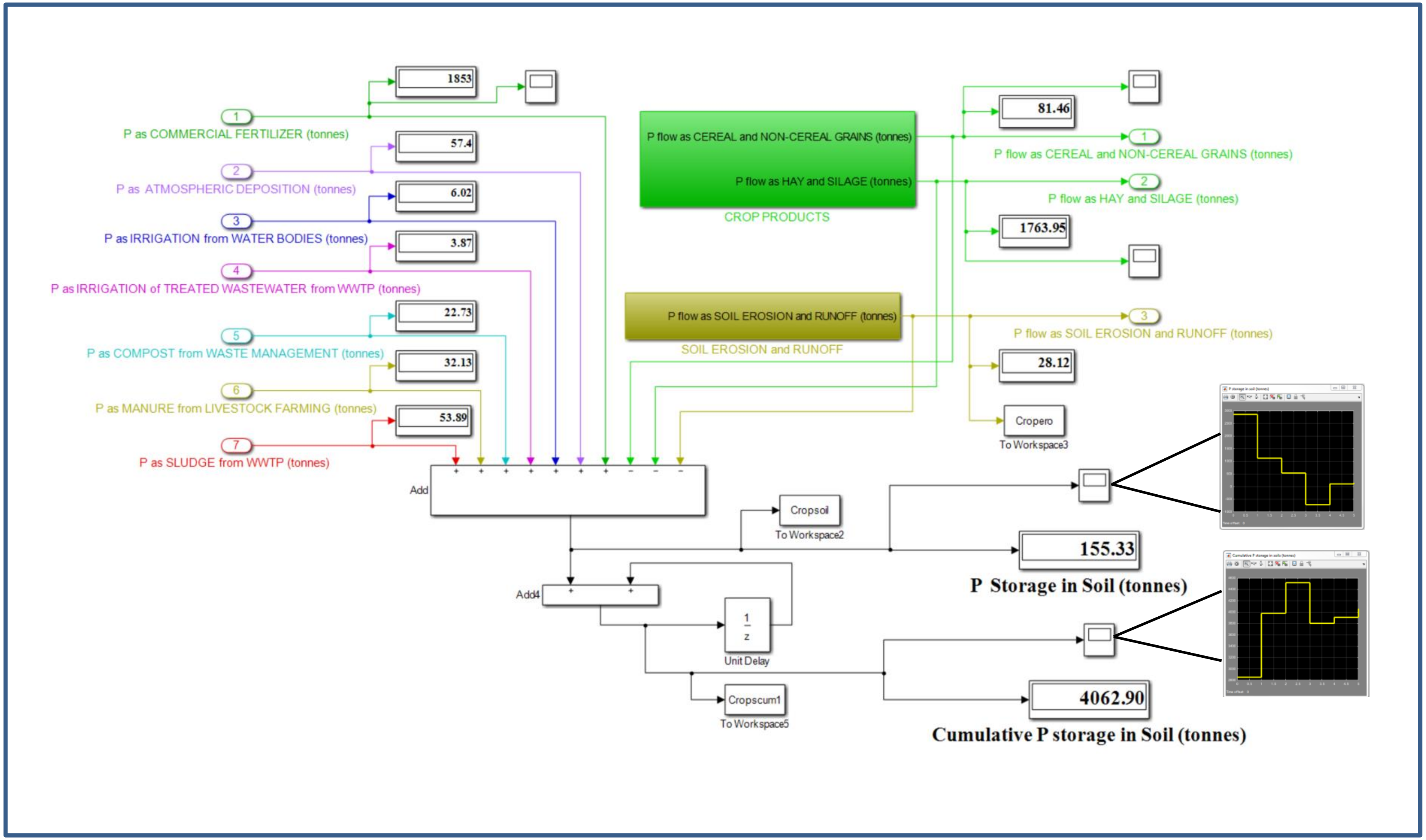


Fig. 4.2 A typical method of calculating net storage and cumulative storage of P in a system by the model. The example of the P storage in soil of the crop farming system has been presented here.

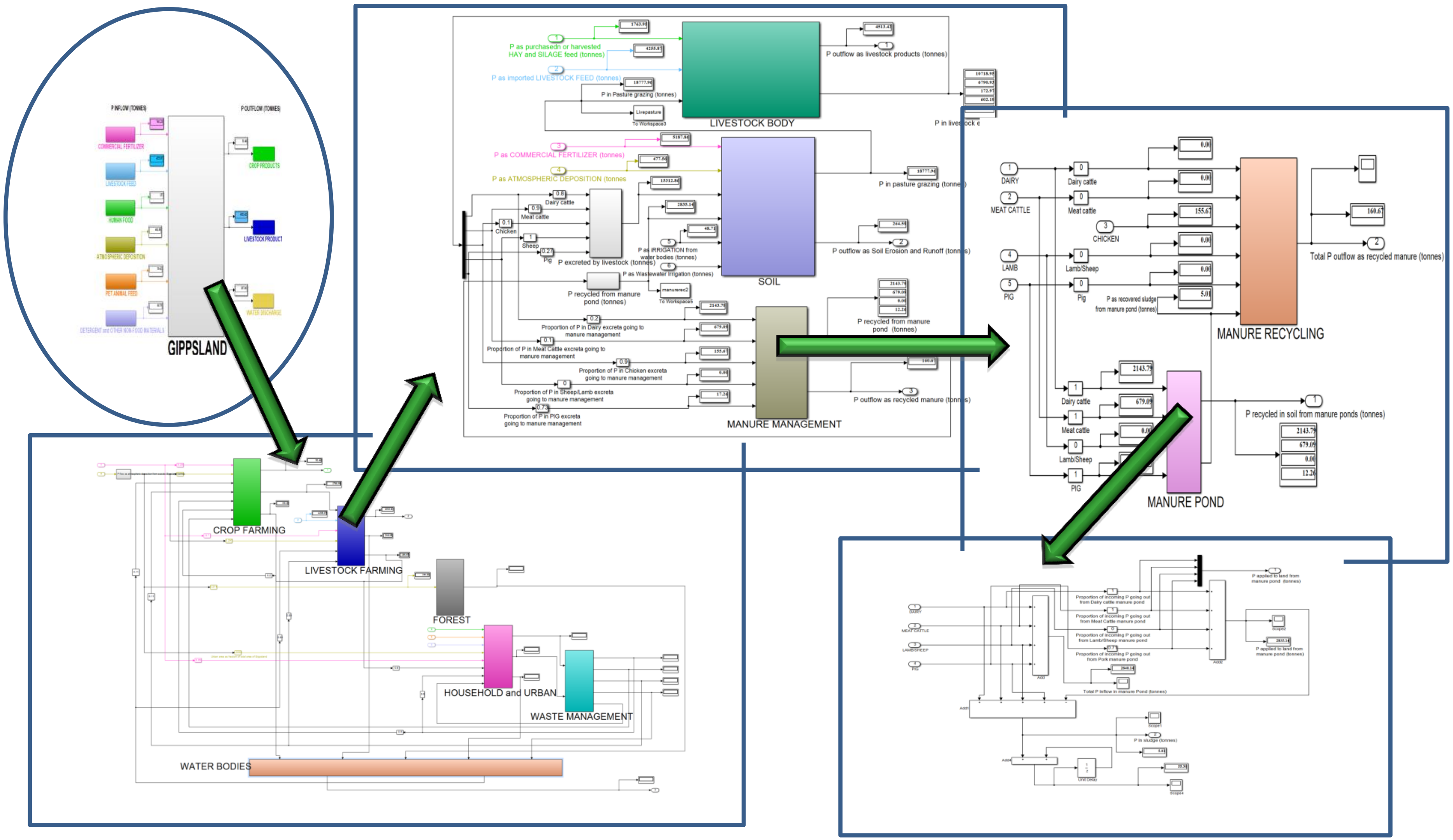


Fig. 4.3 An overall view of the regional scale P flow model as developed in the MATLAB/Simulink® software platform. Here, the analysis of only the livestock farming system has been presented in some details, with the big green arrows indicating the hierarchy from the overall region to the substance flow analysis of the manure pond subsystem. The model also includes detailed analysis for all other subsystems.

concentration data that already exist in the model, can give a rough estimate of the magnitude of P flow in the case of any region upon the input of only material mass flow data. However, for increased accuracy and reliability of the model results, case/region specific P concentration data should be utilized.

4.1.2. Reliability of the model

Since the model has been developed based on a comprehensive literature based understanding of P flow system at the regional scale as well as by utilizing the basic mass flow and mass balance equations that are usually considered for the SFAs of P, the model must be structurally and operationally sound. The initial experiment also confirmed that each and every component of the model is accurately following the principle of mass balance. However, this is a SFA model, and it generates results based on the given data input. Therefore, the output of model is only as good as the input data, and in order to obtain reliable results from the model, the accuracy and reliability of the input data must be ensured first. For investigating the efficacy of this model in analysing the nature and magnitude of regional scale P flow, the model has been utilized in the case of Gippsland region, Australia (the reason for selecting this region has been discussed in **Section 3.2.5.1**). With a view to obtaining sound result from the model, the best set of reliable and accurate material mass flow and P concentration data for the Gippsland region has been utilized. The model outputs relating to the magnitude of some key P flows and storage has been then compared to the findings of actual field based study, independent literature data, and/or alternative calculations according to the procedure of 'reality check' as explained in the **Section 3.2.5.4**. These comparisons have revealed that the model produced reliable results in the case of analysing multi-year P flow for the Gippsland region. The reality check for the model results relating to some significant P flows and storage has been presented in details in **Appendix 5**.

This section has presented an assessment of the regional scale P flow model developed in this study. The following section presents a detailed analysis of the nature and magnitude of multi-year P flow in the case of Gippsland region as performed through utilizing this model.

4.2. An analysis of the nature and magnitude of P flow and storage over multiple years in the Gippsland region

This section presents and illustrates the key findings of the multi-year SFA of P in the case of Gippsland region. It includes a comprehensive analysis of the nature and magnitude of six-year (2008-2013) mean annual P flow (inflow, outflow, storage, internal flow) relating to the Gippsland region as a whole and all subsystems within this region. Simultaneously, an analysis of the P flow relating to each year of the study period has been presented and discussed to provide an understanding of the variation in annual P flow as well as the overall trends in P flow over that period. Based on the current analysis, priority areas for improving P management in the Gippsland region are identified, and recommendations made to achieve P sustainability in this region. An overall picture of six-year mean annual P flow in the Gippsland region including all subsystems has been presented in **Fig. 4.4**.

In the following sections, the magnitude of six-year mean annual P flows and storage are presented with the standard deviation in brackets. Where standard deviation is not presented indicates insufficient data availability to calculate that.

4.2.1. Gippsland region as a whole

The quantitative modelling of P flow and storage relating to the Gippsland region for the study period has revealed that the mean annual total inflow of P into this region was approximately 15,349 (3,450) tonnes, while the mean annual total outflow of P from this region was approximately 4,445 (190) tonnes. This indicates that nearly 71% (10,904 (3,549) tonnes) of the mean annual total inflow was eventually stored within this region (**Fig. 4.5**).

A comparative assessment of the findings (regarding total inflow, total outflow and total storage) of the current analysis for the Gippsland region and other six regional scale P flow analyses (the majority of which are single year analysis) from around the world as presented in **Table 4.1** indicates that the proportion of the annual total inflow of P that eventually exited the system is lower (29%) in the case of Gippsland, where it ranged from about 53% to 81% in case of other studies. This implies that the proportion of the annual total P inflow that stored within the system is comparatively higher in the case of Gippsland. This difference is probably because most of these studies are from China, where the regional scale includes fertilizer production sector, and therefore, there is a substantial amount of P outflow as mineral fertilizer; whereas the Gippsland region does not include any fertilizer production industry. Another reason for this variation could be the way the system and system boundaries were defined, for instance in some studies, water bodies have been kept outside the main system and therefore, P loss as soil erosion and runoff to water bodies has been considered as P outflow from the main system, while in the current study water bodies have been considered as a subsystem within the main system. Moreover, Gippsland is a net agricultural region, where unlikely to other reported regional scale studies, the land uses are mostly dominated by extensive grazing based livestock (mainly dairy and meat cattle) farming. Therefore, in this region, a substantial amount of P inflow occurs as commercial fertilizers which are eventually applied to soils for pasture production. A considerable amount of P inflow in this region also occurs as grain based livestock feed, which also ends up in soil as livestock excreta. The current analysis has revealed that annually, a massive amount of P is produced as livestock (mainly dairy and meat cattle) excreta in the Gippsland region, which eventually find their way in the soils of the livestock farming system. Although some of these P are lost as soil erosion and runoff, these P are ultimately retained in the water bodies (streams, rivers and lakes) within this region. Probably, owing to all these reasons, higher P storage has been found in the case of Gippsland region.

The inflow of P in the Gippsland region mainly occurred as commercial fertilizer (10,263 (3,461) tonnes) and livestock feed (4,443 (271) tonnes), that together account for about 95% of the mean annual total inflow. A considerable amount of about 402 tonnes P inflow into this region also occurred as atmospheric deposition (**Fig. 4.5**). This finding is different to the outcomes of available P flow analyses at different geographical scales in which, as reviewed by Chowdhury et al. (2014), P inflow as atmospheric deposition has been either overlooked or identified to be a minor or negligible amount. However, when summed up the mass of P in atmospheric deposition that originated from both inside and outside the Gippsland region then the annual total P mass flow as atmospheric deposition is appeared to be about 1,608 tonnes, which is a substantial amount of P. Therefore, future analysis should carefully investigate both inflow and total mass flow of P as atmospheric deposition. The review of Chowdhury et al. (2014) has also revealed that the main inflow of P at the regional scale generally occurs as either mineral ore (particularly in the regions that have P fertilizer production sector), or chemical fertilizer or livestock feed (mainly in the regions without fertilizer production sector), and the later has been observed in the current case of Gippsland region. However, the outflow of P from this region mainly occurred as livestock products (4,181 (187) tonnes) which accounts for approximately 94% of the mean annual total P

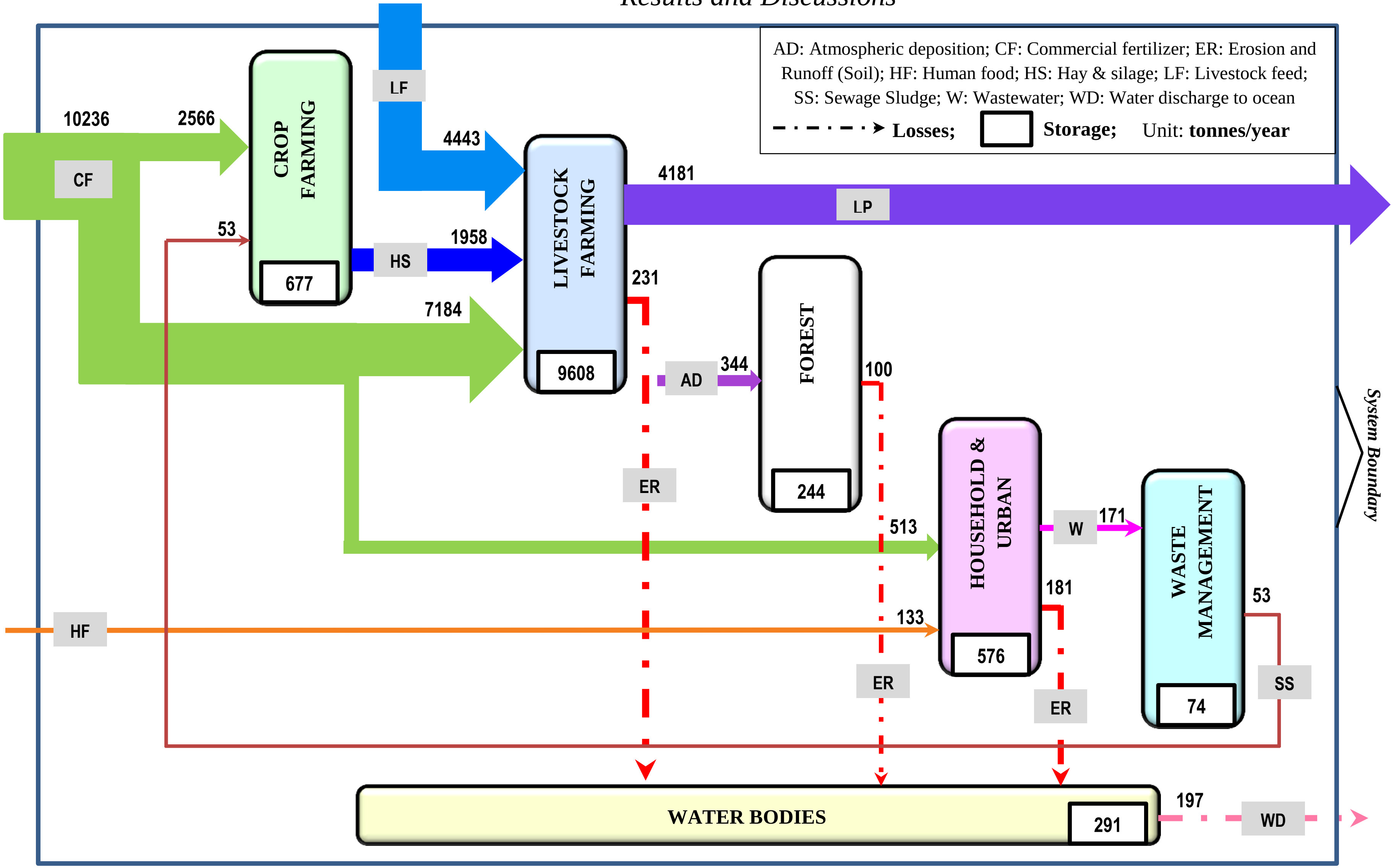


Fig. 4.4 An overall picture of the nature and magnitude of six-year (2008-2013) mean annual P flow in the Gippsland region including all subsystems. Here, only the major P flows relating to different subsystems are presented. The minor flows of P along with a more detailed picture are presented in the following figures and tables. The size of the arrow is indicative of the magnitude of P flow.

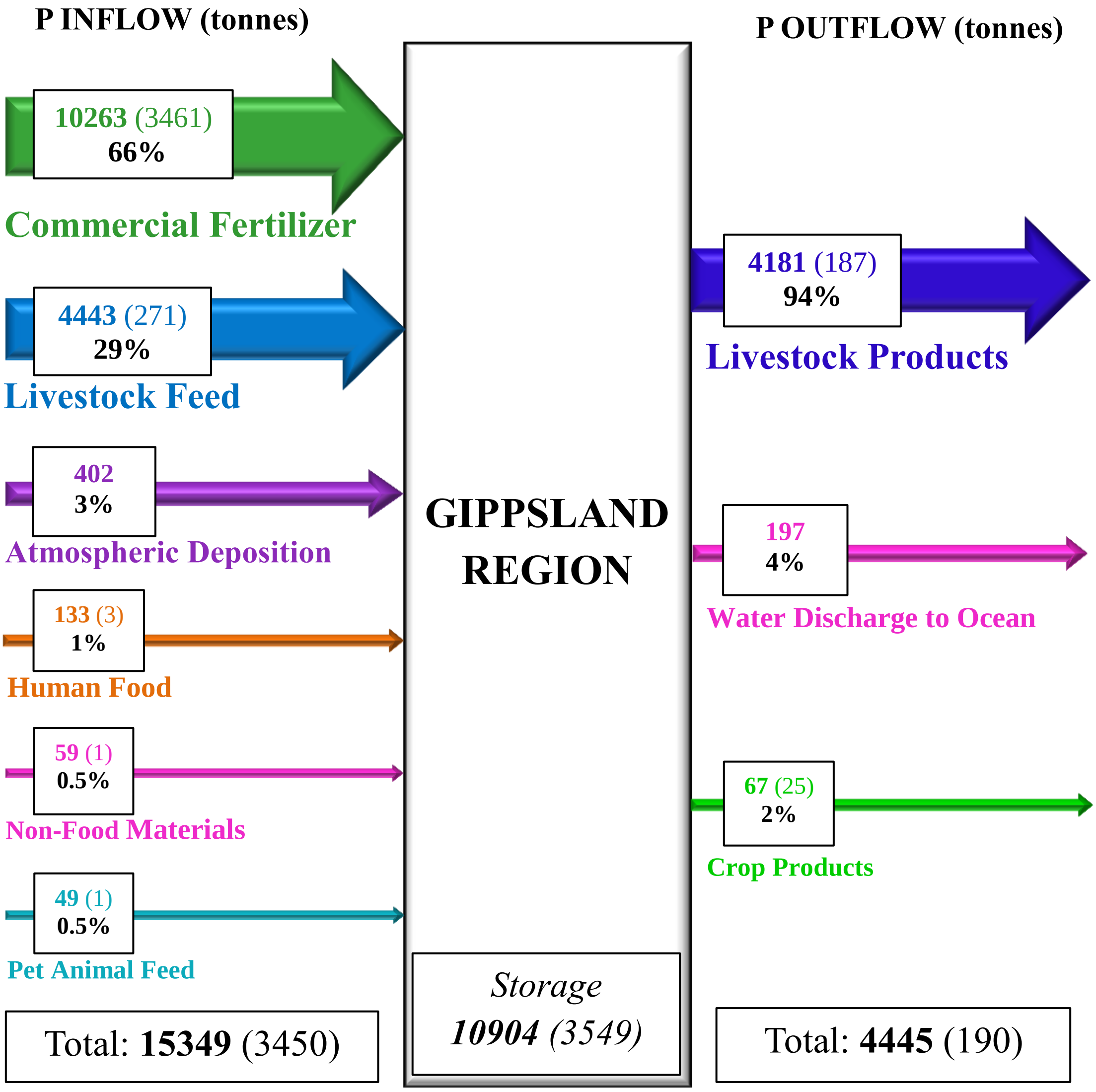


Fig. 4.5 Nature and magnitude of mean annual P flows and storage in the Gippsland region for 2008-2013. The number within bracket indicates the standard deviation (SD), and where SD is not presented indicates insufficient data availability to calculate that. The number with percent (%) in the left side, denotes the proportion of the total inflow, and in the right side, denotes the proportion of the total outflow. The size of the arrow is indicative of the magnitude of P flow.

outflow, whereas about 197 tonnes of P outflow (representing only 4% of the mean annual total outflow) occurred as water discharge to ocean (**Fig. 4.5**). The review of Chowdhury et al. (2014) indicates that at the regional scale, the key outflows of P usually takes place as either mineral P fertilizer (mainly in the regions with fertilizer production sector), or crop and livestock products or soil erosion and runoff (particularly in the regions without fertilizer production sector). In terms of P storage within the Gippsland region, the majority (66% or

7,218 (2,413) tonnes per annum) occurred in soils of the livestock production system, while about 22% (2,390 (514) tonnes per annum) occurred in the livestock body. However, soils of either the crop production or the agricultural (both crop and livestock) production system have been found to be the main place of P storage in other regional scale P flow analyses from around the world (Chowdhury et al., 2014).

Table 4.1 A comparative picture of the findings (regarding total inflow, total outflow and total storage) of the analysis of P flow for the Gippsland region and other regional scale analyses from around the world. The information in this table has been systematically extracted from **Table 2.1** and **Table 2.2** to present a concise picture of the magnitude of regional scale P flow.

Location of the study	Type of system of P flow	Year of P flow analysis	Measuring Unit[1]	Inflow	Outflow		Storage		Reference
				Total Inflow	*Total Outflow*	*% of total inflow*	*Total Storage*	*% of total inflow*	
Hefei, China	Anthropogenic	2008	t/a	7810	4160	53	3650	47	*Li et al., 2010*
Lujiang , China	Anthropogenic	2008	t/a	8310	5670	68	2640	32	*Yuan et al., 2011a*
Hanam, Vietnam	Rural Area	2008	t/a	120	65	54	55	46	*Do-Thu et al., 2011*
Linkoping, Sweden	Food production and consumption	2000	kg/cap/a	2.095	1.345	64	0.75	36	*Neset et al., 2008*
Chaohu, China	Anthropogenic	2008	t/a	8520	5260	62	3260	38	*Yuan et al., 2011b*
Feixi, China	Socio-Economic	2008	t/a	19150	15600	81	3550	19	*Wu et al., 2012*
Gippsland, Australia	**Anthropogenic**	**2008-2013**	**t/a**	**15349**	**4445**	**29**	**10904**	**71**	***Current study***

[1] t/a: tonnes per annum; kg/cap/a: kilogram per capita per annum

An assessment of the nature and magnitude of key P inflow, outflow and storage of the Gippsland region as a whole for each years of the study period has been presented in **Fig. 4.6**. This assessment indicates that the annual total inflow of P showed a decreasing trend over the study period, where it decreased from about 20,795 tonnes in 2008 to approximately 14,886 tonnes in 2010 and about 12,317 tonnes in 2013. In each year of the study period, P inflow mainly occurred as commercial fertilizers, which showed a decreasing trend similar to the annual total inflow. The inflow of P as commercial fertilizer decreased from nearly 15,933 tonnes in 2008 to about 9,736 tonnes in 2010 and approximately 7,411 tonnes in 2013. Imported livestock feed, which also accounts for a substantial amount of P inflow, was the second highest in terms of the magnitude of P inflow in each years, where it remained roughly same (ranging from 4,155 to 4,772 tonnes) in all years. In contrast, the annual total outflow of

P from the Gippsland region showed a little variation over the study period, where it ranged from approximately 4,239 to 4,792 tonnes. Almost similar trend has been observed in terms of P outflow as livestock products from this region, which accounts for more than 90% (ranging from 4,120 to 4,513 tonnes) of the total outflow in each years of the study period. **Fig. 4.6** also

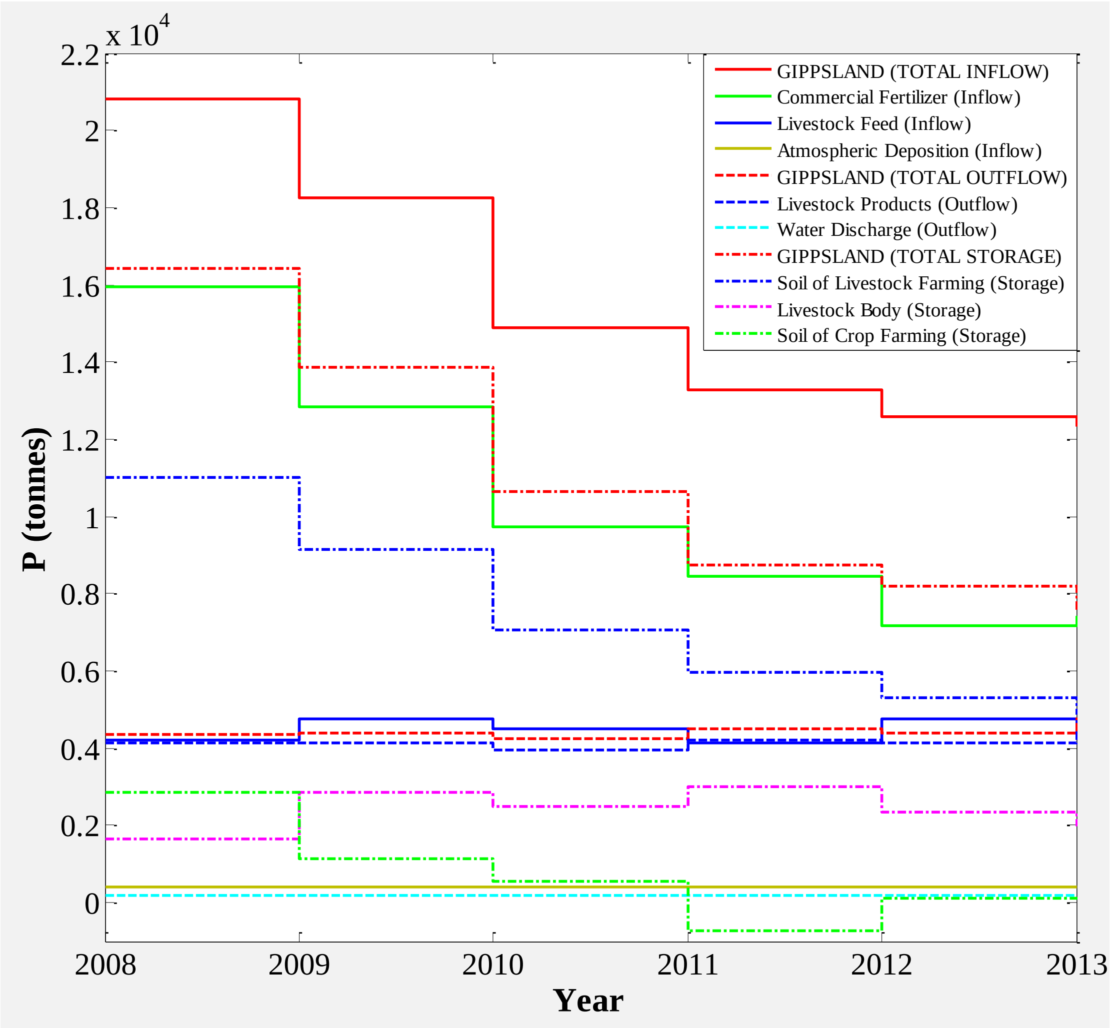


Fig. 4.6 Nature and magnitude of the key annual inflow, outflow and storage of P relating to the Gippsland region over the study period.

indicates that likewise the annual total P inflow, the annual total P storage within the Gippsland region also showed a decreasing trend over the study period, where it reduced from approximately 16,441 tonnes in 2008 to about 10,646 tonnes in 2010 and around 7,525 tonnes in 2013. In all years, the majority of the P storage within the Gippsland region occurred in soil of the livestock farming system, which showed a decreasing trend from approximately 11,016 tonnes in 2008 to about 7,047 tonnes in 2010, and around 4,851 tonnes in 2013. This analysis indicates that over the study period, similar annual P output (mainly as livestock products) has been maintained while minimizing the annual P input (mainly as mineral fertilizers) and P storage (mainly in soils of the livestock farming system), which is an indication of better P management.

Along with the analysis for the Gippsland region as a whole system, in this study, a detailed analysis of the nature and magnitude of P flow and storage relating to all subsystems within this region has been conducted. **Fig. 4.7** presents a comparative picture of the magnitude of mean annual P flow (total inflow, total outflow and total storage) relating to all these various subsystems. This figure indicates that the majority of P flow in this region is associated with the livestock farming system, where it is observed that the magnitude of mean annual total inflow, total outflow and total storage of P associated with this subsystem is almost equal to that of the Gippsland region as a whole.

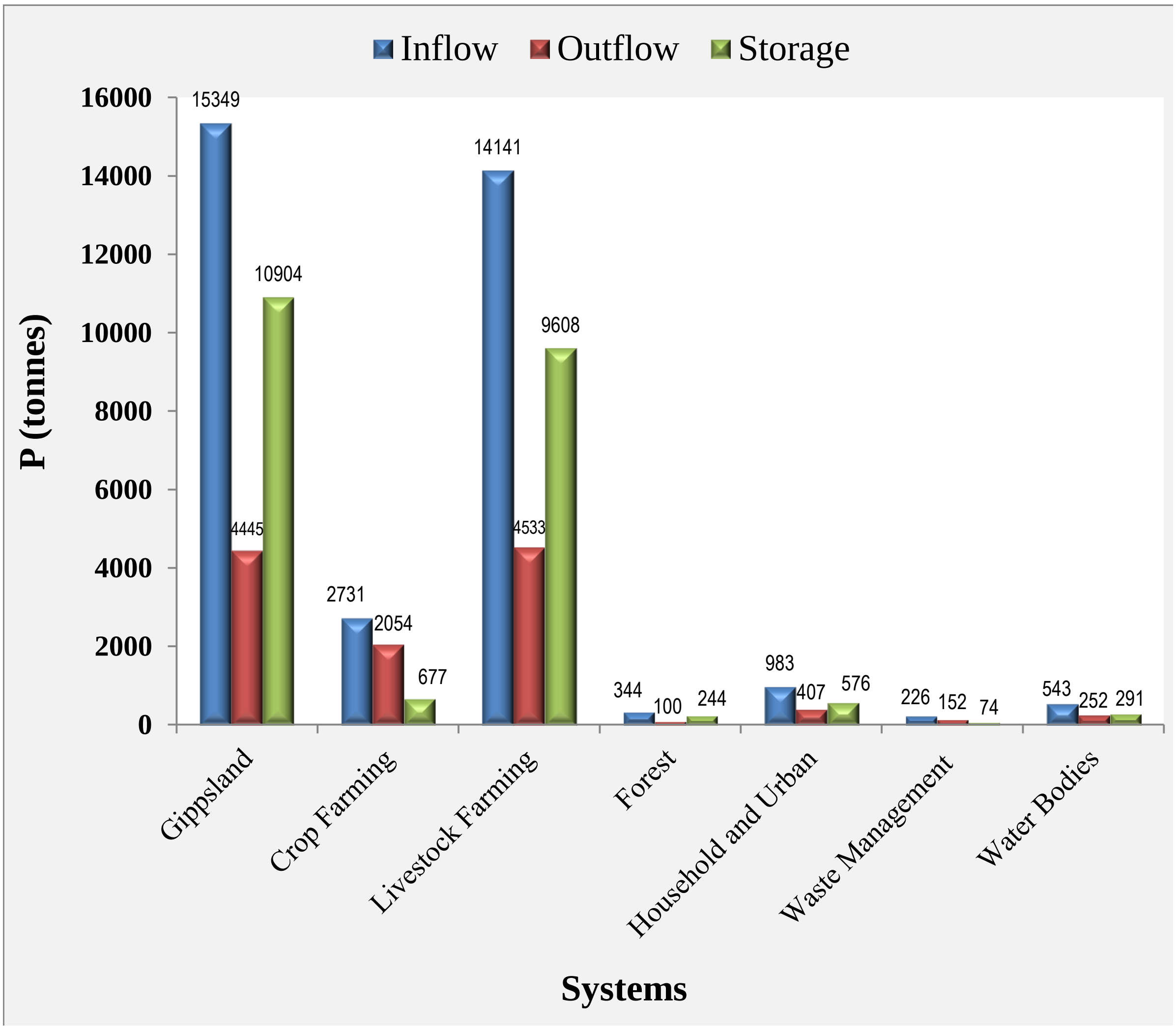


Fig. 4.7 A comparative picture of the magnitude mean annual total inflow, total outflow, and total storage of P relating to the Gippsland region and all subsystems within it for 2008-2013.

As presented in **Fig. 4.8**, the current analysis has revealed that in each year of the study period too, the livestock farming system accounted for the highest proportion of the overall P flow (total inflow, total outflow, and total storage) in the Gippsland region. The crop farming system comprised the second highest proportion in each year of the study period, which is followed by the household and urban system except for the total P storage in 2011, 2012 and 2012 when the total P storage in the crop farming system was lower than the total P storage in

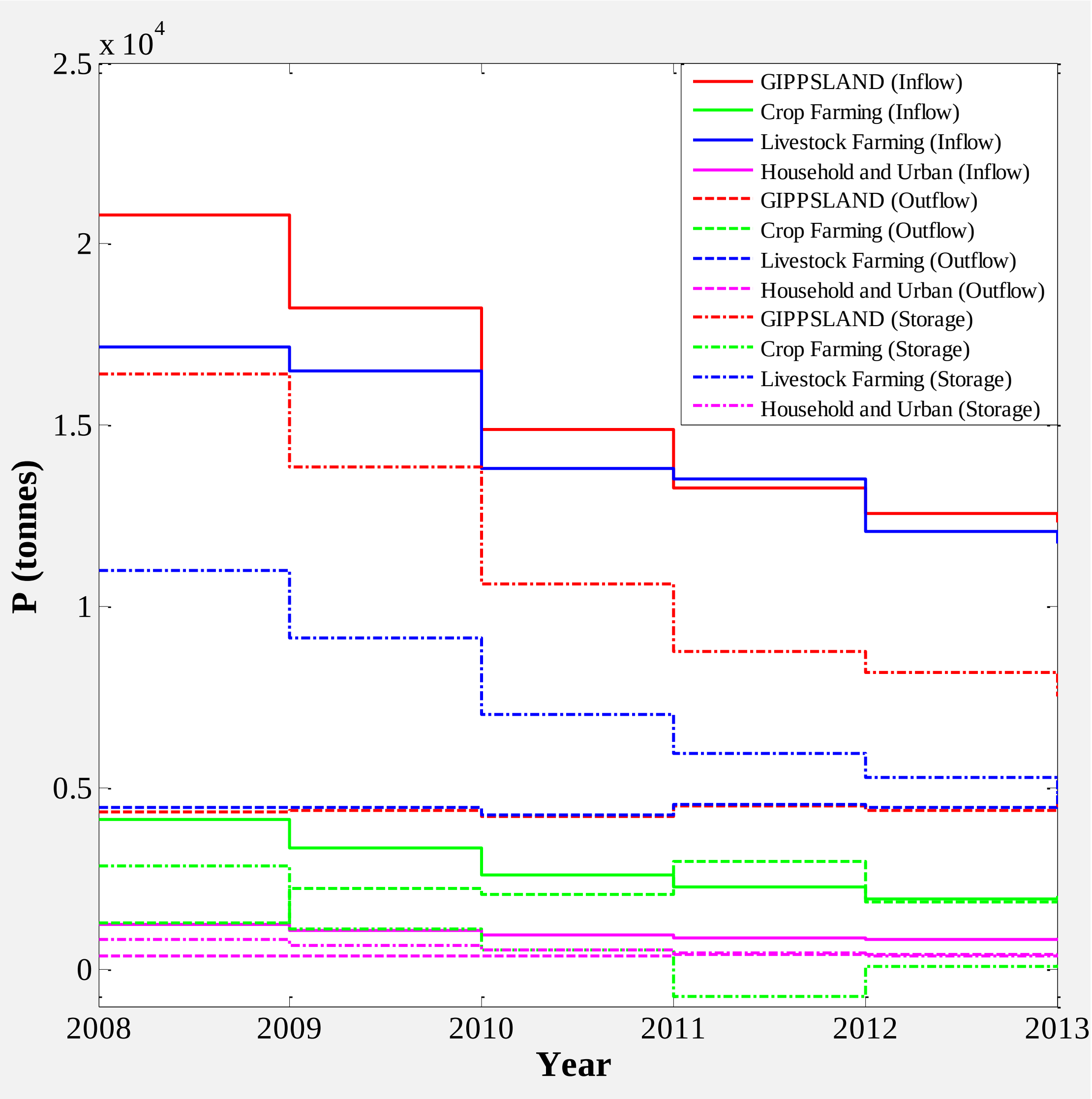


Fig. 4.8 Magnitude of the annual total inflow, total outflow and total storage of P relating to the Gippsland region (main system) and other key subsystems within this region over the study period.

the household and urban system. However, the proportions of subsystem contributions to the overall P flow and storage in the Gippsland region remained roughly same in each year of the study period. Over the study period, the livestock farming system showed a decreasing trend in terms of annual total inflow and total storage of P, and almost no variation in terms of annual total P outflow. The similar trend has been reflected in terms of annual total inflow, total storage, and total outflow of P for the Gippsland region as a whole (**Fig. 4.8**). It is apparent that the livestock farming is a key subsystem in terms of the magnitude of P flow in the Gippsland region, and therefore, in this study, special focus has been given on illustrating the findings relating to this subsystem. Among other subsystems; the crop farming, and the household and urban systems account for a substantial amount of P flow and storage and therefore, a detailed analysis relating to these subsystems has also been presented. In contrast, the magnitude of mean annual total P flow (inflow, outflow and storage) relating to the waste management, and the water systems have been found to be less significant compared to other subsystems in this region. However, given the potential for P recovery, and the significant environmental consequences associated with P flow relating to these subsystems, there is need for having a sound understanding of the nature and magnitude of P flow of these subsystems.

4.2.2. Livestock farming system

The analysis of the nature and magnitude of mean annual P flow relating to the livestock farming system in Gippsland region over the study period as presented in **Fig. 4.9** indicates that annually a total of about 14,141 (2,234) tonnes P entered into the system, and about 4,533 (220) tonnes P left from the system. This indicates that the majority (68% or 9,608 (2,336) tonnes) of the P that was imported annually into this system were eventually stored. Based on the current analysis, the mean annual P use efficiency (a measure of the proportion of the imported nutrient on to the livestock farming system within a production year, which is exported in product) in the livestock farming system of the Gippsland region can be calculated as 31%. A field based study of Dairy Australia on the whole farm nutrient balance in 44 dairy farms (which include 10 Gippsland farms) in Australia (Gourley et al., 2010) confirmed that the findings of the current analysis regarding P use efficiency in the livestock farming system (where as observed in **Table 4.2**, P flow in mostly dominated by the dairy farming system) is roughly consistent with the findings of the Dairy Australia study on a number of Gippsland farms.

As presented in **Fig 4.10**, over the study period, a decreasing trend has been observed in the annual total P inflow in the livestock farming system, where it decreased from approximately 17,166 tonnes in 2008 to nearly 13,811 tonnes in 2010 and approximately 11,765 tonnes in 2013. Similar trend has been observed in terms of the annual total P storage,

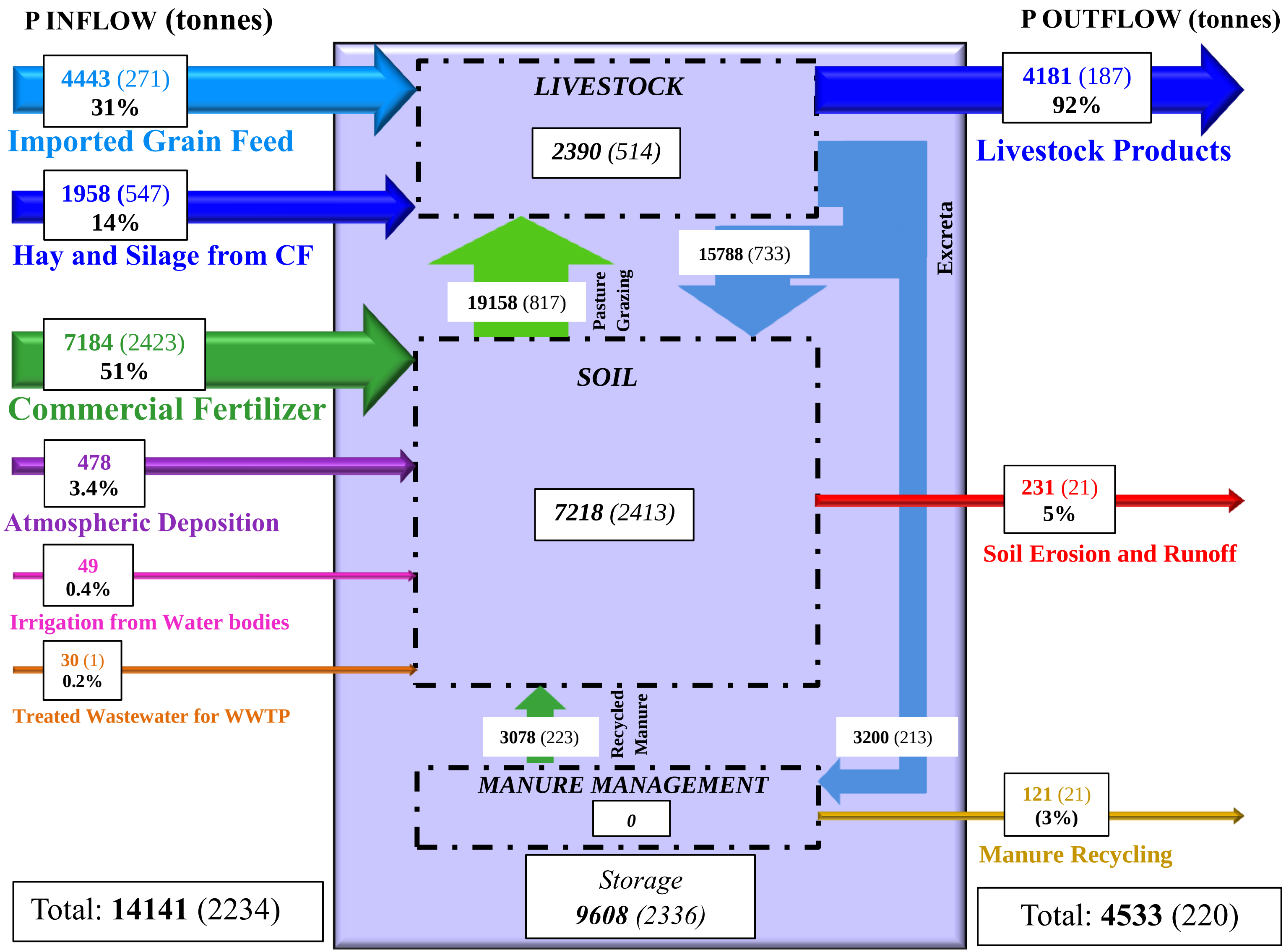


Fig. 4.9 Nature and magnitude of mean annual P flows and storage relating to the livestock farming system in the Gippsland region for 2008-2013. Explanations for numbers within brackets and with percent are same as presented in **Fig. 4.5** caption.

where it decreased from about 12,677 tonnes in 2008 to approximately 9,540 tonnes in 2010 and nearly 6,827 tonnes in 2013. However, the annual total P outflow has been observed to be more or less same over the study period, where it initially decreased from approximately 4,488 tonnes in 2008 to about 4,271 tonnes in 2010 and then increased to around 4,939 tonnes in 2013. In 2008, the total outflow was about 26% of the total inflow indicating 74% storage; while in 2013, the total outflow and total storage were about 42% and 58% of the total inflow respectively, indicating a high variation between these two years. From the current analysis it is observed that similar to the Gippsland region as a whole, the annual total inflow and total storage in the livestock farming system have significantly decreased over the study period, while the annual total outflow remained more or less same. This indicates, nearly same annual P output (mainly as livestock products) has been achieved from the livestock farming system while minimizing the annual P input (mainly as mineral fertilizer) and the annual P storage (mainly in soil), which implies that crops might have utilized some fraction of P from the initial soil P reserves (P stock) or P that were accumulated in soils over many years. However, the evaluation of the reasons or drivers for these changes in total inflow and total storage over the study period is crucial for obtaining essential information to make improved P management decisions, and therefore, should receive greater attention in future research.

The assessment of mean annual P flow and storage over the study period also indicates that the inflow of P in the livestock farming system mainly occurred as commercial fertilizer (mainly super phosphate and ammonium phosphate fertilizers) and imported grain based feed which accounts for about 51% (7,184 (2,423) tonnes) and about 31% (4,443 (271) tonnes) of the mean annual total inflow respectively. A substantial amount of about 1,958 (547) tonnes P were also imported annually as hay and silage from the crop farming system to this system (**Fig. 4.9**). Of the annually imported 4,443 (271) tonnes P in grain feed from outside Gippsland, about 73% (3,251 (345) tonnes) were brought to dairy farming, while about 18% (817 (74) tonnes) and 6% 262 (72) were dedicated to beef cattle and chicken farming respectively. However, nearly the entire P outflow from this system occurred as livestock products which accounts for about 4,181 (187) tonnes P or 94% of the mean annual total outflow, whereas about 231 (21) tonnes (about 5% of the mean annual total outflow) of P outflow took place as soil erosion and runoff loss. Of the total 4,181 (187) tonnes P in livestock products, livestock (mainly meat cattle) bones account for the highest proportion (49% or 2,056 (209) tonnes), while milk of dairy cow comprises approximately 46% or 1,929 (99) tonnes. If focused on the P storage within livestock farming system, it is observed that about 75% (7,218 (2,413) tonnes) of the mean annual total P storage occurred in soils of this system, while the remainder (25% or 2,390 (514) tonnes P) occurred in livestock body (**Fig. 4.9**). The amount of P that was stored annually within soil of the livestock farming system is equivalent to about 51% of the mean annual total inflow in this system, indicating a substantial amount of P remained unutilized in soil.

A more detailed analysis of the nature and magnitude of mean annual P flow and storage relating to the livestock farming system has been presented in **Table 4.2**. In this table, the mean values of P flow have been presented along with standard deviation and co-efficient of variation (CV). The CV has been presented just to provide a comparative view of variation in values for different types of P flow. However, no further discussion relating to CV has been presented in the text. The analysis of internal P flow in the livestock farming system as presented in **Table 4.2** indicates that on an average, annually about 19,267 (813) tonnes P came into livestock body as pasture grazing from soil, of which about 59% (11,377 (1,209) tonnes P) were grazed by dairy cattle and about 38% (7,351 tonnes P) by meat cattle. On the other hand, a total of about 18,987 (941) tonnes P were excreted annually by livestock between 2008 and 2013, the majority (65% or 12,319 (1,309) tonnes) of which were excreted by dairy cattle; while about 31% (5,920 (536) tonnes) excreted by meat/beef cattle. However, of the total amount of P excreted annually by livestock, about 83% or 15,788 (733) tonnes were directly excreted to soil by grazing animals, while the rest (17% or 3,199 (213) tonnes) were collected by the manure management system. Nearly all (96% or 3,078 (223) tonnes) of the total amount of P collected by the manure management system were internally recycled to the soils of the livestock farming system, while only 4% or 121 (21) tonnes were exported as recycled manure to other subsystems within Gippsland.

An analysis of key P flows and storage in the livestock farming system for each year over the study period (**Fig. 4.10**) indicates a decreasing trend in P inflow as commercial fertilizer (which has been found to be the main inflow in each year) from about 11,153 tonnes in 2008 to approximately 6,816 tonnes in 2010 and around 5,000 tonnes in 2012 and 2013. In contrast, the annual P inflow as imported grain feed for livestock showed a little variation (ranging from 4,155 to 4,772 tonnes) over the study period. In 2008, P inflow as commercial fertilizer was more than twice the amount of P inflow as imported grain feed; while in 2013, it was almost equal to the amount of imported grain feed. In each year over the study period, the main storage of P within the livestock farming system occurred in soils which showed a decreasing trend from approximately 11,016 tonnes in 2008 to about 7,047 tonnes in 2010,

Table 4. 2 A detailed assessment of the nature and magnitude of mean annual P flow and storage (expressed in tonnes per annum) relating to the livestock farming system in the Gippsland region for 2008-2013. The information of this table is additional to that presented in **Fig. 4.9.**

Flow type	**Materials/processes**	**Magnitude of P flow**	
		Mean (Standard deviation[a])	*Coefficient of Variation*
Feed (total)	All livestock	25667 (1128)	4
	Dairy cattle	16585 (1666)	10
	Meat cattle	8168 (739)	9
	Sheep	599 (66)	11
	Chicken	262 (72)	27
	Pig	54 (18)	33
Feed (imported)	Dairy cattle (grain based, from outside Gippsland)	3251 (345)	11
	Dairy cattle (pasture based, from within Gippsland)	1958 (547)	28
	Meat cattle (grain based, from outside Gippsland)	817 (74)	9
	Chicken (grain based, from outside Gippsland)	262 (72)	27
	Sheep (grain based, from outside Gippsland)	60 (7)	11
	Pig (grain based, from outside Gippsland)	54 (18)	33
Feed (pasture grazing)	Total	19267 (813)	4
	Dairy cattle	11377 (1209)	11
	Meat cattle	7351 (666)	9
	Sheep	539 (59)	11
Products (total)	Meat cattle (meat, bone and fat)	2017 (183)	9
	Dairy cattle (milk)	1929 (99)	5
	Sheep (meat, bone and fat)	121 (20)	16
	Chicken (meat, bone, fat and eggs)	99 (67)	67
	Pig (meat, bone and fat)	15 (5)	33
Bones	Total	2056 (209)	10
	Meat cattle	1852 (168)	9
	Sheep	111 (18)	16
	Chicken	79 (63)	79
	Pig	14 (5)	33
Meat	Total	169 (16)	9
	Meat cattle	156 (14)	9
	Sheep	9 (1)	16
	Chicken	3 (3)	79
	Pig	1 (0.35)	33
Other products	Chicken egg	16 (1)	7
	Eggshell	13 (1)	7
Excreta	Total	18987 (941)	5
	Dairy cattle	12319 (1309)	11
	Meat cattle	5920 (536)	9
	Sheep	580 (64)	11
	Chicken	124 (25)	20
	Pig	44 (14)	33
Excreta to soil (direct)	Total	15788 (733)	5
	Dairy cattle	9855 (1047)	11
	Meat cattle	5328 (482)	9
	Sheep	580 (64)	11
	Chicken	12 (3)	20
	Pig	12 (4)	33
Excreta to manure management	Total	3199 (213)	7
	Dairy cattle	2463 (262)	11
	Meat cattle	592 (54)	9
	Chicken	112 (23)	20
	Pig	32 (10)	33
Recycled manure to soil	Total	3078 (223)	7
	Dairy cattle	2464 (262)	11
	Meat cattle	592 (54)	9
	Pig	23 (7)	33
Soil erosion and runoff	Soil erosion	151 (14)	9
	Runoff water	79 (7)	9

[a]Standard deviation less than 1 is presented in decimal, and greater than 1 is rounded.

and approximately 4,851 tonnes in 2013. Interestingly, in each year of the study period, the amount of P stored within soils of the livestock farming system was almost equal the amount of P imported as commercial fertilizer in this system, indicating a substantial storage of unutilized P in soil. However, in order to supply sufficient amount of plant available P for optimum growth, a certain level of P storage should always be maintained in the soil. Any storage beyond that level (excess) could be considered as P wastage because it increases the risk of P loss as soil erosion and runoff. As the model deals with averages across the region, the spatial variation from one farm to another is not assessed, and therefore, the general advice to reduce P application may be inappropriate in farming systems that are yet to obtain optimum soil P storage.

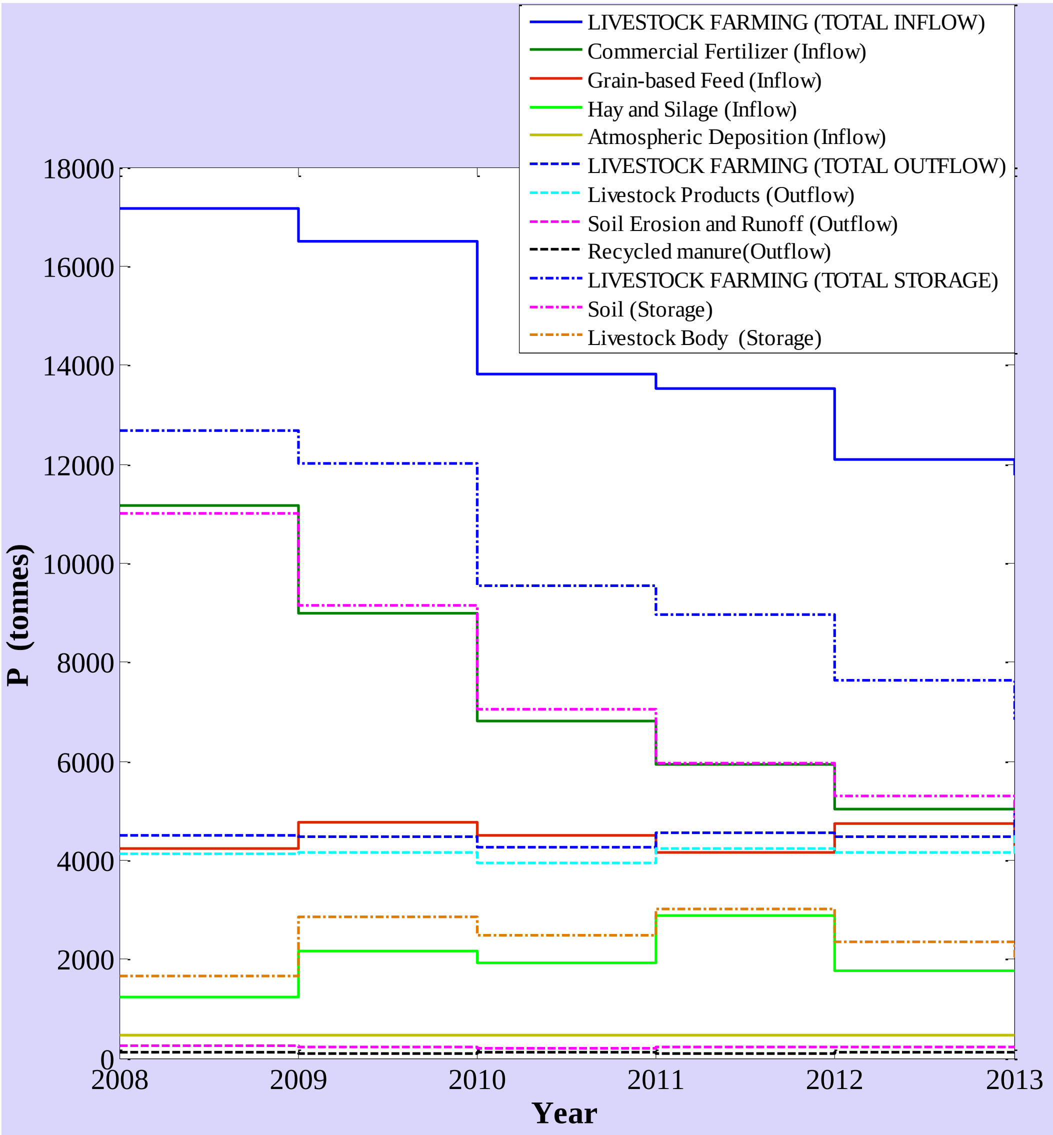


Fig. 4.10 Nature and magnitude of the key annual inflow, outflow and storage of P relating to the livestock farming system in the Gippsland region over the study period.

4.2.3. Crop farming system

The analysis of mean annual P flow relating to the crop farming system in the Gippsland region as presented in **Fig. 4.11** has revealed that the annual total inflow of P in this system was about 2,731 (862) tonnes and the annual total outflow was approximately 2,054 (561) tonnes. This indicates that only 25% (677 (1,224) tonnes P) of the mean annual total inflow were stored within this system.

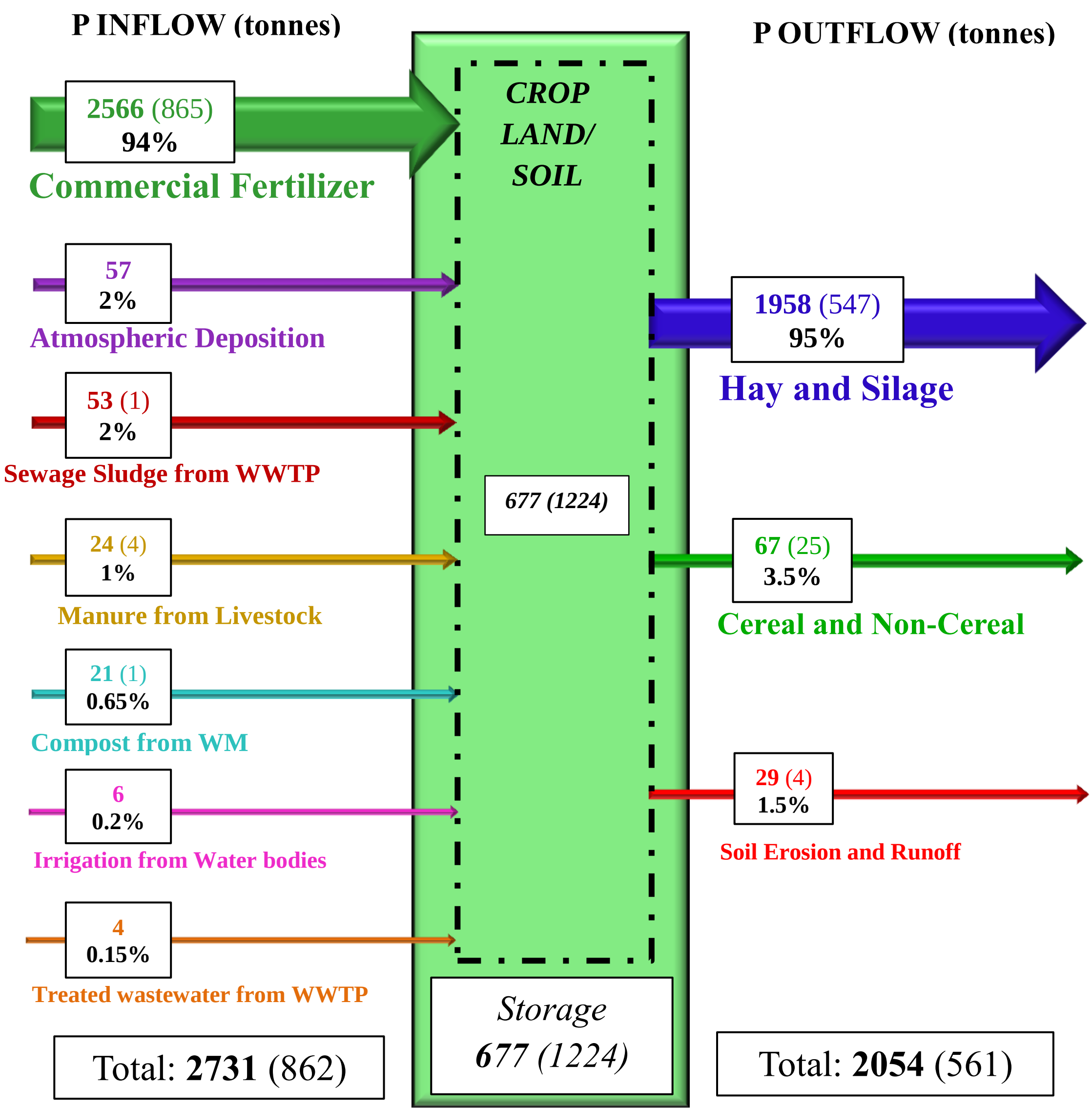


Fig. 4.11 Nature and magnitude of mean annual P flows and storage relating to the crop farming system in the Gippsland region for 2008-2013. Explanations for numbers within brackets and with percent are same as presented in **Fig. 4.5** caption.

Almost all inflow of P in the crop farming system occurred as commercial fertilizer (mainly super phosphate and ammonium phosphate fertilizers), which amounted about 2,566 (865) tonnes or about 94% of the mean annual total inflow. On the other hand, nearly all (about 95% or 1,958 (547) tonnes) outflow of P from this system occurred as hay and silage, while about 67 (25) tonnes or only around 3% of the mean annual total P outflow took place as cereal and non-cereal grains mainly as wheat, maize, barley, and canola oilseed. More than half (55% or 1,084 (637) tonnes) of the annual total P outflow in hay and silage occurred as silage of pasture, cereal and other crops, and the remainder (45%) occurred as cereal, pasture and other hay (**Table 4.3**). However, all of the P storage within this system occurred in soil.

Table 4.3 A detailed assessment of the nature and magnitude of mean annual P flow and storage (expressed in tonnes per annum) relating to the crop farming system in the Gippsland region for 2008-2013. The information of this table is additional to that presented in **Fig. 4.11**.

Flow type	**Materials/processes**	**Magnitude of P flow**	
		Mean (Standard deviation[a])	*Coefficient of Variation*
Crop products (cereals)	Total	56 (19)	34
	Wheat	36 (12)	34
	Barley	9 (6)	68
	Maize	5 (4)	91
	Triticale	3 (4)	132
	Oat	2 (1)	74
Crop products (non-cereals)	Total	12 (8)	67
	Canola seeds	10 (7)	71
	Lupins	1 (1)	69
Crop products (hay)	Total	874 (227)	26
	Pasture hay	742 (238)	32
	Other hay	97 (63)	65
	Cereal hay	35 (19)	55
Crop products (silage)	Silage of pasture, cereal and other crops	1084 (637)	59
Soil erosion and runoff	Total	29 (4)	14
	Soil erosion	19 (3)	14
	Runoff water	10 (1)	14

[a]Standard deviation less than 1 are presented in decimal, and greater than 1 are rounded.

An assessment of the magnitude of key P flows and storage relating to the crop farming system for each year over the study period has been presented in **Fig 4.12.** This assessment indicates that the annual total inflow of P (which mainly occurred as commercial fertilizers in all years) in this system showed an overall decreasing trend from about 4,146 tonnes in 2008 to approximately 2,599 tonnes in 2010, and about 2,029 tonnes in 2013. In contrast, the annual total outflow of P (that mainly took place as hay and silage) from this system showed a great variation over the study period, where it increased from about 1,292 tonnes in 2008 to about 2,061 tonnes in 2010, and further increased to approximately 3,000 tonnes in 2011, and finally, decreased to about 1,874 tonnes in 2013. In contrast, the annual total P storage (all of which occurred in soils) in this subsystem decreased from about 2,854 tonnes in 2008 to about 538 tonnes in 2010, and finally, about 155 tonnes in 2013. Interestingly, a negative storage of P (approximately -715 tonnes P) within this system was observed in 2011, which ultimately lessen the overall P storage within Gippsland in the same year. This kind of variation in annual P flow and storage implies that making judgements based on a single year analysis may not represent the true picture of the magnitude of P flow relating to a system, and may lead to improper reactions by farmers, and therefore, justifies the significance for multi-year analysis.

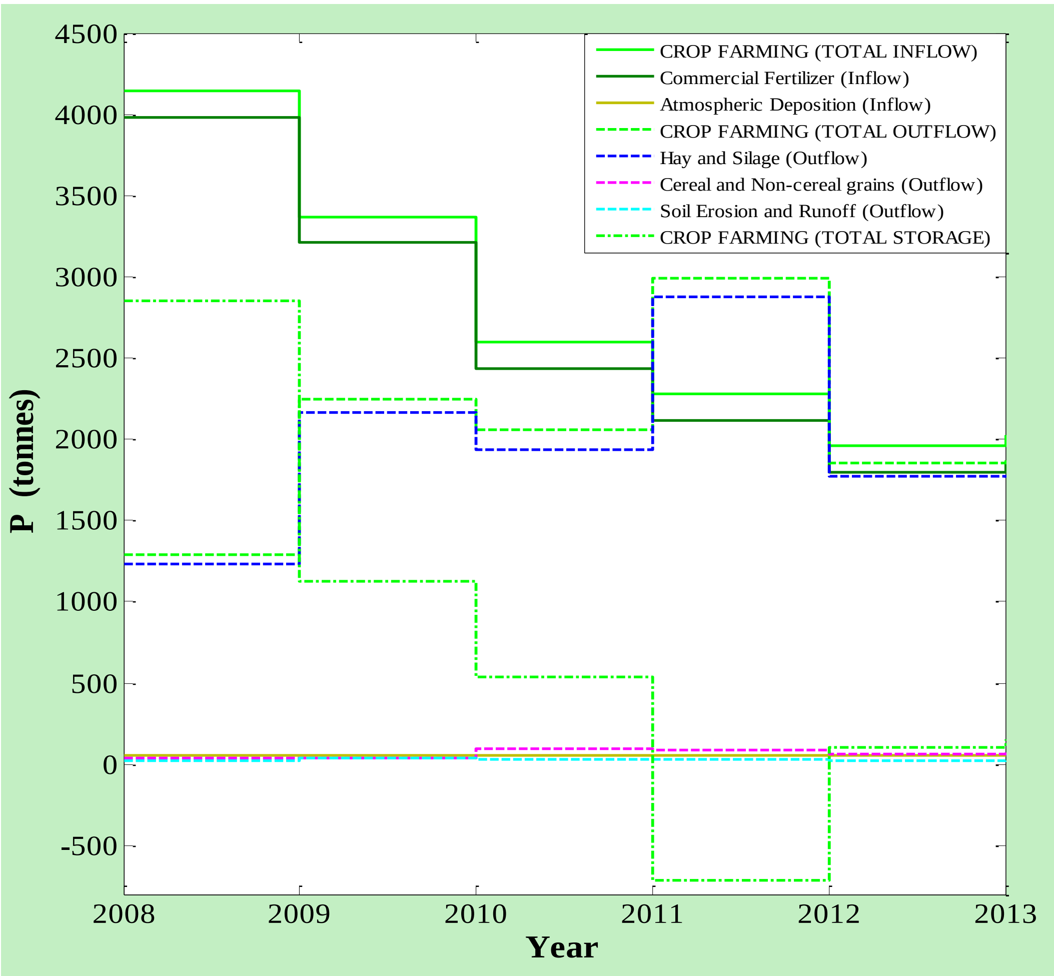


Fig. 4.12 Nature and magnitude of the key annual inflow, outflow and storage of P relating to the crop farming system in the Gippsland region over the study period.

4.2.4. Household and urban system

Household and urban system mainly accounts for P flow and storage that associated with the household or human consumption unit and urban landscape. As presented in **Fig. 4.13**, an analysis of the mean annul P flow and storage relating to the household and urban system this system indicates that a total of about 983 (162) tonnes P entered into this system, while about 41% (407 (13) tonnes) of that eventually left the system, causing a net storage of about 576 (175) tonnes P.

Of the total amount of P inflow in this system, about 75% were dedicated to urban landscape, while the rest (25%) brought to urban consumption unit. The inflow of P in this system primarily occurred as commercial fertilizer which accounts for about 52% (513 (173) tonnes) of the mean annual total inflow, while about 133 (3) tonnes (about 14% of the mean annual total inflow) and 97 tonnes (about 10% of the mean annual total inflow) P inflow occurred as human food and livestock manure respectively. A considerable amount of P inflow also occurred as atmospheric deposition (89 tonnes), non-food (mainly soap and detergent) materials (59 (1) tonnes), and pet (mainly dog and cat) animal feed (49 (1) tonnes). However, the outflow of P from this system occurred mainly as soil erosion and runoff (181 (4) tonnes) or about 44% of the mean annual total outflow) from urban landscape, and wastewater (171 (4) tonnes) or 42% of the mean annual total outflow) from consumption unit. The reason for the high P outflow as soil erosion and runoff from the urban area is that the majority of the urban landscape have paved surface which result in the high volume of runoff water and associated P loss. A mentionable amount of about 55 (5) tonnes (about 15% of the mean annual total outflow) P outflow also occurred as solid waste from this system. The majority (about 74% or 126 (3) tonnes) of the annual total P outflow in wastewater came from human excreta, where urine and faeces account for about 46% (78 (2) tonnes) and 28 % (48 (1) tonnes) of the mean annual total P outflow as wastewater respectively. In case of solid waste, about 62% (34 (1) tonnes) P originated from garbage (mainly food waste), while about 35% or 19 (4) tonnes P originated from green organics (mainly plants, leaves and grass clippings) (**Table 4.4**). All these outflows from the household and urban system are crucial because in most cases, a substantial amount of P loss has been observed to occur through these outflows, and there is also a potential scope for P recovery from materials associated with these outflows. The analysis has also revealed that a substantial amount of P storage occurs within the household and urban system, the majority (97% or 561 (172) tonnes per annum) of which take place in the urban landscape/soil.

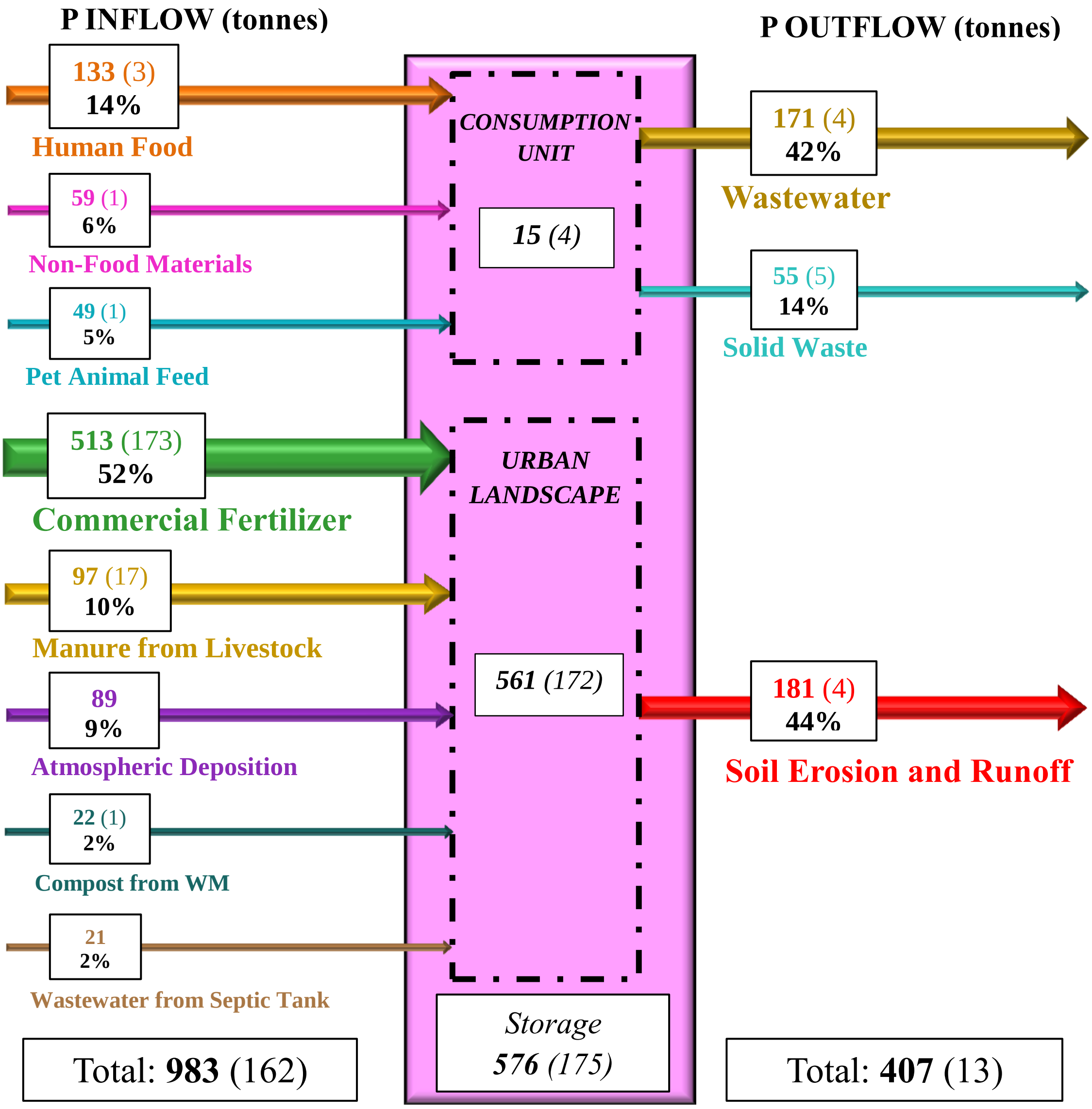


Fig. 4.13 Nature and magnitude of mean annual P flows and storage relating to the household and urban system in the Gippsland region for 2008-2013. Explanations for numbers within brackets and with percent are same as presented in **Fig. 4.5** caption.

Table 4. 4 A detailed assessment of the nature and magnitude of mean annual P flow and storage (expressed in tonnes per annum) relating to the household and urban system in the Gippsland region for 2008-2013. The information of this table is additional to that presented in **Fig. 4.13**.

Flow type	Materials/processes	Magnitude of P flow	
		Mean (Standard deviation[a])	*Coefficient of Variation*
Pet animal feed	Dog	47 (1)	2
	Cat	2 (0.05)	2
Non-food materials	Detergent and soap	57 (1)	2
	Paper and cardboard	3 (0.07)	3
Solid waste	Garbage (total)	34 (1)	4
	Garbage (food waste)	27 (1)	4
	Garbage (garden waste)	6 (0.24)	4
	Green organics	19 (4)	20
	Recyclable (paper and cardboard)	2 (0.04)	2
Domestic wastewater	Human excreta (urine and faeces)	126 (3)	2
	Urine	78 (2)	2
	Faeces	48 (1)	2
	Greywater	45 (1)	2

[a]Standard deviation less than 1 are presented in decimal, and greater than 1 are rounded.

The analysis of P flow and storage of the household and urban system for each year of the study period as presented in **Fig. 4.14** shows an overall decreasing trends in the annual total P inflow from about 1,258 tonnes in 2008 to about 953 tonnes in 2010, and 880 tonnes in 2013. A decreasing trend has also been observed for P inflow as commercial fertilizer, which accounted for the highest proportion of the total inflow in each year. However, annual P inflow as human food has been found to be almost same over the study period. Similarly, the annual total P storage within this system also showed a declining trend from about 870 tonnes in 2008 to approximately 550 tonnes in 2010 and about 460 tonnes in 2013; whereas, the magnitude of annual total P outflow from this system showed a little variation (ranging from 388 to 420 tonnes) over the study period. In each year of the study period, the outflow of P mainly occurred as soil erosion and runoff, and wastewater. The annual magnitude of these outflows did not vary much over the study period, where P outflow as soil erosion and runoff ranged from approximately 175 to 185 tonnes, and as wastewater ranged from approximately 165 to 176 tonnes. However, as mentioned earlier in this study, a reduction in the annual total inflow and total storage of P, while keeping the annual total P outflow nearly same over the study period is a sign of improvement in P management.

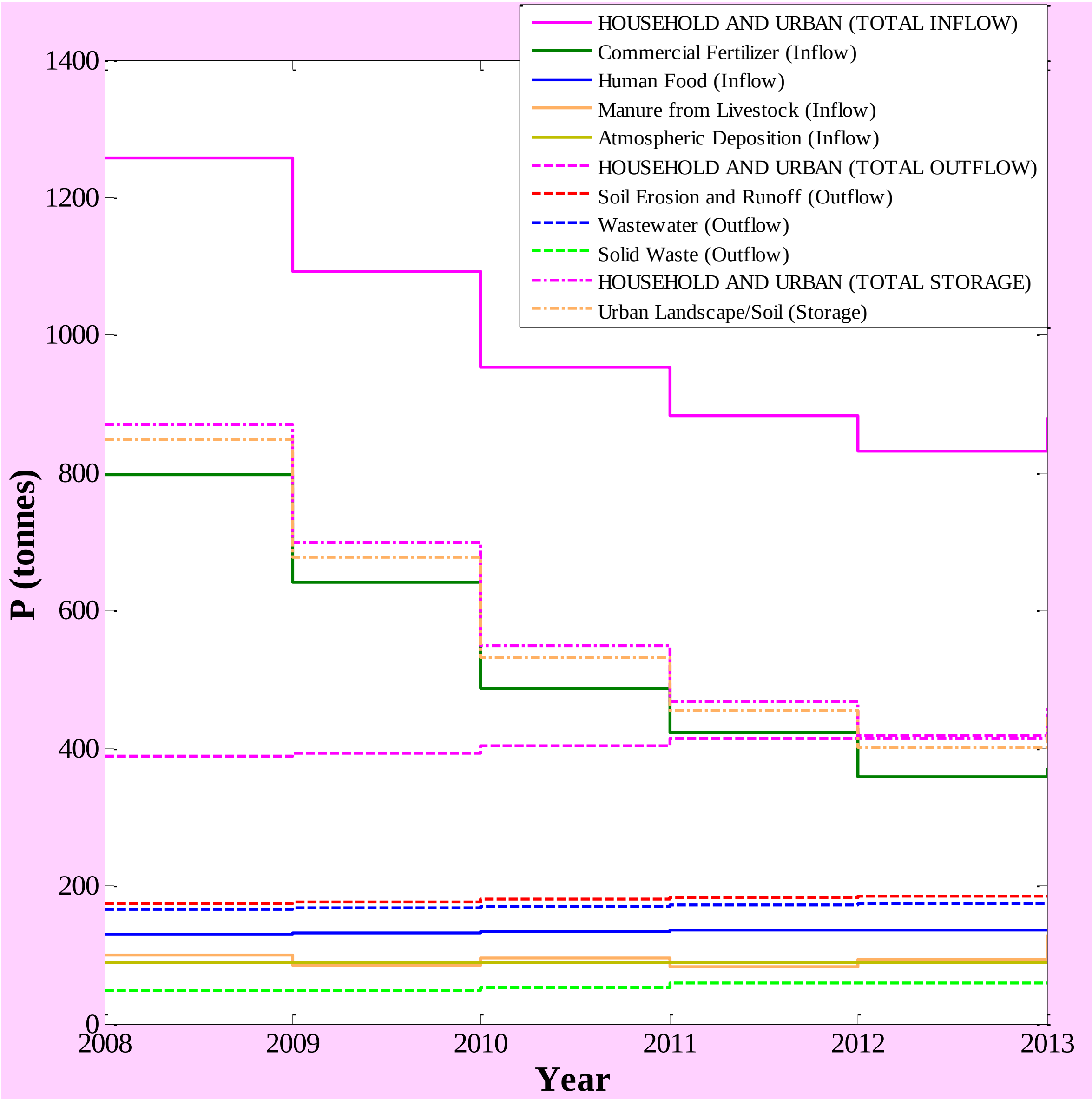


Fig. 4.14 Nature and magnitude of the key annual inflow, outflow and storage of P relating to the household and urban system in the Gippsland region over the study period.

4.2.5. Waste management system

The waste management system mainly comprises P flows and storage associated with solid wastes and wastewater generated from the household and urban system. The analysis of mean annual P flow and storage of this system indicates that a total of about 226 (9) tonnes P mainly as domestic wastewater (171 (4) tonnes or about 76% of the total mean annual total inflow) and solid waste (55 (5) tonnes or about 24% of the mean annual total inflow) entered into this system. On the other hand, annually, a total of about 152 (5) tonnes P left from the system, of which about 35% (53 (1) tonnes) occurred as sewage sludge and approximately 28% (43 (2) tonnes) and 23% (34 (1) tonnes) took place as solid waste compost and treated wastewater respectively (**Fig 4.15**). This indicates that approximately 33% (74 (4) tonnes) of the mean annual total P inflow were eventually stored within this system mainly as landfill storage. The mean annual total P outflow (mainly as recycled waste) towards beneficial purpose from the waste management system was about 130 (5) tonnes or 58% of the mean annual total inflow, indicating about 42% (96 (5) tonnes P) of the mean annual total P inflow remained unrecovered or ultimately wasted.

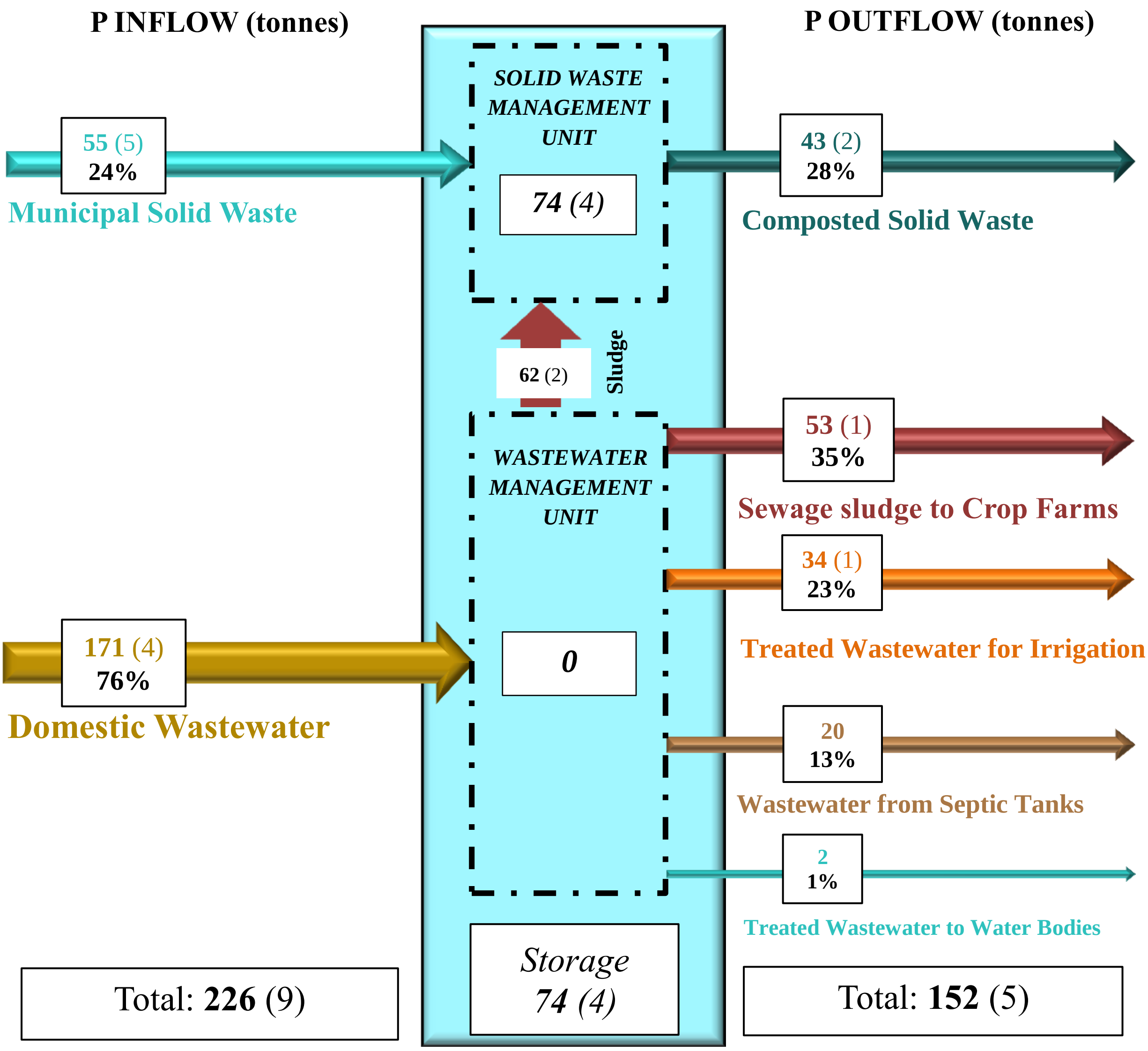


Fig. 4.15 Nature and magnitude of mean annual P flows and storage relating to the waste management system in the Gippsland region for 2008-2013. Explanations for numbers within brackets and with percent are same as presented in **Fig. 4.5** caption.

The analysis of mean annual internal P flows and storage in this system indicates that of the total 171 (4) tonnes P inflow as wastewater, about 77% (132 (3) tonnes) were brought to the wastewater treatment plants and the remainder (23% or 39 (1) tonnes P) were collected by the septic tank system (**Table 4.5**). Of the total 132 (3) tonnes P collected as wastewater in the treatment plants, about 72% (95 (2) tonnes) ended up in sludge and about 26% or 34 (1) tonnes were ultimately utilized as treated wastewater for irrigation. In contrast, approximately 51% (20 tonnes) of the total 39 (1) tonnes P collected as wastewater in the septic tank system were discharged as wastewater to the environment, and the remainder (49% or 19 tonnes P) ended up in sludge. However, both wastewater treatment plants and septic tank system produced a total of about 114 (3) tonnes P in sludge annually, of which about 66% or 75 (2) tonnes P (approximately 53 (1) tonnes in agricultural lands and about 22 (1) tonnes P in composting plants) were eventually utilized for beneficial purpose, and the remainder (34% or 39 (1) tonnes) ended up in landfill. In contrast, of total P in solid waste stream, about 58% or 32 (3) tonnes P in garbage (mainly food wastes) were disposed of in landfill areas, while about 38% or 21 (2) tonnes P in green organics were taken to the composting plants (**Table 4.5**).

Table 4. 5 A detailed assessment of the nature and magnitude of mean annual P flow and storage (expressed in tonnes per annum) relating to the waste management in the Gippsland region for 2008-2013. The information of this table is additional to that presented in **Fig. 4.15**.

Flow type	**Materials/processes**	**Magnitude of P flow**	
		Mean (Standard deviation[a])	*Coefficient of Variation*
Raw Wastewater	Total	171 (4)	2
	Inflow to treatment plants	132 (3)	2
	Inflow to septic tanks	39 (1)	2
Sludge	Total	114 (3)	3
	Outflow from wastewater treatment plant	95 (2)	2
	Outflow from septic tank	19 (0.45)	2
	Productive purpose	75 (2)	2
	Unproductive purpose	39 (1)	2
Waste to landfill	Total	71 (4)	6
	Garbage	32 (3)	9
	Sludge from wastewater treatment plants	30 (1)	2
	Sludge from septic tanks	9 (0.22)	2
Waste to composting	Total	43 (2)	6
	Green waste	21 (2)	9
	Sludge from wastewater treatment plants	13 (0.31)	2
	Sludge from septic tanks	9 (0.22)	2

[a]Standard deviation less than 1 are presented in decimal, and greater than 1 are rounded.

As presented in **Fig. 4.16,** the annual total inflow of P in the waste management system showed an increasing trend from about 214 tonnes in 2008 to approximately 224 tonnes in 2010, and about 235 in 2013. As waste generation is mostly associated with population, the increasing trend in P inflow as waste stream is possibly due to an increase in population number in Gippsland over the study period which is according to ABS (2014) from about 248,334 in 2008 to about 256,142 in 2010, and about 263,858 in 2013.

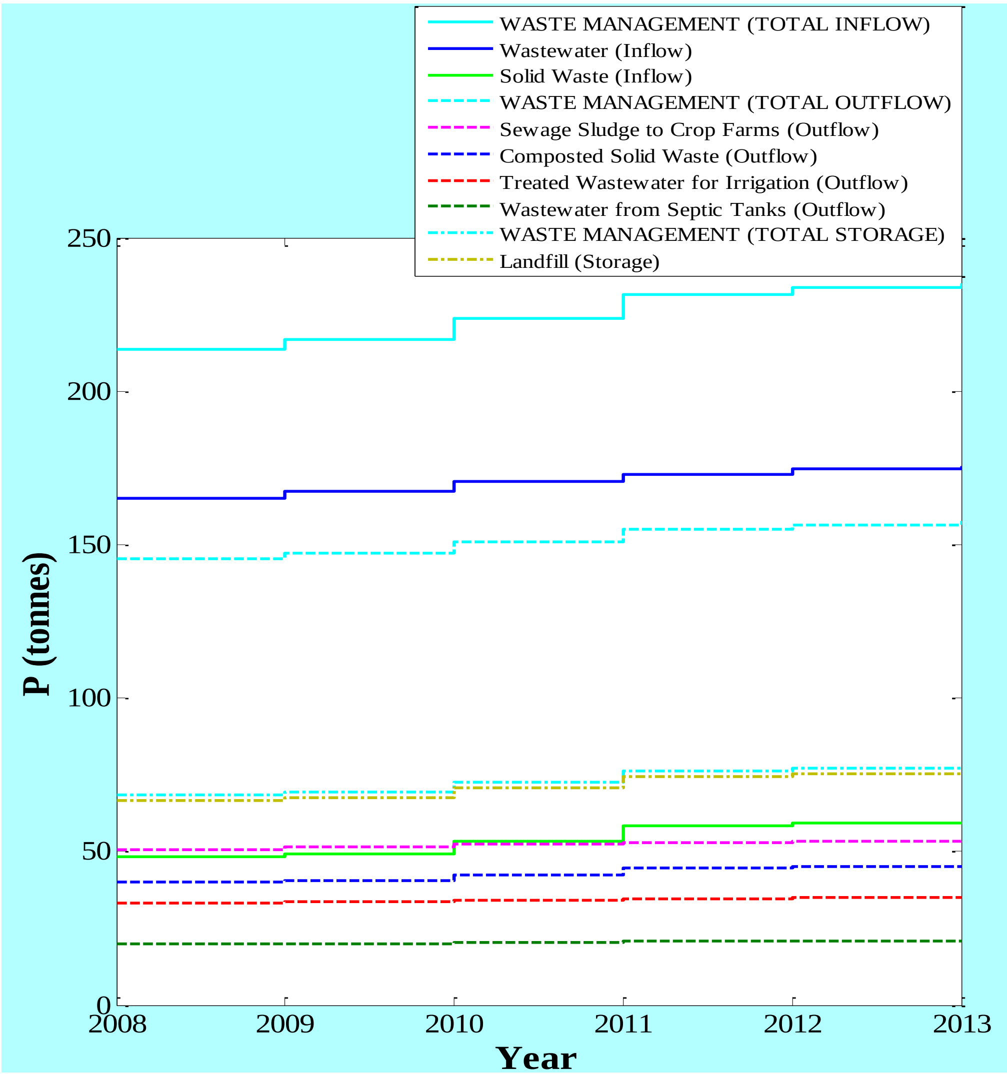


Fig. 4.16 Nature and magnitude of the key annual inflow, outflow and storage of P relating to the waste management system in the Gippsland region over the study period.

Likewise the annual total P inflow, the annual total outflow which mainly occurred as sewage sludge and compost products, and the annual total storage that mostly occurred in landfill areas also showed an increasing trend over the study period. The annual total outflow of P increased from about 145 tonnes in 2008 to about 151 tonnes in 2010, and about 158 tonnes in 2013; while the annual total storage increased from about 68 tonnes in 2008 to about 72 tonnes in 2010, and about 78 tonnes in 2013. Apparently, these increments are not much significant compared to the overall magnitude of P flow in the Gippsland region. The current analysis has identified that a considerable proportion of the annual total inflow of P in the waste management system remains unrecovered mainly as landfill storage. Lederer et al. (2014) in an assessment of the cost for P recovery from the anthropogenic P stock in Austria revealed that P recovery from landfill wastes is not economically feasible. Therefore, necessary policy intervention is required to ensure optimum recovery of P from waste stream before reaching to landfill areas.

4.2.6. Water system

Due to the critical of role P in algal bloom and eutrophication of water bodies, the analysis of P flow relating to water system is essential. As presented in **Fig. 4.17**, the analysis of mean annual P flow and storage relating to the water system in the Gippsland region indicates that annually, on an average, about 543 (21) tonnes P that mainly lost as soil erosion and runoff from other systems enters into this system. The majority of this inflow originates from the livestock farming system (231 (21) tonnes or 43% of the mean annual total inflow) and the household and urban system (181 (4) tonnes or 33% of the mean annual total inflow). The annul inflow of this substantial amount of P in water bodies ultimately contributes to accelerating harmful aquatic processes such as algal bloom and eutrophication, and there are enough evidence of lakes in Gippsland suffering from such problems that ultimately cause significant environmental and economic damage to this region (Connolly and Hylands, 2009; Holland et al., 2011). However, the mean annual total outflow of P from this system is about 252 tonnes, the majority (about 78% or 197 tonnes) of which is permanently lost as water discharge to ocean. This indicates that approximately 54% (291 (21) tonnes) of the mean annual total inflow is eventually stored within this system. Once P finds its way in water bodies, it is difficult to recover or recycle, and therefore, this type of storage of P within water bodies can be regarded as P loss. The storage of P in this manner can lead to enormous destructive consequences on water bodies in the long run.

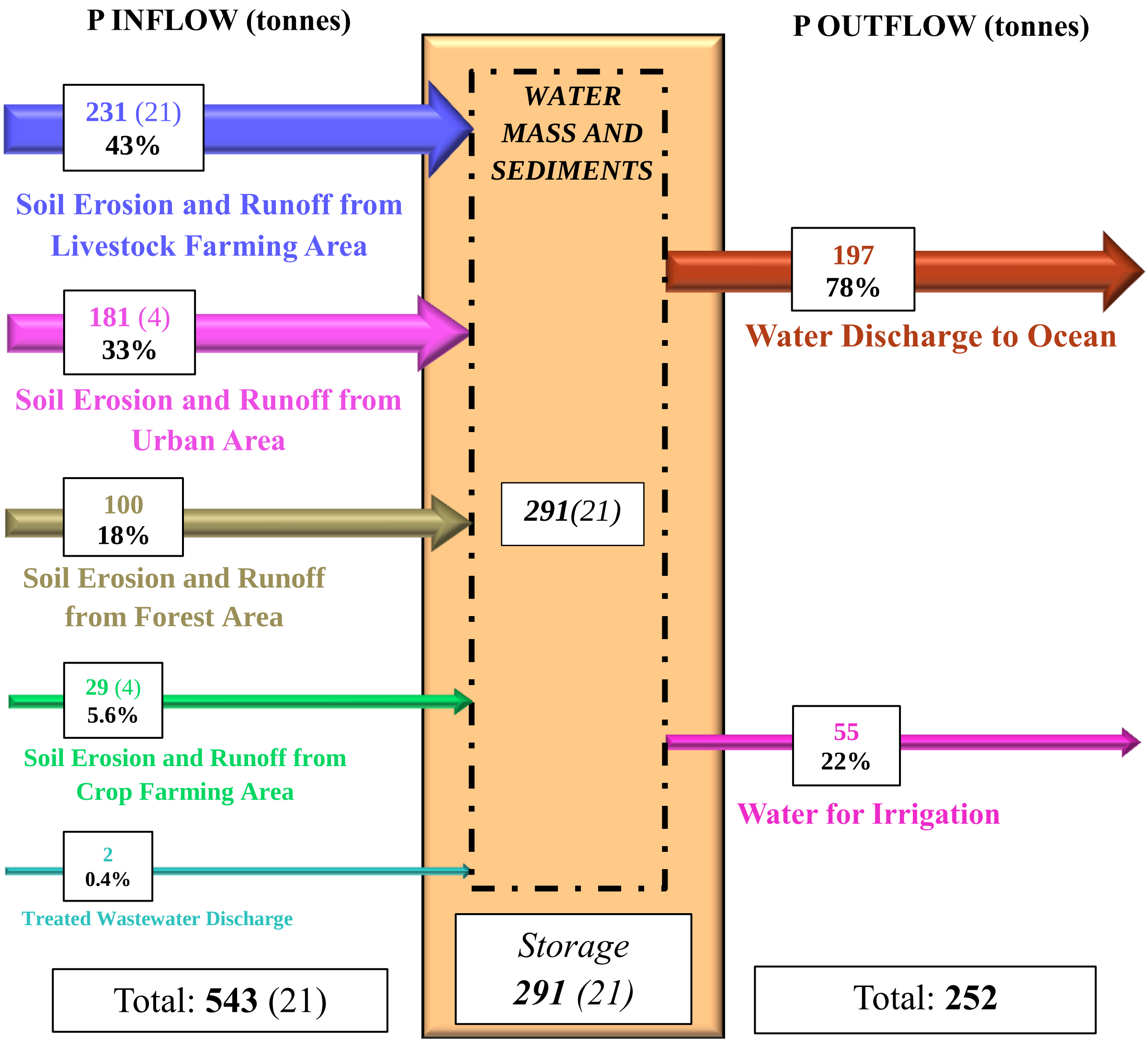


Fig. 4.17 Nature and magnitude of six-year mean annual P flows and storage relating to the water system in the Gippsland region for 2008-2013. Explanations for numbers within brackets and with percent are same as presented in **Fig. 4.5** caption.

An analysis of the P flow and storage relating to the water system for each year as presented in **Fig. 4.18** indicates that the annual total inflow showed a little variation (ranged from approximately 520 to 580 tonnes) over the study period. Similarly, the annual total P storage slightly varied over the study period. However, the reason for annual total outflow to be the same over the study period is that because of a lack of water discharge and irrigation data for all years, a particular data has been utilized for each year of the study period to get an approximate estimate. A better explanation in this regard has been provided at **Table 3.3** in **Section 3.2.5.3**.

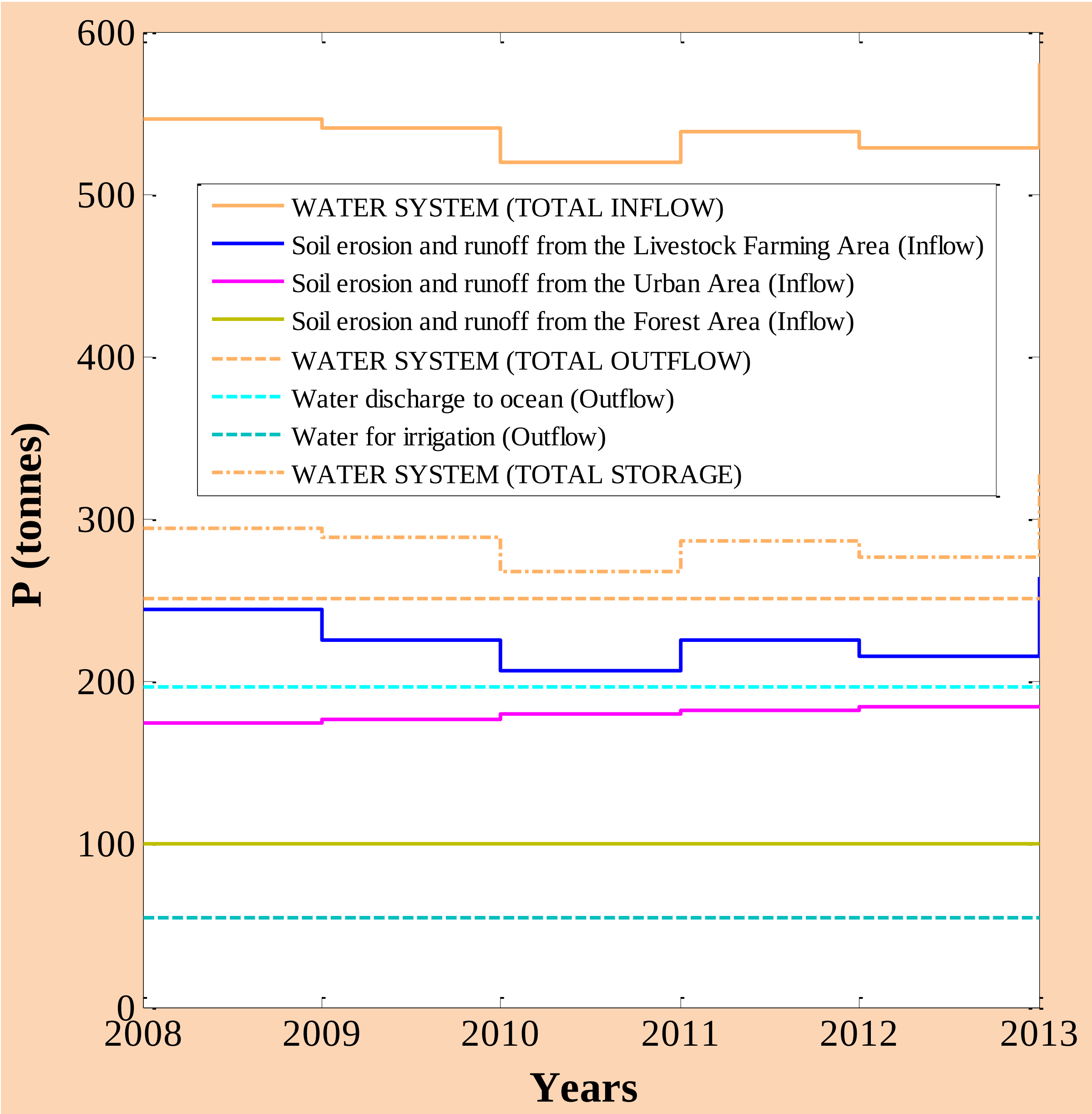


Fig. 4.18 Nature and magnitude of the key annual inflow, outflow and storage of P relating to the water system in the Gippsland region over the study period.

4.2.7. Forest system

In the current analysis, the forest system mainly includes natural forest or conservation areas, which are likely to be almost free from anthropogenic influences. Owing mainly to this reason as well as lack of yearly data, the magnitude of P flow and storage in this system has been assumed to be the same in all years of the study period. The analysis of P flow and storage relating to this system as presented in **Fig. 4.19** indicates that the annual total inflow of P in this system was about 344 tonnes, all of which occurred as atmospheric deposition; while the annual total outflow was about 100 tonnes (29% of the total inflow), all of which took place as soil erosion and runoff loss.

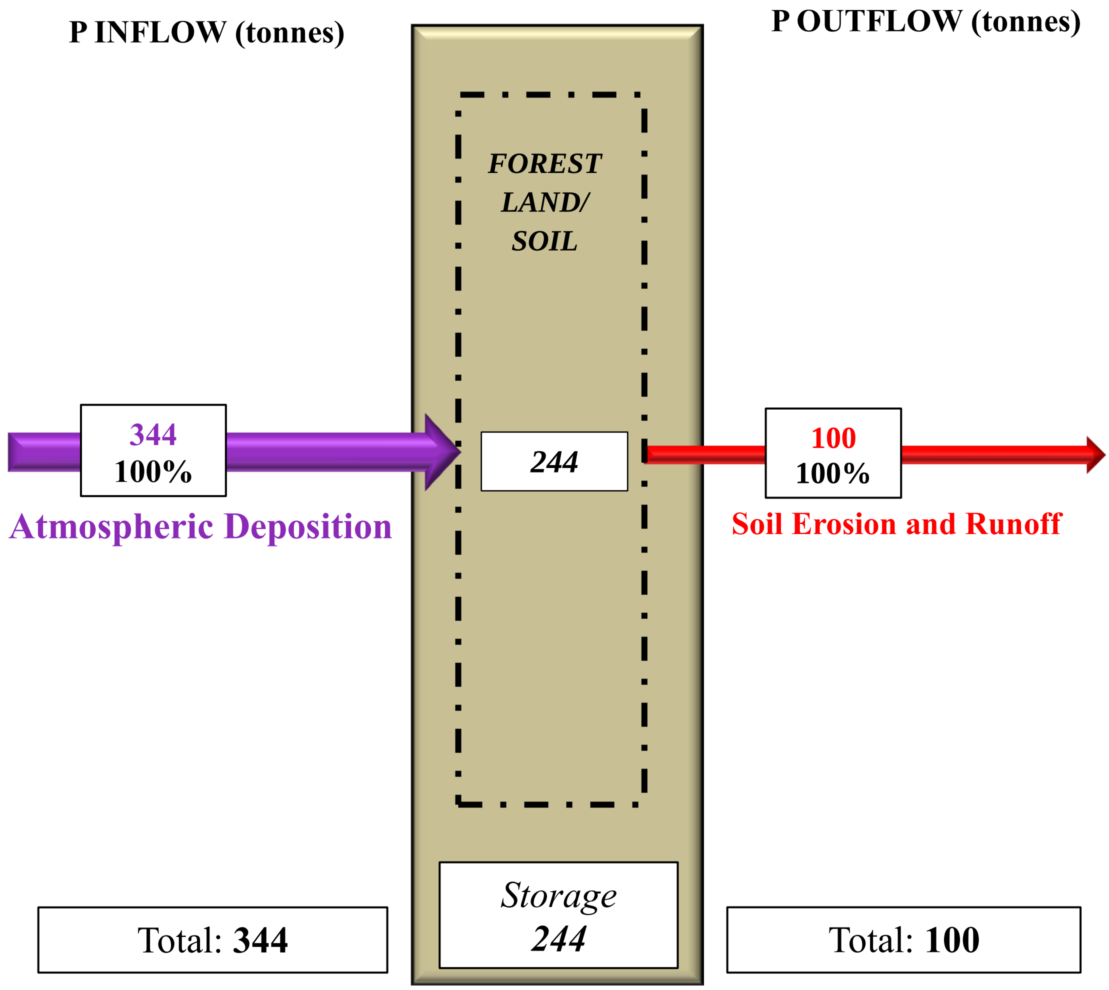


Fig. 4.19 Nature and magnitude annual P flows and storage relating to the forest system in the Gippsland region for 2008-2013. Explanations for numbers with percent are same as presented in **Fig. 4.5** caption.

It should be mentioned that natural forest or conservation areas could be affected from bushfires in some years, which may eventually result in increased P loss in soil erosion and runoff and subsequent downstream transport in the post-fire years (Smith et al., 2011). Traditionally, natural forests in the Gippsland region suffers from bushfires, and therefore, likely to have consequences on P loadings to water bodies. For instance, in 2006/2007, bushfire burned approximately 34% of the forested catchment of the Gippsland lakes. It was estimated that P loadings to the Gippsland lakes following the 2006/2007 bushfires were higher than any available estimates over past 30 years, where it was 900 tonnes of P for 2007/2008 compared to the average annual loads of 300 tonnes for 1975-1999 period (Sinclair Knight Merz, 2008). Therefore, in future analysis of P flow in this region, the influence of bushfire on the magnitude of P loss from forest system should be considered. However, the current analysis has identified that about 71% (244 tonnes) of the annual total P inflow were eventually stored in the forest land within this system. Because the land/floor in natural forest is rich in litter and dense vegetation, the majority of the P in runoff water are eventually absorbed within this system.

4.2.8. An overall assessment of P loss and storage, and potential areas for improving P management in the Gippsland region

4.2.8.1. Assessment of cumulative P loss

The assessment of cumulative P loss in the Gippsland region as presented in **Fig. 4. 20** indicates that over a six year period a total of about 3,807 tonnes P lost in this region. Although, this cumulative loss is equivalent to only about 6% of the cumulative P import (61,578 tonnes) as commercial fertilizer over the study period (**Fig. 4.21**), it is equivalent to approximately 37% of the annual total P import (10,263 (3,461) tonnes) as commercial fertilizer in this region, indicating a considerable amount of P loss. However, the major concern is that the majority (85% or 3,241 tonnes) of this cumulative P loss occurred as soil erosion and runoff from different subsystems mainly the livestock farming (about 1,384 tonnes) and the household and urban systems (1,084 tonnes) to the water system. This implies that over the study period, the surface water bodies in the Gippsland region received an enormous amount of P which is likely to be destructive to the water bodies. As mentioned earlier, once P enters a water bodies, it is nearly impossible to recover and it is either deposited in the bottom sediments or discharged to coastal waters.

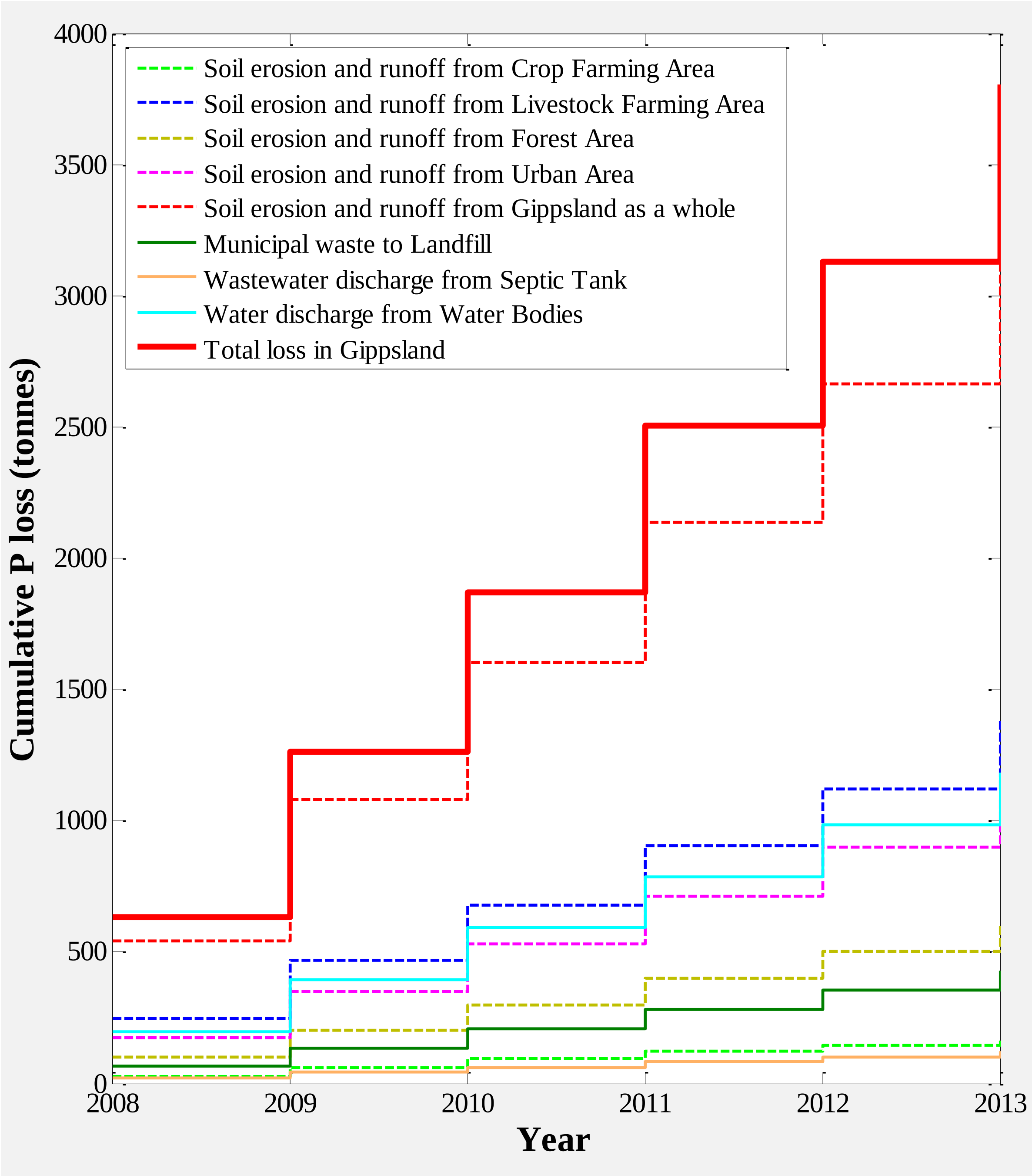


Fig. 4.20 Magnitude of cumulative P loss relating to the Gippsland region and different subsystems within this region over the study period.

This analysis shows that between 2008 and 2013, a total of approximately 1,182 tonnes P were discharged to coastal waters from water bodies in the Gippsland region (**Fig. 4.20**). Therefore, it is evident that both fresh water and marine water ecosystems in the Gippsland region are vulnerable to P induced pollution and associated detrimental consequences such as algal bloom and eutrophication. If adequate measures are not taken in an urgent basis, cumulative discharge of P in this manner could create long-term and irreparable damage to the surface and costal water bodies of the Gippsland region in future.

4.2.8.2. Assessment of cumulative P storage

The current analysis has revealed that a substantial amount of P storage occurs in soils of different subsystems within the Gippsland region. Although the sufficient storage of P in soil is necessary to supply optimal level of P for plant growth, excessive storage may intensify the risk of P loss as soil erosion and runoff. However, in order to assess what fraction of the soil P storage is productive, it is important to know in which forms (solution P, active P and fixed P) these stored P in soil exist and what are the magnitude of P in each form. Even though the stored soil P is somewhat utilizable by plants, the recovery and recycling of P from these pools are not economically feasible (Lederer et al., 2014). Application of P fertilizer in soil with excessive P storage could also result in P wastage, which in turn may intensify the problem of dwindling phosphate rock reserves as discussed in the **Section 1.2.2**. Owing to all these concerns, in this study, a greater attention has been paid on the analysis of P storage in the Gippsland region. As presented in **Fig. 4.21**, the analysis of cumulative P storage in the Gippsland region and different subsystems within this region indicates that over a six-year period, a total of about 65,424 tonnes P stored within this region. This amount of stored P is greater than the total (cumulative) quantity of P (61,578 tonnes) that were imported as commercial fertilizer in this region over that period. However, the majority of the P storage within this region occurred in soils of the livestock farming system, where the cumulative P storage in this system was approximately 43,309 tonnes over the six-year period (**Fig. 4.21**). This is equivalent to about 70% of the cumulative P import as commercial fertilizer in the Gippsland region. With the same amount of P that were stored alone in soil of the livestock farming system over six years, it is possible to meet the commercial fertilizer demand of the Gippsland region for nearly four years. A considerable amount of P storage also occurred in soils of the crop farming and the household and urban systems, where the cumulative P storage in soils of these subsystems were approximately 4,063 and 3,362 tonnes respectively.

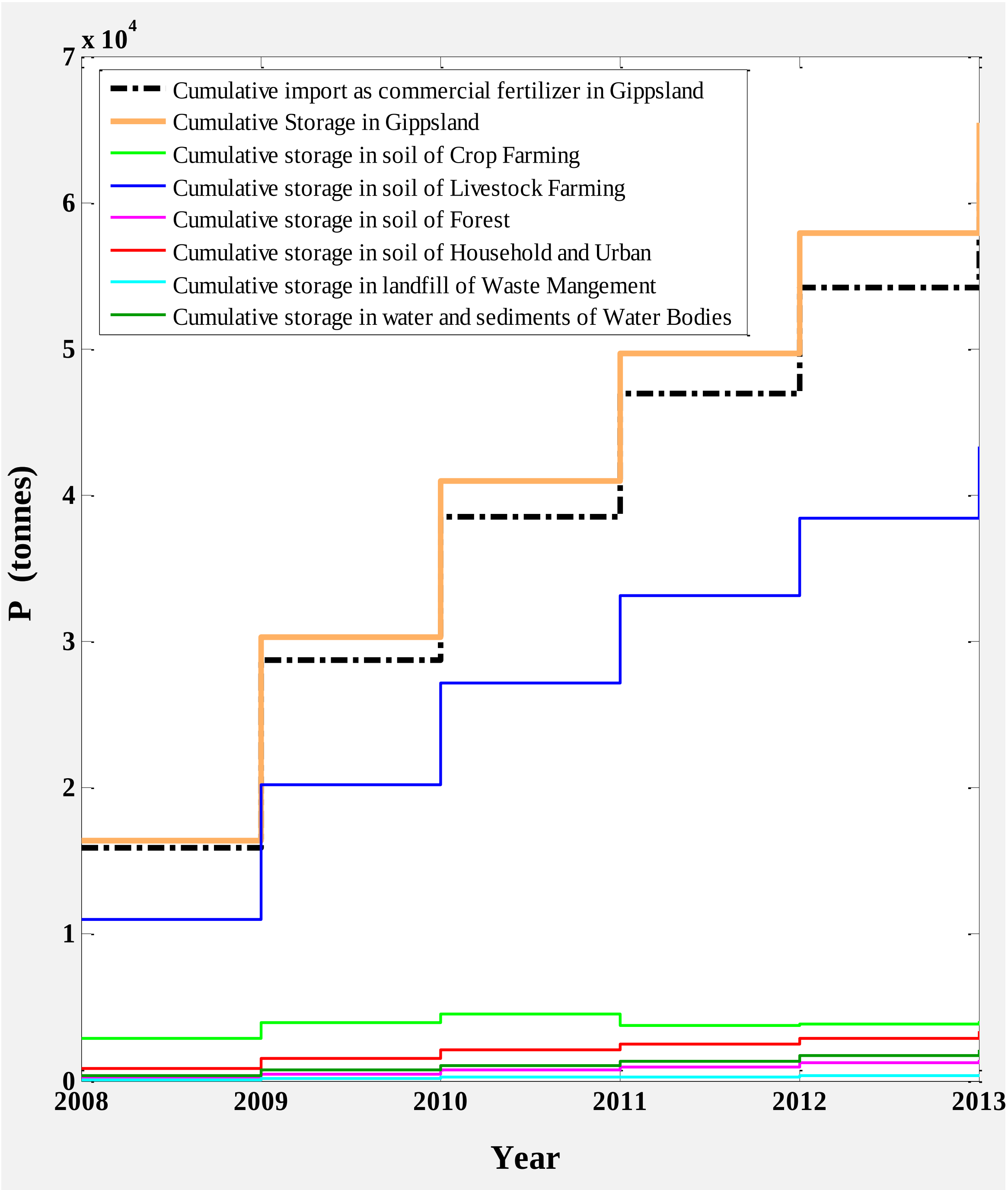


Fig. 4.21 Magnitude of cumulative P storage relating to the Gippsland region and different subsystems within this region over the study period as compared to the cumulative P import as commercial fertilizer in that period.

4.2.8.3. Assessment of the magnitude of P flow associated with materials suitable for P recovery

The magnitude of P flow relating to materials suitable for P recovery in the Gippsland region has been presented in **Fig. 4.22**. This assessment indicates that a substantial amount of nearly 20,000 tonnes of P excreted annually in manure by the livestock (mainly by grazing cattle) within this region, where it ranged from approximately 18,008 to 20,278 tonnes over the study period. The amount of P excreted annually by livestock is greater than the amount of annual P import as commercial fertilizer in this region, where it was nearly 116% and 158 % in 2008 and 2009 respectively, and more than twice the amount in years after 2010 (**Fig. 4.22**).

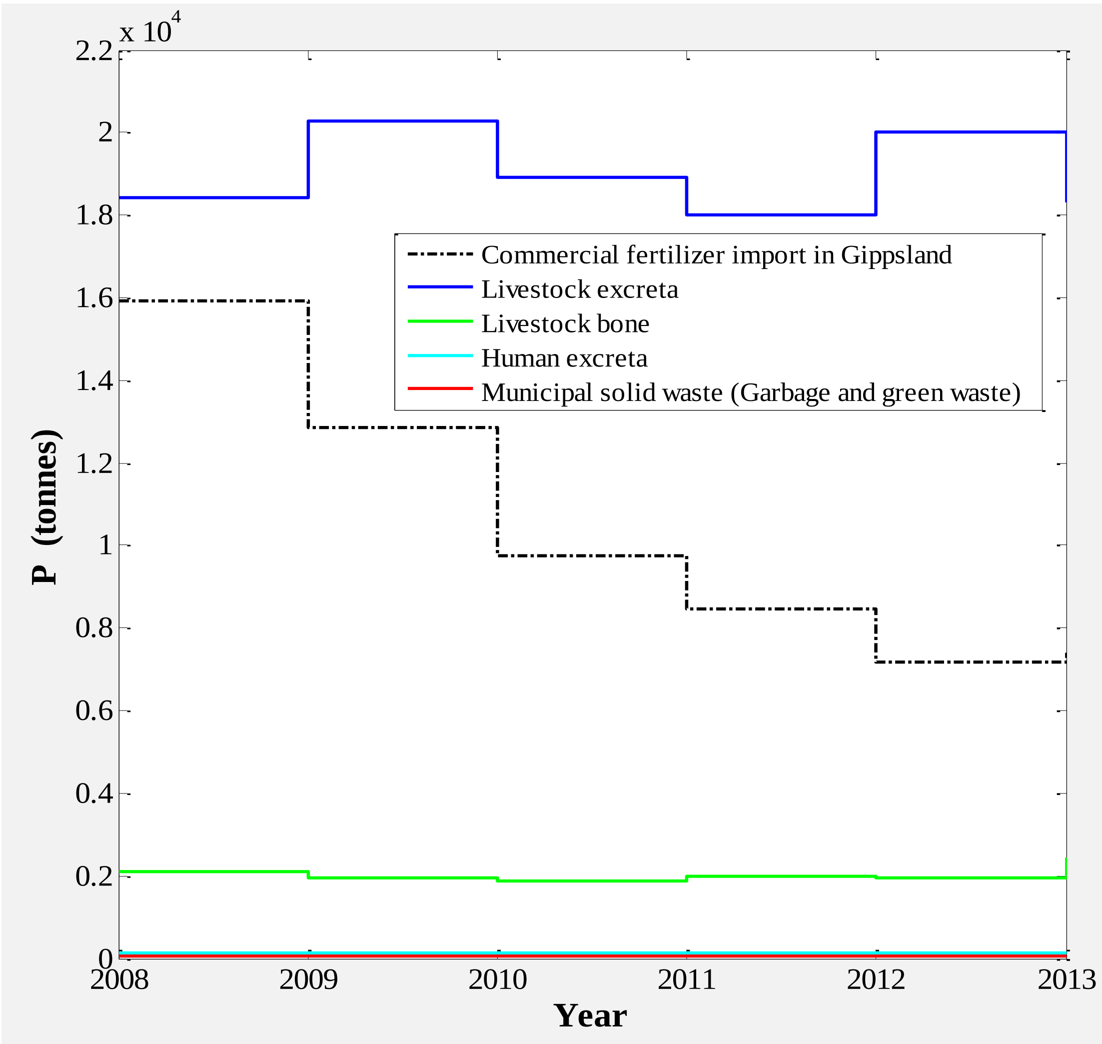


Fig. 4.22 Magnitude of P flow associated with materials suitable for P recovery in the Gippsland region over the study period.

This study has observed that nearly all of the P excreted annually by livestock eventually ends up in soil of the livestock farming sector. This is likely to be the prime reason for high P storage in soil of this system as assessed in this study. The current analysis has also revealed that a considerable amount of approximately 2,000 tonnes of P outflow also occurs annually as animal bones. Generally, the bone wastes produced in slaughter house or meat processing industries in the Gippsland region are utilized for producing bone meals. However, a considerable proportion of P in bones along with meats may find its way to human consumption and eventually ends up in solid waste. Currently, there is lack of information relating to the magnitude of P associated with bones in municipal solid waste, food waste, or waste that ends up in landfill. Given the significant amount of P flow associated with animal bones, there is a need for further investigation regarding the fate of P associated with animal bones. Compared to the livestock excreta and livestock bones (2,000 tonnes), P associated with human excreta (ranged from approximately 122 to 129 tonnes annually) and municipal solid wastes (ranged from approximately 48 to 60 tonnes annually) in the Gippsland region were not significant.

4.2.8.4. Assessment of P recycling

The analysis of the nature and magnitude of P recycling flow in the Gippsland region as presented in **Fig. 4.23** indicates that through the existing recycling practices, annually more than 3,000 tonnes of P recycling occurred in this region, where it ranged from approximately 3,123 to 3,593 tonnes over the study period. The majority of this recycling occurs through the land application of effluent or slurry from the manure pond within the livestock farming system, which ranged from approximately 2,835 to 3,363 tonnes P over the study period. A considerable amount of P (that ranged from approximately 103 to 161 tonnes) in livestock manure were also recycled from the livestock farming to other subsystems within this region. This analysis indicates that annually, less than 20% of the total P excreted by livestock is ultimately recycled through the existing recycling facilities. Although less significant compared to the overall P recycling in this region, the magnitude of P recycling as sewage sludge (ranging from approximately 50 to 53 tonnes), compost (ranging from approximately 38 to 43 tonnes), and treated wastewater (ranging from approximately 32 to 34 tonnes) from the waste management system to the crop farming areas and urban landscapes are worth mentioning. However, just above half (130 (5) tonnes) of the mean annual total inflow of P (226 (9) tonnes) in the waste management were eventually recycled for beneficial purpose, indicating a potential scope for improving P management.

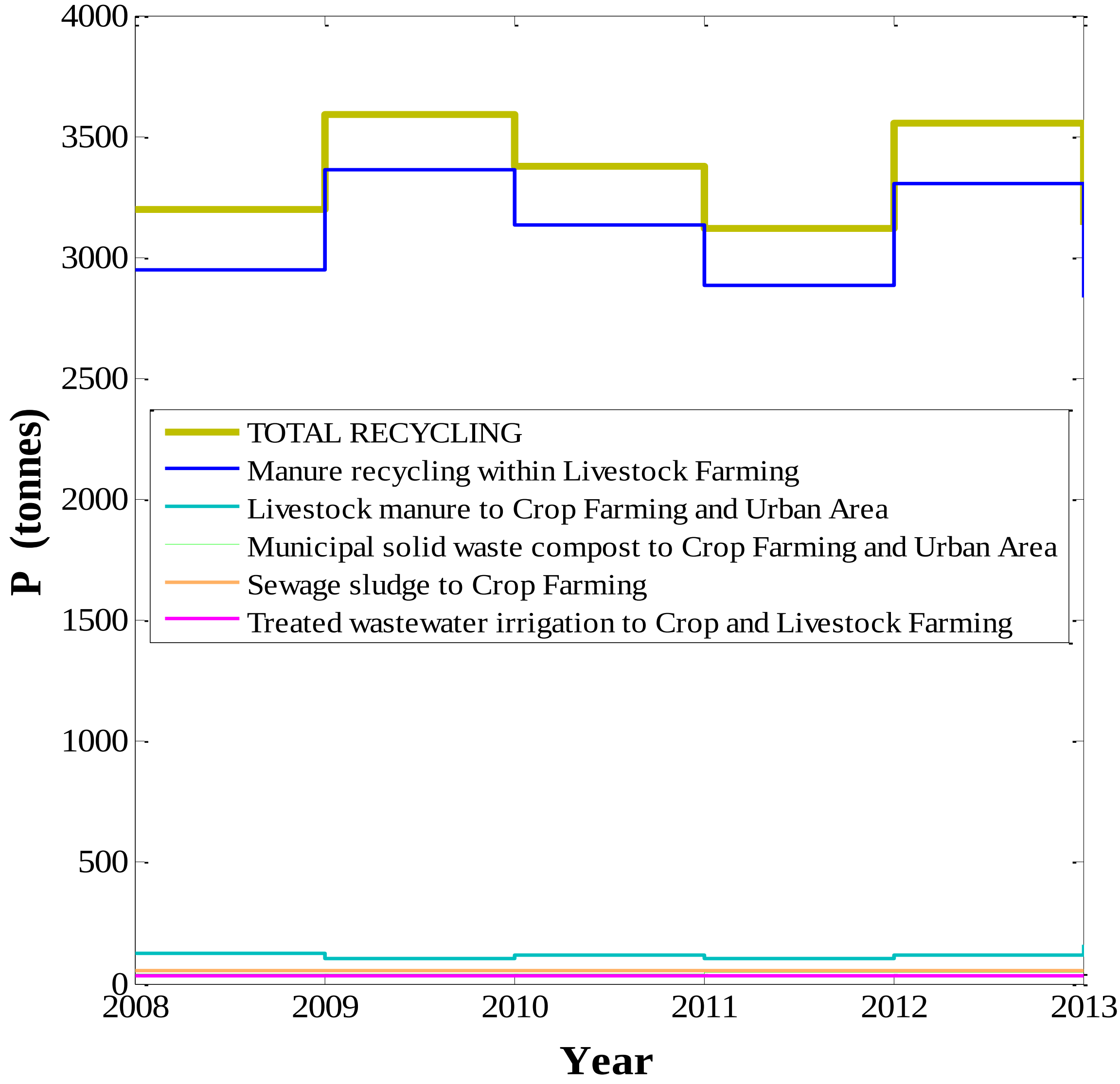


Fig. 4.23 Nature and magnitude of P recycling flow in the Gippsland region over the period of 2008-2013.

On the basis of an in-depth analysis of the nature and magnitude of multi-year P flow and storage relating to the Gippsland region as a whole and all subsystems within this region, it can be concluded that a substantial amount of P wastage and loss occurs in this region. Therefore, the mitigation of these wastage and loss are crucial for achieving P sustainability in this region. The next section presents a broad-range of system-specific P management strategies that could be effectively utilized in this regard.

4.3. Recommendations for making better P management decisions to achieve P sustainability in the Gippsland region

Based on the current analysis, the priority areas for improving P management in the Gippsland region have been identified, and necessary policy and management options have been suggested as follows:

4.3.1. Recommendations for the livestock farming and the crop farming system

This study has identified that the livestock farming and the crop farming systems are the two key subsystems in terms of the magnitude of P flow and storage in the Gippsland region, and the majority of P wastage and loss in this region are associated with these systems. Therefore, in order to proceed towards P sustainability in the Gippsland region, special attention should be given on minimizing P wastage and loss in these systems. The analysis of P flow and storage relating to the livestock farming system has revealed that over the study period, approximately 43,309 tonnes P were accumulated in the soils of this system. Given the mean annual inflow of 7,184 tonnes P as commercial fertilizer against the soil accumulation of such a huge amount of P over the study period, it might be interesting to experiment the pasture and crop productivity of a particular year without any commercial P fertilizer inputs in this system, at least for some intensive dairy farms. However, if soil P accumulation in this manner is allowed continue, it will lead to a massive stocks of P in livestock grazing lands in future, which will ultimately intensify the risk of P loss as soil erosion and runoff. Taking the fact of substantial soil P accumulation into consideration, it will also be useful to perform an extensive soil survey to assess P level particularly in soils of the intensives dairy and meat cattle grazing lands in Gippsland. If the survey results confirm that these soils have greater P level than that is required by plants for optimum growth, then the input of P as commercial fertilizer must be reduced accordingly. The economic productivity of farms from avoiding/minimizing commercial P fertilizer application should also be investigated. Moreover, communicating the findings of current study to Gippsland farmers could be useful to motivate them towards undertaking such investigations, and improving P management. Provided the huge amount (18,987 tonnes per annum) of P generation in livestock excreta in Gippsland which mostly ends up in soils, it might be worthwhile to identify the potentials for systematic integration of the livestock farming and crop cultivation that enables the amount of P necessary for optimum plant growth are supplied from livestock excreta rather than applying commercial P fertilizers. A number of studies (MacDonald et al., 2011; Metson et al., 2012a; Costa et al., 2014) suggested that systematic integration of livestock farming and crop cultivation could help to reduce chemical P input in the agricultural system. However, Bateman et al., (2011) suggested that such integration should be capable to overcome the spatial and temporal challenges of recycling livestock manure to crop production.

The current analysis has also revealed that a considerable amount of P in the livestock farming system also imported as grain based feed (for instance, annually 3,251 tonnes in dairy feed) from outside the region, most of which eventually ends up in soils as livestock excreta. If such grains are produced in Gippsland through systematic utilization of P and other nutrients in livestock manure, and utilized as livestock feed; then it may minimize the region's dependency on the external supply of livestock feed in one side, and reduce the P input as imported grain based feed on the other side. It may also substantially reduce farm's cost from livestock feed import, and therefore the possibilities of such interventions should be investigated. Schröder et al. (2011) suggested that a harmonized set of actions including optimization of land use, improvement of fertilizer decision and application procedure, alteration of livestock diets, and fine-tuning of livestock densities to available land could greatly minimize P inputs in the agriculture sector whilst sustaining better crop production and reducing P wastage. Apart from these interventions, creation of awareness on the importance of P sustainability, and the provision of necessary education and training to Gippsland farmers on the strategies of sustainable P management could minimize P wastage and loss in the agricultural system. Such a strategy for instance, is the concept of '4R' that denotes 'apply the right source of nutrient, at the right rate, at the right time and in the right place' (IPNI, 2014). The current analysis has also identified that annually a substantial amount (about 2,056 tonnes per annum) of P outflow occurs in livestock (mainly meat cattle) bones from this system. Currently, there is insufficient availability of information regarding the fate of P contained in these bones. Therefore, a life cycle assessment of P associated with animal bones from the livestock farming system in the Gippsland region could generate information that is necessary to formulate effective strategies for attaining systematic recovery and recycling of these bone-bound P. Although a number projects have already been initiated by GippsDairy to improve nutrient management in the dairy farms of the Gippsland region (GippsDairy, 2008, 2010, 2012, 2014a), there has been a limited information available regarding ‘how many dairy farms in Gippsland are involved in these projects or have adopted improved management strategies as planned in this projects, or to what extent these strategies are being currently practiced by Gippsland farmers, or to what extent P management has been improved through these projects’. There is also lack of information regarding the number of farms in Gippsland that are performing best management practices for instance, assessing initial soil P level before fertilizer application. Therefore, there is need for an extensive field survey based assessment on the current approaches towards improving nutrient management in Gippsland farms.

4.3.2. Recommendations for the household and urban system

The household and urban system is another key subsystem of P flow in the Gippsland region, and a considerable amount of P wastage and loss associated with it. Therefore, initiative towards minimizing P wastage in this system could also contribute towards the P sustainability in this region. This study has identified that in the urban areas of the Gippsland region, a considerable amount (about 513 tonnes per annum) of P inflow occurred as commercial fertilizer input, the majority of which is either stored in soils or lost as soil erosion and runoff. Over the study period, a considerable amount of about 3,362 tonnes P stored in urban soils. From the urban areas, annually about 181 tonnes of P loss occurred as soil erosion and runoff. Therefore, a reduction in commercial fertilizer application in the lawns in residential areas of the Gippsland region could help to minimize excessive P storage and P loss in the household and urban system of this region. Considering the fact of high P storage in soils of the household and urban system of this region, it might be useful to perform an extensive soil test to identify the level of P in the urban landscape, particularly in the lawns of residential areas. Based on the results of that experiment, the households/residents of urban areas should be provided with recommendation for applying the appropriate dose of commercial P fertilizers in their home gardens or lawns. The local Shire councils and other relevant government organizations could play a vital role in this regard. A survey of 942 residents in Minnesota metropolitan area indicates that people’s beliefs/knowledge and attitudes play a crucial role in determining the amount and frequency of lawn fertilization (Martini et al., 2015). A similar survey on urban residents of the Gippsland region, while taking this key fact into consideration, could also identify useful information for formulating effective strategies to motivate residents towards minimizing unnecessary lawn fertilization. Although not significant compared to the overall P flow in this region, some amount of P inflow was also associated with human food, pet food, and detergent use in the household and urban system. P associated with these types of inflow are eventually lost as wastewater, and soil erosion and runoff. Therefore, it might be useful to minimize P inflow associated with these materials. Strategies such as changing resident's attitudes towards decreasing P intake in human food for instance, by shifting diet from meat to plant based (Metson et al., 2012b); providing low P containing feed to pets; and using P free detergent and soap could help to improve the situation in the Gippsland region in this regard. However, this shift in diet may have some consequences on the livestock and crop production systems, which may eventually alter the magnitude of P flow associated with these systems. Therefore, before implementing such change, a better understanding of its consequences on overall P cycle should be investigated. Crews et al. (2013) assessed that cultural and social attributes have significant influence on the magnitude P wastage at the food consumption level. Therefore, creation of awareness about the risk of P scarcity and associated adverse consequences on food security could also encourage the urban residents of this region to minimize P wastage.

4.3.3. Recommendations for the waste management system

Improved P management in the waste management system could also contribute to progress towards achieving P sustainability in the Gippsland region. This analysis has revealed that nearly half of the annual total P inflow in the waste management system remained unrecovered or unutilized, which mainly ended up in landfill areas as disposal of garbage (from solid waste stream) and sludge (from wastewater treatment plants). Therefore, it is necessary to ensure the recovery of P from these wastes before disposing to landfills. This study has observed that nearly all of the P associated with green wastes generated from the residential areas in this region were recycled through Gippsland Water's Soil and Organics Recycling Facility (SORF). However, P associated with food wastes mostly remained unrecovered and are disposed of in landfill areas. So, the capacity of SORF should be enhanced or new recycling facilities need to be created to ensure the recovery and recycling of P from food wastes. SORF is also involved in recycling a small proportion of the overall P that generates in sludge through the region's domestic wastewater treatment facilities, and nearly three times P in sludge which is about 30 tonnes per annum is ultimately disposed of in landfill areas. Therefore, the capacity of SORF towards P recycling from sludge should also be enhanced. However, given the fact that the amount of P that remained unrecovered in the waste management system is not significant compared to the overall P flow in the Gippsland region, before enhancing the capacity of SORF or establishing new composting facilities, an overall economic and environmental feasibility assessment of P recycling through such enhancements should be conducted. This study has observed that a considerable amount of wastewater particularly in the un-sewered areas of this region are locally managed through septic tank system, where the septic tank effluents containing about 19 tonnes of P per annum are discharged to the local environment. In areas of Gippsland region which are not possible to bring under centralized sewer system and treatment plants due to distance and high extension cost, the introduction of small-scale decentralized systems for P recovery particularly that associated with the septic tank systems could improve the situation.

4.3.4. Recommendations for mitigating P discharge to water bodies

This study has identified that in the Gippsland region, a considerable amount of P is discharged from different subsystems to water bodies, which can cause massive detrimental consequences on aquatic ecosystems. Therefore, there is a necessity for minimizing P discharge to water bodies in this region, and the proper implementation of the key P management strategies for different subsystems as suggested so far in this study could significantly help in this regard. Considering the fact of significant P accumulation in soils of the livestock farming system and P loss as soil erosion and runoff to water bodies as identified in this study, an extensive field experiment should be performed to identify the spatial patterns and hot spots of P loss that associated with the livestock farming system of the Gippsland region. Based on the findings of such investigations, site specific P loss reduction strategies should be implemented. For instance, strategy such as crop plantation across the pathways of P loss or in low lying lands in the interface between extensive livestock farming areas and streams could help to minimize P loss to water bodies in this region. However, before large scale implementation of such strategy, small scale field trial should be conducted for the quantitative evaluation of reduction in P loss through such intervention as well as to identify suitable crop types. Development of appropriate ‘P index’ to regularly assess the risk of P loss from the fields or farms, and mitigation measures applied accordingly (Sharpley et al., 2003; Nelson and Shober, 2012; Bolster et al., 2014) could also help to minimize P loadings to water bodies in this region. Moreover, intervention such as strict P discharge standards could drive Gippsland farmers towards increasing recovery and recycling of P, and therefore, could minimize P transport to water bodies. Elser and Bennett (2011) suggested that creation of a P emission market like carbon markets could also encourage farmers to minimize P discharge to water bodies. A phosphorus credit trading program to reduce TP (total phosphorus) loadings to streams for the S-191sub-basin located in the Lake Okeechobee watershed in the USA was found to be successful where about 81% of the TP credits available for trading were exchanged among agricultural farms (Corrales et al., 2014). Such a program, on a trial basis, could be implemented among Gippsland farmers along with a feasibility study to identify its significance in minimizing P loss and increasing farm's economic productivity. It is a good sign that some initiatives have already been undertaken in the Gippsland region to reduce P loadings to water bodies. For instance, in 2002, a target of 40% reduction in annual P transport to Gippsland lakes from surrounding catchment by 2022 has been set by the Gippsland Lakes Task Force (GLTF) under the Gippsland Lakes Future Directions and Actions Plan 2002 (DNRE, 2002). To move towards achieving that goal, the implementation of a wide range of Best Management Plans (BMPs) for activities in the Gippsland Lakes Catchment has been suggested by expert panel (Ladson and Tilleard, 2006). Later, discussions with stakeholders have identified the key priority considerations for the GLTF to refine the Gippsland Lakes Future Directions and Actions Plan. Some of these considerations include continue implementation of BMPs, assess economic feasibility of increasing levels of adoption of BMPs, assess nutrient generation from different land uses, estimate nutrient reduction through existing BMPs under various climate change scenarios, assess feasibility of setting nutrient reduction goals for various land uses, and develop a tool for determining nutrient export areas of high risk (Peter Cottingham & Associates, 2008). A recent study by Roberts et al. (2012) to assess the need for changing agricultural management to achieve the reduction target of GLTF and to investigate the economic feasibility of these changes revealed that a 40% reduction target is technically feasible but requires more than the existing environmental budgets of AUD 1 billion over 25 years and is not cost-effective. In contrast, a 20% reduction target is achievable at much lower cost and needs only modest level of changes in agricultural management. This information can be utilized for rendering the P reduction targets to be environmentally and economically feasible.

This chapter concludes that the regional scale P flow model as developed in this study is unique and can be utilized as effective tool for analysing P flow over multiple years at the regional scale. The model application for analysing P flow and storage in the case of the Gippsland region indicates that there is a substantial scope for improving P management in this region. The wide range of system specific P management strategies as outlined in this chapter can be utilized as effective guidelines for formulating appropriate policy and management interventions to achieve P sustainability in this region. The next chapter presents a thorough discussion on the uncertainty and limitations associated with the current study.

Chapter-5

DISCUSSIONS ON LIMITATIONS AND UNCERTAINTIES

A review of the published literature on SFAs of P at different geographical and temporal scales as presented in **Chapter 2** indicates that nearly all studies, to a considerable extent, have experienced limitations relating to model, data, and associated uncertainties. The majority of these studies have addressed these limitations particularly as they relate to data uncertainty (Seyhan, 2009; Li et al., 2010; Yuan et al., 2011a; Yuan et al., 2011b; Wu et al., 2012; Cooper and Carliell-Marquet, 2013; Egle et al., 2013; Roy et al., 2014).The current study is not an exception and has some shortcomings which are addressed in two sections viz. *limitations and uncertainties associated with the model,* and *limitations and uncertainties associated with data.*

5.1. Limitations and uncertainties associated with the model

Although the model has overcome various limitations associated with existing SFA models for instance, inability to analyse P flow over multi-year at the regional scale; it has some shortcomings too. One of the limitations of the current model which is also common in all available SFA models is that it cannot adequately explain or analyse some important processes that determine or regulate the key P flow and storage within a system or subsystem. For instance, the model directly calculates the total P loss in soil erosion and runoff from a subsystem on the basis of the data on the total land area and the annual rate (kg/ha) of P loss in soil erosion and runoff from per unit area. But, in practice, the total P loss in soil erosion and runoff depends on a number of key factors for instance, soil type, rainfall intensity, fertilizer application rate and timing, slope of land, vegetation pattern, and land use type; which are generally considered in process based models. However, in order to overcome this limitation of the SFA model, future research should focus on finding way for integrating process based model into SFA model. Another key shortcoming is that the model by itself cannot make any decision or optimize the resource use; but based on the given input data, it can generate useful information relating to the magnitude of P flow and storage which can be utilized in formulating improved P management policy. For example, this model cannot explain the mechanism in which the increased recycling of P as manure application results in lower input of P as mineral fertilizer and optimizes P use; however, it provides the information regarding the magnitude of P in manure produced and commercial fertilizer used. Currently, the model cannot perform error propagation and data reconciliation by taking data uncertainty into account; while SFA model of P that built in STAN software platform is capable to do that (Cencic and Rechberger, 2008). Although the model can calculate the mean annual flow and associated standard deviation in a multi-year analysis; the standard deviation for the total inflow, total outflow, or total storage relating to each system or subsystem as calculated by the current model does not take into account the variability over years in each individual inflow, outflow, or storage; rather it is based on the variability in total inflow, total outflow, or total storage over years. Even though this model can analyse P flow over multiple years, it does the analysis in a discrete time (annual time step) and therefore, cannot provide the continuous picture of the flow.

The limitations of the regional scale P flow model discussed so far, are mostly relating to the operational aspects. However, there are some limitations associated with the structural aspects of the model too. The shortcomings of this kind have originated in an attempt to build a model that is capable to analyse P flow with minimal data input. Although a more complex model which requires diverse and fine scale data input may generate more accurate results; the data availability for such models is generally very limited. For instance, the mass of P inflow as human food in the current model is analysed through simply multiplying total population by daily per capita intake of P in food. The other way of analysing P inflow as human food is, multiplying total population by daily per capita consumption of different types of food (rice, bread, nut, meat, milk, etc.) first, and then multiplying their product by P concentration in each types of food, and finally, summing up P intake in each type of food. Consideration of the age structure of the population would add further value. However, as mentioned earlier, the model offers greater flexibility to incorporate any degree of complexity at any instances and therefore, necessary improvements can be made through the inclusion of such complexity given that sufficient data of high quality are available. As the model has been developed keeping the fact of limited data availability in mind, it can be utilized for the analysis of P flow and storage even in the case of data limited region. Moreover, like other SFA models, the output of our model is as good as the input data, and therefore, in order to obtain reliable results from the model, the accuracy and reliability of the input data must be ensured first.

5.2. Limitations and uncertainties associated with data

Similar to other recent SFAs of P, data limitations have been found to be a key challenge to accurately analyse P flow and storage in the case of Gippsland region. As described in the 'methods of analysis' chapter, an exhaustive effort yielded the best set of reliable data (both for material mass flow and P concentration) relating to the Gippsland region. However, in many instances, necessary data specific to the Gippsland region were non-existent, and in such cases, data relating to other regions or places of Australia or of other countries of the world have been utilized. A degree of uncertainty is always present when data from other regions or places are utilized in the case of the Gippsland region, which eventually reduces the accuracy and reliability of the result. Keeping this concern in mind, as described in **Section 3.2.5.2.3**, a criterion has been developed to define the degree of reliability of data collected from various sources. The mass flow data of materials/processes and the associated P concentration data along with their assigned degree of reliability (ranging from high to moderate to low) has been presented in **Appendix 2** and **Appendix 3**. Since P flow and storage in the current analysis are calculated mainly based on the input of material mass flow and P concentration data, it is likely that the degree of reliability assigned with data is directly reflected in the results. For instance, taking the example of P outflow as milk, the model has analysed this based on the input data relating to the 'quantity of milk produced' which is of high to moderate reliability, and 'P concentration of milk' which is of moderate reliability, and therefore, the result relating to P outflow as milk is likely to be of high to moderate reliability. Similarly, the model has calculated total annual P inflow as atmospheric deposition in the Gippsland region based on the 'total land area of Gippsland region' which is of moderate quality and the 'annual rate atmospheric deposition of P which is of moderate to low reliability, therefore, the results relating to P inflow as atmospheric deposition are likely to be of moderate to low reliability. In the similar way, the degree of reliability of the results obtained from the model for all other P flows and storage relating to the Gippsland region can be understood to some extent. Although this study has attempted to perform a 'reality check' for the results obtained from the model in the case of Gippsland region; given the low availability of independent literature data and actual field experiment based data, it was possible to perform this check only for some significant P flows and storage. Moreover, due to the unavailability of data on the rate of P loss in soil erosion and runoff for each year of the study period, a typical rate of P loss in soil erosion and runoff based on the study of Hancock et al. (2007) that involved estimating P loads through spatial modelling and sediment tracing in the Gippsland lakes catchment was utilized in this study. However, before utilizing such data, it was confirmed that the rate is in consistent with long term averaged value reported by other studies. Therefore, the results based on the current analysis cannot reflect the impact of climatic variations on P loss as soil erosion and runoff.

Owing to the significance of sufficient baseline data for accurately analysing P flow and storage in the Gippsland region to generate better information for effective policy recommendation, the quality analysis of data presented in **Appendix 2** and **Appendix 3** indicates future priority areas for data collection. The mass flow data of materials and P concentration data which have been indicated with moderate, moderate to low, or low reliability in the tables should receive the top priority in future data collection for the Gippsland region. There is need for the acquisition of more accurate data through local monitoring or experimentation in this regard. However, because significant resources in terms of time, money, and expertise are needed for collecting good quality data, focus should be given on data that are necessary for calculating the highly significant P flows (in terms of the magnitude) in the Gippsland region as identified in this study. Emphasis should also be given on data relating to the flows that have substantial influence on determining the magnitude of P flow relating to various subsystems. P flow as commercial fertilizer, livestock feed, livestock excreta, livestock bones, wastewater etc. are the examplea of such flows. The present study has only addressed the uncertainty associated with data and therefore, efforts are needed in future research for minimizing such uncertainty. Wu et al. (2014b) proposed a number of suggestions for minimizing the data uncertainty in SFA study of P, and demonstrated that Monte Carlo methodology is a potential tool for solving the data uncertainty in SFA.

Another source of uncertainty in the current analysis of P flow and storage relating to the Gippsland region is the inclusion of a number of assumptions in case of missing data or information. Although the assumptions have been made based on a number of logical judgements as explained in **Table 3.3**, a certain degree of uncertainty must be associated with these, eventually hampering the reliability of the model results. For instance, the commercial fertilizer import data for the Gippsland region is available for 2008, 2010, 2012 and 2013, but not available for 2009 and 2011. In such case, the data for 2009 and 2011 has been assumed to be the average value of data of the previous and next year, for instance, the average of the 2008 and 2010 data has been considered for 2009. However, in reality, the actual P fertilizer import data for 2009 and 2011 could be significantly different to that have been assumed in this study, therefore, the results of the current analysis may not reflect the real situation of P flow for those years. Taking another example of assumption, which is, the data relating to the total annual meat cattle number in Gippsland is available but what proportion of that were slaughtered is not known, however, this proportion is known only at the national scale for Australia. In such case, national level data have been considered for the analysis of P flow in the Gippsland region, eventually introducing some degree of uncertainty in the model results. As presented in **Table 3.3**, there are many other assumptions considered in the current analysis of P flow in the case of the Gippsland region. All these assumptions might have incorporated some degree of uncertainties in the findings of the current analysis. Therefore, while considering for policy recommendation, the findings of the current research relating to the P flow situation of the Gippsland region should be viewed with caution and utilized only after having appropriate understanding of the assumptions used.

Moreover, the generalization of the data utilized in the current analysis may also have contributed to the uncertainty of the results. For instance, due to lack of adequate and detailed data, when analysed the P flow associated with the livestock, it is considered that all livestock are of equal age or equal size or equal weight, and therefore, while calculating P flow associated with livestock feed or livestock excreta, a standard or average value of P intake rate or P excretion rate have been used, which is clearly not the actual case. The similar kind of generalization has been made when analysing P flow associated with the human food and human excreta, as well as in several other instances. The generalization of this kind might also have introduced some level of uncertainty in the findings of the current analysis. In addition, due to lack of data relating to actual or initial soil P reserves, the soil P stock has not been calculated in this study; only the change in stock over the study year period has been analysed. The current analysis assumes that the P stock (initial P reserves) of soils at the beginning of a year is zero and P outflow (crop uptake, soil erosion and runoff) from soils in a given year originates from the total amount of P supplied to soil in that year as chemical fertilizer or manure or in any other means. In reality, crops can uptake only a part of the P applied to soil as fertilizer or manure, and the losses of P in soil erosion and runoff may partly come from initial soil P reserves. Therefore, the non-consideration of initial soil P reserves in the current analysis due to lack of data availability may also have contributed to the uncertainty of the results. This study recommends that relevant authorities should pay special attention to the estimation of actual soil P reserves. Upon the availability of initial soil P reserves data, future SFAs should include the analysis of the soil P stock to attain more comprehensive picture for better P management.

In the light of above discussion, this chapter concludes that there are some shortcomings associated with both the model developed and the data utilized for the analysis of P flow, which might have contributed some degree of uncertainties in the findings of the current analysis of P flow in case of Gippsland region. For a better judgement of the reliability and accuracy of the findings relating to the current analysis, future research should perform an uncertainty analysis considering the key limitations as discussed in this chapter. The next chapter presents the main conclusions that are drawn from the current research.

Chapter-6

CONCLUSIONS

This study has assessed that there are a number key challenges (such as dwindling geological reserves, increasing demand, geopolitical constraints, excessive loss from different systems, and high discharge to water bodies and associated harmful consequences) to the sustainability of the global phosphorus resource. If not properly tackled, these challenges may lead to the scarcity of this vital resource, which in turn may hinder global food security. Countries such as Australia and most of the EU countries, which do not have significant domestic reserves of phosphate rocks, may suffer greatly from such scarcity. In order to provide effective policy and management response to overcome these challenges and to safeguard global P sustainability, there is need for a sound understanding of the nature and magnitude of P flow through different systems at various geographical and temporal scales. Based on extensive search and preliminary review of available literature, this study has observed that in the recent times, a considerable number of studies have been performed in this regard. Therefore, this study has conducted an in-depth review of available P flow analyses at different geographical and temporal scales to identify knowledge gaps and priority areas for future research. This review involved assessing the nature and magnitude of key inflow, outflow, and storage of P at the city, regional, and country scales. The review revealed that the regional scale, which is significant in terms of the magnitude of P flow, has received limited attention in the multi-year analysis of P flow. This implies that there is a lack of knowledge regarding the nature and magnitude of P flow and storage over multiple years at the regional scale. However, a sound understanding in this aspect is vital for making long-term and effective P management decisions towards achieving P sustainability. Therefore, with a broad objective to develop improved understandings of the major P flows over multiple years at the regional scale, this study has specified its research objective (**Section 2.6**) as; i) To develop a generic P flow model that is capable to analyse the nature and magnitude of P flows and storage relating to all potential systems and subsystems of P use over multiple years at the regional scale, and ii) To utilize the model for the analysis of P flow in the case of the Gippsland region, a key agricultural region of Australia; and based on that analysis, suggest specific P management decisions towards achieving P sustainability.

As set in the research objectives, in order to perform the quantitative modelling of the multi-year P flow at the regional scale, this study has utilized the method of 'Substance Flow Analysis (SFA)' that applies the mass-balance principle for a systematic quantitative analysis of flows and storage of a substance within a system defined in space and time. Using the basic mass flow and mass balance equations according to the procedure of SFA, this study has developed the regional scale P flow model in the MATLAB/Simulink® software platform, which is a very powerful and commonly used tool for modelling complex and dynamic systems.

The regional scale P flow model as developed in this study has taken into account both structurally and operationally, all the relevant P flows and storage associated with all key systems, subsystems, processes or components, and associated interactions of P flow to represent a typical P flow system at the regional scale. The main advantage of this model over available regional scale SFA models is that it is capable of analysing the trends or dynamic changes in P flow and storage over many years at an annual time step, whereas the available P flow models are static and can analyse P flow only for a particular year at a time. The unique capability of the model to comprehensively analyse various P flows and storage in a system, subsystem, or/and different components within subsystems and sub-subsystems while taking into account all interactions of P flow, ultimately render it as a robust and powerful tool for the regional scale P flow analysis. The model also offers greater degree of flexibility and allows making necessary modifications and improvements as well as the inclusion of any level of complexity at any point at any instance of time, which is normally not offered by available SFA models. The results of P flow analysis in the case of Gippsland region obtained from the model, particularly relating to some major P flows and storage, were verified through a reality check that involved comparing model results with the findings of actual field based study, independent data, and alternative calculations. The reality check confirmed that model results relating to the case of Gippsland region are reliable. In order to further investigate the strength of the model and the reliability and accuracy of the results obtained, it should be utilized for P flow analysis in the cases of other regions along with subsequent reality check. However, the model has some limitations too. For instance, it cannot thoroughly explain the important processes that determine or regulate P flow and storage within the systems or subsystems. Moreover, the model itself cannot make any decision or optimize the resource use; but based on the given input data, it can generate essential information relating to the magnitude of P flow and storage which could be utilized for formulating improved P management decisions. The future research should focus on overcoming the shortcomings of the model as highlighted in this study, and make necessary improvement to render it as more powerful tool for the regional scale P flow analysis.

Utilizing the best set of reliable data as selected based on the criteria developed in the study, an analysis of the nature and magnitude of P flow and storage relating to the Gippsland region and all subsystems within this region for a six-year period (2008-2013) has been performed by the model. This analysis has revealed that approximately 29% (4,445 (190) tonnes) of the mean annual total inflow (15,349 (3,450) tonnes) of P in this region eventually exited the system, indicating a greater amount (10,904 (3,549) tonnes) of P stored within this region. This finding is different to available single-year SFAs of P at the regional scale in which the magnitude of annual total P outflow was identified to be higher than the annual total P storage. The inflow of P in the Gippsland region mainly occurred as commercial fertilizer (10,263 (3,461) tonnes) and livestock feed (4,443 (271) tonnes) that together account for about 95% of the mean annual total inflow; whereas the outflow mainly occurred as livestock products (4,181 (187) tonnes) that accounts for approximately 94% of the mean annual total outflow. In terms of P storage within this region, the majority (66% or 7,218 (2,413) tonnes) occurred in soils of the livestock production system, while about 22% (2,390 (514) tonnes) occurred in the livestock body. The analysis of annual P flow has revealed that in the Gippsland region, both the annual total inflow and annual total storage have significantly decreased over the study period, but the annual total outflow remained roughly same. This implies that nearly same output of P (mainly as livestock products) has been achieved while minimizing the P input (mainly in mineral fertilizer) and P storage (mainly in soil of the livestock farming system), which is an indication of better P management. A comparative assessment of the magnitude of P flow (total inflow, total outflow and total storage) relating to various subsystems within the Gippsland region has revealed that the majority (approximately 90%) of the P flow in this region is associated with the livestock farming system. Therefore, the trends in the magnitude of P flow and storage in the livestock farming system is highly reflected in that for the Gippsland region as a whole. In case of the main system and all subsystems, a significant annual variation in the magnitude of nearly all P flow and storage has been observed. This kind of variations in annual P flow and storage implies that making judgement based on a single year analysis may not represent the actual and detailed picture of the magnitude of P flow relating to particular system, and therefore, emphasises the significance for multi-year analysis. An assessment of the overall P loss in the Gippsland region indicates that over a six-year period, a total of about 3,241 tonnes P were lost as soil erosion and runoff from different subsystems to water bodies in this region, eventually causing significant environmental and economic damage. The analysis of cumulative P storage over the study period has also revealed that a total of about 65,424 tonnes P stored within this region (mainly as soil storage in the livestock farming system), which is greater than the total quantity of P imported as commercial fertilizer to this region in that period. The storage of P in this manner over many years may cause the accumulation of a substantial amount of unutilized P in soil, which ultimately can increase the intensity of P loss as soil erosion, surface runoff water, and leaching.

As a whole, the main contribution of this study is a novel SFA model that can be utilized for analysing the nature and magnitude of P flow over multiple years at the regional scale to identify priority areas for improving P management. The utilization of this model in the case of Gippsland region has also created a detailed picture of the nature and magnitude of multi-year P flow and storage at the regional scale which is thus far missing from the available literature. The findings of this case study can be effectively utilized for making better P management decisions in this region. The wide range of system specific P management strategies as outlined in this study could also be utilized as effective guidelines for formulating appropriate policy and management interventions to achieve P sustainability in this region. However, provided that some degree of uncertainty associated with both the model developed and the data utilized for the analysis of P flow as discussed in this study, while utilizing for policy formulation, the findings of the current analysis should be viewed with caution. The shortcomings regarding the availability and reliability of the data as highlighted in this study can be a utilized as an effective guideline for determining the priority areas for data collection to improve the accuracy and reliability of the SFA results. In this connection, emphasis should be given on data relating to the P flows that are significant in terms of the magnitude and are linked to many subsystems and components within the system. However, this research has only assessed the nature and magnitude of P flow in the Gippsland region over 2008-2013 period, it neither assessed the reasons for variation in P flow among years nor analysed the causes for trends in P flow over that period. Therefore, the future research should investigate the reasons for the variations and trends in P flow as identified in this study. Such investigation may identify the influence of socioeconomic, climatic and land use changes on the nature and magnitude of P flow in the Gippsland region and help to make better decisions towards P sustainability.

APPENDIX 1: Paper (Chowdhury et al., 2014) published on the findings of the literature review of this study.

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Review

A review of recent substance flow analyses of phosphorus to identify priority management areas at different geographical scales

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ABSTRACT

The dwindling global reserves of extractable phosphorus (P) and its growing demand to produce the required food for a burgeoning global population (the global P crisis) necessitate the sustainable use of this crucial resource. To advert the crisis requires informed policy decisions which can only be obtained by a better understanding of the nature and magnitude of P flow through different systems at different geographical scales. Through a systematic and in-depth review of twenty one recent substance flow analyses of P, we have assessed the key P inflows, outflows, stocks, internal flows, and recycling flows at the city, regional, and country scales. The assessment has revealed, the main inflow and outflow of P at the city scale occurs through food and wastewater respectively, while the main stock of P occurs in landfill. At the regional scale, mineral ore is the main P inflow and chemical P fertilizer is the main outflow particularly in the regions that have P fertilizer production sector. In contrast, either chemical P fertilizer or animal feed is the key inflow and either food and agricultural products or soil losses (erosion, runoff, and/or leaching) is the major outflow especially in the regions without P fertilizer production sector. At the country scale, the key P inflow occurs either through mineral ore or chemical P fertilizer and the key outflow takes place either as food and agricultural products, waste (both solid and liquid), or soil losses (erosion, runoff, and/or leaching). The main stock of P both at the regional and country scales occurs in the soil of the agricultural production sector. As identified in this assessment, the key unproductive outflows and stocks at different geographical scales indicate that there is a potential scope to improve P management through the increased P recovery and recycling, and by the utilization of available soil P stocks. In many of the studies at all the geographical scales, P recycling flow has been found to be less than 20% of the total inflow, and even in some studies at the country scale, P recycling has been found to be entirely absent, which is a clear indication of poor P management. This study has also identified, there is a clear knowledge gap in relation to understanding the P flow over multiple years at the regional scale. The information about the key flows and stocks at different geographical scales as we identified can be utilized to make better P policy and management decisions for a city, region, or country. The information can also be used to guide future research that aims to analyze P flow at the city, regional, and country scales.

Contents

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1. Introduction

The issue of the global phosphorus (P) crisis and its threat to global food security is not new. It has been well addressed in the published literature (Cordell et al., 2009; Gilbert, 2009; Smit et al., 2009; Vaccari, 2009; Schroder et al., 2010; Ashley et al., 2011; Childers et al., 2011; Cordell and White, 2011; Dawson and Hilton, 2011; Elser and Bennett, 2011; Elser, 2012; Neset and Cordell, 2012) over recent years. Even a few years back, Cordell et al. (2009) argued, in spite of P being a limited, non-renewable and non-substitutable but very crucial resource for sustaining global food production, the issue of the global P crisis is missing from the key international debates on global food security. This attitude has changed over the last few years, and the global P crisis is now considered amongst the biggest challenges to the existence and development of global population. For instance, the UNEP (United Nations Environment Programme) Year Book (UNEP, 2011) titled 'Emerging Issues in Our Global Environment' emphasized the necessity of sustainable P management for achieving global food security and minimizing environmental pollution. In 2011, two special journal issues titled 'Phosphorus Sustains Life' (Rengel and Zhang, 2011) and papers therein, and 'The Phosphorus Cycle' (Vaccari, 2011a) and papers therein, and in 2012, one special journal issue titled 'Phosphorus Biotechnology' (Shilton and Blank, 2012) and papers therein have been published on different aspects of P research. In response to the global P crisis, some scientists have been even looking for P substitutes. For instance, a NASA study claimed that arsenic could substitute for P to sustain growth of a bacterium, strain GFAJ-1 of the Halomonadaceae found in the Mono Lake, California (Wolfe-Simon et al., 2011). Thus, it is apparent that the global scientific community is now aware of the importance of this issue, and has concentrated its research efforts to find a way of achieving sustainable management of P resources to feed an increasing global population.

To tackle the global P crisis and to secure a sustainable supply of P for global food production, an integrated set of policy options and technical measures that ensures efficient management of this vital resource are required at the local, national and international scales (UNEP, 2011). Formulation of better policy and management response in turn requires a better understanding of the nature and magnitude of P flow through different systems at different geographical scales, and efforts are underway to identify this information. A number of recent studies conducted quantitative assessments of P flow through different systems at various geographical scales such as the global scale (Liu et al., 2008; Villalba et al., 2008; Bouwman et al., 2009; Van Vuuren et al., 2010), multiple country scale (Ott and Rechberger, 2012), country scale (Antikainen et al., 2005, 2008; Saikku et al., 2007; Chen et al., 2008; Fan et al., 2009; Jeong et al., 2009; Matsubae-Yokoyama et al., 2009; Seyhan, 2009; Dairy Australia, 2010; Smit et al., 2010; White et al., 2010; Ghani and Mahmood, 2011; Suh and Yee, 2011; Ma et al., 2012; Senthilkumar et al., 2012; Cooper and Carliell-Marquet, 2013; Cordell et al., 2013), regional scale (Neset et al., 2008; Li et al., 2010; Do-Thu et al., 2011; Yuan et al., 2011a,b; Wu et al., 2012), city scale (Tangsubkul et al., 2005; Neset et al., 2010; Baker, 2011; Fissore et al., 2011; Qiao et al., 2011; Metson et al., 2012a), and some studies at smaller geographical scales (Baker et al., 2007; Kupkanchanakul and Kwonpongsagoon, 2011). These quantitative assessments allowed the researchers to identify the nature and magnitude of P wastage from the system, and thus helped to ascertain the potential for minimizing P loss, and increasing P recovery and reuse. Based on the outcome of the assessments, these studies were also able to suggest improved site specific P management decisions.

Although a considerable number of P flow analyses have already been conducted at different geographical scales, we are unaware of any systematic review of the available knowledge to provide baseline information about the nature and magnitude of geographical scale specific key P flows and stocks. This baseline information could be very useful to identify geographical scale specific priority areas of P flow which is in turn a requisite for making better P management decisions. Due to variation in the spatial extent as well as in the availability and size of different sectors of P use, the nature and magnitude of major P flows may vary from one geographical scale to another. The type and magnitude of key P flows for the same geographical scale can also differ from one country to another and even from one location to another within the same country. Thus, understanding the variations and similarities of the type and magnitude of the main P flows at various geographical scales as well as at different locations for the same geographical scale is essential to generate baseline information about geographical scale specific key P flows and stocks. Through a systematic and in-depth review of twenty-one recent analyses of P flow, we attempt to evaluate the nature and magnitude of the key P flows and stocks at the city, regional, and country scales. This evaluation will be based on assessing the main inflows, outflows, stocks, internal flows, and recycling flows. Based on this evaluation, we attempt to identify the priority areas of P management at the city, regional, and country scales; and suggest some necessary policy and management initiatives in this regard. We also aim to identify the knowledge gaps in the available P flow analysis literature and discuss options of future research to develop new knowledge for making better P management decisions.

2. Methods of assessment

For this assessment, thirty-two recent analyses of P flow have been initially selected according to the following criteria:

- studies that used Substance or Material Flow Analysis (SFA/MFA) as a method for the quantitative assessment of P flow through a system;
- peer-reviewed articles written in English;
- published between 2005 and 2012;

- conducted at any of the geographical scales such as global, multiple country, country, regional, city;
- single or multiple years flow and
- considered single or multiple sectors or subsystems within the system.

A preliminary review of these studies revealed that quantitative information regarding the key P inflows, outflows, stocks, internal flows, and recycling flows were not identifiable in some studies, particularly at the global scale and scales smaller than the city. Therefore, such studies have been excluded from our assessment.

The majority of the studies that we considered for this review utilized 'SFA/MFA' which applies mass balance principles to assess the flows and stocks of a substance within a system defined in space and time (Voet, 2002; Brunner and Rechberger, 2004; Brunner, 2010) as the method for analyzing P flow. Although a few of the studies did not denote their method explicitly as SFA/MFA, they applied mass balance principles to quantify P flows and stocks consistent with this methodology and therefore, have been considered in this review.

In most studies, the analysis of P flow was limited to a particular year. In the case of multiple-year and historical analyses, we have considered the average P flow per annum and the most recent year P flow respectively for our review. In some studies, the agricultural production sector was differentiated into the crop and livestock production sectors. In our study, we use the term 'agricultural production sector' to mean both the crop and livestock production sectors unless further differentiation is made. In two studies (Ghani and Mahmood, 2011; Senthilkumar et al., 2012), several regions within a country were considered for the analysis of P flow, which in our assessment, have been categorized as the country scale analysis. Studies that analyzed P flow of only one region within a country, have been categorized as the regional scale analysis. To avoid the uncertainties that may originate from comparing data of different scope and methods used in various studies, we do not attempt to compare the quantitative information of P flow between different studies. We first attempt to generate qualitative information related to P flow by evaluating the quantitative information within each study. Then, by comparing the qualitative information of P flow between studies, we attempt to identify the key flows at different geographical scales.

In our review, P inflow means, the quantity of P that enters into a particular geographical scale or system in a given time through a particular medium. At the country scale, P flow as phosphate rock mining from the geological deposits has also been considered as inflow in this study. P outflow means, the amount of P that leaves a particular geographical scale or system in a given time through a particular medium. We considered P discharge to a water body as P outflow where we found the water body (stream, river, or lake) may extend beyond the boundary of the geographical scale under consideration or ultimately discharge its water outside the boundary of the geographical scale or at least, connected to another water body that extend beyond the boundary. P stock means, the amount of P that is stored in a component or sector within a particular geographical scale or system in a given time. Internal flow means, the amount of P that flows from one sector to another through a medium within a particular geographical scale or system in a given time. P recycling flow means, the amount of P that is recovered from waste and is recycled back to any sector within a particular geographical scale or system in a given time. Here, we considered 'sector' as a particular type of system that has some unique properties, and consists of a set of component or processes working together as parts of a complex process or an interconnecting network. For instance; mining, crop production, waste management, and streams and rivers all are different sectors.

3. Assessment outcomes regarding key P flows and stocks at different geographical scales

3.1. Key sectors of P flow

The outcome of any P flow analysis depends upon how the system under consideration is defined in terms of geographical scale and key sectors of P flow. As the availability and size of the key sectors for P flow vary from one geographical scale to another, the priority areas of P flow might be different at various geographical scales.

Based on the current review, Fig. 1 presents a holistic view of all the key sectors that are usually considered in P flow analyses at different geographical scales. At the city scale, human consumption and waste management are the two key sectors of P flow. Though the trade and commerce sector is quite important in terms of P flow at the city scale, it was usually omitted in the city scale studies, probably to reduce the complexity of P flow analysis. Agricultural production is the main sector at the regional scale, and the key difference between the city and regional scale lies in the presence of this sector. However, the small scale agricultural sector is sometimes found in some cities, and occasionally considered in the city scale analysis. The phosphorus fertilizer production sector is not usually found at the regional scale, and in some cases, at the country scale too, except for those in countries having high reserves of phosphate rock and/or P fertilizer production such as China and the US. The country scale is spatially far bigger than the city and regional scales, and usually includes the P mining and/or fertilizer production sectors, and a coastal water sector along with other key sectors that are contained in the city and regional scales (Fig. 1). The global and multiple country scales consider the sectors available at the country scale along with the sectors that extend beyond the country scale such as river systems, coastal waters and the ocean.

Fig. 1 provides a complete and contrasting picture of the different geographical scales along with their relevant sectors and intersectoral interactions. This analysis is, so far, missing from the available literature and may be utilized as a guide to choose the appropriate geographical scale for any P flow study. The selection of the proper geographical scale is important to ensure the inclusion or exclusion of any vital sector because the outcome of the P flow analysis often depends on this. For instance, the selection of only the city scale may exclude the agricultural production sector which is one of the vital sectors in terms of P flow, although this sector could be included if the regional scale is selected. Sectors such as coastal waters, P mining, and fertilizer production may not be present in some countries, thus, may be excluded in some country scale analyses, yet these sectors will become relevant for SFA across multiple countries or the global scale. It is therefore apparent that P flow analysis without informed choice of geographical scale will often exclude certain sectors, and may not provide the comprehensive information required to make policy decisions, which ultimately indicates the necessity of cross-scale or multi-scale analysis (Cordell et al., 2012). Fig. 1 also indicates that the city, regional, and country scales are nested and linked to each other. Analysis of P flow utilizing the linkages between different geographical scales could generate new knowledge required to achieve better P management. For instance, if P recovered from a waste stream at the city scale is utilized in the agricultural production sector at the regional scale, it will eventually reduce the P inflow as imported fertilizer at the country scale.

3.2. Key inflows and outflows

Understanding the key P inflows and outflows related to a particular geographical scale is vital to identify the priority areas of P management for that scale. Table 1 summarizes this information

Table 1
Nature and magnitude of the key P inflows and outflows through different systems at different geographical scales.

[1]Studies	Geographical scale		[3]Type of system	Year of flow	[4]Measuring unit	Inflow			Outflow		
	[2]Extent	Location				Total inflow	[5]Key flows (From–to)	% of total inflow	Total outflow	[6]Key flows (From–to)	[7]% of total outflow
Qi	Ci	Beijing, China	FoC	2008	kt/a	6.22	Fo (FoP–UrC): 5.37 Fo (FoP–RuC): 0.85	86 14	1.72	*UWw (UrC–Aq): 1* *TWw (STP–Aq): 0.39* *UWw (RuC–Aq): 0.33*	*58* *23* *19*
		Tianjin, China				4.18	Fo (FoP–UrC): 3.18 Fo (FoP–RuC): 0.99	76 24	1.51	*UWw (UrC–Aq): 0.63* *UWw (RuC–Aq): 0.45* *TWw (STP–Aq): 0.44*	*41* *30* *29*
Ba	Ci	Twin Cities, US	UrEc	2000	kt/a	4.07	Fo (IFo–C): 1.67 De (IDe–C): 1.37 Fe (IFe–Pets, LiP): 0.59	41 34 15	1.43	*Ww (Wm–O): 1.14*	*80*
Ne10	Ci	Linkoping, Sweden	FoC & San	2000	kg/cap*a	0.57	Fo (FoP–C): 0.57	100	0.562	*Waste (SlH–O): 0.512*	*92*
Me	Ci	Phoenix, Arizona, US	UrEc	2005	kt/a	7.98	Fo (IFo–C): 3.83 Fr (FrP–CrP, ReS): 1.9	48 24	0.056	No significant outflow reported	-
Ta	Ci	Sydney, Australia	UrEc	2000	kt/a	5.99	Fo (IFo–ITC): 2.09 Fe (IFe–ITC): 1.55 De (IDe–ITC): 1.24	35 26 21	2.91	*TWw (STP–CoW): 2.66*	*91*
Li	Re	Hefei City, China	An	2008	kt/a	7.81	Mo & Cr (IMo, ICr–InP, FdP): 3.7 Fr (IFr–CrP): 3.1	47 40	4.16	Fr (FrP–O): 2.4 *SoL (CrP–Aq): 1*	58 *24*
Yu-a	Re	Lujiang County, China	An	2008	kt/a	8.31	Mo (IMo–FrP): 5.7 Fe (IFe–LiP): 2.23	69 27	5.67	CrPr (CrP–O): 3.7 *Ww (LiP–Aq): 1.66*	65 *30*
Yu-b	Re	Chaohu City, China	An	2008	kt/a	8.52	Mo (IMo–FrP): 4.75 Fe (IFe–LiP): 1.81 Fr (IFr–CrP): 1.68	56 21 20	5.26	Fr (FrP–O): 3.34 CrPr & LiPr (CrP, LiP–O): 1.38	64 26
Wu	Re	Feixi, China	SoEc	2008	kt/a	19.15	Fe (IFe–LiP): 13.31 Fr (IFr–CrP): 3.75 Mo (IMo–InP): 1.9	70 20 10	15.6	*SoL (CrP–Aq): 5.33* *UWw (LiP–Aq): 4.93* Fo (LiP–O): 3.10	*34* *32* 20
Ne08	Re	Linkoping, Sweden	FoP & C	2000	kg/cap*a	2.095	Fr (IFr–CrP): 2.0	95	1.345	LiPr (LiP–O): 0.69 *Waste (Wm–O): 0.43*	51 *41*
Do	Re	Hanam, Vietnam	RuA	2008	kt/a	0.12	Fo & Fr (IFo, IFr–ITC): 0.109	91	0.065	Cr, LiPr (ITC–O): 0.024 *SoL (Cr–Soil/G): 0.014* *Ww (Wm–Aq): 0.014* *Waste (AqC–Soil): 0.013*	37 *21* *21* *20*
Ma	Co	China	An	1984–2008	kt/25 y	167,300	Mo (N–MiP): 154,500	92	129,000	*Waste (Wm–Aq, Soil): 124,300*	*96*
Su	Co	US	Fo	2007	kt/a	5616	Mo (N–MiP): 3773 Fe (Grazing–LiP): 748	67 13	4001	*Waste: 1671* Fr (InP–O): 1291 CrPr & LiPr (CrP, LiP–O): 435	*42* 32 11
Sm	Co	Netherlands	Ag, IP & Ho	2005	kt/a	108	Fe (IFe–FeP): 50.4 Fo (IFo–FoP): 28 Fr (IFr–CrP): 21	47 26 19	48	Fo (InP–O): 37.5 ExM (LiP–O): 7	78 15
Gh	Co	Malaysia	An	2007	kt/a	218	Mo (IMo–FrP): 162	75	254	*SoL (AgP–Env): 132* Fr (InP–O): 40 *Ww (Wm–Aq): 31*	*52* 16 *12*
Se	Co	Turkey	An	2001	kg/cap*a	4.33	Mo & Fr (IMo, IFr–ITC): 3.75	86	4.05	*Waste (La–Env): 1.33* *UWw (HoC–Env): 1.07* *SoL (AgP–Aq & Soil): 1*	*33* *26* *25*
Je	Co	South Korea	Dom	2005	kt/a	380	Mo (IMo–FrP): 179 Fr (IFr–AgP): 68.9 OMi (IMo–InP): 58.1	47 18 15	77	Fr (FrP–O): 72.9	95
Mat	Co	Japan	Dom	2002	kt/a	747.8	Fo (IFo–HuC): 173.52 OMi (IMo–InP): 156.50 ChS (ICh–InP): 155.92 Fr (IFr–FrP): 151.32 Mo (IMo–InP): 110.56	23 21 21 20 15	55.67	*SoL (AgP–Aq): 32.93* *Ww (HuC–Aq): 16.12*	*59* *29*

Ant	Co	Finland	Ag & Fo	1995–1999	kt/a	33.3	Fr (FrP–CrP, LiP): 29.5	89	6.2	Fo & Fe (Fo, FdP–O): 2.9 *SoL (CrP, LiP–Aq): 2.4* *TWw (STP–Aq): 0.7*	47 *39* *11*
Sen	Co	Centre, France Brittany, France	Ag	2002–2006	kg/h * a	17.1 38.8	Fr (IFr–Soil): 12.9 Fe (IFe–LiP): 28.9	75 75	16.2 21.1	CrPr (CrP–O): 13.4 LiPr (LiP–O): 12.3	83 58
Ot	MCo	EU	An	2006–2008	kg/cap * a	5.3	Mo & Fr (IMo, IFr–ITC): 4.1	77	1.433	Fr (ITC–O): 0.43 Fo & Fd (ITC–O): 0.33	30 23

[1] Ant: Antikainen et al., 2005; Ba: Baker, 2011; Do: Do-Thu et al., 2011; Gh: Ghani and Mahmood, 2011; Je: Jeong et al., 2009; Li: Li et al., 2010; Ma: Ma et al., 2012; Mat: Matsubae-Yokoyama et al., 2009; Me: Metson et al., 2012a; Ne08: Neset et al., 2008; Ne10: Neset et al., 2010; Ot: Ott and Rechberger, 2012; Qi: Qiao et al., 2011; Se: Seyhan, 2009; Sen: Senthilkumar et al., 2012; Sm: Smit et al., 2010; Su: Suh and Yee, 2011; Ta: Tangsubkul et al., 2005; Wu: Wu et al., 2012; Yu-a: Yuan et al., 2011a; Yu-b: Yuan et al., 2011b.

[2] Ci: City; Co: Country; MCo: Multiple country; Re: Regional.

[3] Ag: Agricultural; Ag & Fo: Agricultural and food; Ag, IP & Ho: Agricultural, industrial production and household; An: Anthropogenic; Dom: Domestic; Fo: Food; FoC: Food consumption; FoC & San: Food consumption and sanitation; FoP & C: Food production and consumption; RuA: Rural area; SoEc: Socio-economic; UrEc: Urban ecosystem.

[4] kt/a: kilotonne (1000 metric tonnes) per annum; kt/25 y: kilotonne per 25 years; kg/cap * a: kilogram per capita per annum; kg/ha * a: kilogram per hectare per annum.

[5,6] Flows less than 10% of the total inflow or outflow are not presented here. AgP: Agricultural (crop and livestock) production; Aq: Aquatic system; AqC: Aqua-culture; C: Consumption; ChS: Chemical substance; CoW: Coastal waters; Cr: Crop; CrP: Crop production; CrPr: Crop products; De: Detergent; Env: Environment; ExM: Exported manure; Fd: Fodder; FdP: Fodder production; Fe: Feed (pets or livestock); FeP: Feed production; Fo: Food; FoP: Food production; Fr: Fertilizer; FrP: Fertilizer production; G: Groundwater; HoC: Household consumption; HuC: Human consumption; ICh: Imported chemical; ICr: Imported crop; IDe: Imported detergent; IFe: Imported feed; IFo: Imported food; IFr: Imported fertilizer; IMo: Imported mineral ore; InP: Industrial production; ITC: Industry, trade and commerce; La: Landfill; LiP: Livestock production; LiPr: Livestock products; MiP: Mine production; Mo: Mineral ore; N: Nature (Mine); O: Outside the system; OMi: Other minerals; ReS: Residential soil; RuC: Rural consumption; SlH: Sludge handling; SoL: Soil losses (erosion, runoff and/or leaching); STP: Sewage treatment plant; TWw: Treated wastewater; UrC: Urban consumption; UWw: Untreated wastewater; Waste: Solid and liquid waste; Wm: Waste management; Ww: Wastewater.

[6,7] Italic marked texts and numbers indicate various types of unproductive outflows of P.

for the selected P flow analyses with regard to the geographical and temporal scales, type of systems, total inflow, total outflow, key inflows and outflows, and the type of sectors receiving the inflows and releasing the outflows. We illustrate two typical cases of a city and a country scale analysis below (from Table 1) and further information can be obtained for the remaining nineteen studies by the careful use of the list of abbreviations provided at the bottom of the Table 1.

Tangsubkul et al. (2005) reported a city scale study in which P flow through the Urban Ecosystem (UrEc) of Sydney (Australia) was analyzed for the year 2000. The analysis revealed that, the total inflow was 5.99 kt (kilotonnes) P, with a total outflow of 2.91 kt. The balance of 3.08 kt P was stored in different sectors within the system (P stocks will be discussed separately in Section 3.3.1). The three key inflows were human food (2.09 kt P or 35% of the total inflow), animal feed (1.55 kt P or 26% of the total inflow), and detergent (1.24 kt P or 21% of the total inflow) as imported products from outside of Sydney to the commerce sector. Most of this imported P was consumed in the household sector, which ultimately resulted in a large discharge (2.66 kt P) as treated wastewater to coastal water. Thus, about 91% of the total outflow occurred because P recovery from wastewater was entirely absent in Sydney. Their study suggested that better P management in Sydney could be achieved by incorporating P recovery options to wastewater management on the outflows or by using P free detergents for the inflows.

Jeong et al. (2009) conducted a country scale analysis in which the domestic P flow of South Korea was analyzed for the year 2005. The total P inflow in South Korea was about 380 kt, while the total outflow was about 77 kt. The balance of the P which is about 303 kt, was stored in various sectors within the system. The key P inflow was imported mineral ore (179 kt or 47% of the total inflow) to the fertilizer production sector, while the main outflow (72.9 kt or 95% of the total outflow) occurred as P fertilizer export to other countries. The majority (about 80%) of the P that entered in South Korea in 2005, remained within the system either as soil stock in the crop and livestock production sectors, products and by-products of chemical and other industries, or wastes in landfills and steel-making slags. Their study recommended that P recovery from steel making slags could be one of the best P management options for South Korea.

3.2.1. *Key inflows*

A comparative view of the magnitude of the key P inflows at different geographical scales has been presented in Fig. 2. The main P inflow at the city scale occurs through imported food to the human consumption sector, and this has been concluded for each of the five city scale analyses we reviewed. In two city scale studies, one that analyzed P flow through the food consumption system in Beijing (China) for 2008 (Qiao et al., 2011) and another that analyzed P flow through the food consumption and sanitation system in Linkoping (Sweden) for the year 2000 (Neset et al., 2010), food has been identified to account for nearly 100% of the total P inflow (Fig. 2A). In some of the city scale studies, either chemical P fertilizer, animal feed, or detergent has been observed to be one of the key P inflows after food however, these flows account for less than 35% of the total inflow. This indicates that all aspects of food consumption and wastage should be considered when forming any city scale P management decision because, even though the opportunity for changes such as reducing food spoilage may be limited in percentage terms, they can potentially operate on a large base.

At the regional scale, the major P inflow has been identified to occur either as fertilizer, mineral ore, or animal feed (Fig. 2B). For instance, in another study of Linkoping (Sweden) which considered the food production sector along with the food consumption sector for the analysis of P flow for 2000, about 95% (2 kg per capita) of the total inflow has been found to occur through chemical P

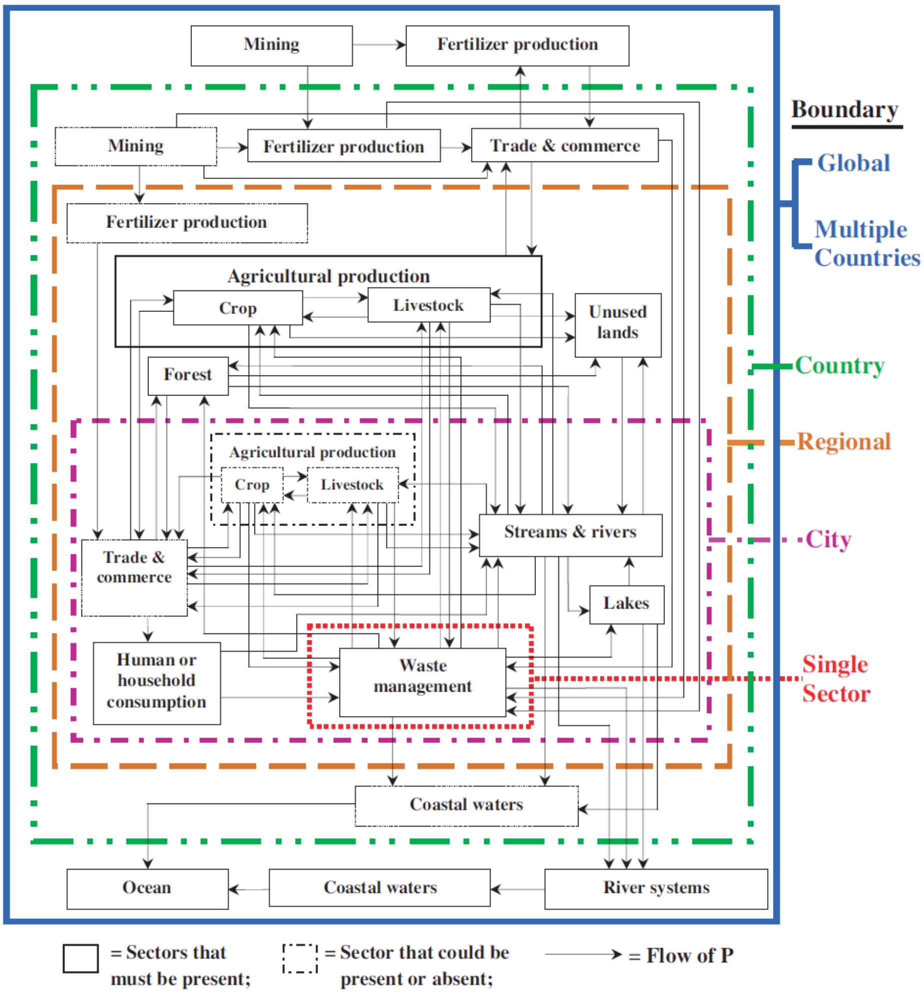

Fig. 1. Key sectors of P flow across different geographical scales, and the intersectoral interactions in terms of P flow.

fertilizer import (Neset et al., 2008). In contrast, in the P flow analyses through the anthropogenic system by Yuan et al. (2011a,b) in two different regions of China, P inflow as mineral ore import has been observed to account for respectively about 69% (5.7 kt) and 56% (4.75 kt) of the total inflow in 2008. In another regional scale study by Wu et al. (2012) that analyzed P flow through the socio-economic system in Feixi County (China), animal feed has been identified as the main inflow, where it accounts for about 70% (13.31 kt P) of the total inflow in 2008. It can be concluded that in the absence of P fertilizer production industry, the major P inflow at the regional scale occurs either through the import of chemical P fertilizer or animal feed, and with its presence, the main P inflow usually occurs as mineral ore import.

In most of the country scale studies presented in Fig. 2C, either mineral ore or chemical P fertilizer import has been observed to be the key P inflow. In the analyses of P flow through the anthropogenic system of China for 1984–2008 (Ma et al., 2012), of Malaysia for 2007 (Ghani and Mahmood, 2011), through the food system of the US for 2007 (Suh and Yee, 2011), and through the domestic system of Korea for 2005 (Jeong et al., 2009); P mineral ore has been identified to account for respectively about 92% (154,500 kt/25 years), 75% (162 kt), 67% (3773 kt), and 47% (179 kt) of the total inflow. Import of P as chemical fertilizer is another main inflow at the country scale particularly in the countries with low reserves of phosphate rock. For instance, in the study by Antikainen et al. (2005) regarding the analysis of P flow through the agriculture and food system of Finland, P import as chemical fertilizer has been identified to account for about 89% (29.5 kt) of the total annual P inflow between 1995 and 1999, while the case study by Seyhan (2009) identified, in Turkey, P mineral ore and chemical fertilizer together accounts for about 86% (3.75 kg/cap) of the total inflow in 2001. Both these countries lack adequate phosphate rock reserves to meet their domestic P demand and thus, rely on P import as chemical fertilizer from other countries. Apart from mineral ore and chemical fertilizer import, significant P inflow in the country scale can also occur either through the import of animal feed which has been identified to be 47% (50.4 kt) of the total inflow in the Netherlands in 2005 (Smit et al., 2010) or human food which accounts for about 23% (173.52 kt) of the total inflow in Japan in 2002 (Matsubae-Yokoyama et al., 2009).

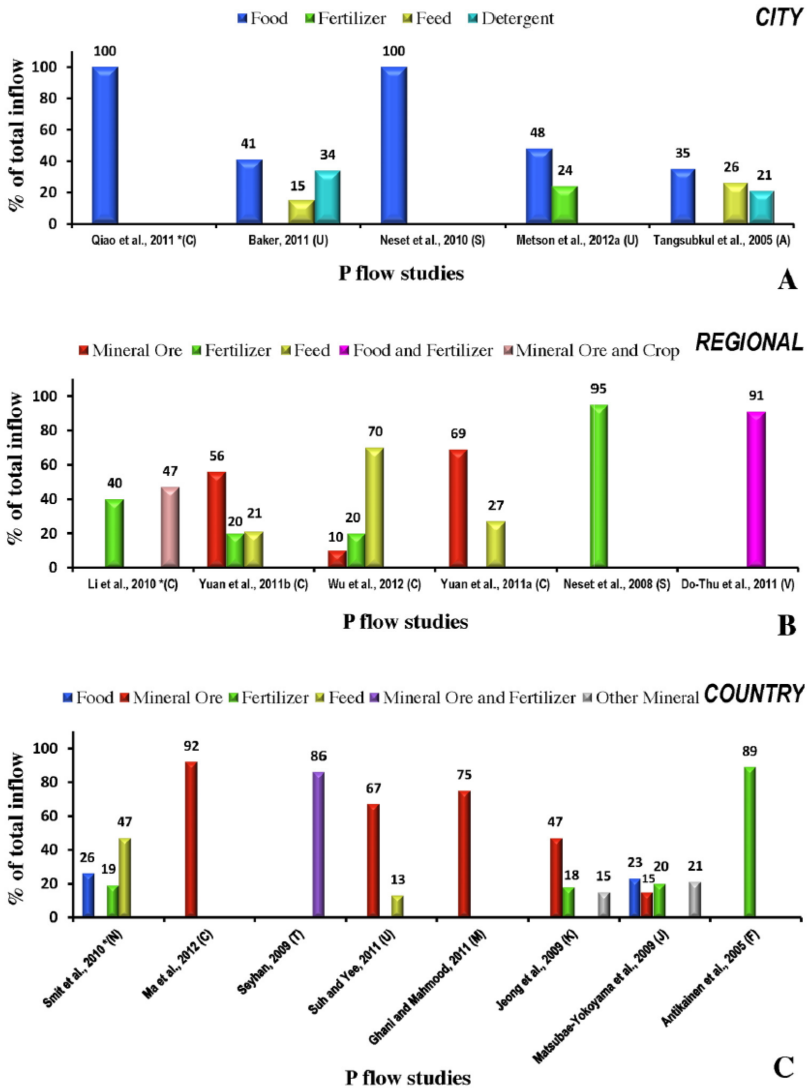

Fig. 2. Key inflows of P at the (A) city, (B) regional, and (C) country scales. Flows less than 10% of the total inflow are not presented here. Details of the studies are presented in Table 1. *( ): country of study indicated by the letter within the brackets in the horizontal axis - A: Australia; C: China; F: Finland; J: Japan; K: South Korea; M: Malaysia; N: Netherlands; S: Sweden; T: Turkey; U: US; V: Vietnam.

Our assessment has revealed, the main inflow of P occurs as human food at the city scale, either as chemical P fertilizer or animal feed at the regional scale, and either as mineral ore, chemical P fertilizer, animal feed, or human food at the country scale. Thus, future P management decision should focus on reducing P input through these materials. Strategies such as shifting human diet from meat to plant based (Tangsubkul et al., 2005; Cordell et al., 2009; Metson et al., 2012b) and red to white meats (Suh and Yee, 2011; Vaccari, 2011b); changing animal diet from high P containing feed to low P feed (Smit et al., 2010; Van Vuuren et al., 2010; Wu et al., 2012); and using recycled P from the waste stream to replace chemical fertilizer in crop production (Li et al., 2010; Van Vuuren et al., 2010; Ma et al., 2012) can minimize P inflow. Metson et al. (2012b) calculated, if the demand of protein in human diet could be met by substituting meat with pulses, the global average per capita P input would reduce about 20% of the 2007 level by 2050. Minimizing P inflows at different geographical scales can lower the extraction rate of phosphate rocks, and thus, can help to sustain available global P reserves for longer time and defer the onset of the global P crisis.

3.2.2. Key outflows

Fig. 3 provides a comparative picture of the magnitude of the key P outflows at different geographical scales. In three of the four city scale analyses as presented in Fig. 3A, wastewater has been observed to account for around 90% of the total P outflow. Wastewater has been found to be about 100% (1.72 kt or 28% of the total inflow), 91% (2.66 kt or 44% of the total inflow), and 80% (1.14 kt or 28% of the total inflow) of the total outflow respectively in Beijing (China) in 2008 (Qiao et al., 2011), Sydney (Australia) in 2005 (Tangsubkul et al., 2005), and Twin Cities (US) in 2000 (Baker,

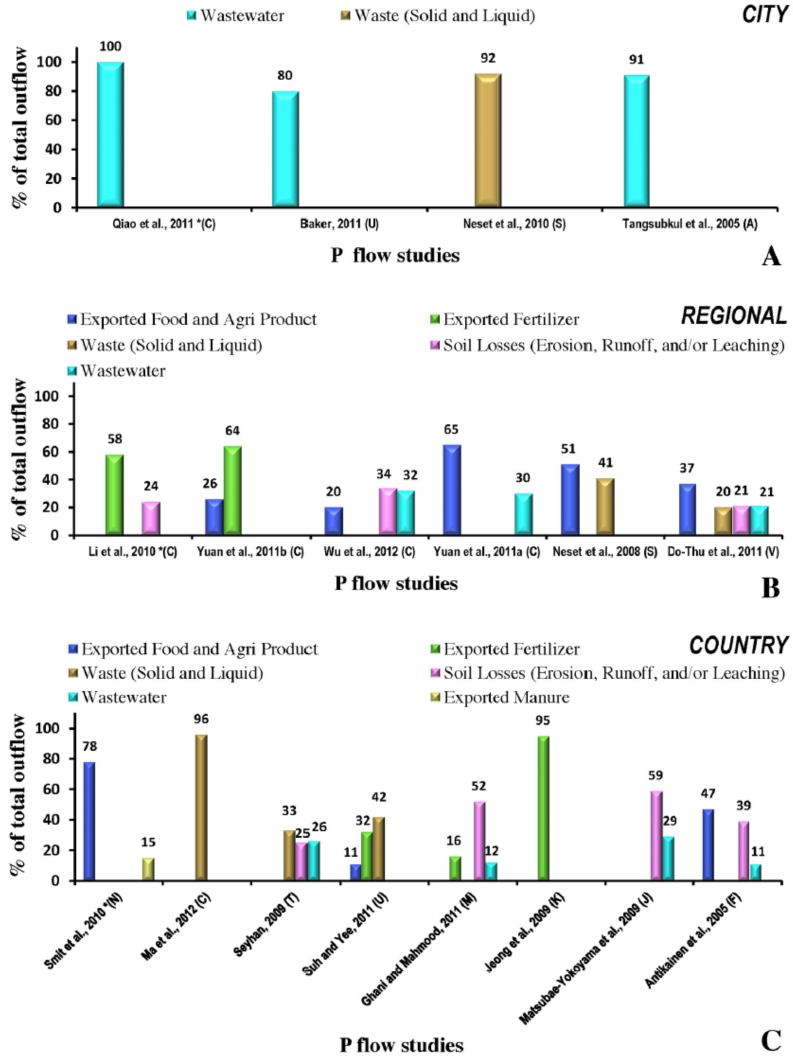

Fig. 3. Key outflows of P at the (A) city, (B) regional, and (C) country scales. Flows less than 10% of the total outflow are not presented here. Details of the studies are presented in Table 1. *( ): country of study indicated by the letter within the brackets in the horizontal axis - A: Australia; C: China; F: Finland; J: Japan; K: South Korea; M: Malaysia; N: Netherlands; S: Sweden; T: Turkey; U: US; V: Vietnam.

2011). P outflow as wastewater to water bodies is an unproductive outflow as this potentially soluble nutrient is lost to producers of agricultural commodities or other end users, and may also lead to the eutrophication of receiving waters. So, it is apparent that the wastewater sector is very important in terms of P outflow at the city scale, and to achieve better P management at this scale, greater emphasis should be given to the recovery and recycling of P from wastewater.

At the regional scale, the main outflow of P has been observed to occur either through exported chemical P fertilizer or food and agricultural products (Fig. 3B). Key outflows as exported chemical P fertilizer occur in regions having the P fertilizer production sectors which are usually found in countries with high reserves of phosphate rocks such as China. Thus, chemical P fertilizer export has been found to be the main P outflow in two regional scale studies (Li et al., 2010; Yuan et al., 2011b) of China, where it accounts for more than 50% of the total outflow in both cases. But in most other studies, P outflow at the regional scale occurs through the export of food and agricultural products, where it has been identified as about 65% (3.7 kt or 45% of the total inflow) and 51% (0.69 kg/cap or 33% of the total inflow) of the total outflow respectively in Lujiang County (China) in 2008 (Yuan et al., 2011a) and in Lingkoping (Sweden) in 2000 (Neset et al., 2008). Among the other P outflows at the regional scale, either waste (both solid and liquid), wastewater, or soil losses (erosion, runoff, and/or leaching) has been identified to be quite significant. Most of these outflows are unproductive and harmful to the environment. Soil losses (erosion, runoff, and/or leaching) has been found to be the main outflow in the case of Feixi County

(China), where it accounts for about 34% of the total outflow (5.33 kt or 28% of the total inflow) in 2008 (Wu et al., 2012) . In contrast, waste has been identified to be the second main outflow in Linkoping (Sweden) in 2000, where it accounts for about 41% (0.43 kg/cap or 21% of the total inflow) of the total outflow (Neset et al., 2008).

At the country scale, the nature and magnitude of the key P outflows have been observed to vary from one country to another. In three of the eight reviewed country scale analyses, waste (both solid and liquid) has been found to be the main outflow. For instance, waste accounts for about 96% (124,300 kt/25 years, or 74% of the total inflow) and 42% (1671 kt or 30% of the total inflow) of the total P outflow in the analysis by Ma et al. (2012) of China for 1984–2008 and Suh and Yee (2011) of US for 2007 respectively (Fig. 3C). In some studies, exported food and agricultural products has been identified to be the main P outflow, where it accounts for about 78% (37.5 kt or 35% of the total inflow) and 47% (2.9 kt or 9% of the total inflow) of the total annual outflow respectively in the Netherlands in 2005 (Smit et al., 2010) and in Finland between 1995 and 1999 (Antikainen et al., 2005). In another country scale study by Jeong et al. (2009) that analyzed domestic P flow in South Korea for the year 2005, exported fertilizer has been observed to occupy about 95% (72.9 kt or 19% of the total inflow) of the total outflow. Again, in some studies at this scale, P outflow as soil losses (erosion, runoff, and/or leaching) has been found to be quite significant, where it accounts for about 59% (32.9 kt or only 4% of the total inflow), 52% (132 kt or 61% of the total inflow), and 39% (2.4 kt or 7% of the total inflow) of the total annual outflow respectively in Japan in 2002 (Matsubae-Yokoyama et al., 2009), in Malaysia in 2007 (Ghani and Mahmood, 2011), and in Finland between 1995 and 1999 (Antikainen et al., 2005).

Assessment of the key P outflows at different geographical scales as presented in Table 1 and Fig. 3 revealed that a significant quantity of P leaves the system as unproductive outflows, which is as wastewater at the city scale, and either as soil losses (erosion, runoff, and/or leaching), waste, or wastewater at the regional and country scales. The majority of these outflows ultimately find their ways to surface water bodies. A number of studies (Correll, 1998; Daniel et al., 1998; Hiscock et al., 2003; Carpenter, 2005, 2008; Garnier et al., 2005; Davis and Koop, 2006; Jarvie et al., 2006; Torrent et al., 2007; Withers and Haygarth, 2007; Bowes et al., 2008; Chen et al., 2008; Schindler et al., 2008; Boesch et al., 2009; Conley et al., 2009a,b; HELCOM, 2009; Smith and Schindler, 2009; Xu et al., 2010; Murphy et al., 2011; Conley, 2012) from different parts of the world have reported that P discharge to water bodies makes a significant contribution to algal blooms, hypoxia, or eutrophication, and the reduction of P discharge to water bodies can substantially restrict these problems. The excessive outflows of P to water bodies not only causes water pollution but also results in scarcity of the P resource. Therefore, focusing on the major unproductive outflows as identified in the current assessment, future P management decisions at different geographical scales should incorporate adequate measures to achieve increased recovery and recycling of P to ensure reduced discharge to water bodies. The paper of Cordell et al. (2011) which presents an integrated system framework to evaluate the full range of sustainable P recovery and reuse options, starting from small-scale low-cost to large-scale high-tech options, provides some useful guidelines in this regard.

3.3. Key stocks, internal flows and recycling flows

Table 2 represents our review of findings related to the key P stocks, internal flows, and recycling flows at various geographical scales. To illustrate the information in Table 2, the details of three studies at three different scales are presented here:

Qiao et al. (2011) reported a city scale study that analyzed P flow through the food consumption system in two major cities (Beijing and Tianjin) of China for the year 2008. The analysis revealed, in Beijing, about 72% (4.5 kt) of the total inflow of P was stored within the system, and the majority of this P (2.94 kt or 47% of the total inflow) was stored in landfills. Phosphorus flow as wastewater (3.86 kt or 62% of the total inflow) from the urban consumption sector to the sewage treatment plant was the main internal flow of P in that city. The study also identified that a significant amount of about 1.01 kt P (16% of the total inflow) was recycled as organic fertilizer from the waste management sector to the agricultural (food) production sector in Beijing.

Wu et al. (2012) analyzed P flow through the socio-economic system of Feixi County in China for 2008. They identified, about 19% (3.70 kt) of the total amount of P that entered Feixi in 2008 was stored within the system, particularly, in the soil of the crop production sector. P flow as livestock excreta (5.25 kt or 27% of the total inflow) from the livestock production sector to the crop production sector was the main internal flow. Again, 6 kt P which is about 31% of the total inflow was recycled as manure from the livestock production sector to the crop production sector, while a small amount of about 0.54 kt P (only 3% of the total inflow) was recycled as organic fertilizer (mainly human excreta) from the rural consumption sector to the crop production sector.

Antikainen et al. (2005) reported a country scale study in which annual P flow through the Finnish agriculture and food system was analyzed for the period of 1995–1999. This study revealed that, about 81% (27.1 kt) of the total annual inflow of P was stored within the system, and the majority of this (about 23.7 kt) was retained in the soil of the agricultural production sector. P flow as chemical fertilizer (29.5 kt or 89% of the total annual inflow) from the industrial production sector to the agricultural production sector was the main annual internal flow. About 15.9 kt P (48% of the total annual inflow) and 6.2 kt P (19% of the total annual inflow) were recycled back to the food and agricultural system respectively as manure from the livestock production sector to the crop production sector and as recycled feed from the food processing sector to the livestock production sector. Similar illustrations can be given for the key findings of all other P flow analyses presented in Table 2.

3.3.1. Key stocks

Our review revealed, at all the three scales (city, regional, and country), a substantial proportion of the total quantity of P that entered into the system, is retained within the system as stocks (Fig. 4).

In all the city scale analyses as shown in Fig. 4A, more than 50% of the total inflow of P has been found to be stored within the system. Landfill has been identified to be the key place of P stock at this scale, where it accounts for the storage of about 47% (2.94 kt), 43% (1.76 kt), and 14% (0.81 kt) of the total inflow of P respectively in Beijing (China) in 2008 (Qiao et al., 2011), in Twin cities (US) in 2000 (Baker, 2011), and in Sydney (Australia) in 2000 (Tangsubkul et al., 2005). However, in the case of Sydney, about 31% (1.88 kt P) of the total inflow of P has been found to be stored within the soil of the agricultural production sector. The latter is due to the inclusion of the agricultural sector within the system boundary, which is usually overlooked in the studies at this scale. Our review indicates, the recovery of P from waste streams prior to landfill, as well as the secondary recovery of P from available landfill wastes, and the utilization in crop production can substantially reduce the input of chemical P fertilizer.

In all the reviewed regional scale studies, a considerable proportion (about one third) of the total inflow of P has been observed to be retained within the system (Fig. 4B). In majority of the studies at this scale, the soil of the crop production sector has been found to be the main place of P stock. For instance, in 2008, about 19% (3.66 kt) and 31% (2.60 kt) of the total inflow of P respectively in

Table 2
Nature and magnitude of the key P stocks, internal flows, and recycling flows through different systems at different geographical scales.

[1]Studies	Geographical scale		[3]Type of system	Year of flow	[4]Measuring unit	Total inflow	Stock				[6]Key internal flow (From–to)	Recycling flow	
	[2]Extent	Location					Sum of all stocks	% of total inflow	[5]Key stocks (From–to)	% of total inflow		[7]Key flows (From–To)	% of total inflow
Qi	Ci	Beijing, China	FoC	2008	kt/a	6.22	4.50	72	La: 2.94 AgP (soil): 1.01	47 16	Ww (UrC–STP): 3.86	OFr (Wm–AgP): 1.01 ReW (Wm–UrL): 0.54	16 9
		Tianjin, China				4.18	2.67	64	La: 1.8 AgP (soil): 0.86	43 21	Ww (UrC–STP): 2.24	OFr (Wm–AgP): 0.86	21
Ba	Ci	Twin Cities, US	UrEc	2000	kt/a	4.07	2.64	65	La: 1.76 EcoStor (Soil): 0.66	43 16	Sl (UrC–Wm): 1.46	Fe (Wm–LiP): 0.03 OFr (Wm–AgP): 0.02	0.7 0.5
Ne10	Ci	Linkoping, Sweden	FoC& San	2000	kg/cap * a	0.57	0.008	1.5	SeTP: 0.003	0.5	Sl (SeTP–SH): 0.55	OFr (Wm–AgP): 0.033	6
Ta	Ci	Sydney, Australia	UrEc	2000	kt/a	5.99	3.08	51	AgP (Soil): 1.88 La: 0.81	31 14	Ww (HoC–STP): 3.45	OFr (Wm–AgP): 1.33 Man (AgP–AgP): 1.08	23 18
Li	Re	Hefei City, China	An	2008	kt/a	7.81	3.66	47	CrP (Soil): 2 La: 0.7	26 9	Fe & Fr (InP–LiP): 1.2	Man (LiP–CrP): 0.5 OFr (RuC–CrP): 0.21	6 3
Yu-a	Re	Lujiang County, China	An	2008	kt/a	8.31	2.65	32	CrP (Soil): 2.6	31	Fr (InP–CrP): 5.6	Man (LiP–CrP): 2.3 RSt (CrP–CrP): 1.07 OFr (RuC–CrP): 0.73	28 13 9
Yu-b	Re	Chaohu City, China	An	2008	kt/a	8.52	3.25	38	AgP (Soil): 2.48	29	Fr (InP–CrP): 1.35	Man (LiP–CrP): 1.05 OFr (RuC–CrP): 0.44	12 5
Wu	Re	Feixi, China	SoEc	2008	kt/a	19.15	3.70	19	CrP (Soil): 3.66	19	LiEx (LiP–CrP): 5.25	Man (LiP–CrP): 6.01 OFr (RuC–CrP): 0.54	31 3
Ne08	Re	Linkoping, Sweden	FoP & C	2000	kg/cap * a	2.095	0.75	36	CrP (Soil): 0.72	34	Fe (CrP–LiP): 3	Man (LiP–CrP): 1.8 OFr (Wm–CrP): 0.12	86 6
Do	Re	Hanam, Vietnam	RuA	2008	kt/a	0.12	0.055	46	La: 0.021 CrP (Soil): 0.018	17 15	Fe (ITC–LiP): 0.044	Man (LiP–CrP): 0.011	9
Ma	Co	China	An	1984–2008	kt/25 y	167,300	43,000	26	AgP (Soil): 38,300	23	Waste (C–Wm): 138,300	OFr (Wm–AgP): 78,700	47
Su	Co	US	Fo	2007	kt/a	5616	1615	29	LiP (Pasture): 943 CrP (Soil): 672	17 12	Mo (MiP–InP): 3771	Man (LiP–CrP): 422 Fe (FoPr–LiP): 121	8 2
Sm	Co	Netherlands	Ag, Ip & Ho	2005	kt/a	108	60	56	AgP (Soil): 31.4	29	Fe (InP–LiP): 44.4	Man (LiP–CrP): 54.8	51
Gh	Co	Malaysia	An	2007	kt/a	218	–	–	–	–	De (InP–HoC): 129	No recycling reported	–
Se	Co	Turkey	An	2001	kg/cap * a	4.33	0.28	7	La: 0.21	5	CrPr (AgP–ITC): 1.8	No recycling reported	–
Je	Co	South Korea	Dom	2005	kt/a	380	303	80	AgP (Soil): 125 Pr/by-Pr: 70.2 Sw (La): 52 Slag: 35.7	33 23 14 9	Fr (InP–AgP): 163	Man (LiP–CrP): 36 OFr (Wm–AgP): 8.5	9 2
Mat	Co	Japan	Dom	2002	kt/a	747.8	692.1	93	AgP (Soil): 376 Slag: 93.1 La: 91.7	54 14 13	Fr (InP–AgP): 400.5	Man (LiP–CrP): 145.2	19
Ant	Co	Finland	Ag & Fo	1995–1999	kt/a	33.3	27.1	81	AgP (Soil): 23.7	71	Fr (InP–AgP): 29.5	Man (LiP–CrP): 15.9 Fe (FoPr–LiP): 6.2	48 19
Sen	Co	Centre, France	Ag	2002–2006	kg/h * a	17.1	0.9	5	CrP (Soil): 0.9	5	P uptake (Soil–Crop): 20.2	RSt (CrP–Soil): 4 Man (Li–Soil): 4.2	23 25
		Brittany, France				38.8	17.7	46	LiP (Soil): 17.1	44	LiEx (LiP–Soil): 29.1	Man (Li–Soil): 29.1	75
Ot	MCo	EU	An	2006–2008	kg/cap * a	5.3	4.13	73	AgP (Soil): 2.9 Wm: 1.4	55 26	Fr (ITC–AgP): 2.7	OFr (Wm–AgP): 0.76	14

[1,2,3,4]Details are same as stated for Table 1.
[5,6,7]AgP: Agricultural (crop and livestock) production; C: Consumption; CrP: Crop production; CrPr: Crop products; De: Detergent; Fe: Feed (livestock); FoPr: Food processing; Fr: Fertilizer; EcoStor: Ecosystem storage; HoC: Household consumption; InP: Industrial production; ITC: Industry, trade and commerce; La: Landfill; Li: Livestock; LiEx: Livestock excreta; LiP: Livestock production; Man: Manure; MiP: Mine production; Mo: Mineral ore; OFr: Organic fertilizer; Pr/by-Pr: Products/by-products; ReW: Reclaimed water; RSt: Recycled straw; RuC: Rural consumption; SeTP: Secondary treatment plant; SH: Sludge handling; Slag: Steelmaking slag; Sl: Sludge; STP: Sewage treatment plant; Sw: Solid waste; UrC: Urban consumption; UrL: Urban landscape; Waste: Solid and liquid waste; Wm: Waste management; Ww: Wastewater.

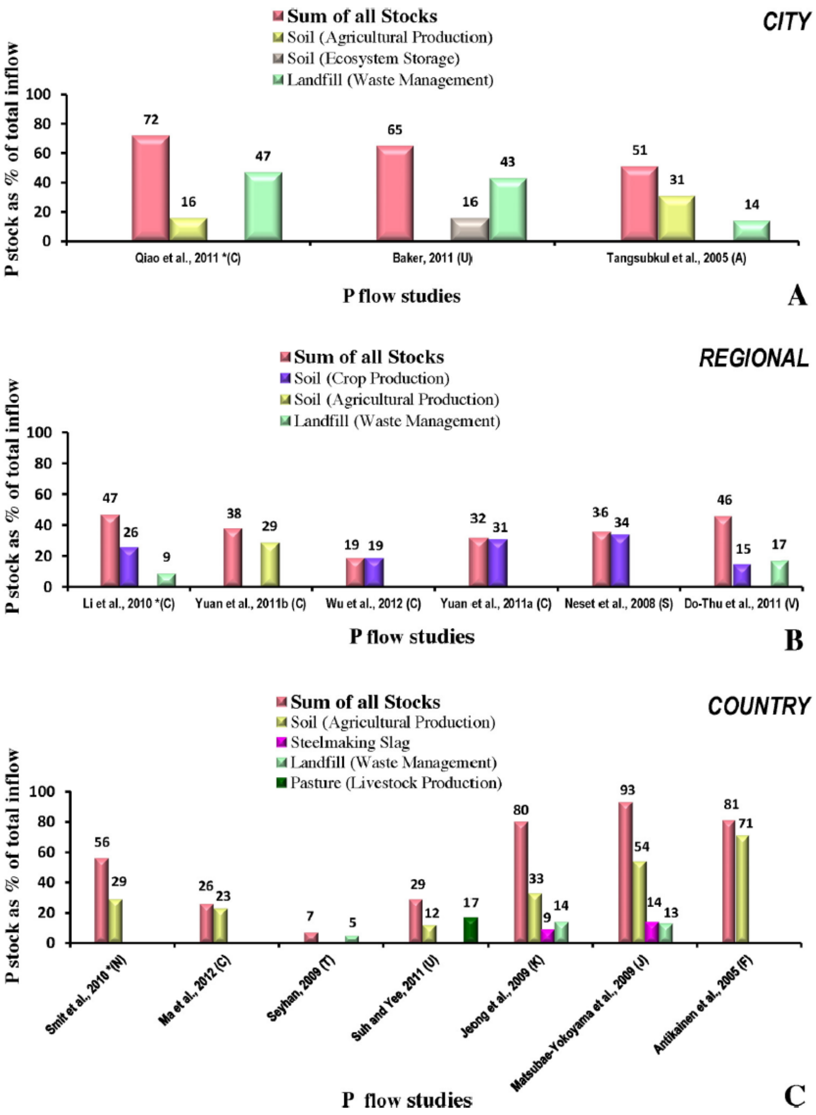

Fig. 4. Key places or components of P stock at the (A) city, (B) regional, and (C) country scales. In most of the regional scale studies, the agricultural production sector was differentiated into the crop and livestock production sectors. Details of the studies are available in Table 2. *( ): country of study indicated by the letter within the brackets in the horizontal axis - A: Australia; C: China; F: Finland; J: Japan; K: South Korea; N: Netherlands; S: Sweden; T: Turkey; U: US; V: Vietnam.

Feixi (Wu et al., 2012) and Lujiang County (Yuan et al., 2011a) of China was stored within the soil of the crop production sector.

In three of the seven reviewed country scale analyses as presented in Fig. 4C, almost 80% of the total inflow of P has been found to be retained within the system. The current assessment has revealed, the soil of the agricultural production sector stores a great proportion of the total P inflow at the country scale. For instance, about 71% (23.7 kt), 54% (376 kt), and 33% (125 kt) of the total annual inflow of P were eventually retained within the soil of the agricultural production sector respectively in Finland between 1995 and 1999 (Antikainen et al., 2005), in Japan in 2002 (Matsubae-Yokoyama et al., 2009), and in Korea in 2005 (Jeong et al., 2009). In most other country scale studies, agricultural soils have been found to be the key place of P stock within the system.

It is apparent that at both the regional and country scales in different parts of the world, every year, a significant proportion of the total inflow of P is retained within the soil of either the crop or agricultural (both crop and livestock) production sector. Accumulation of P in this manner over a number of years can result in the presence of excessive P in the agricultural soil. In most of the traditional agricultural management systems in many countries, P fertilizer is applied to the land without assessing the initial soil P status, which ultimately results in the application of more P than plants require. It also increases the risk of P outflow as soil erosion, leaching, or as particulate or dissolved P in runoff water. Moreover, it increases the farm's financial outlay for fertilizer. Thus, before deciding on any P fertilizer strategy for an agricultural farm, it is advisable to test the soil P status to avoid over fertilization (GRDC, 2012). Utilization of the available soil P stocks for crop production can reduce the demand of chemical P fertilizer input, which ultimately helps to reduce the resource scarcity problem. Therefore, we suggest, future P management decisions at the regional and country scales should put greater focus on assessing the P stock in the soil of the agricultural production sector. Manipulation of plant species for greater P uptake and internal P use efficiency could also help to realize this goal.

3.3.2. Key recycling flows

The type and magnitude of the key P recycling flows at a particular geographical scale can be viewed as an indicator of the P management status of that scale. Greater recovery and recycling in a system means the system is more efficient in terms of P management. The assessment of the key P recycling flows at different geographical scales as presented in Fig. 5 reveals that in most of the reviewed studies, recycling flows have been identified to account for only a small proportion of the total P inflow.

In only one (Tangsubkul et al., 2005) of the four reviewed city scale analyses, does total P recycling flow approach 50% of the total inflow (Fig. 5A), while it accounts for only 1% (0.05 kt P), 6% (0.033 kt P), and 25% (1.55 kt P) of the total inflow respectively in the studies of Baker (2011), Neset et al. (2010), and Qiao et al. (2011). Organic fertilizer from the waste management sector to the agricultural production sector has been identified to be the main P recycling flow in almost all the studies at this scale, where it has been observed to occupy about 23% (1.33 kt) and 16% (1.01 kt) of the total P inflow respectively in the analysis by Tangsubkul et al. (2005) of Sydney for 2000 and Qiao et al. (2011) of Beijing for 2008.

The majority of the P recycling flow at the regional scale has been identified to occur as manure from the livestock production sector to the crop production sector, where it accounts for about 86% (1.8 kg/cap), 31% (6 kt), and 28% (2.3 kt) of the total inflow of P respectively in Linkoping (Sweden) in 2000 (Neset et al., 2008), in Feixi (China) in 2008 (Wu et al., 2012), and in Lujiang county (China) in 2008 (Yuan et al., 2011a). In other reviewed studies (Li et al., 2010; Do-Thu et al., 2011; Yuan et al., 2011b) at this scale, total recycling of P has been found to occupy less than 20% of the total inflow. P recycling as organic fertilizer (mainly human excreta) from the waste management sector to the agricultural production sector has been identified to be the second main recycling flow at this scale, where it accounts for less than 10% of the total inflow in all the studies (Fig. 5B).

In five of the eight reviewed country scale analyses as presented in Fig. 5C, total recycling of P has been observed to account for less than 20% of the total inflow, where recycling of P has been found to be entirely absent in the P flow analyses by Seyhan (2009) of Turkey for the year 2001 and by Ghani and Mahmood (2011) of Malaysia for 2007. In three other studies (Antikainen et al., 2005; Smit et al., 2010; Ma et al., 2012), total recycling of P has been found to be nearly or more than 50% of the total inflow. Manure from the livestock production sector to the crop production sector has been identified to be the key recycling flow in two studies, where it accounts for about 51% (54.8 kt) and 48% (15.9 kt) of the total annual inflow respectively in the Netherlands in 2005 (Smit et al., 2010) and in Finland between 1995 and 1999 (Antikainen et al., 2005). At this scale, P recycling flow as organic fertilizer from the waste management sector to the agricultural production sector has been found only in the analysis by Ma et al. (2012) of China for 1984–2008, where it occupies about 47% (78,700 kt/25 y) of the total inflow.

Our review has revealed, the magnitude of P recycling flow was quite low in most of the cases at different geographical scales, and even in some cases, P recycling was entirely absent. This indicates, there is a potential scope for improving P management through increased recycling at all the geographical scales. Use of recycled P in the agricultural production sector in a country can reduce the needs of P fertilizer import from other countries. For instance, Metson et al. (2012c) identified, in Maricopa County of Phoenix (US), that a 'closed' loop system could be developed using dairy manure to fertilize alfalfa, and feeding alfalfa to dairy cattle. This system decreased P demand by about 50% between 1978 and 2008, through increased internal recycling, and reduced P export in harvested products. Increased P recycling can also be achieved by utilizing human excreta in crop production; producing composts from food or vegetable wastes, garden wastes, sludge or other biodegradable fraction of municipal solid wastes, and utilizing these for agricultural production; and using P containing recycled wastewater for irrigation.

4. Knowledge gaps and recommendations for future research

Along with the identification of priority areas of P flow at different geographical scales, this study has identified knowledge gaps in the available analyses of P flow, and recommended areas for future research. Among all the geographical scales, the regional and the multiple country scales have been the least studied. The regional scale is much more important in terms of P flow because this scale intimately considers the agricultural (both crop and livestock) production sector, which in our assessment, has been identified to be the most crucial sector in terms of P flow and stock. Usually, the majority of the P that enters as mineral ore or chemical fertilizer into a country is utilized in the agricultural sector. Again, most of the P stock resides in the soil of this sector, and the majority of the P outflow occurs either as food and agricultural products, or soil losses (erosion, runoff, and/or leaching) from this sector. Thus, the regional scale which closely considers this sector should receive more attention in the future analysis of P flow. Focus should also be given on the multiple country scale studies because P flow analysis at this scale can divulge important insights particularly where there are large river systems such as the Mekong or Ganges, and where there are large international exports of human food and animal feed such as occurs from the Mekong Delta.

We have also observed that none of the SFA's under current review has considered the influence of climate change or land use change on P flows and stocks. A number of non-SFA studies (Mander et al., 1998, 2000; Chang et al., 2001; McKee et al., 2001; Bouraoui et al., 2002; Jennings et al., 2009; Jeppesen et al., 2009) have identified that climate change and land use change can significantly influence the fate and magnitude of P flow through different systems particularly at the catchment scale. Without understanding the impact of these changes and their interaction on P flows and stocks, it is not possible to form effective P management policy to achieve future P sustainability. Therefore, we recommend, future analysis of P flow should investigate the impact of climate change and land use change on P flow.

In addition, we have observed most of the SFA/MFA P budgets under current review did not consider the spatial distribution of P flows and stocks. Thus, these studies were not able to capture the influence of spatial heterogeneity on P flows and stocks. For instance, Metson et al. (2012a) used a spatially corrected budget to assess the areal distribution of P flows and stocks across the Greater Phoenix city (US). By using a spatially corrected budget, they were able to identify some important flows (for instance; paper, cardboard, concrete, textile, human immigration) and stocks (for example; asphalt, vegetation, desert soil, residential and non-residential soil) of P which usually are overlooked in traditional P flow analysis. Moreover, spatial referencing allows the feasibility of the redistribution of P flows and stocks to be assessed and therefore, we suggest, future analysis of P flow should utilize this methodology.

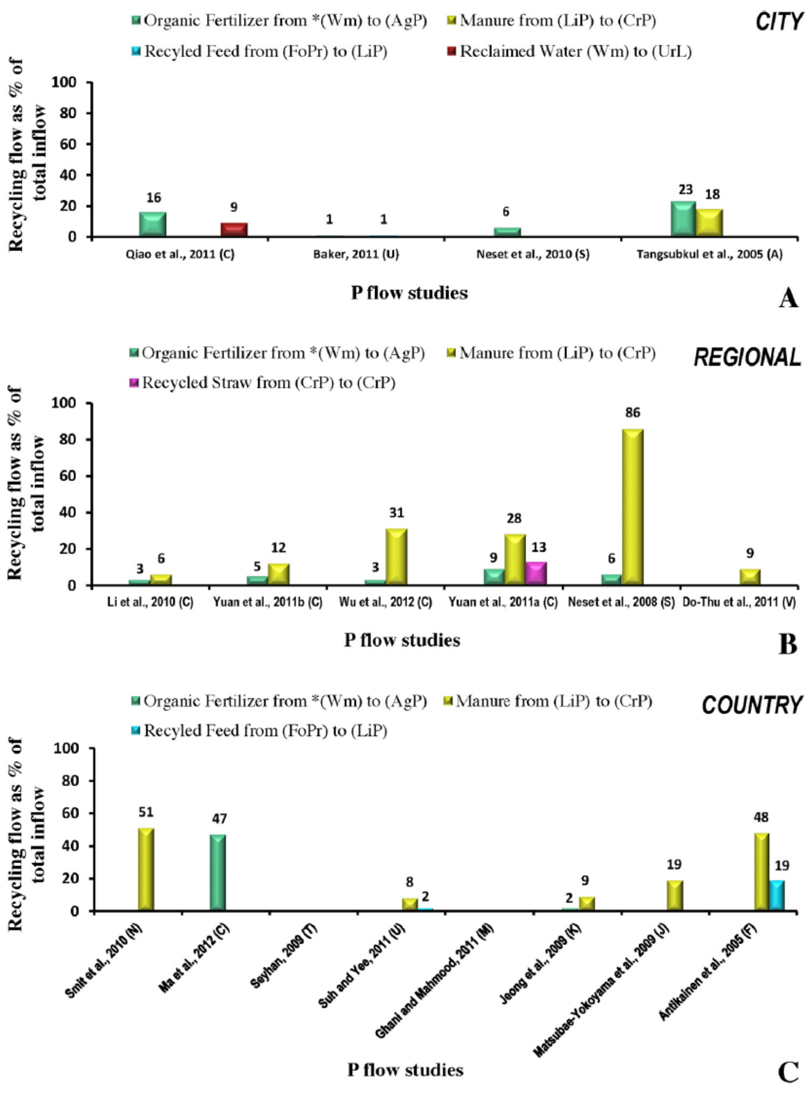

Fig. 5. Key P recycling flows at the (A) city, (B) regional, and (C) country scales. Details of the studies are available in Table 2. *( ): sector indicated by the abbreviation within the brackets in the legend - AgP: Agricultural (Crop and Livestock) Production; CrP: Crop Production; FoPr: Food Processing; LiP: Livestock Production; UrL: Urban Landscape; Wm: Waste Management.

This review has also revealed, in most of the studies at different geographical scales except some at the country scale, P flow has been analyzed for a single year only. There have been a limited number of multiple year P flow analyses particularly at the city and regional scales. Thus, it is evident that there is a gap of knowledge about the fate and magnitude of P flow over multiple years at the city and regional scales. Studies of a single year of P flow cannot necessarily identify the change traits of P flow over several years because at all the different geographical scales, there are some important processes related to P flow which may take several years to become effective. For instance, at the regional scale, there could be a large influence of variable natural processes such as acute erosion, floods, droughts, and bush fire on the nature and magnitude of P flow, but it usually takes more than one year for these processes to return and have their impact on P flow.

Besides, in a single year analysis, the influences of long term changes of the socioeconomic, political, and technological factors on P flow which take many years to become effective, cannot be covered. However, the influences of these factors can be vital in determining the fate and magnitude of P flow through different systems over several years. For instance, Ma et al. (2012) in a country scale analysis of P flow over 25 years (1984–2008) in China identified that different socioeconomic variables such as urbanization, improved living standards, and growth of population were responsible for increasing the magnitudes of P flows related to ore extraction, use and waste generation, and decreasing the recycling ratio of P in wastes. They recognized, financial and policy support along with technological advancement greatly promoted the progress of P fertilizer industry in China which ultimately transformed the country from a net P importer into a net P exporter after 2000. Another important finding of their study was the identification of anthropogenic P stocks in China between 1984 and 2008, which include respectively 38,300, 19,000 and 105,300 kt P in agricultural soil, natural water, and natural soil. Moreover, their study revealed that the natural soil includes a stock of 41,400 kt P in mining waste which can be utilized as a useful man-made mine for the secondary recovery of P in future. Again, Neset et al. (2010) in a city scale analysis of historical P flow of Linkoping, Sweden for the period of 1870–2000 identified that changes in sanitation arrangements significantly influence P flow. They observed the rate of productive reuse of P varied markedly over the period from very high, up until the 1920s, to almost nil around 1950, and then picking up again after the introduction of P removal units at wastewater treatment plants and sludge use in agriculture from the 1970s, followed by a sharp decline at the end of the 20th century due to the rejection of sludge use by the Swedish Farmers Union. Thus, it is evident that multiple year analyses are vital for understanding the long-term fate and magnitude of P flow through system. Knowledge of this is again essential for the analysis of future scenarios related to P flow as well as for making long term and better P management decisions, which usually are not possible to achieve with single year analysis. Therefore, future studies should focus on multiple year analysis of P flows and stocks at different geographical scales particularly at the city and regional scales.

One major challenge related to the multiple year analysis of P flow could be the lack of availability of good quality P flow data particularly in the data-poor countries. They might have data for a particular region or for a particular year but might not have for all the regions or for all years. Lack of availability of data has been identified as one of the main reasons that discourage researchers from conducting multiple year analysis of P flow. The issue of data quality and availability, and its impact in the outcome of P flow analysis has also been addressed in the review of Cordell et al. (2012). Therefore, we recommend, national bureaus of statistics consider giving greater emphasis to the collection of data on P flows, transformations, and uses at different geographical and temporal scales as part of their regular census processes.

5. Limitations of this assessment

Although most of the geographical scales have been covered in this study, the assessment of the key P inflows, outflows, stocks, internal flows, and recycling flows at the global scale and scales smaller than city has not been considered. The knowledge of the key flows and stocks at the global scale or at the scale smaller than city such as farm, street, or single sector scale could also contribute to improved P management at the global or local scales. Another major issue is that the majority of the analyses utilized here were conducted for a single year P flow. Thus, the findings of our review regarding the geographical scale specific key flows and stocks may not be the representative of temporal P flow. Besides, all the studies that have been considered in this review were conducted in different countries at different geographical locations, and the systems they considered for P flow analysis differed. Thus, the categorization of the studies that we made according to different geographical scales should be viewed with caution, likewise the outcomes of this review in terms of the geographical scale specific key P flows and stocks. Moreover, this review has considered the major P flows and stocks, whilst minor flows and stocks have been omitted in most cases. Clearly some minor inflows, stocks, and outflows could also play significant role in polluting the environment and causing resource scarcity if considered over longer periods, and viewed from the strict environmental policy and resource management perspective. Thus, as identified in different analyses, some minor P inflows such as asphalt, concrete, paper and cardboard (Metson et al., 2012a), atmospheric deposition (Yuan et al., 2011a; Metson et al., 2012a; Ott and Rechberger, 2012; Wu et al., 2012), coal (Jeong et al., 2009; Matsubae-Yokoyama et al., 2009; Yuan et al., 2011a; Wu et al., 2012), iron ore (Jeong et al., 2009; Matsubae-Yokoyama et al., 2009), pet food (Baker, 2011), pesticides and seeds (Yuan et al., 2011a,b; Wu et al., 2012); minor P stocks as storage in urban non-residential soil, pets (Metson et al., 2012a), septic tanks (Baker, 2011); and minor P outflows as leaching from soil to groundwater (Metson et al., 2012a), leaching from landfill (Ott and Rechberger, 2012), straw or crop waste (Yuan et al., 2011b; Wu et al., 2012), steel (Jeong et al., 2009; Matsubae-Yokoyama et al., 2009) along with their spatial distribution should also receive better attention for future P management decisions. Another source of uncertainty in this review could be the smaller number of the studies at the city and regional scales, and therefore, different conclusions could be made as more studies become available. Furthermore, in this study, we have attempted only a particular way of analyzing the data available from published SFA analyses, that is, to identify the geographical scale specific key flows and stocks. An alternative approach could be to use a life cycle perspective to attach a value to key P flows and stocks which may drive policy settings for better P management.

6. Conclusions

As set out in the research objective, this study has successfully identified the geographical scale specific key P inflows, outflows, stocks, internal flows, and recycling flows. Our study concludes, at the city scale, the inflow of P occurs mainly as food, and the outflow occurs mainly as wastewater. The majority of the P stocks at this scale relate to landfill. At the regional scale, the key inflow of P occurs either as chemical P fertilizer or animal feed, and the key outflow occurs either as exported food and agricultural products, waste (solid and liquid), or soil losses (erosion, runoff, and/or leaching). At the country scale, the majority of the P inflow occurs either through mineral ore or chemical P fertilizer, and the main outflow occurs either as food and agricultural products or soil losses (erosion, runoff, and/or leaching), and this is particularly the case for the countries without adequate reserves of phosphate rock. The majority of the P stock at the regional scale occurs in the soil of the crop production sector, and at the country scale, it occurs in the soil of the agricultural (both crop and livestock) production sector. Phosphorus recycling flows were identified to be nearly or less than one fifth of the total inflow in most of the studies at different geographical scales. At the regional and country scales, recycling of P occurs mainly as manure from the livestock production sector to the crop production sector, and at the city scale, it occurs mainly as organic fertilizer from the waste management sector to the agricultural production sector. Thus, it is evident that the nature and magnitude of the key P flows and stocks vary from one geographical scale to another. Therefore, to achieve better P management in a country, there is a need for the geographical scale specific P management decisions. The information about the key flows and stocks as we identified can be very useful in achieving geographical scale specific improvements in P management. These information could also be utilized as baseline data while forming policies and guidelines that aim to achieve P sustainability in a country. Moreover, we believe, the findings of our review can be utilized as an effective guideline for future studies that aim to analyze P flow at the city, regional, and country scales.

This study has also identified that there is a clear gap of knowledge about the fate and magnitude of P flow over a multi-year durations at the regional scale, which is a very important scale in terms of P flows and stocks. Thus, future research should put greater emphasis on the multi-year analysis of P flow at the regional scale. Future analyses of P flow should also consider the influence of the short and long-term social, economic, technological, and political changes on P flows and stocks. Moreover, the impacts of climate change and land use change on P flow should be considered. We also recommend, greater emphasis be placed on conceptual and simulation modelling of P flow so that tentative understanding of the P cycle can be further developed to integrate the geographical scale, and allows consideration of temporal change.

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References

Antikainen R, Lemola R, Nousiainen JI, Sokka L, Esala M, Huhtanen P, et al. Stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system. Agriculture, Ecosystems and Environment 2005;107(2–3):287–305.

Antikainen R, Haapanen R, Lemola R, Nousiainen JI, Rekolainen S. Nitrogen and phosphorus flows in the Finnish agricultural and forest sectors, 1910–2000. Water, Air & Soil Pollution 2008;194(1):163–77.

Ashley K, Cordell D, Mavinic D. A brief history of phosphorus: from the Philosopher's stone to nutrient recovery and reuse. Chemosphere 2011;84(6):737–46.

Baker LA. Can urban P conservation help to prevent the brown devolution? Chemosphere 2011;84(6):779–84.

Baker LA, Hartzheim PM, Hobbie SE, King JY, Nelson KC. Effect of consumption choices on fluxes of carbon, nitrogen and phosphorus through households. Urban Ecosystem 2007;10(2):97–117.

Boesch DF, Boynton WR, Crowder LB, Diaz RJ, Howarth RW, Mee LD, et al. Nutrient enrichment drives Gulf of Mexico hypoxia. Eos, Transactions American Geophysical Union 2009;90(14):117–28.

Bouraoui F, Galbiati L, Bidoglio G. Climate change impacts on nutrient loads in the Yorkshire Ouse catchment (UK). Hydrology and Earth System Sciences 2002;6(2):197–209.

Bouwman AF, Beusen AHW, Billen G. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. Global Biogeochemical Cycles 2009;23(4):1–16.

Bowes MJ, Smith JT, Jarvie HP, Neal C. Modelling of phosphorus inputs to rivers from diffuse and point sources. Science of the Total Environment 2008;395(2–3):125–38.

Brunner PH. Substance flow analysis as a decision support tool for phosphorus management. Journal of Industrial Ecology 2010;14(6):870–3.

Brunner PH, Rechberger H. Practical handbook of material flow analysis. Boca Raton, FL: CRC; 2004.

Carpenter SR. Eutrophication of aquatic ecosystems: bistability and soil phosphorus. Proceedings of the National Academy of Science 2005;102(29):10002–5.

Carpenter SR. Phosphorus control is critical to mitigating eutrophication. Proceedings of the National Academy of Science 2008;105(32):11039–40.

Chang H, Evans BM, Easterling DR. The effects of climate change on stream flow and nutrient loading. Journal of the American Water Resources Association (JAWRA) 2001;37(4):973–85.

Chen M, Chen J, Sun F. Agricultural phosphorus flow and its environmental impacts in China. Science of the Total Environment 2008;405(1–3):140–52.

Childers DL, Corman J, Edwards M, Elser JJ. Sustainability challenges of phosphorus and food: solutions from closing the human phosphorus cycle. Bioscience 2011;61(2):117–24.

Conley DJ. Save the Baltic Sea. Nature 2012;486:463–4.

Conley DJ, Paerl HW, Howarth RW, Boesch DF, Seitzinger SP, Havens KE, et al. Controlling eutrophication: nitrogen and phosphorus. Science 2009a;323(5917):1014–5.

Conley DJ, Bonsdorff E, Carstansen J, Destouni G, Gustafsson BG, Hansson LA, et al. Tackling hypoxia in the Baltic Sea: is engineering a solution? Environmental Science and Technology 2009b;43(10):3407–11.

Cooper J, Carliell-Marquet C. A substance flow analysis of phosphorus in the UK food production and consumption system. Resource, Conservation and Recycling 2013;74:82–100.

Cordell D, White S. Peak phosphorus clarifying the key issues of a vigorous debate about long-term phosphorus security. Sustainability 2011;3(10):2027–49.

Cordell D, Drangert JO, White S. The story of phosphorus: global food security and food for thought. Global Environmental Change 2009;19(2):292–305.

Cordell D, Rosemarin A, Schroder JJ, Smit AL. Towards global phosphorus security: a systems framework for phosphorus recovery and reuse options. Chemosphere 2011;84(6):747–58.

Cordell D, Neset TSS, Prior T. The phosphorus mass balance: identifying 'hotspots' in the food system as a roadmap to phosphorus security. Current Opinion in Biotechnology 2012;23(6):1–7.

Cordell D, Jackson M, White S. Phosphorus flows through the Australian food system: identifying intervention points as a roadmap to phosphorus security. Environmental Science & Policy 2013;29:87–102.

Correll DL. The role of phosphorus in the eutrophication of receiving waters: a review. Journal of Environmental Quality 1998;27(2):261–6.

Dairy Australia. Accounting for nutrients on Australian dairy farms-final report; June 2010, available at: http://www.accounting4nutrients.com.au/projectreports.aspx

Daniel TC, Sharpley AN, Lemunyon JL. Agricultural phosphorus and eutrophication: a symposium overview. Journal of Environmental Quality 1998;27(2):251–7.

Davis JR, Koop K. Eutrophication in Australian rivers, reservoirs and estuaries – a southern hemisphere perspective on the science and its implications. Hydrobiologia 2006;559(1):23–76.

Dawson CJ, Hilton J. Fertiliser availability in a resource-limited world: production and recycling of nitrogen and phosphorus. Food Policy 2011;36:S14–22.

Do-Thu N, Morel A, Nguyen-Viet H, Pham-Duc P, Nishida K, Kootattep T. Assessing nutrient fluxes in a Vietnamese rural area despite limited and highly uncertain data. Resources, Conservation and Recycling 2011;55(9–10):849–56.

Elser JJ. Phosphorus: a limiting nutrient for humanity? Current Opinion in Biotechnology 2012;23(6):833–8.

Elser JJ, Bennett E. A broken biogeochemical cycle. Nature 2011;478:29–31.

Fan Y, Hu S, Chen D, Li Y, Shen J. The evolution of phosphorus metabolism model in China. Journal of Cleaner Production 2009;17(9):811–20.

Fissore C, Baker A, Hobbie SE, King JY, Mcfadden JP, Nelson KC, et al. Carbon, nitrogen, and phosphorus fluxes in household ecosystems in the Minneapolis-Saint Paul, Minnesota, urban region. Ecological Applications 2011;21(3):619–39.

Garnier J, Nemery J, Billen G, Thery S. Nutrient dynamics and control of eutrophication in the Marne River system: modelling the role of exchangeable phosphorus. Journal of Hydrology 2005;304(1–4):397–412.

Ghani LA, Mahmood NZ. Balance sheet for phosphorus in Malaysia by SFA. Australian Journal of Basic and Applied Sciences 2011;5(12):3069–79.

Gilbert N. The disappearing nutrient. Nature 2009;461:716–8.

GRDC (Grain Research and Development Corporation). Crop nutrition, fact sheet. Grain Research and Development Corporation, Australian Government; 2012.

HELCOM. Eutrophication in the Baltic Sea – an integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region. In: Baltic Sea Environment Proceedings, No. 115B; 2009.

Hiscock JG, Thourot CS, Zhang J. Phosphorus budget-land use relationships for the northern Lake Okeechobee watershed, Florida. Ecological Engineering 2003;21(1):63–74.

Jarvie HP, Neal C, Withers PJA. Sewage-effluent phosphorus: a greater risk to river eutrophication than agricultural phosphorus? Science of the Total Environment 2006;360(1-3):246–53.

Jennings E, Allott N, Pierson DC, Schneiderman EM, Lenihan D, Samuelsson P, et al. Impacts of climate change on phosphorus loading from a grassland catchment: implications for future management. Water Research 2009;43(17):4316–26.

Jeong YS, Matsubae-Yokoyama K, Kubo H, Pak J, Nagasaka T. Substance flow analysis of phosphorus and manganese correlated with South Korean steel industry. Resources, Conservation and Recycling 2009;53(9):479–89.

Jeppesen E, Kronvang B, Meerhoff M, Søndergaard M, Hansen KM, Andersen HE, et al. Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. Journal of Environmental Quality 2009;38(5):1930–41.

Kupkanchanakul W, Kwonpongsagoon S. Nitrogen and phosphorus flow analysis from pig farming in Bang Pakong Basin, Eastern Thailand. Environment Asia 2011;4(2):27–32.

Li S, Yuan Z, Bi J, Wu H. Anthropogenic phosphorus flow analysis of Hefei City, China. Science of the Total Environment 2010;408(23):5715–22.

Liu Yi, Villalba G, Ayres RU, Schroder H. Global phosphorus flows and environmental impacts from a consumption perspective. Journal of Industrial Ecology 2008;12(2):229–47.

Ma D, Hu S, Chen D, Li Y. Substance flow analysis as a tool for the elucidation of anthropogenic phosphorus metabolism in China. Journal of Cleaner Production 2012:188–98, 29-30:.

Mander U, Kull A, Tamm V, Kuusemets V, Karjus R. Impact of climatic fluctuations and land use change on runoff and nutrient losses in rural landscapes. Landscape and Urban Planning 1998;41(3–4):229–38.

Mander U, Kull A, Kuusemets V, Tamm V. Nutrient runoff dynamics in a rural catchment: influence of land-use changes, climatic fluctuations and ecotechnological measures. Ecological Engineering 2000;14(4):405–17.

Matsubae-Yokoyama K, Kubo H, Nakajima K, Nagasaka T. A material flow analysis of phosphorus in Japan. Journal of Industrial Ecology 2009;13(5):687–705.

McKee LJ, Eyre BD, Hossain S, Pepperell PR. Influence of climate, geology and humans on spatial and temporal nutrient geochemistry in the subtropical Richmond River catchment, Australia. Marine Freshwater Research 2001;52(2):235–48.

Metson GS, Hale RL, Iwaniec DM, Cook EM, Corman JR, Galletti CS, et al. Phosphorus in Phoenix: a budget and spatial representation of phosphorus in an urban ecosystem. Ecological Applications 2012a;22(2):705–21.

Metson GS, Bennett EM, Elser JJ. The role of diet in phosphorus demand. Environmental Research Letters 2012b;7(4):1–10.

Metson GS, Aggarwal R, Childers DL. Efficiency through proximity: changes in phosphorus cycling at the urban – agricultural interface of a rapidly urbanizing desert region. Journal of Industrial Ecology 2012c;16(6):914–27.

Murphy RR, Kemp WM, Ball WP. Long-term trends in Chesapeake Bay seasonal hypoxia, stratification, and nutrient loading. Estuaries and Coasts 2011;34(6):1293–309.

Neset TSS, Cordell D. Global phosphorus scarcity: identifying synergies for a sustainable future. Journal of the Science of Food and Agriculture 2012;92(1):2–6.

Neset TSS, Bader HP, Scheidegger R, Lohm U. The flow of phosphorus in food production and consumption – Linkoping, Sweden, 1870–2000. Science of the Total Environment 2008;396(2–3):111–20.

Neset TSS, Drangert JO, Bader HP, Scheidegger R. Recycling of phosphorus in urban Sweden: a historical overview to guide a strategy for the future. Water Policy 2010;12(4):611–24.

Ott C, Rechberger H. The European phosphorus balance. Resources, Conservation and Recycling 2012;60:159–72.

Qiao M, Zheng YM, Zhu YG. Material flow analysis of phosphorus through food consumption in two megacities in northern China. Chemosphere 2011;84(6):773–8.

Rengel Z, Zhang F. Phosphorus sustains life. Plant and Soil 2011;349(1–2):1–2.

Saikku L, Antikainen R, Kauppi PE. Nitrogen and phosphorus in the Finnish energy system, 1900–2003. Journal of Industrial Ecology 2007;11(1):103–19.

Schindler DW, Hecky RE, Findlay DL, Stainton MP, Parker BR, Paterson MJ, et al. Eutrophication of lakes cannot be controlled by reducing nitrogen input: results of a 37-year whole-ecosystem experiment. Proceedings of the National Academy of Science 2008;105(32):11254–8.

Schroder JJ, Cordell D, Smit AL, Rosemarin R. Sustainable use of phosphorus. Report No. 357. Plant Research International, Wageningen University and Research Centre, the Netherlands, and Stockholm Environment Institute; 2010.

Senthilkumar K, Nesme T, Mollier A, Pellerin S. Regional-scale phosphorus flows and budgets within France: the importance of agricultural production systems. Nutrient Cycling in Agroecosystem 2012;92(2):145–59.

Seyhan D. Country-scale phosphorus balancing as a base for resources conservation. Resources, Conservation and Recycling 2009;53(12):698–709.

Shilton AN, Blank LM. Phosphorus biotechnology. Current Opinion in Biotechnology 2012;23(6):830–2.

Smit AL, Bindraban PS, Schroder JJ, Conijn JG, Van der Meer HG. Phosphorus in agriculture: global resources, trends and developments, Report to the Steering Committee Technology Assessment of the (Dutch) Ministry of Agriculture, Nature and Food Quality, Report 282, Plant Research International, Wageningen; 2009, 36 pp.

Smit AL, Van Middelkoop JC, Van Dijk W, Van Reuler H, De Buck AJ, Van De Sanden PACM. A quantification of phosphorus flows in the Netherlands through agricultural production, industrial processing and households. P.O. Box 616, 6700 AP Wageningen, The Netherlands: Plant Research International, Part of Wageningen UR. Business Unit Agrosystems; 2010, 56 pp.

Smith VH, Schindler DW. Eutrophication science: where do we go from here? Cell 2009;24(4):201–7.

Suh S, Yee S. Phosphorus use-efficiency of agriculture and food system in the US. Chemosphere 2011;84(6):806–13.

Tangsubkul N, Moore S, Waite TD. Incorporating phosphorus management considerations into wastewater management practice. Environmental Science & Policy 2005;8(1):1–15.

Torrent J, Barberis E, Gil-Sotres F. Agriculture as a source of phosphorus for eutrophication in southern Europe. Soil Use and Management 2007;23(S1):25–35.

UNEP (United Nations Environment Program). UNEP year book 2011: emerging issues in our global environment; 2011, 79 pp.

Vaccari DA. Phosphorus: a looming crisis. Scientific American 2009;300(6):54–9.

Vaccari DA. The phosphorus cycle. Chemosphere 2011a;84(6):735–6.

Vaccari DA. Sustainability and the phosphorus cycle: inputs, outputs, material flow, and engineering. Environmental Engineer: Applied Research & Practice 2011b;12:1–11.

Van Vuuren PV, Bouwman AF, Beusen AHW. Phosphorus demand for the 1970–2100 period: a scenario analysis of resource depletion. Global Environmental Change 2010;20(3):428–39.

Villalba G, Liu Y, Schroder H, Ayres RU. Global phosphorus flows in the industrial economy from a production perspective. Journal of Industrial Ecology 2008;12(4):557–69.

Voet EVD. Substance flow analysis methodology. In: Ayres RU, Ayres LW, editors. A handbook of industrial ecology. Northampton, USA: Edward Elgar Publishing Limited; 2002. p. 91–101.

White S, Cordell D, Moore D. Securing a sustainable phosphorus future for Australia: implications of global phosphorus scarcity and possible solutions. Review prepared by the Institute for Sustainable Futures, for CSIRO Sustainable Agriculture Flagship; 2010.

Withers PJA, Haygarth PM. Agriculture, phosphorus and eutrophication: a European perspective. Soil Use and Management 2007;23:1–4.

Wolfe-Simon F, Blum JS, Kulp TR, Gordon GW, Hoeft SE, Ridge JP, et al. A bacterium that can grow by using arsenic instead of phosphorus. Science 2011;332(6034):1163–6.

Wu H, Yuan Z, Zhang L, Bi J. Eutrophication mitigation strategies: perspectives from the quantification of phosphorus flows in socioeconomic system of Feixi, Central China. Journal of Cleaner Production 2012;23(1):122–37.

Xu H, Paerl HW, Qin B, Zhu G, Goa G. Nitrogen and phosphorus inputs control phytoplankton growth in eutrophic Lake Taihu, China. Limnology and Oceanography 2010;55(1):420–32.

Yuan Z, Liu X, Wu H, Zhang L, Bi J. Anthropogenic phosphorus flow analysis of Lujiang County, Anhui Province, Central China. Ecological Modelling 2011a;222(8):1534–43.

Yuan Z, Shi J, Wu H, Bi J. Understanding the anthropogenic phosphorus pathway with substance flow analysis at the city level. Journal of Environmental Management 2011b;92(8):2021–8.

APPENDIX 2: Material data considered for the analysis of P flow in the Gippsland region.

Material	Types	Unit	2008	2009	2010	2011	2012	2013	Reliability	Data Source
Population	Resident	number	248334	251818	256142	259952	262259	263858	High	*ABS, 2014*
Commercial fertilizer	SSP	tonnes	37401	32065	26730	22245	17760	38400	Moderate	*ABS, 2009, 2011, 2013, 2014a*
	DSP	tonnes	9992	12441	14890	11425	7960	6073	Moderate	*ABS, 2009, 2011, 2013, 2014a*
	MAP	tonnes	5729	5489	5249	4435	3621	6214	Moderate	*ABS, 2009, 2011, 2013, 2014a*
	Other fertilizers	tonnes	94743	64103	33284	32627	31970	17560	Moderate	*ABS, 2009, 2011, 2013, 2014a*
	Manure	tonnes	48220	39826	31432	33651	35870	9388	Moderate	*ABS, 2009, 2011, 2013, 2014a*
Livestock	Dairy cattle	number	513150	619115	578837	510182	612388	480638	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Meat cattle	number	603626	557687	509978	557778	532772	652817	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Sheep	number	664857	661869	671153	845646	808775	763811	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Pork/pig	number	20382	13968	12095	20652	14465	8118	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Chicken (layer)	number	612226	520026	516065	500926	532772	553878	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Chicken (broiler)	number	970000	970000	2023045	784948	1555805	4601567	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Lamb (slaughtered)	number	244268	256133	327206	337732	373302	334904	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Pork (slaughtered)	number	18021	10621	10914	18092	13112	7262	Moderate to low	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Egg	dozen	12248477	12248477	12126690	12263665	11008408	13893608	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Meat cattle (slaughtered)	number	362176	334612	305987	334669	319663	391690	Moderate to low	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b; and ABS, 2014c*

	Milk	kilolitre	1900000	2100000	1990000	2149000	2115000	1930000	High to moderate	*GippsDairy, 2009, 2010; and Dairy Australia, 2011, 2012, 2013*
Crop (hay and silage)	Cereal hay	tonnes	13857	6809	28951	27710	11809	11517	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Pasture hay	tonnes	458818	225459	299986	360716	258407	199178	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Other hay	tonnes	21209	10422	16835	22058	55577	53297	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Silage of pasture, cereal and other crops	tonnes	0	406220	279769	482786	241153	279232	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
Crop (cereal grains)	Wheat	tonnes	9682	6802	16951	10030	7840	12510	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Oat	tonnes	58	846	15	735	751	559	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Barley	tonnes	978	756	5643	2789	2591	2596	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Maize	tonnes	0	1615	0	2246	1602	3608	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Triticale	tonnes	0	633	0	3479	907	827	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Other cereal Grains	tonnes	0	165	994	645	176	247	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
Crop (non-cereal grains)	Lupins	tonnes	0	287	264	342	683	315	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Canola oilseed	tonnes	0	665	2211	3076	1487	1806	Moderate	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
Solid waste	Garbage	tonnes	47529	47825	49494	51156	51670	51980	Moderate	*ABS, 2014; and Sustainability Victoria, 2010, 2011, 2013*
	Recyclable	tonnes	28360	28370	28719	29224	29512	29689	Moderate	*ABS, 2014; and Sustainability Victoria, 2010, 2011, 2013*
	Green organics	tonnes	12022	12442	14887	18337	18622	18734	Moderate	*ABS, 2014; and Sustainability Victoria, 2010, 2011, 2013*
Wastewater	Domestic	kilolitre	33525	33995	34579	35094	35408	35621	Moderate	*ABS, 2014; and RMIT Handbook, 2008*

Pet animal	Dog	number	39733	40291	40983	41592	41966	42217	Moderate to low	*ABS, 2014; and ACAC, 2010*
	Cat	number	27317	27700	28176	28595	28851	29024	Moderate to low	*ABS, 2014; and ACAC, 2010*
Water	Discharge from water bodies to ocean	megalitre	4925100	4925100	4925100	4925100	4925100	4925100	Moderate	*DSE, 2011*
	Irrigation	megalitre	1368280	1368280	1368280	1368280	1368280	1368280	Moderate	*DSE, 2011*
Land use	Total land area of Gippsland	hectare	3828406	3828406	3828406	3828406	3828406	3828406	Moderate	*ABS, 2013b*
	Crop farming	hectare	131311	189296	163513	145386	136775	148145	Moderate to low	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b*
	Livestock farming	hectare	1289021	1190920	1089039	1191114	1137715	1394066	Moderate to low	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b; and ABS, 2013b*
	Residential and urban	hectare	200579	203393	206886	209963	211848	213140	Moderate	*ABS, 2014; and ABS, 2013b*
	National park, conservation areas and forest	hectare	819733	819733	819733	819733	819733	819733	Moderate	*ABS, 2013b*

APPENDIX 3: Phosphorus (elemental) content data relating to different materials and processes considered for the analysis of P flow in the Gippsland region.

Materials/Process	Types	Unit	P	Reliability	Data Source
Commercial fertilizer	SSP	%	8.2	High to moderate	*DEPI,2010*
	TSP	%	20	High to moderate	*DEPI,2010*
	MAP	%	20	High to moderate	*DEPI,2010*
	DAP	%	19	High to moderate	*DEPI,2010*
	MKP	%	20	High to moderate	*DEPI,2010*
	NPKS	%	18	High to moderate	*DEPI,2010*
	NPSZn	%	20	High to moderate	*DEPI,2010*
	PSCa	%	13	High to moderate	*DEPI,2010*
	Nitrophoska special	%	5.2	High to moderate	*IPL, 2014*
	Goldphos	%	18	Moderate to low	*Allan et al., 1997*
	Manure	%	0.7	Moderate	*FSA Consulting, 2009*
Pet animal – Feed	Dog	g/dog/day	3.13	Moderate to low	*Hill et al., 2001*
	Cat	g/cat/day	0.207	low	*Kienzle et al., 1998*
Pet animal – Excreta	Dog	g/dog/day	2.19	Moderate to low	*Hill et al., 2001*
	Cat	g/cat/day	0.187	low	*Kienzle et al., 1998*
Livestock – Feed	Dairy cattle	g/cow/day	80.61	High	*Gourley et al., 2010; Powell et al., 2012*
	Meat cattle	g/cow/day	39.32	Moderate to low	*Block et al., 2004*
	Sheep/lamb	g/sheep/day	2.23	Moderate	*Leech, 2009*
	Pork/pig	g/pig/day	9.9	Moderate to low	*Sopade et al., 2013*
	Broiler chicken	g/chicken/day	0.90	Moderate	*Poultry CRC, 2014; Roberts, 2003*
	Layer chicken	g/chicken/day	0.95	Moderate	*Roberts, 2003*
Livestock – Excreta	Dairy cattle	g/cow/day	61.1	High to moderate	*Gourley et al., 2010*
	Meat cattle	g/cow/day	28.5	Moderate	*Watts et al., 2011*
	Sheep/lamb	g/sheep/day	2.16	Moderate	*Leech, 2009*
	Pork/pig	g/pig/day	7.98	Moderate to low	*Lorimor et al., 2004*
	Broiler chicken	g/chicken/day	0.33	Moderate to low	*ASAE, 2005*
	Layer chicken	g/chicken/day	0.48	Moderate to low	*ASAE, 2005*
Livestock – Bone	Meat cattle	g/ kg	102.9	low	*Beighle et al., 1994*
	Sheep/lamb	g/ kg	73.6	low	*Ternouth et al., 1980*
	Pork	g/ kg	83	Moderate to low	*Varley et al., 2010*
	Chicken	g/ kg	83.2	Moderate to low	*Suchý et al., 2009*
Livestock – Meat	Beef	g/ kg	2.35	Moderate	*Williams et al., 2007*
	Lamb	g/ kg	2.3	Moderate	*Williams et al., 2007*
	Pork	g/ kg	2.27	Moderate	*FSANZ, 2013*

	Chicken	g/ kg	2.25	Moderate	*FSANZ, 2013*
Livestock – Fat	Beef	g/ kg	0.87	Moderate	*FSANZ, 2013*
	Lamb	g/ kg	0.56	Moderate	*Williams et al., 2007*
	Pork	g/ kg	0.84	Moderate to low	*USDA, 2013*
	Chicken	g/ kg	0.99	Moderate	*FSANZ, 2013*
Livestock – Milk	Cow	g/litre	0.95	Moderate	*Dairy Australia, 2014; NHMRC, 2006*
Livestock - Egg (chicken)	Edible portion	g/kg	2	Moderate	*AECL, 2013*
	Eggshell	%	0.3	Moderate to Low	*Gupta, 2008*
Crop - Hay and Silage	Lucerne hay	%	0.36	High	*Gourley et al., 2010*
	Pasture hay	%	0.247	High	*Gourley et al., 2010*
	Cereal hay	%	0.206	High	*Gourley et al., 2010*
	Oat hay	%	0.218	High to moderate	*Gourley et al., 2010*
	Clover hay	%	0.387	High to moderate	*Gourley et al., 2010*
	Canola hay	%	0.314	High to moderate	*Gourley et al., 2010*
	Sorghum hay	%	0.347	High to moderate	*Gourley et al., 2010*
	Pasture silage	%	0.385	High	*Gourley et al., 2010*
	Maize silage	%	0.264	High to moderate	*Gourley et al., 2010*
	Canola silage	%	0.297	High to moderate	*Gourley et al., 2010*
	Cereal silage	%	0.326	High to moderate	*Gourley et al., 2010*
	Kikuyu silage	%	0.386	High to moderate	*Gourley et al., 2010*
	Lucerne silage	%	0.423	High to moderate	*Gourley et al., 2010*
	Oats & Peas silage	%	0.389	High to moderate	*Gourley et al., 2010*
	Paspalum silage	%	0.324	High to moderate	*Gourley et al., 2010*
	Seteria silage	%	0.267	High to moderate	*Gourley et al., 2010*
	Prairie grass silage	%	0.186	High to moderate	*Gourley et al., 2010*
Crop - Cereal Grains	Wheat	%	0.3364	High to moderate	*Gourley et al., 2010*
	Oats	%	0.345	High to moderate	*Gourley et al., 2010*
	Barley	%	0.364	High to moderate	*Gourley et al., 2010*
	Maize	%	0.309	High to moderate	*Gourley et al., 2010*
	Triticale	%	0.311	High to moderate	*Gourley et al., 2010*
	Sorghum	%	0.325	High to moderate	*Gourley et al., 2010*
Crop - Non Cereal Grains	Lupins	%	0.365	High to moderate	*Gourley et al., 2010*
	Canola meal	%	1.158	High to moderate	*Gourley et al., 2010*
	Chickpeas	%	0.366	Moderate to low	*USDA, 2013*
	Cowpeas	%	0.438	Moderate to low	*USDA, 2013*
	Soybean meal	%	0.777	High to moderate	*Gourley et al., 2010*
	Sunflower seed	%	0.66	Moderate to low	*USDA, 2013*
	Safflower grain	%	0.474	Moderate to low	*USDA, 2013*
	Faba beans	%	0.421	Moderate to low	*USDA, 2013*
	Red kidney beans	%	0.407	Moderate to low	*USDA, 2013*
	White beans	%	0.301	Moderate to low	*USDA, 2013*

Human – Food	Average P intake by person 2 years and over	g/capita/day	1.422	Moderate	*ABS, 2014d*
Human – Excreta	Urine and faeces	g/capita/day	1.37	Moderate to low	*Jonsson and Vinneras, 2004*
	Urine	g/litre	0.7	Moderate to low	*Pradhan et al., 2009*
	Faeces	g/kg	3.59	Moderate to low	*Vinneras, 2002; Vinneras, 2006*
Municipal solid waste	Treated food waste	%	0.12	Moderate to low	*Bernstad and Jansen, 2012*
	Paper/cardboard	%	0.013	Moderate to low	*Bernstad and Jansen, 2011*
	Fruit and vegetable waste (12% moisture)	%	0.17	Moderate to low	*Garcı´a et al., 2005*
	Organic (plant, soil) waste	% DS	0.198	Moderate to low	*Bernstad and Jansen, 2011*
Domestic wastewater	Raw sewage	mg/litre	13.5	Moderate	*Melbourne Water, 2005*
	Wastewater to water bodies	mg/litre	0.33	Moderate	*CGRWC, 2012*
	Wastewater for irrigation	mg/litre	9.7	Moderate	*CGRWC, 2012*
	Dried sludge	%	0.9	Moderate	*ANZBP, 2009*
	Dewatered sludge	%	0.47	Moderate to low	*García-Albacete et al., 2012*
Irrigation water	From water bodies	mg/litre	0.04	Moderate	*Gourley et al., 2010*
Atmospheric deposition	Average of different types of land use	kg/ha/yr	0.42	Moderate to low	*Gourley et al., 2010; Anderson and Downing, 2006; Ahn and James, 2001; Winter et al., 2002; Redfield, 2002*
Soil erosion and runoff - Catchment scale	Channel/ river bank erosion	kg/ha/yr	0.09	Moderate	*Hancock et al., 2007*
	Hillslope erosion	kg/ha/yr	0.028	Moderate	*Hancock et al., 2007*
	Gully and tunnelling erosion	kg/ha/yr	0.0064	Moderate	*Hancock et al., 2007*
	Dissolved surface or subsurface runoff	kg/ha/yr	0.0654	Moderate	*Hancock et al., 2007*
	Total loss in soil Erosion and runoff	kg/ha/yr	0.191	Moderate	*Hancock et al., 2007*
Runoff - Urban area	Surface runoff	kg/ha/yr	0.87	Moderate	*Marston et al., 1995*
Total P input in different types of land use	Dairy	kg/ha/yr	24	Moderate	*Weaver and Wong, 2011*
	Beef	kg/ha/yr	11.1	Moderate	*Weaver and Wong, 2011*
	Cropping	kg/ha/yr	11.75	Moderate	*Weaver and Wong, 2011*
	Mixed grazing	kg/ha/yr	9.9	Moderate	*Kelsey et al., 2010*
	Urban area	kg/ha/yr	19.7	Moderate	*Kelsey et al., 2010*

APPENDIX 4: A detailed picture of the regional scale P flow model developed in MATLAB/Simulink® software platform. Here, the view of the model for different subsystems has been presented. However, the model has too many components, and it is not possible to present each and every component of the model. Therefore, some representative view for different subsystems has been presented. The numeric values (except those for cumulative storage which indicates total storage over six years) in the figures indicate the model results for the latest year (2013) of the study period in the case of Gippsland region.

Crop Farming system:

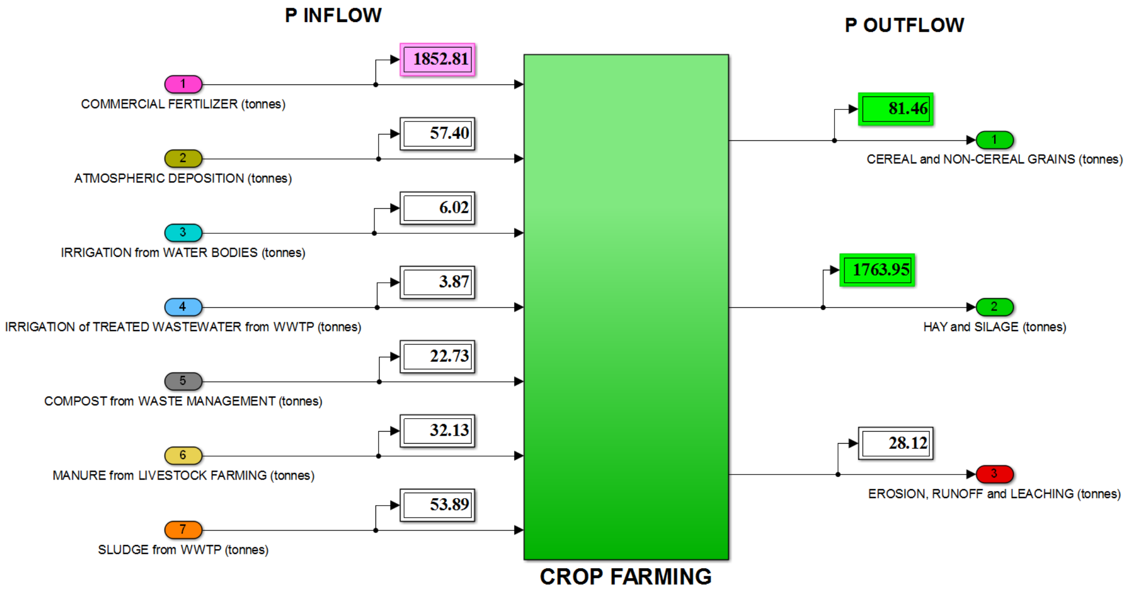

Fig. A. Inflows and outflows of P relating to the crop farming system.

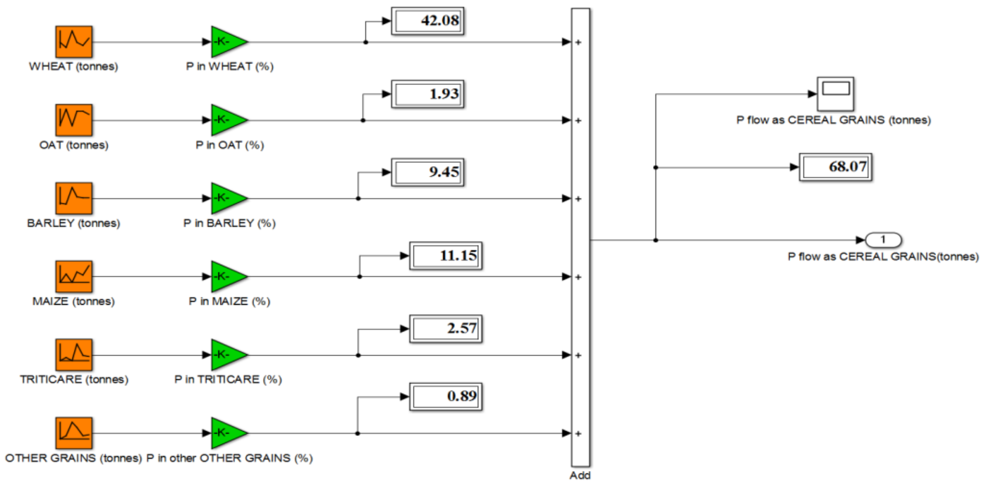

Fig. B. Analysis of P flow associated with cereal crops.

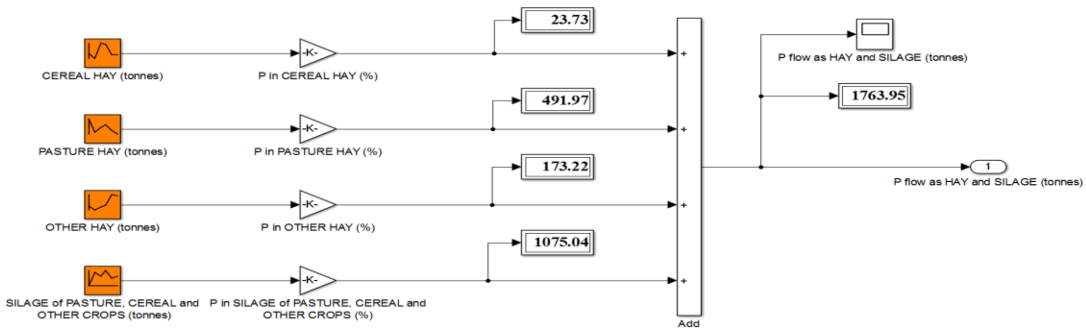

Fig. C. Analysis of P flow associated with hay and silage.

Livestock Farming system:

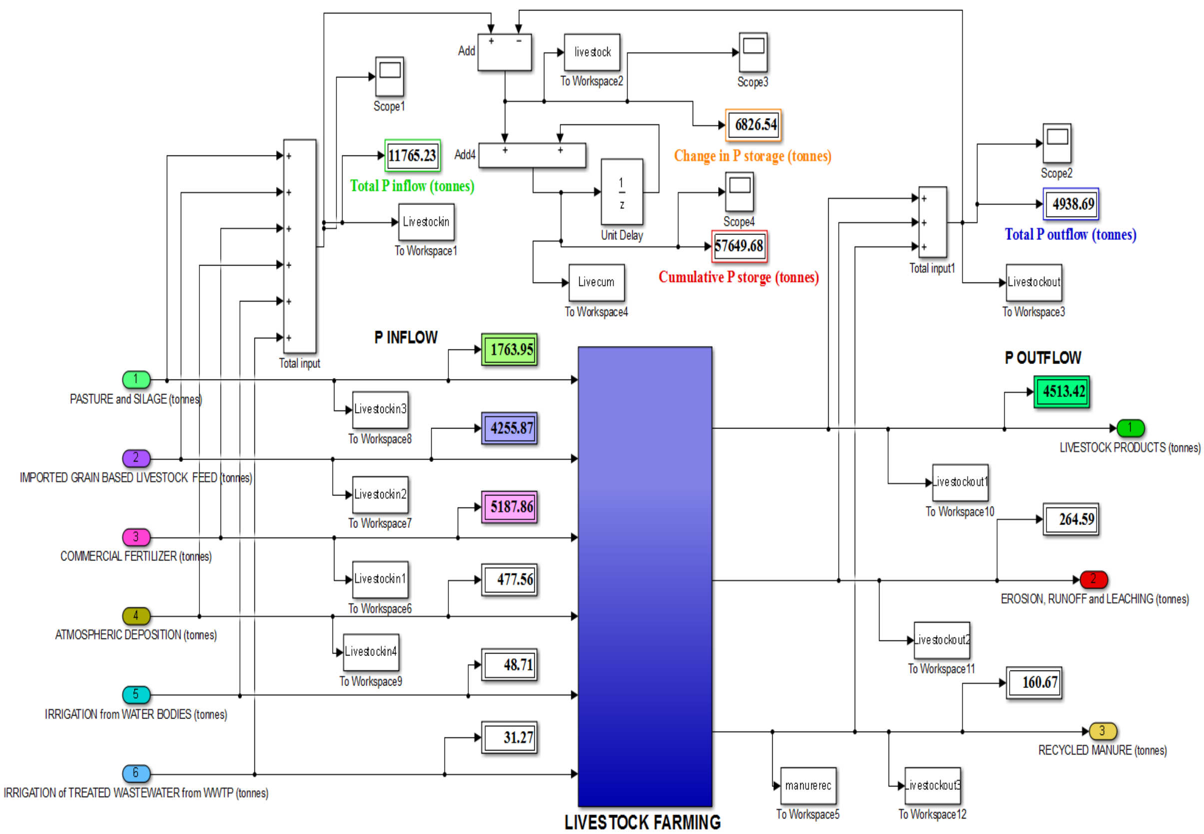

Fig. D. Inflows and outflows of P relating to the livestock farming system.

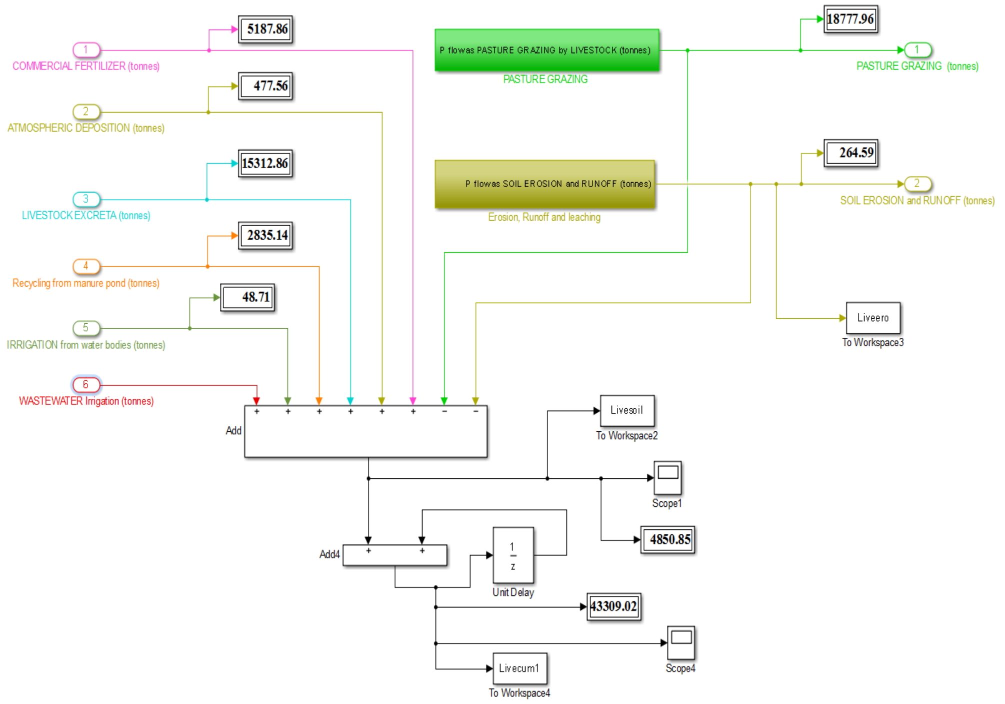

Fig. E. Analysis of soil P storage in the livestock farming system.

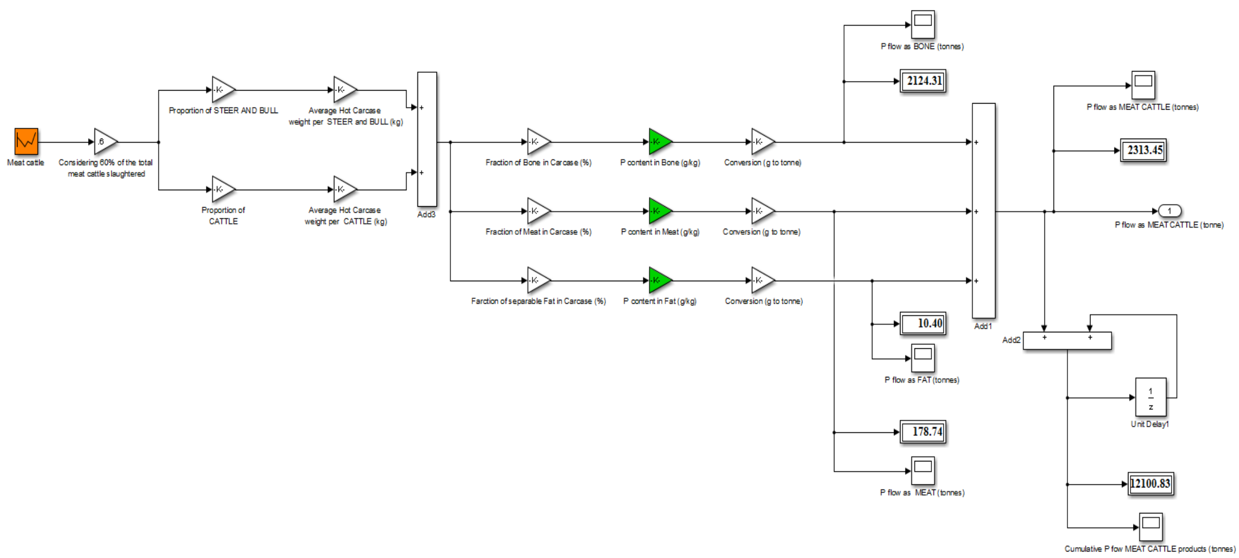

Fig. F. Analysis of P flow associated with meat cattle products.

Household and Urban system:

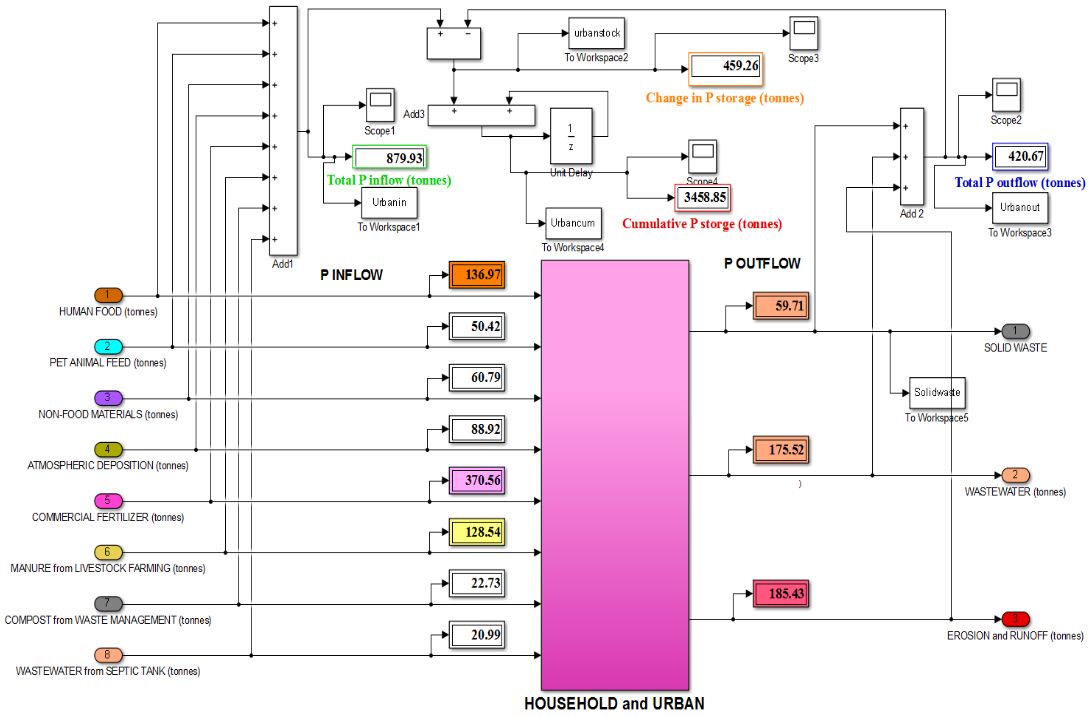

Fig. G. Inflows and outflows of P relating to the household and urban system.

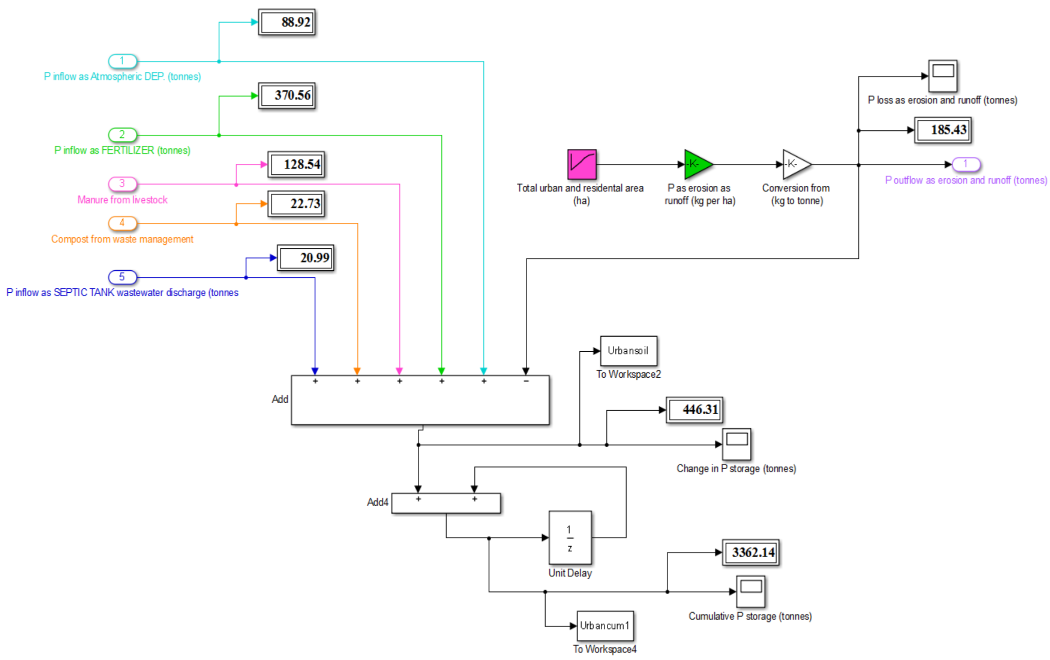

Fig. H. Analysis of soil P storage in the household and urban system.

Waste Management system:

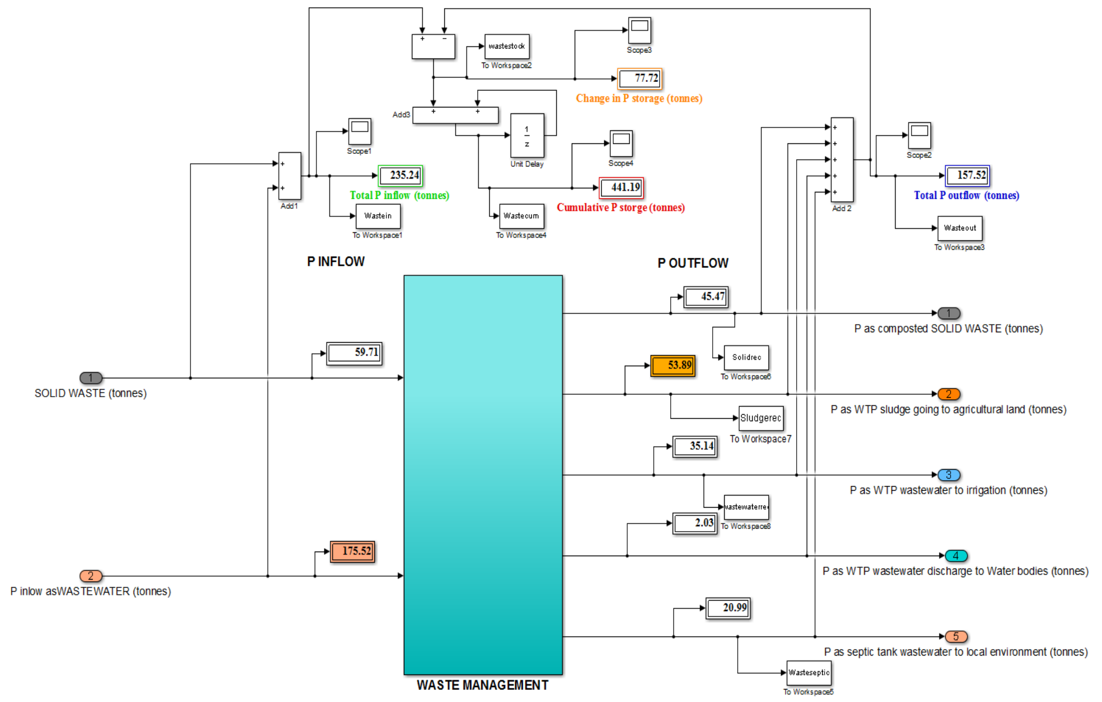

Fig. I. Inflows and outflows of P relating to the waste management system.

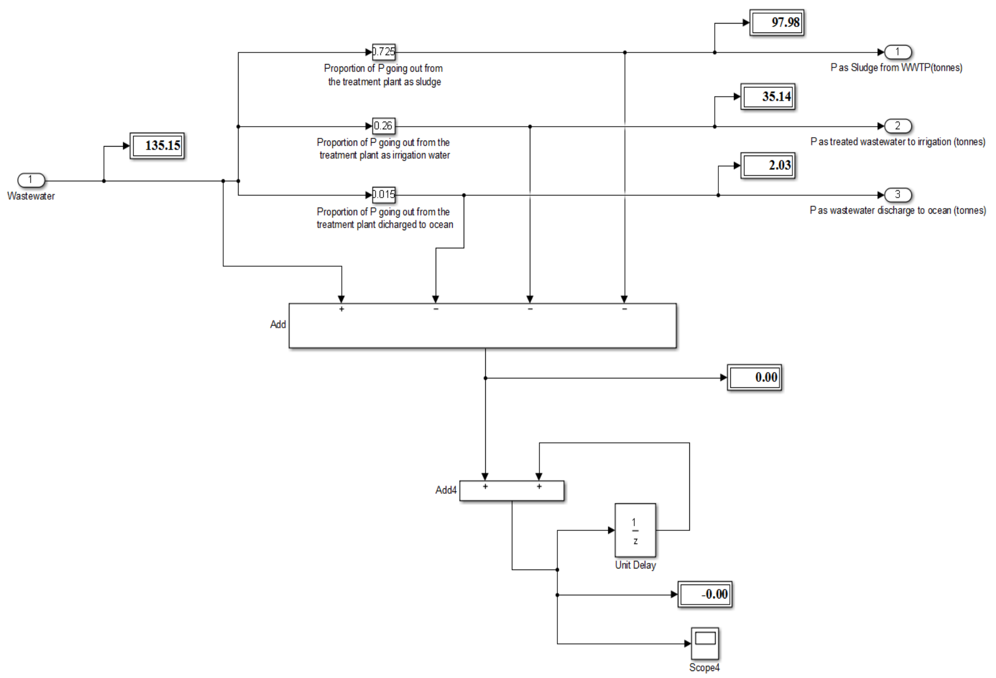

Fig. J. Analysis of P flow associated with wastewater treatment plants.

Water system:

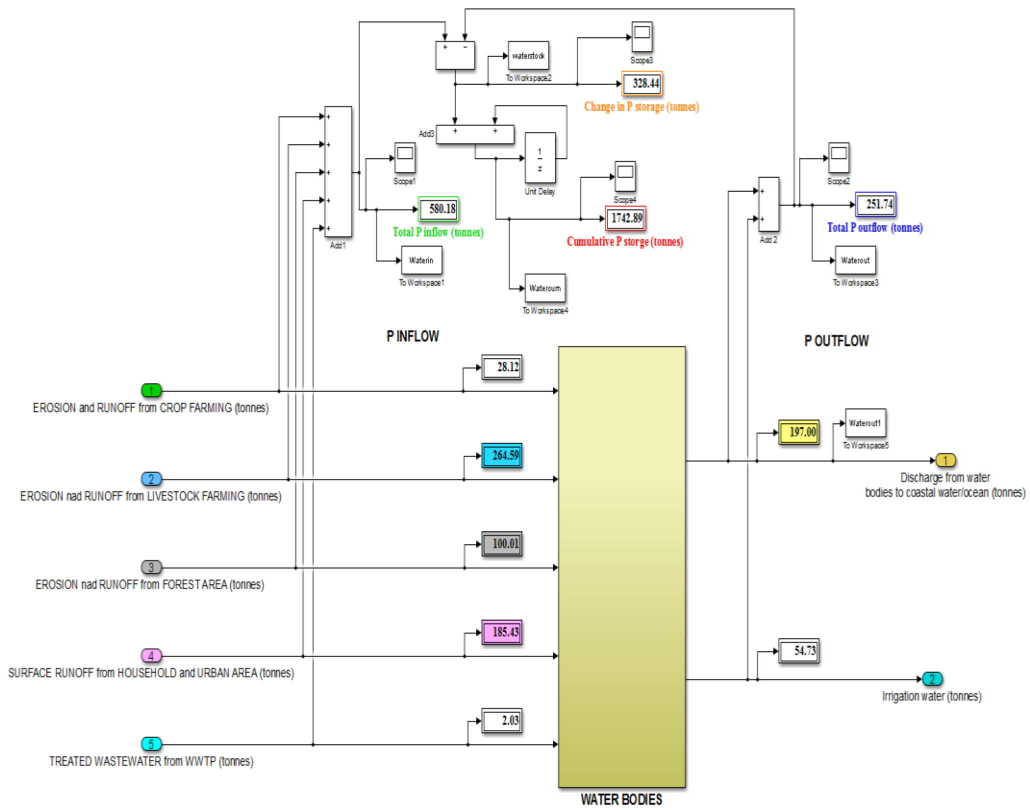

Fig. K. Inflows and outflows of P relating to the water system.

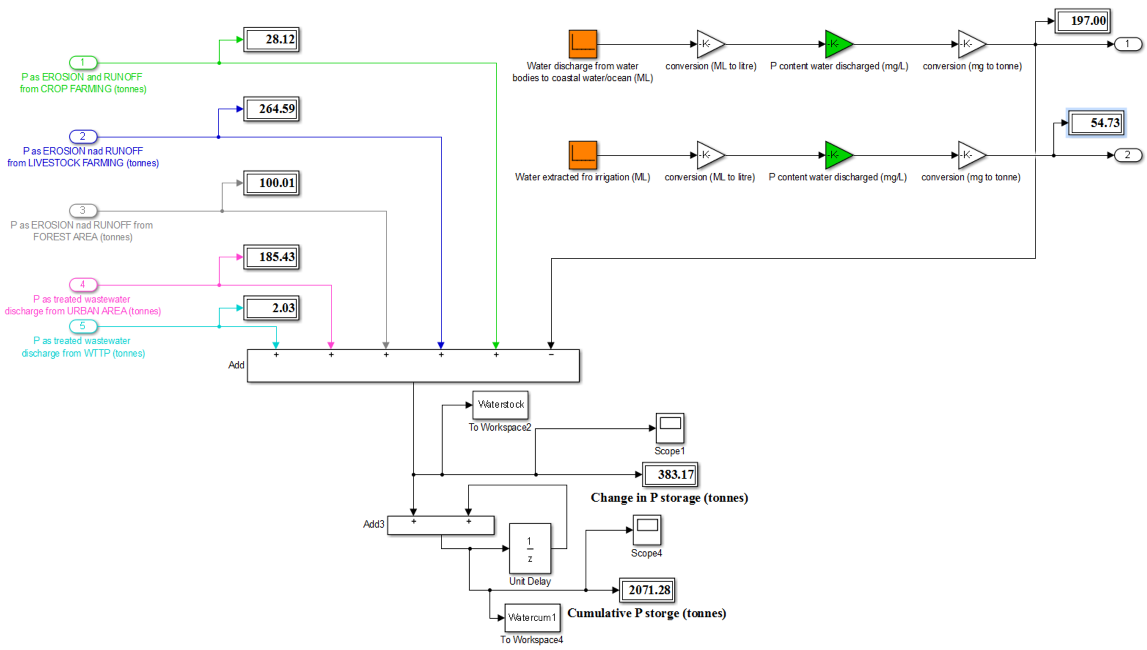

Fig. L. Analysis of P storage in the water column and bottom sediments.

APPENDIX 5: Reality check for model results regarding some major P flow and storage in the case of the Gippsland region. Details of the 'reality check' for each of the flow have been presented next to the table.

Type of P flow or storage	Model value (tonnes)	Reality check value (tonnes)	Model value falling in the range of the reality check value	Reality check method	Reference
1. P intake as pasture grazing by dairy cattle (mean annual flow)	11377	8214	+39%	Alternative calculations	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b; Powell et al., 2011*
2. P excretion by dairy cattle (mean annual flow)	12319	9725	+27%	Alternative calculations	*ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b; ASAE, 2005; Dairy Australia, 2008*
3. Cumulative soil P storage in crop farming area over six years	4063	6704	-40%	Actual field based study	*Personal communication*
4. Loadings to water bodies (Mean annual flow)	543	613	-12%	Independent literature data	*Ladson and Tilleard, 2006*

1. P intake as pasture grazing by dairy cattle

Currently, the model calculates P flow as pasture grazing by directly multiplying the total dairy cattle number with the daily rate of total P intake in feed per cattle, and then multiplying the product with 0.7 (based on the information from available literature this study consider that 70% of the P intake in feed by dairy cattle in Gippsland occurs thorough pasture grazing) and finally multiplying the product with 365 days.

The calculation presented below is based on a method alternative to that has been calculated in the model:

Total dairy cattle (six-year average) = 552385 (ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b)
Average daily dry matter (DM) intake through pasture grazing per cattle = 8.23 kg (Powell et al., 2012)
Average P content in pasture = 4.95 g/kg DM (Powell et al., 2012)

Annual P flow as pasture grazing by dairy cattle;
{(552385*8.23*4.95*365)/1000000} tonnes
= 8214 tonnes

2. P excretion by dairy cattle

Currently, the model calculates P flow as dairy cattle excreta by directly multiplying the total dairy cattle number with the daily P excretion rate per cattle, and then multiplying the product with the number of days in a year.

The calculation below is based on a method alternative to that has been calculated in the model:

Total dairy cattle (six-year average) = 552985 (ABS, 2009a, 2010, 2011a, 2012, 2013a, 2014b).
Excretion of faeces = 32 kg/day/cow (ASAE, 2005)
Excretion of urine = 22 kg/day/cow (ASAE, 2005)
P concentration in faeces = 1.32 g/kg (Dairy Australia, 2008)
P concentration in urine = 0.27 g/kg (Dairy Australia, 2008)

Annual P flow as dairy cattle excreta;
[{(552985*32*1.32*365) + (552985*22*0.27*365)}/1000000] tonnes
= 9725 tonnes

3. Cumulative soil P storage in crop farming area over six years

The calculation below is based on actual field experiment based study in the crop farming area in the Gippsland region. This information has been collected through personal communication with the help of supervisor (Dr Anthony Weatherley).

Over 24 years in a long-term cropping trial a continuous wheat crop with annual additions of 10 kgP/ha

Total P increased from 295 to 486 mgP/kg soil

So 200 mgP/kg soil (depth not specified but assume 0-10 cm)

Use bulk density 1 g/cm^3 or 1 tonne /m^3

1 ha = 10,000 m^2

Volume to 10 cm = 10,000 m^2*0.1 m = 1000 m^3

V = mass/density => mass = v*density

= 1000m^3*1000kg/m^3

= 10^6 kg

Therefore, soil increased by 200*10^6 mgP/ha

=200 kg P/ha

With this rate, the cumulative P storage in crop farming areas in the Gippsland region over 24 years can be calculated as;

{(134071*200)/1000} tonnes

=26814 tonnes

Therefore, the cumulative P storage over 6 years is;

{(26814/24)* 6} tonnes

=6704 tonnes

4. P loadings to Gippsland lakes

The current modelling in this study has assessed that in the Gippsland region (total area of 3828406 hectares), the mean annual P loadings to water bodies is about 543 tonnes.

According to Ladson and Tilleard (2006), approximate annual P loading to the Gippsland lakes from the surrounding catchment area (total area of 2060000 hectares) is about 329 tonnes.

With this information, the rate of P loadings can be calculated as (329000/2060000) kg/ha or 0.16 kg/ha.

Using this rate, the total annual P loadings to the water bodies in the Gippsland region can be calculated as;

(3828406*0.16/1000) tonnes

= 613 tonnes

REFERENCES

ABARES. (2014). *Agriculture, Fisheries and Forestry in the Latrobe-Gippsland region of Victoria 2014: About my region 14.20*. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, Australia.

ABS. (2008). *3222.0 Population Projections, Australia, 2006 to 2101*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3222.02006%20to%202101?OpenDocument

ABS. (2009). *46270DO001_200708 Land Management and Farming in Australia, 2007-08*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4627.02007-08?OpenDocument

ABS. (2009a). *71210DO001_200809 Agricultural Commodities, Australia, 2007-08*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02007-08?OpenDocument

ABS. (2010). *71210DO001_200809 Agricultural Commodities, Australia, 2008-09*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02008-09?OpenDocument

ABS. (2011). *46270DO006_200910 Land Management and Farming in Australia, 2009-10*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4627.02009-10?OpenDocument

ABS. (2011a). *71210DO002_200910 Agricultural Commodities, Australia, 2009-10*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02009-10?OpenDocument

ABS. (2012). *71210DO006_201011 Agricultural Commodities, Australia, 2010-11*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02010-11?OpenDocument

ABS. (2013). *46270DO002_201112 Land Management and Farming in Australia, 2011-12*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. doi: http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4627.02011-12?OpenDocument

ABS. (2013a). *71210DO004_201112 Agricultural Commodities, Australia, 2011-12*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02011-12?OpenDocument

ABS. (2013b). *4609055002DO002_2012 Land Account: Victoria, Experimental Estimates, 2012*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4609.0.55.0022012?OpenDocument

ABS. (2014). *3218.0 Regional Population Growth, Australia*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02012-13?OpenDocument

ABS. (2014a). *46270DO002_201213 Land Management and Farming in Australia, 2012-13*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4627.02012-13?OpenDocument

ABS. (2014b). *71210DO004_201213 Agricultural Commodities, Australia, 2012-13*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02012-2013?OpenDocument

ABS. (2014c). *7218.0.55.001 Livestock and Meat, Australia*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7218.0.55.001Aug%202014?OpenDocument

ABS. (2014d). *43640DO001_20112012 Australian Health Survey: Nutrition First Results - Foods and Nutrients, 2011-12 -Australia*. Australian Bureau of Statistics, Australian Government, Canberra, Australia. Retrieved from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4364.0.55.0072011-12?OpenDocument

ACAC. (2010). *Contribution of the Pet Care Industry to the Australian Economy*. 7th Edition; Australian Companion Animal Council Inc., Unit 40, 6 Herbert Street, St Leonards NSW 2065, Australia. Retrieved from http://www.acac.org.au/pdf/ACAC%20Report%200810_sm.pdf

ACCC. (2008). *ACCC examination of fertiliser prices*. Australian Competition and Consumer Commission, GPO Box 3131, Canberra ACT 2601, Australia. Retrieved from http://www.accc.gov.au/publications/accc-examination-of-fertiliser-prices

AECL. (2013). *Egg Labelling Guide- Guide to Australian laws, regulations and standards for egg producers*. Australian Egg Corporation, Suite 4.02, 107 Mount St North Sydney NSW 2060, Australia. Retrieved from http://www.humanechoice.com.au/Resources/Documents/Egg-Labelling-Guide-March-2013-FINAL-1.pdf

Ahn, H., & James, R. T. (2001). Variability, Uncertainty, and Sensitivity of Phosphorus Deposition Load Estimates in South Florida. *Water, Air, and Soil Pollution, 126*(1-2), 37-51. doi: 10.1023/A:1005235118716

Akhtar, M. K., Wibe, J., Simonovic, S. P., & MacGee, J. (2013). Integrated assessment model of society-biosphere-climate-economy-energy system. *Environmental Modelling & Software, 49*, 1-21. doi: http://dx.doi.org/10.1016/j.envsoft.2013.07.006

Allan, H., Havilah, E., & Kemp, H. (1997). *Establishing Pastures*. NSW Agriculture, NSW, Australia. Retrieved from http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0020/163109/establishing-pastures-full.pdf

Anderson, K., & Downing, J. (2006). Dry and wet atmospheric deposition of nitrogen, phosphorus and silicon in an agricultural region. *Water, Air, and Soil Pollution, 176*(1-4), 351-374. doi: 10.1007/s11270-006-9172-4

Antikainen, R., Haapanen, R., Lemola, R., Nousiainen, J., & Rekolainen, S. (2008). Nitrogen and Phosphorus Flows in the Finnish Agricultural and Forest Sectors, 1910–2000. *Water, Air, and Soil Pollution, 194*(1-4), 163-177. doi: 10.1007/s11270-008-9705-0

Antikainen, R., Lemola, R., Nousiainen, J. I., Sokka, L., Esala, M., Huhtanen, P., & Rekolainen, S. (2005). Stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system. *Agriculture, Ecosystems & Environment, 107*(2–3), 287-305. doi: http://dx.doi.org/10.1016/j.agee.2004.10.025

ANZBP. (2009). *Land Application of Biosolids- Fact Sheet*. Australia & New Zealand Biosolids Partnership, Australian Water Association, PO Box 222, St Leonards, NSW 1590, Australia. Retrieved from http://www.biosolids.com.au/factsheets.php

APL. (2011). *Australian Pork Limited Industry Survey Report*. Australian Pork Limited, 2 Brisbane Avenue, Barton ACT 2600, Australia.

APL. (2014). *The Big Questions*. Australian Pork Limited, 2 Brisbane Avenue, Barton ACT 2600, Australia. Retrieved from http://www.aussiepigfarmers.com.au/bigquestions/

Arena, U., & Di Gregorio, F. (2013). Element partitioning in combustion- and gasification-based waste-to-energy units. *Waste Management, 33*(5), 1142-1150. doi: http://dx.doi.org/10.1016/j.wasman.2013.01.035

ASAE. (2005). *Manure Production and Characteristics*. ASAE-The Society for engineering in agricultural, food, and biological systems 2950 Niles Rd., St. Joseph, MI 49085-9659, USA. Retrieved from http://extension.psu.edu/animals/dairy/nutrient-management/certified-dairy/tools/manure-prod-char-d384-2.pdf

Ashley, K., Cordell, D., & Mavinic, D. (2011). A brief history of phosphorus: From the philosopher's stone to nutrient recovery and reuse. *Chemosphere, 84(*6), 737-746. doi: http://dx.doi.org/10.1016/j.chemosphere.2011.03.001

Atech Group. (2000). *Cost of Algal Blooms*. Occasional Paper 26/99; Prepared for Land and Water Resources Research and Development and Murray Darling Basin Commission, LWRRDC, Canberra, Australia. Retrieved from http://www.lwa.gov.au/publications_search_details.asp?id=61

Baker, L., Hartzheim, P., Hobbie, S., King, J., & Nelson, K. (2007). Effect of consumption choices on fluxes of carbon, nitrogen and phosphorus through households. *Urban Ecosystems, 10*(2), 97-117. doi: 10.1007/s11252-006-0014-3

Baker, L. A. (2011). Can urban P conservation help to prevent the brown devolution? *Chemosphere, 84*(6), 779-784. doi: http://dx.doi.org/10.1016/j.chemosphere.2011.03.026

Bala, B. K., Arshad, F. M., Alias, E. F., Sidique, S. F., Noh, K. M., Rowshon, M. K., . . . Islam, M. M. (2014). Sustainable exploitation of hilsa fish (Tenualosa ilisha) population in Bangladesh: Modeling and policy implications. *Ecological Modelling, 283,* 19-30. doi: http://dx.doi.org/10.1016/j.ecolmodel.2014.03.013

Barson, M. (2013). *Land management practice trends in Victoria's grazing (beef cattle/sheep) industries*. Caring for our Country Sustainable Practices fact sheet 12; Department of Agriculture, Fisheries and Forestry, Canberra, Australia.

Bateman, A., van der Horst, D., Boardman, D., Kansal, A., & Carliell-Marquet, C. (2011). Closing the phosphorus loop in England: The spatio-temporal balance of phosphorus capture from manure versus crop demand for fertiliser. *Resources, Conservation and Recycling, 55*(12), 1146-1153. doi: http://dx.doi.org/10.1016/j.resconrec.2011.07.004

Beighle, D. E., Boyazoglu, P. A., Hemken, R. W., & Serumaga-Zake, P. A. (1994). Determination of calcium, phosphorus, and magnesium values in rib bones from clinically normal cattle. *American journal of veterinary research, 55*(1), 85-89.

Bernstad, A., & la Cour Jansen, J. (2011). A life cycle approach to the management of household food waste – A Swedish full-scale case study. *Waste Management, 31*(8), 1879-1896. doi: http://dx.doi.org/10.1016/j.wasman.2011.02.026

Bernstad, A., & la Cour Jansen, J. (2012). Review of comparative LCAs of food waste management systems – Current status and potential improvements. *Waste Management, 32*(12), 2439-2455. doi: http://dx.doi.org/10.1016/j.wasman.2012.07.023

Bi, J., Chen, Q., Zhang, L., & Yuan, Z. (2013). Quantifying Phosphorus Flow Pathways Through Socioeconomic Systems at the County Level in China. *Journal of Industrial Ecology, 17*(3), 452-460. doi: 10.1111/j.1530-9290.2012.00555.x

Block, H. C., Erickson, G. E., & Klopfenstein, T. J. (2004). Review: Re-evaluation of Phosphorus Requirements and Phosphorus Retention of Feedlot Cattle. *The Professional Animal Scientist, 20*(4), 319-329.

Boesch, D. F., Boynton, W. R., Crowder, L. B., Diaz, R. J., Howarth, R. W., Mee, L. D., . . . Turner, R. E. (2009). Nutrient Enrichment Drives Gulf of Mexico Hypoxia. *Eos, Transactions American Geophysical Union, 90*(14), 117-118. doi: 10.1029/2009EO140001

Boesch, D. F., Brinsfield, R. B., & Magnien, R. E. (2001). Chesapeake Bay Eutrophication. *J. Environ. Qual., 30*(2), 303-320. doi: 10.2134/jeq2001.302303x

Bolster, C. H., Horvath, T., Lee, B. D., Mehlhope, S., Higgins, S., & Delgado, J. A. (2014). Development and testing of a new phosphorus index for Kentucky. *Journal of Soil and Water Conservation, 69*(3), 183-196. doi: 10.2489/jswc.69.3.183

Bouwman, A. F., Beusen, A. H. W., & Billen, G. (2009). Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. *Global Biogeochemical Cycles*, *23*(4), GB0A04. doi: 10.1029/2009GB003576

Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H. W., Van Vuuren, D. P., Willems, J., . . . Stehfest, E. (2011). Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *Proceedings of the National Academy of Sciences, 110*(52), 20882-20887 doi: 10.1073/pnas.1012878108

Breitburg, D. (2002). Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries, 25*(4), 767-781. doi: 10.1007/BF02804904

Brodie, J. E., Devlin, M., Haynes, D., & Waterhouse, J. (2011). Assessment of the eutrophication status of the Great Barrier Reef lagoon (Australia). *Biogeochemistry, 106*(2), 281-302. doi: 10.1007/s10533-010-9542-2

Brunner, P. H. (2004). *Practical handbook of material flow analysis*. Boca Raton, FL.

Brunner, P. H. (2010). Substance Flow Analysis as a Decision Support Tool for Phosphorus Management. *Journal of Industrial Ecology, 14*(6), 870-873. doi: 10.1111/j.1530-9290.2010.00300.x

Bush, R. A. Y. (2010). Food Riots: Poverty, Power and Protest[1]. *Journal of Agrarian Change, 10*(1), 119-129. doi: 10.1111/j.1471-0366.2009.00253.x

Carpenter, S. R. (2008). Phosphorus control is critical to mitigating eutrophication. *Proceedings of the National Academy of Sciences, 105*(32), 11039-11040. doi: 10.1073/pnas.0806112105

Carstensen, J., Conley, D., Bonsdorff, E., Gustafsson, B., Hietanen, S., Janas, U., . . . Voss, M. (2014). Hypoxia in the Baltic Sea: Biogeochemical Cycles, Benthic Fauna, and Management. *AMBIO, 43*(1), 26-36. doi: 10.1007/s13280-013-0474-7

Cencic, O., & Rechberger, H. (2008). Material flow analysis with software STAN. *Journal of Environmental Engineering and Management, 18*(1), 3-7. doi: http://enviroinfo.eu/sites/default/files/pdfs/vol119/0440.pdf

CGRWC. (2009). *2008-09 Gippsland Water Annual Report*. State of Victoria, Central Gippsland Region Water Corporation; Gippsland Water, Hazelwood Road PO BOX 348 Traralgon VIC 3844, Australia. Retrieved from http://www.gippswater.com.au/Portals/0/ABOUT%20US/Annual_Report_2008-09.pdf

CGRWC. (2010). *2009-10 Gippsland Water Annual Report*. State of Victoria, Central Gippsland Region Water Corporation; Gippsland Water, Hazelwood Road PO BOX 348 Traralgon VIC 3844, Australia. Retrieved from http://www.gippswater.com.au/Portals/0/ABOUT%20US/Annual_Report_2009-10.pdf

CGRWC. (2012). *Annual Performance Statement - Central Gippsland Region Water Corporation Financial year 2011/12*. Central Gippsland Region Water Corporation, Hazelwood Road PO BOX 348 Traralgon VIC 3844, Australia. Retrieved from http://www.epa.vic.gov.au/our-work/licences-and-approvals/~/media/Files/compliance-enforcement/licences/Docs/APS201112/Unreformed/CL62999CentralGippslandRegionWaterCorpAPS201112.pdf

Chen, M., Chen, J., & Sun, F. (2008). Agricultural phosphorus flow and its environmental impacts in China. *Science of The Total Environment, 405*(1–3), 140-152. doi: http://dx.doi.org/10.1016/j.scitotenv.2008.06.031

Chesapeake Bay Program. (2012). *Phosphorus Loads and River Flows to the Bay*. Chesapeake Bay Program; Annapolis, Maryland 21403, USA. Retrieved from http://www.chesapeakebay.net/indicators/indicator/P_loads_and_river_flow_to_the_bay (accessed: 05.08.2013)

Childers, D. L., Corman, J., Edwards, M., & Elser, J. J. (2011). Sustainability Challenges of Phosphorus and Food: Solutions from Closing the Human Phosphorus Cycle. *BioScience, 61*(2), 117-124. doi: 10.1525/bio.2011.61.2.6

Chlot, S., Widerlund, A., Siergieiev, D., Ecke, F., Husson, E., & Öhlander, B. (2011). Modelling nitrogen transformations in waters receiving mine effluents. *Science of The Total Environment, 409*(21), 4585-4595. doi: http://dx.doi.org/10.1016/j.scitotenv.2011.07.024

Chowdhury, R. B., Moore, G. A., Weatherley, A. J., & Arora, M. (2014). A review of recent substance flow analyses of phosphorus to identify priority management areas at different geographical scales. *Resources, Conservation and Recycling, 83*, 213-228. doi: http://dx.doi.org/10.1016/j.resconrec.2013.10.014

Clark, C. (2014). *Toil and Soil*. ABC, Australia. doi: http://www.abc.net.au/landline/content/2014/s4020946.htm

CNN (2008, April 14). Riots, instability spread as food prices skyrocket. *Cable News Network*. Retrieved from http://edition.cnn.com/2008/WORLD/americas/04/14/world.food.crisis/ (accessed: 30.07.2013).

Conley, D. J. (2012). Ecology: Save the Baltic Sea. *Nature, 486*, 463-464. doi: 10.1038/486463a

Conley, D. J., Bonsdorff, E., Carstensen, J., Destouni, G., Gustafsson, B. G., Hansson, L.-A., . . . Zillén, L. (2009). Tackling Hypoxia in the Baltic Sea: Is Engineering a Solution? *Environmental Science & Technology, 43*(10), 3407-3411. doi: 10.1021/es8027633

Conley, D. J., Paerl, H. W., Howarth, R. W., Boesch, D. F., Seitzinger, S. P., Havens, K. E., . . . Likens, G. E. (2009a). Controlling Eutrophication: Nitrogen and Phosphorus. *Science, 323*(5917), 1014-1015. doi: 10.1126/science.1167755

Connolly, B., & Hylands, P. (2009). *Economic Impact of the 2008 Blue Green Algal Bloom on the Gippsland Lakes Tourism Industry*. Nexus Consulting (Aust) Pty Ltd, PO Box 24 Bairnsdale 3875, Victoria, Australia. Retrieved from http://www.gcb.vic.gov.au/publications/inlakeresearch/Full%20final%20Report.pdf

Cooper, J., & Carliell-Marquet, C. (2013). A substance flow analysis of phosphorus in the UK food production and consumption system. *Resources, Conservation and Recycling, 74*, 82-100. doi: http://dx.doi.org/10.1016/j.resconrec.2013.03.001

Cooper, J., Lombardi, R., Boardman, D., & Carliell-Marquet, C. (2011). The future distribution and production of global phosphate rock reserves. *Resources, Conservation and Recycling, 57*, 78-86. doi: http://dx.doi.org/10.1016/j.resconrec.2011.09.009

Cordell, D., Drangert, J.-O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change, 19*(2), 292-305. doi: http://dx.doi.org/10.1016/j.gloenvcha.2008.10.009

Cordell, D., Jackson, M., & White, S. (2013). Phosphorus flows through the Australian food system: Identifying intervention points as a roadmap to phosphorus security. *Environmental Science & Policy, 29*, 87-102. doi: http://dx.doi.org/10.1016/j.envsci.2013.01.008

Cordell, D., Neset, T.-S. S., & Prior, T. (2012). The phosphorus mass balance: identifying 'hotspots' in the food system as a roadmap to phosphorus security. *Current Opinion in Biotechnology, 23*(6), 839-845. doi: http://dx.doi.org/10.1016/j.copbio.2012.03.010

Cordell, D., White, S., & Lindström, T. (2011). Peak phosphorus: the crunch time for humanity? . *The Sustainability Review*. doi: https://thesustainabilityreview.org/peak-phosphorus-the-crunch-time-for-humanity/

Cordell, D., & White, S. (2011). Peak Phosphorus: Clarifying the Key Issues of a Vigorous Debate about Long-Term Phosphorus Security. *Sustainability, 3(*10), 2027-2049.

Corrales, J., Naja, G. M., Bhat, M. G., & Miralles-Wilhelm, F. (2014). Modeling a phosphorus credit trading program in an agricultural watershed. *Journal of Environmental Management, 143*, 162-172. doi: http://dx.doi.org/10.1016/j.jenvman.2014.04.031

Costa, S. E. V. G. A., Souza, E. D., Anghinoni, I., Carvalho, P. C. F., Martins, A. P., Kunrath, T. R., . . . Balerini, F. (2014). Impact of an integrated no-till crop–livestock system on phosphorus distribution, availability and stock. *Agriculture, Ecosystems & Environment, 190*, 43-51. doi: http://dx.doi.org/10.1016/j.agee.2013.12.001

Cottingham, P., Grayson, R., Ladson, T., & Tilleard, J. (2006). *Priority nutrient reduction activities for the Gippsland Lakes and catchments; Part 2 – Application of Best management Practices to reduce nutrient loads*. Report prepared for Gippsland Lakes Task Force; Peter Cottingham & Associates. Retrieved from http://www.gippslandlakes.net.au/wp-content/uploads/2012/11/Priorities_for_nutrient_reductions.pdf

Crews, T., Cotner, J., & McCreary, C. (2013). Cultural beliefs, values, and the biogeochemical cycling of phosphorus. In K. A. Wyant, J. R. Corman & J. J. Elser (Eds.*), Phosphorus, food and our future* (pp. 142-166). Oxford: Oxford University Press.

CSBP. (2012). *Soil and plant nutrition*. CSBP Limited, 2 Altona Street Bibra Lake WA 6163, Australia. Retrieved from http://www.csbp-fertilisers.com.au/research-trials/research/soil-and-plant-nutrition (Accessed: 21/10/2014)

Dace, E., Bazbauers, G., Berzina, A., & Davidsen, P. I. (2014). System dynamics model for analyzing effects of eco-design policy on packaging waste management system. *Resources, Conservation and Recycling, 87*, 175-190. doi: http://dx.doi.org/10.1016/j.resconrec.2014.04.004

DAF. (2007). *Supplementary feeding for sheep*. Department of Agriculture and Food. Government of Western Australia, Australia. Retrieved from http://archive.agric.wa.gov.au/PC_91898.html?s=0

DAFF. (2011). *Australian Food Statistics 2009-10*. Department of Agriculture, Fisheries and Forestry; Australian Government, GPO Box 858, Canberra ACT 2601, Australia. Retrieved from http://www.agriculture.gov.au/ag-farm-food/food/publications/afs

Dairy Australia. (2008). *Effluent and Manure Management Database for the Australian Dairy Industry*. Dairy Australia Ltd, Level 5, IBM Centre, 60 City Road Southbank VIC 3006, Australia. Retrieved from http://www.dairyingfortomorrow.com/index.php?id=48

Dairy-Australia. (2011). *Dairy 2011: Situation and Outlook*. Dairy Australia Ltd, Level 5, IBM Centre, 60 City Road Southbank VIC 3006, Australia. Retrieved from http://www.dairyaustralia.com.au/Markets-and-statistics/Market-situation-and-outlook.aspx

Dairy-Australia. (2012). *Dairy 2012: Situation and Outlook*. Dairy Australia Ltd, Level 5, IBM Centre, 60 City Road Southbank VIC 3006, Australia. Retrieved from http://www.dairyaustralia.com.au/Markets-and-statistics/Market-situation-and-outlook.aspx

Dairy-Australia. (2013). *Dairy 2013: Situation and Outlook*. Dairy Australia Ltd, Level 5, IBM Centre, 60 City Road Southbank VIC 3006, Australia. Retrieved from http://www.dairyaustralia.com.au/Markets-and-statistics/Market-situation-and-outlook.aspx

Dairy-Australia. (2014). *Nutrient-Rich Vs Nutrient-Poor*. Dairy Australia Ltd, Level 5, IBM Centre, 60 City Road Southbank VIC 3006, Australia. Retrieved from http://www.dairy.edu.au/discoverdairy/Teachers/Fuel-for-Life-Module/Energy-vs-Nutrients.aspx

Das, R., Evan, A., & Lawrence, D. (2013). Contributions of long-distance dust transport to atmospheric P inputs in the Yucatan Peninsula. *Global Biogeochemical Cycles, 27*(1), 167-175. doi: 10.1029/2012GB004420

Dawson, C. J., & Hilton, J. (2011). Fertiliser availability in a resource-limited world: Production and recycling of nitrogen and phosphorus. *Food Policy, 36*, Supplement 1, S14-S22. doi: http://dx.doi.org/10.1016/j.foodpol.2010.11.012

DEPI. (2010). *The Victorian fertiliser survey 2008-09*. Department of Primary Industries, 1 Spring Street, Melbourne 3000. Retrieved from http://www.depi.vic.gov.au/__data/assets/pdf_file/0008/187856/The-Victorian-fertiliser-survey-2008-09.pdf

DEPI. (2013). *Victoria's Beef Cattle Industry*. Department of Environment and Primary Industries, PO Box 500, Melbourne VIC 8002, Australia. Retrieved from http://www.depi.vic.gov.au/agriculture-and-food/livestock/beef/victorias-beef-cattle-industry

DEPI. (2014). *Region Overview: Gippsland*. Department of Environment and Primary Industries, 8 Nicholson Street, East Melbourne VIC 3002, Australia. Retrieved from http://www.depi.vic.gov.au/agriculture-and-food/food-and-fibre-industries/region-overviews/gippsland

DEPI. (2014a). *Feedlotting Lambs*. Department of Environment and Primary Industries, PO Box 500, Melbourne VIC 8002, Australia. Retrieved from http://www.depi.vic.gov.au/agriculture-and-food/livestock/sheep/victorias-sheep-meat-and-wool-industry/feeding-and-nutrition/feedlotting-lambs

Diaz, R. J., & Rosenberg, R. (2008). Spreading Dead Zones and Consequences for Marine Ecosystems. *Science, 321(*5891), 926-929. doi: 10.1126/science.1156401

DNRE. (2002). *Gippsland Lakes future directions and action plan*. Department of Natural Resources and Environment, Melbourne, Australia.

Do-Thu, N., Morel, A., Nguyen-Viet, H., Pham-Duc, P., Nishida, K., & Kootattep, T. (2011). Assessing nutrient fluxes in a Vietnamese rural area despite limited and highly uncertain data. *Resources, Conservation and Recycling, 55*(9–10), 849-856. doi: http://dx.doi.org/10.1016/j.resconrec.2011.04.008

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., . . . Thornbrugh, D. J. (2009). Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. *Environmental Science & Technology, 43*(1), 12-19. doi: 10.1021/es801217q

Domagalski, J. L., & Johnson, H. (2012). *Phosphorus and Groundwater: Establishing Links between Agricultural Use and Transport to Streams*. Fact Sheet: Prepared as part of the National Water-Quality Assessment Program, Agricultural Chemicals Team (ACT); U.S Department of Interior, U.S. Geological Survey. Retrieved from http://pubs.usgs.gov/fs/2012/3004/pdf/fs20123004.pdf

DPCD. (2013). *Draft Regional Growth Plan*. Department of Planning and Community Development, 1 Spring Street, Melbourne 3000, Australia. Retrieved from http://www.dtpli.vic.gov.au/__data/assets/pdf_file/0005/229424/Gippsland-plan-final-web-1-23072013.pdf

DSE. (2009). *Gippsland Region Sustainable Water Strategy*. Department of Sustainability and Environment, State Government of Victoria, Melbourne, Australia. Retrieved from http://www.depi.vic.gov.au/__data/assets/pdf_file/0005/188888/GRSWS_DP_Complete.pdf

DSE. (2011). *Gippsland region sustainable water strategy*. Department of Sustainability and Environment, State Government of Victoria, Melbourne, Australia. Retrieved from http://www.depi.vic.gov.au/__data/assets/pdf_file/0003/188832/DSE_GRWS_accessible_linked.pdf

E. E. Muir and Sons. (2012). *Fertilizer*. E.E. Muir and Sons, Laverton Nth, Victoria 3026, Australia. Retrieved from http://eem.greatisland.com.au/shopDisplayCategories.asp?id=2&cat=FERTILISERS+-+CAMPBELLS

East Gippsland Shire Council. (2014). *Domestic Wastewater*. East Gippsland Shire Council, Bairnsdale, Victoria 387, Australia. Retrieved from http://www.eastgippsland.vic.gov.au/Services/Public_Health/Domestic_Wastewater

Edixhoven, J. D., Gupta, J., & Savenije, H. H. G. (2013). Recent revisions of phosphate rock reserves and resources: reassuring or misleading? An in-depth literature review of global estimates of phosphate rock reserves and resources. *Earth Syst Dynam Discuss, 4,* 1005–1034. doi: 10.5194/esdd-4-1005-2013

Egle, L., Zoboli, O., Thaler, S., Rechberger, H., & Zessner, M. (2014). The Austrian P budget as a basis for resource optimization. *Resources, Conservation and Recycling, 83,* 152-162. doi: http://dx.doi.org/10.1016/j.resconrec.2013.09.009

EGRWC. (2010). *East Gippsland Water Annual Report 2009/2010*. East Gippsland Region Water Corporation, East Gippsland Water, 133 Macleod Street Bairnsdale 3875 Victoria, Australia. Retrieved from http://www.egwater.vic.gov.au/NewsandPublications/Publications/AnnualReports/tabid/152/Default.aspx

Elser, J., & Bennett, E. (2011). Phosphorus cycle: A broken biogeochemical cycle. *Nature, 478*, 29-31. doi: 10.1038/478029a

Elser, J. J. (2012). Phosphorus: a limiting nutrient for humanity? *Current Opinion in Biotechnology, 23*(6), 833-838. doi: http://dx.doi.org/10.1016/j.copbio.2012.03.001

Elshkaki, A. (2007). System analysis of stock buffering: Development of a dynamic substance flow-stock model for the identification and estimation of future resources, waste streams and emissions. Institute of Environmental Sciences (CML), Leiden University, The Netherlands.

Elshkaki, A. (2013). An analysis of future platinum resources, emissions and waste streams using a system dynamic model of its intentional and non-intentional flows and stocks. *Resources Policy, 38*(3), 241-251. doi: http://dx.doi.org/10.1016/j.resourpol.2013.04.002

EPA Victoria. (2009). *EPA Victoria Corporate Licence - Licence Holder: Central Gippsland Regional Water Corporation*. EPA Information Centre, 40 city road, Southbank, Victoria 3001, Australia. Retrieved from http://www.epa.vic.gov.au/our-work/licences-and-approvals/~/media/Files/compliance-enforcement/licences/Docs/corporate-licences-2010-11/CL62999-CENTRAL-GIPPSLAND-REGION-WATER-CORPORATION.pdf

EPHC. (2010). *National Waste Report-2010: Chapter 2- Resource recovery and waste management in Australia today*. Department of Environment, Waste and Heritage and the Arts, the Australian Government. Retrieved from http://www.scew.gov.au/system/files/resources/020c2577-eac9-0494-493c-d1ce2b4442e5/files/wastemgt-nat-waste-report-final-20-fullreport-201005-0.pdf

Fagan, J. E., Reuter, M. A., & Langford, K. J. (2010). Dynamic performance metrics to assess sustainability and cost effectiveness of integrated urban water systems. *Resources, Conservation and Recycling, 54*(10), 719-736. doi: http://dx.doi.org/10.1016/j.resconrec.2009.12.002

Fan, Y., Hu, S., Chen, D., Li, Y., & Shen, J. (2009). The evolution of phosphorus metabolism model in China. *Journal of Cleaner Production, 17*(9), 811-820. doi: http://dx.doi.org/10.1016/j.jclepro.2008.12.007

FAO. (1996). *Rome Declaration on World Food Security and World Food Summit Plan of Action*. World Food Summit 13-17 November 1996. Rome, Italy. Retrieved from http://www.fao.org/docrep/003/w3613e/w3613e00.HTM (accessed: 13.08.2013)

FAO. (2004). *Fertilizer use by crop in Brazil*. Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from ftp://ftp.fao.org/agl/agll/docs/fertusebrazil.pdf

FAO. (2008). *The State of Food Insecurity in the World 2008: High food prices and food security-threats and opportunities*. Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from ftp://ftp.fao.org/docrep/fao/011/i0291e/i0291e00.pdf

FAO. (2008a). *Current World Fertilizer Trends and Outlook to 2010/11*. Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from ftp://ftp.fao.org/agl/agll/docs/cwfto11.pdf

FAO. (2009). *The 2007–2008 Food Price Swing: Impact and Policies in Eastern and Southern Africa*. FAO Commodities and Trade Technical Paper; Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from ftp://ftp.fao.org/docrep/fao/012/i0984e/i0984e00.pdf

FAO. (2009a). *Global agriculture towards 2050*. High Level Expert Forum on How to feed the world in 2050; Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf

FAO. (2011). *Current World Fertilizer Trends and Outlook to 2015*. Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from ftp://ftp.fao.org/ag/agp/docs/cwfto15.pdf

FAO. (2011a). *Lessons from the world food crisis of 2006–08*. Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from http://www.fao.org/docrep/014/i2330e/i2330e04.pdf

FAO. (2011b). *Safeguarding Food Security in Volatile Global Markets*. Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from http://www.fao.org/docrep/013/i2107e/i2107e.pdf

FAO. (2013). *FAO Initiative on Soaring Food Prices*. Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from http://www.fao.org/isfp/background/en/ (accessed: 17.08.2013)

FAO Statistical Yearbook. (2014). *Africa food and agriculture, Part-2: Hunger Dimension*. Food and Agricultural Organizations of the United Nations, Rome, Italy. Retrieved from http://www.fao.org/3/a-i3620e.pdf

Feng, Y. Y., Chen, S. Q., & Zhang, L. X. (2013). System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China. *Ecological Modelling, 252*, 44-52. doi: http://dx.doi.org/10.1016/j.ecolmodel.2012.09.008

Fernández, C., Espinós, F. J., López, M. C., García-Diego, F. J., & Cervera, C. (2013). Representation of a mathematical model to predict methane output in dairy goats. *Computers and Electronics in Agriculture, 91*, 1-9. doi: http://dx.doi.org/10.1016/j.compag.2012.11.013

FIFA. (2013). *The Australian Fertilizer Market*. Fertilizer Australia; Locked Bag 916, Canberra ACT 2601, Australia. doi: http://www.fertilizer.org.au/default.asp?V_DOC_ID=1174

Fissore, C., Baker, L. A., Hobbie, S. E., King, J. Y., McFadden, J. P., Nelson, K. C., & Jakobsdottir, I. (2011). Carbon, nitrogen, and phosphorus fluxes in household ecosystems in the Minneapolis-Saint Paul, Minnesota, urban region. *Ecological Applications, 21*(3), 619-639. doi: 10.1890/10-0386.1

Fixen, P. E. (2009). World Fertilizer Nutrient Reserves - A View to the Future. *Better Crops*, *93*(3), 8-11.

FSA Consulting. (2009). *Improving Manure Reuse in Intensive Livestock Industries Using Electro-Magnetic Induction Technology Beef Cattle Feedlot Case Study*. Report no. 7080/1, 7080 Feedlot Industry Case Study Final Report prepared for Condamine Alliance, Toowoomba Head Office, Toowoomba, QLD 4350, Australia.

FSANZ. (2013). *AUSNUT 2011-13 food nutrient database*. Food Standards Australia New Zealand, PO Box 7186, Canberra BC ACT 2610, Australia. Retrieved from http://www.foodstandards.gov.au/science/monitoringnutrients/ausnut/ausnutdatafiles/Pages/foodnutrient.aspx

García-Albacete, M., Martín, A., & Cartagena, M. C. (2012). Fractionation of phosphorus biowastes: Characterisation and environmental risk. *Waste Management, 32*(6), 1061-1068. doi: http://dx.doi.org/10.1016/j.wasman.2012.02.003

García, A. J., Esteban, M. B., Márquez, M. C., & Ramos, P. (2005). Biodegradable municipal solid waste: Characterization and potential use as animal feedstuffs. *Waste Management, 25*(8), 780-787. doi: http://dx.doi.org/10.1016/j.wasman.2005.01.006

Georgiadis, P. (2013). An integrated System Dynamics model for strategic capacity planning in closed-loop recycling networks: A dynamic analysis for the paper industry. *Simulation Modelling Practice and Theory, 32*, 116-137. doi: http://dx.doi.org/10.1016/j.simpat.2012.11.009

Geoscience Australia. (2013). *Australia's identified Mineral Resources 2012*. Geoscience Australia, Canberra, Australia. Retrieved from http://www.ga.gov.au/corporate_data/75326/75326.pdf

Ghani, L. A., & Mahmood, N. Z. (2011). A Balance Sheet for Phosphorus in Malaysia by SF. *Australian Journal of Basic and Applied Sciences*, *5*(12), 3069-3079.

Gilbert, N. (2009). Environment: The disappearing nutrient. *Nature, 461*, 716-718. doi: 10.1038/461716a

GippsDairy. (2008). GippsDairy Annual Report 2007/08. GippsDairy, Unit 4/71 Korumburra Road, PO Box 1059 McMillan Campus, Warragul VIC 3820, Australia. Retrieved from http://www.gippsdairy.com.au/LinkClick.aspx?fileticket=jH9KjV77f08%3d&tabid=80&mid=465

GippsDairy. (2009). *GippsDairy Annual Report 2008/09*. GippsDairy, Unit 4/71 Korumburra Road, PO Box 1059 McMillan Campus, Warragul VIC 3820, Australia. Retrieved from http://www.gippsdairy.com.au/LinkClick.aspx?fileticket=ZcuUwgoXXKM%3d&tabid=80&mid=465

GippsDairy. (2010). *GippsDairy Annual Report 2009/10*. GippsDairy, Unit 4/71 Korumburra Road, PO Box 1059 McMillan Campus, Warragul VIC 3820, Australia. Retrieved from http://www.gippsdairy.com.au/LinkClick.aspx?fileticket=RuMTIddWbRM%3d&tabid=80&mid=465

GippsDairy. (2012). GippsDairy Annual Report 2011/12. GippsDairy, Unit 4/71 Korumburra Road, PO Box 1059 McMillan Campus, Warragul VIC 3820, Australia. Retrieved from http://www.gippsdairy.com.au/LinkClick.aspx?fileticket=biBraRb2WF8%3d&tabid=80&mid=465

GippsDairy. (2014). *Dairy in Gippsland*. GippsDairy, Unit 4/71 Korumburra Road, PO Box 1059 McMillan Campus, Warragul VIC 3820, Australia. Retrieved from http://www.gippsdairy.com.au/

GippsDairy. (2014a). GippsDairy Annual Report 2013/14. GippsDairy, Unit 4/71 Korumburra Road, PO Box 1059 McMillan Campus, Warragul VIC 3820, Australia. Retrieved from http://www.gippsdairy.com.au/LinkClick.aspx?fileticket=bhwWQcQncVk%3d&tabid=80&mid=465

Gippsland Bulk Spreaders Pty Ltd. (2011). *Fertilizers; Products and Services*. Gippsland Bulk Spreaders Pty Ltd., Drouin, Victoria, Australia. Retrieved from http://www.gippslandbulkspreaders.com.au/products.html

Gippsland Water. (2013). *Multi-million dollar injection into Warragul sewer system.* Media Release; Gippsland Water, Hazelwood Road PO BOX 348, Traralgon VIC 3844, Australia. Retrieved from http://www.gippswater.com.au/Portals/0/Media%20Release%20Multi-million%20dollar%20injection%20into%20Warragul%20sewer%20system.PDF

GLMAC. (2013). *Gippsland Lakes Environmental Strategy*. Gippsland Lakes Ministerial Advisory Committee, Bairnsdale, Victoria, Australia. Retrieved from http://www.gippslandlakes.net.au/wp-content/uploads/2013/04/Gippsland-Lakes-Environmental-Strategy_web.pdf

Gokhale, Y., Kay, J., Simmonds, K., & Schliephake, K. (Year Unknown). *Evaluation of Biosolids Treatment Technologies for Combined Industrial and Domestic Wastes*. CH2M HILL, Sydney, NSW, Australia. Retrieved from https://www.ch2m.com/corporate/worldwide/assets/white-papers/australia/CH2M-HILL-biosolids-treatment-technologies.pdf

Gourley, C., Dougherty, W., Aarons, S., & Hannah, M. (2010). *Accounting for Nutrients on Australian Dairy Farms.* Final Report June 2010; Department of Environment and Primary Industries, PO Box 500, Melbourne VIC 8002, Australia. Retrieved from http://accounting4nutrients.com.au/projectreports.html

GRWMG. (2010). *Business Plan 2011-12 to 2013-14*. Gippsland Regional Waste Management Group, PO Box 444, Trafalgar Victoria 3824, Australia. Retrieved from http://www.grwmg.vic.gov.au/assets/files/2011-12%20Gippsland%20Regional%20Waste%20Management%20Group%20Draft%20Business%20Plan-Final.pdf

Gsodam, P., Lassnig, M., Kreuzeder, A., & Mrotzek, M. (2014). The Austrian silver cycle: A material flow analysis. *Resources, Conservation and Recycling, 88*, 76-84. doi: http://dx.doi.org/10.1016/j.resconrec.2014.05.001

Guo, L. (2007). Doing Battle with the Green Monster of Taihu Lake. *Science, 317*(5842), 1166. doi: 10.1126/science.317.5842.1166

Gupta, L. (2008). *Maintaining Egg Shell Quality*. The PoultrySite - Poultry News, Health, Welfare, Diseases, Markets and Economics, 5m Publishing, Benchmark House, 8 Smithy Wood Drive, Sheffield, S35 1QN, England. Retrieved from http://www.thepoultrysite.com/articles/979/maintaining-egg-shell-quality

Gustafsson, B., Schenk, F., Blenckner, T., Eilola, K., Meier, H. E. M., Müller-Karulis, B., . . . Zorita, E. (2012). Reconstructing the Development of Baltic Sea Eutrophication 1850–2006. *AMBIO, 41*(6), 534-548. Retrieved from 10.1007/s13280-012-0318-x

Hancock, G., Wilkinson, S., & Read, A. (2007). *Sources of sediment and nutrients to the Gippsland Lakes assessed using catchment modelling and sediment tracers*. CSIRO Land and Water Science Report 70/07, CSIRO Land and Water GPO Box 1666 Canberra, ACT 2601, Australia. Retrieved from http://www.clw.csiro.au/publications/science/2007/sr70-07.pdf

Harris, B., Adams, A. L., & H, V. H. H. (2003). *Mineral Needs of Dairy Cattle*. Animal Science Department, Institute of Food and Agricultural Sciences, University of Florida, USA. Retrieved from http://www.textbookalfalfa.com/media/filer_private/2012/01/30/mineral_needs_of_dairy_cattle_study.pdf

Hedbrant, J., & Sörme, L. (2001). Data Vagueness and Uncertainties in Urban Heavy-Metal Data Collection. *Water, Air and Soil Pollution: Focus, 1*(3-4), 43-53. doi: 10.1023/A:1017591718463

HELCOM. (2009). *Eutrophication in the Baltic Sea-An integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region*. Baltic Sea Environment Proceedings, No. 115B. Retrieved from http://helcom.fi/Lists/Publications/BSEP115B.pdf

Hernandez, M. A., & Torero, M. (2011). *Fertilizer Market Situation: Market Structure, Consumption and Trade Patterns, and Pricing Behavior*. IFPRI Discussion Paper 01058; International Food Policy Research Institute. Retrieved from http://www.ifpri.org/sites/default/files/publications/ifpridp01058.pdf

Hill, R. C., Burrows, C. F., Ellison, G. W., & Bauer, J. E. (2001). The effect of texturized vegetable protein from soy on nutrient digestibility compared to beef in cannulated dogs. *Journal of Animal Science, 79*(8), 2162-2171.

Holland, D., & Cook, P. (2009). *November 2008 Gippsland floods-potential impact on the Gippsland Lakes*. Report prepared for the Gippsland Lakes and Catchment Task Force; Water Studies Centre, Monash University, Clayton 3800, Victoria, Australia. Retrieved from http://www.gcb.vic.gov.au/publications/monitoring/GL%20Nov08%20floods%20report-final.pdf

Holland, D., Cook, P., & Beardall, J. (2011). *Targeted monitoring of algal bloom potential in the Gippsland Lakes 2010-2011*. Report prepared for the Gippsland Lakes and Catchment Task Force; Water Studies Centre and School of Biological Science, Monash University, Clayton 3800, Victoria, Australia. Retrieved from http://www.gippslandlakes.net.au/wp-content/uploads/2012/11/Targeted-monitoring-of-algal-bloom-potential-in-the-Gippsland-Lakes-2010-2011.pdf

Holland, D., Cook, P., Beardall, J., & Longmore, A. (2010). *Nutrient cycling and phytoplankton population dynamics in the Gippsland Lakes*. Report prepared for the Gippsland Lakes and Catchment Task Force; Water Studies Centre, Monash University, Clayton 3800, Victoria, Australia. Retrieved from http://www.gcb.vic.gov.au/publications/monitoring/Final%20report.pdf

Hubbert, M. K. (1949). Energy from fossil fuels. *Science, 109*, 103-109.

IFP. (2006). *Phosphorus: a vital source of animal nutrition*. Inorganic Feed Phosphorus, Cefic - Sector Group Inorganic Feed Phosphates, Marc Vermeulen Avenue E. Van Nieuwenhuyse 4, bte 2B-1160 Brussels, Belgium. Retrieved from http://www.feedphosphates.org/guide/phosphorus.html

IPL. (2014). *Nitrophoska Special*. Incitec Pivot Fertilisers, GPO Box 1322, Melbourne Victoria 3001, Australia. Retrieved from http://www.incitecpivotfertilisers.com.au/Products%20%20%20Services/IPF%20%20Products/Nitrophoska%20Special

IPNI. (2014). *4R Nutrient Stewardship Portal*. International Plant Nutrient Institute, 500 Parkway Lane, Suite 550, Peachtree Corners, Georgia 30092-2844, USA. Retrieved from http://www.ipni.net/4R (accessed: 28.05.2014)

Isee systems, Inc. (2014). *STELLA: System Thinking for Education and Research*. Isee systems, Inc., Wheelock Office Park 31 Old Etna Road, Suite 7N Lebanon, NH 03766 USA. Retrieved from http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx

Jackson, D. (2012). *Producer phosphorus manual for the northern cattle industry*. Meat & Livestock Australia Limited, Locked Bag 991, North Sydney NSW 2059, Australia. Retrieved from http://www.mla.com.au/Research-and-development/Final-report-details?projectid=15338

Jeong, Y.-S., Matsubae-Yokoyama, K., Kubo, H., Pak, J.-J., & Nagasaka, T. (2009). Substance flow analysis of phosphorus and manganese correlated with South Korean steel industry. *Resources, Conservation and Recycling, 53*(9), 479-489. doi: http://dx.doi.org/10.1016/j.resconrec.2009.04.002

Johnson, P. T. J., Chase, J. M., Dosch, K. L., Hartson, R. B., Gross, J. A., Larson, D. J., . . . Carpenter, S. R. (2007). Aquatic eutrophication promotes pathogenic infection in amphibians. *Proceedings of the National Academy of Sciences, 104*(40), 15781-15786. doi: 10.1073/pnas.0707763104

Jonsson, H., & Vinneras, B. (2004). *Adapting the nutrient content of urine and faeces in different countries using FAO and Swedish data*. Ecosan – Closing the loop. Proc. 2nd Intern. Symp. Ecological Sanitation, April 2003, Lübeck, Germany, 623-626.

Kelsey, P., King, L., & Kitsios, A. (2010). S*urvey of urban nutrient inputs on the Swan Coastal Plain*. Water Science technical series, Report no. 24; Department of Water, 168 St Georges Terrace, Perth Western Australia 6000, Australia. Retrieved from http://www.water.wa.gov.au/PublicationStore/first/92565.pdf

Kemp, W. M., Boynton, W. R., Adolf, J. E., Boesch, D. F., Boicourt, W. C., Brush, G., . . . Stevenson, J. C. (2005). Eutrophication of Chesapeake Bay: historical trends and ecological interactions. Marine Ecology Progress Series, *303*, 1-29. doi: 10.3354/meps303001

Kienzle, E., Thielen, C., & Pessinger, C. (1998). Investigations on Phosphorus Requirements of Adult Cats. *The Journal of Nutrition, 128*(12), 2598S-2600S.

Kroon, F. J., Kuhnert, P. M., Henderson, B. L., Wilkinson, S. N., Kinsey-Henderson, A., Abbott, B., . . . Turner, R. D. R. (2012). River loads of suspended solids, nitrogen, phosphorus and herbicides delivered to the Great Barrier Reef lagoon. *Marine Pollution Bulletin, 65*(4–9), 167-181. doi: http://dx.doi.org/10.1016/j.marpolbul.2011.10.018

Kruger, I., Mills, G., & Madden, P. (2013). *PigGas: Pork Industry Greenhouse Gas Calculator User Guide*. Australin Pork Limited, 2 Brisbane Avenue, Barton ACT 2600, Australia. Retrieved from http://australianpork.com.au/wp-content/uploads/2013/10/PigGas-User-Guide.pdf

Kupkanchanakul, W., & Kwonpongsagoon, S. (2011). Nitrogen and Phosphorus Flow Analysis from Pig Farming in Bang Pakong Basin, Eastern Thailand. *Environment Asia, 4*(2), 27-32.

Ladson, T., & Tilleard, J. (2006). *BMPs for reducing phosphorus loads to the Gippsland Lakes*. Report on Findings from Expert Panel; Moroka Pty Ltd., PO Box 67C, SOMERS VIC 3927, Australia. Retrieved from http://www.gcb.vic.gov.au/publications/investment/BMPs_for_reducing_phosphorus_loads_to_the_Gippsland_Lakes.pdf

Lederer, J., Laner, D., & Fellner, J. A framework for the evaluation of anthropogenic resources: The case study of phosphorus stocks in Austria. *Journal of Cleaner Production, 84*, 368-381. doi: http://dx.doi.org/10.1016/j.jclepro.2014.05.078

Leech, F. (2009). *Cycling of phosphorus in grazing systems*. NSW Department of Primary Industries, NSW, Australia. Retrieved from http://www.dpi.nsw.gov.au/agriculture/resources/soils/improvement/cycling-phosphorus

Li, F. J., Dong, S. C., & Li, F. (2012). A system dynamics model for analyzing the eco-agriculture system with policy recommendations. *Ecological Modelling, 227*, 34-45. doi: http://dx.doi.org/10.1016/j.ecolmodel.2011.12.005

Li, S., Yuan, Z., Bi, J., & Wu, H. (2010). Anthropogenic phosphorus flow analysis of Hefei City, China. *Science of The Total Environment, 408*(23), 5715-5722. doi: http://dx.doi.org/10.1016/j.scitotenv.2010.08.052

Liu, Y., Villalba, G., Ayres, R. U., & Schröder, H. (2008). Global Phosphorus Flows and Environmental Impacts from a Consumption Perspective. *Journal of Industrial Ecology, 12*(2), 229-247. doi: 10.1111/j.1530-9290.2008.00025.x

Lorimor, J., Powers, W., & Sutton, A. (2004). *Manure Characteristics*. Manure Management System Series, MWPS-18, Section 1 (Second Edition). MidWest Plan Service, Iowa State University, Ames, Iowa 50011-3080, USA.

Lott, J. A., Kolasa, J., Batten, G., & Campbell, L. (2011). The critical role of phosphorus in world production of cereal grains and legume seeds. *Food Security, 3*(4), 451-462. doi: 10.1007/s12571-011-0144-1

Ma, D., Hu, S., Chen, D., & Li, Y. (2012). Substance flow analysis as a tool for the elucidation of anthropogenic phosphorus metabolism in China. *Journal of Cleaner Production, 29–30*, 188-198. doi: http://dx.doi.org/10.1016/j.jclepro.2012.01.033

Ma, D., Hu, S., Chen, D., & Li, Y. (2013). The Temporal Evolution of Anthropogenic Phosphorus Consumption in China and Its Environmental Implications. *Journal of Industrial Ecology, 17*(4), 566-577. doi: 10.1111/jiec.12009

MacDonald, G. K., Bennett, E. M., Potter, P. A., & Ramankutty, N. (2011). Agronomic phosphorus imbalances across the world's croplands. *Proceedings of the National Academy of Sciences, 108*(7), 3086-3091. doi: 10.1073/pnas.1010808108

MacKenzie, L. A., Smith, K. F., Rhodes, L. L., Brown, A., Langi, V., Edgar, M., . . . Preece, M. (2011). Mortalities of sea-cage salmon (Oncorhynchus tshawytscha) due to a bloom of Pseudochattonella verruculosa (Dictyochophyceae) in Queen Charlotte Sound, New Zealand. *Harmful Algae, 11*, 45-53. doi: http://dx.doi.org/10.1016/j.hal.2011.07.003

MACP. (2013). *Rationale for a US-Morocco Strategic Partnership*. Fact Sheet; Morocco-US Strategic Dialogue, Moroccan American Center for Policy (MACP). Retrieved from http://moroccoonthemove.com/wp-content/uploads/2013/07/FINAL_StratDialRationale091012.pdf (accessed: 12.10. 2013)

Marston, F., Young, W., & Davis, R. (1995). *Nutrient Generation Data Book.* Second edition; CSIRO Division of water Resource, CSIRO, Australia.

Martini, N. F., Nelson, K. C., Hobbie, S. E., & Baker, L. A. (2015). Why "Feed the Lawn"? Exploring the Influences on Residential Turf Grass Fertilization in the Minneapolis−Saint Paul Metropolitan Area. Environment and Behavior, 47(2), 158-183. doi: 10.1177/0013916513492418

Matsubae-Yokoyama, K., Kubo, H., Nakajima, K., & Nagasaka, T. (2009). A Material Flow Analysis of Phosphorus in Japan. *Journal of Industrial Ecology, 13*(5), 687-705. doi: 10.1111/j.1530-9290.2009.00162.x

MAV and DSE. (2006). *Model Land Capability Assessment Report*. Prepared by Whitehead and Associates Environmental Consultants Pty Ltd as part of the Victorian Government's Country Towns Water Supply and Sewerage Program; Victoria, Australia. Retrieved from http://www.gippswater.com.au/Portals/0/CUSSERV/Model%20land%20capability%20assessment%20report.pdf

Melbourne Water. (2005). Eastern Treatment Plant-2004/2005 Annual Monitoring Report to the Environment Protection Authority. Melbourne Water, 990 La Trobe Street, Docklands, VIC 3008, Australia. Retrieved from http://melbournewater.com.au/aboutus/reportsandpublications/compliance-reports/Documents/2004-05%20Annual%20Monitoring%20Report%20to%20EPA.pdf

Metcalf & Eddy, Inc. (1991). *Wastewater Engineering: Treatment, Disposal and Reuse*. Third edition; McGraw-Hill, New York, USA.

Metson, G. S., Hale, R. L., Iwaniec, D. M., Cook, E. M., Corman, J. R., Galletti, C. S., & Childers, D. L. (2012). Phosphorus in Phoenix: a budget and spatial representation of phosphorus in an urban ecosystem. *Ecological Applications, 22*(2), 705-721. doi: 10.1890/11-0865.1

Metson, G., Aggarwal, R., & Childers, D. L. (2012a). Efficiency Through Proximity. *Journal of Industrial Ecology, 16*(6), 914-927. doi: 10.1111/j.1530-9290.2012.00554.x

Metson, G. S., M., B. E., & Elser, J. J. (2012b). The role of diet in phosphorus demand. Environmental *Research Letters, 7*(4), 1-10. doi: 10.1088/1748-9326/7/4/044043

Mihelcic, J. R., Fry, L. M., & Shaw, R. (2011). Global potential of phosphorus recovery from human urine and feces. *Chemosphere, 84*(6), 832-839. doi: http://dx.doi.org/10.1016/j.chemosphere.2011.02.046

Minemakers Limited. (2008). *Rock Phosphate Price Rockets to Us$200/Tonne; Feasibility planning initiated on the Wonarah Project, Northern Territory*. ASX and Press Release, January 09, 2008;

Minemakers Limited (ABN 48116296541), Western Australia 6005, Australia. Retrieved from http://www.minemakers.com.au/downloads/News/080109RockPhosphatePriceSkyRockets.pdf (accessed: 06.07.2013)

Moazzem, S., Rasul, M. G., & Khan, M. M. K. (2013). Energy recovery opportunities from mineral carbonation process in coal fired power plant. *Applied Thermal Engineering, 51*(1–2), 281-291. doi: http://dx.doi.org/10.1016/j.applthermaleng.2012.09.021

Murphy, R., Kemp, W. M., & Ball, W. (2011). Long-Term Trends in Chesapeake Bay Seasonal Hypoxia, Stratification, and Nutrient Loading. *Estuaries and Coasts, 34*(6), 1293-1309. doi: 10.1007/s12237-011-9413-7

Nelson, N. O., & Shober, A. L. (2012). Evaluation of Phosphorus Indices after Twenty Years of Science and Development. *J. Environ. Qual., 41*(6), 1703-1710. doi: 10.2134/jeq2012.0342

Neset, T.-S. S., Bader, H.-P., Scheidegger, R., & Lohm, U. (2008). The flow of phosphorus in food production and consumption — Linköping, Sweden, 1870–2000. *Science of The Total Environment, 396*(2–3), 111-120. doi: http://dx.doi.org/10.1016/j.scitotenv.2008.02.010

Neset, T.-S. S., & Cordell, D. (2012). Global phosphorus scarcity: identifying synergies for a sustainable future. *Journal of the Science of Food and Agriculture, 92*(1), 2-6. doi: 10.1002/jsfa.4650

Neset, T.-S. S., Drangert, J.-O., Bader, H.-P., & Scheidegger, R. (2010). Recycling of P in urban Sweden: a historical overview to guide a strategy for the future. *Water policy, 12*(4), 611-624. doi: 10.2166/wp.2009.165

NHMRC. (2006). *Nutrient Reference Values for Australia and New Zealand-Executive Summary*. National Health and Medical Research Council, GPO Box 1421 Canberra ACT 2601, Australia. Retrieved from http://www.nrv.gov.au/sites/default/files/page_pdf/n35-phosphorus_0.pdf

NZWWA. (2003). *Guidelines for the Safe Application of Biosolids to Land in New Zealand*. New Zealand Water & Wastes Association (NZWWA), PO Box 1316 Wellington, New Zealand. Retrieved from http://www.aucklandcouncil.govt.nz/EN/planspoliciesprojects/plansstrategies/unitaryplan/Documents/Material%20incorporated%20by%20reference/upmirbmfeguidelinesforthesafeapplicationofbiosolidstolandinnewzealand.pdf

Obersteiner, M., Penuelas, J., Ciais, P., van der Velde, M., & Janssens, I. A. (2013). The phosphorus trilemma. *Nature Geosci, 6*(11), 897-898. doi: 10.1038/ngeo1990

Orris, G. J., & Chernoff, C. B. (2002). *Data Set of World Phosphate Mines, Deposits, and Occurrences-Part B*. Location and Mineral Economic Data. Tucson, AZ, USGS, USA.

Osmond, D. L., Evans, R. O., Hardy, D. H., Price, L., & Johnson, A. M. (2005). *The North Carolina Phosphorus Loss Assessment Tool (PLAT): A Guide for Technical Specialist*. North Carolina State University, USA. Retrieved from http://www.soil.ncsu.edu/publications/plat/plat_agents.pdf

Ott, C., & Rechberger, H. (2012). The European phosphorus balance. *Resources, Conservation and Recycling, 60*, 159-172. doi: http://dx.doi.org/10.1016/j.resconrec.2011.12.007

Ouyang, Y., Luo, S. M., & Cui, L. H. (2011). Estimation of nitrogen dynamics in a vertical-flow constructed wetland. *Ecological Engineering, 37*(3), 453-459. doi: http://dx.doi.org/10.1016/j.ecoleng.2010.11.008

Parsons, D., Nicholson, C. F., Blake, R. W., Ketterings, Q. M., Ramírez-Aviles, L., Fox, D. G., . . . Cherney, J. H. (2011). Development and evaluation of an integrated simulation model for assessing smallholder crop–livestock production in Yucatán, Mexico. *Agricultural Systems, 104*(1), 1-12. doi: http://dx.doi.org/10.1016/j.agsy.2010.07.006

Pescod. (1992). *Wastewater treatment and use in agriculture*. FAO irrigation and drainage paper 47; Food and Agriculture Organization of the United Nations, Rome, Italy. Retrieved from http://www.fao.org/docrep/t0551e/t0551e03.htm

Peter Cottingham & Associates. (2008). *Refining the Gippsland Lakes Future Directions and Actions Plan*. A scoping study undertaken for the Gippsland Lakes Task Force; Peter Cottingham & Associates. Retrieved from http://www.gippslandlakes.net.au/wp-content/uploads/2012/11/Gipps_Lakes_Future_Actions_Plan_Final_Report.pdf

PMSEIC. (2010). *Australia and Food Security in a Changing World*. The Prime Minister's Science, Engineering and Innovation Council, Canberra, Australia. Retrieved from http://www.chiefscientist.gov.au/wp-content/uploads/FoodSecurity_web.pdf

Poultry CRC. (2014). *Nutrient requirements of meat chickens (broilers)*. Poultry CRC Ltd, PO Box U242, University of New England, ARMIDALE NSW 2351, Australia. Retrieved from http://www.poultryhub.org/nutrition/nutrient-requirements/nutrient-requirements-of-meat-chickens-broilers/

Powell, J. M., Aarons, S. R., & Gourley, C. J. P. (2012). Determinations of feed–milk–manure relationships on grazing-based dairy farms. *Animal, 6*(10), 1702-1710. doi: doi:10.1017/S1751731112000511

Powersim Software AS. (2014). *Powersim Software*. Powersim Software AS, Litleåsvegen 79, N-5132 Nyborg, Norway. Retrieved from http://www.powersim.com/main/products-services/powersim_products/

Pradhan, S. K., Holopainen, J. K., & Heinonen-Tanski, H. (2009). Stored Human Urine Supplemented with Wood Ash as Fertilizer in Tomato (Solanum lycopersicum) Cultivation and Its Impacts on Fruit Yield and Quality. *Journal of Agricultural and Food Chemistry, 57*(16), 7612-7617. doi: 10.1021/jf9018917

Prando, D., Patuzzi, F., Pernigotto, G., Gasparella, A., & Baratieri, M. (2014). Biomass gasification systems for residential application: An integrated simulation approach. *Applied Thermal Engineering, 71*(1), 152-160. doi: http://dx.doi.org/10.1016/j.applthermaleng.2014.06.043

Pretty, J. N., Mason, C. F., Nedwell, D. B., Hine, R. E., Leaf, S., & Dils, R. (2003). Environmental Costs of Freshwater Eutrophication in England and Wales. *Environmental Science & Technology, 37*(2), 201-208. doi: 10.1021/es020793k

Qiao, M., Zheng, Y.-M., & Zhu, Y.-G. (2011). Material flow analysis of phosphorus through food consumption in two megacities in northern China. *Chemosphere, 84*(6), 773-778. doi: http://dx.doi.org/10.1016/j.chemosphere.2011.01.050

Qin, B., Xu, P., Wu, Q., Luo, L., & Zhang, Y. (2007). Environmental issues of Lake Taihu, China. *Hydrobiologia, 581*(1), 3-14. doi: 10.1007/s10750-006-0521-5

Rabalais, N. N., Turner, R. E., Sen Gupta, B. K., Boesch, D. F., Chapman, P., & Murrell, M. C. (2007). Hypoxia in the northern Gulf of Mexico: Does the science support the Plan to Reduce, Mitigate, and Control Hypoxia? *Estuaries and Coasts, 30*(5), 753-772. doi: 10.1007/BF02841332

Redfield, G. W. (2002). Atmospheric Deposition of Phosphorus to the Everglades: Concepts, Constraints, and Published Deposition Rates for Ecosystem Management. *The Scientific World JOURNAL, 2*, 1843-1873. doi: 10.1100/tsw.2002.813

RMIT Handbook. (2008). *Urban Greywater Design and Installation Handbook*. Handbook developed jointly by the Master Plumbers and Mechanical Services Association of Australia (MPMSAA) and RMIT University, Australia. Retrieved from http://www.nwc.gov.au/__data/assets/pdf_file/0017/10754/GREYWATER_handbook_nwc_logo.pdf

Roberts, A. M., Pannell, D. J., Doole, G., & Vigiak, O. (2012). Agricultural land management strategies to reduce phosphorus loads in the Gippsland Lakes, Australia. *Agricultural Systems, 106*(1), 11-22. doi: http://dx.doi.org/10.1016/j.agsy.2011.10.009

Roberts, J. R. (2003). *Effects of commercial feed enzymes in wheat-based diets on egg and egg shell quality in imported strains of laying hen*. A report for the Australian Egg Corporation Limited; Australian Egg Corporation Limited, Suite 502, Level 5,12-14 Ormonde Parade, HURSTVILLE NSW 2220, Australia. Retrieved from https://www.aecl.org/assets/RD-files/Outputs-2/UNE-77AA-Final-Report.pdf

Rosemarin, A. (2004, June 30). The precarious geopolitics of Phosphorous. *Down to Earth: Science and Environment Online*. Retrieved from http://www.downtoearth.org.in/content/precarious-geopolitics-phosphorous (accessed: 10.11.2013)

Roy, E. D., White, J. R., & Seibert, M. (2014). Societal phosphorus metabolism in future coastal environments: Insights from recent trends in Louisiana, USA. *Global Environmental Change, 28*, 1-13. doi: http://dx.doi.org/10.1016/j.gloenvcha.2014.05.009

Saikku, L., Antikainen, R., & Kauppi, P. E. (2007). Nitrogen and Phosphorus in the Finnish Energy System, 1900–2003. *Journal of Industrial Ecology, 11*(1), 103-119. doi: 10.1162/jiec.2007.1116

Saikku, L., & Asmala, E. (2010). Eutrophication in the Baltic Sea. *Journal of Industrial Ecology, 14*(3), 482-495. doi: 10.1111/j.1530-9290.2010.00221.x

Sattari, S. Z., Bouwman, A. F., Giller, K. E., & van Ittersum, M. K. (2012). Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. *Proceedings of the National Academy of Sciences, 109*(16), 6348-6353. doi: 10.1073/pnas.1113675109

Satter, L. D., Klopfenstein, T. J., Erickson, G. E., & Powell, J. M. (2005). *Phosphorus and Dairy/Beef Nutrition*. Paper 549; Faculty Papers and Publications in Animal Science, University of Nebraska-Lincoln, USA. Retrieved from http://digitalcommons.unl.edu/animalscifacpub/549 (accessed: 21.06.2013)

Scavia, D., & Donnelly, K. A. (2007). Reassessing Hypoxia Forecasts for the Gulf of Mexico. *Environmental Science & Technology, 41*(23), 8111-8117. doi: 10.1021/es0714235

Schindler, D. W., Hecky, R. E., Findlay, D. L., Stainton, M. P., Parker, B. R., Paterson, M. J., . . . Kasian, S. E. M. (2008). Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment. *Proceedings of the National Academy of Sciences, 105*(32), 11254-11258. doi: 10.1073/pnas.0805108105

Scholz, R. W., Roy, A. H., Brand, F. S., Hellums, D. T., & Ulrich, A. E. (2014). *Sustainable phosphorus management: a global transdisciplinary roadmap*. Berlin: Springer.

Scholz, R. W., Roy, A. H., & Hellums, D. T. (2014a). Sustainable phosphorus management: a transdisciplinary challenge. In R. W. Scholz, A. H. Roy, F. S. Brand, D. T. Hellums & A. E. Ulrich (Eds.), *Sustainable phosphorus management: a global transdisciplinary roadmap* (pp. 1-113). Berlin: Springer.

Scholz, R. W., & Wellmer, F.-W. (2013). Approaching a dynamic view on the availability of mineral resources: What we may learn from the case of phosphorus? *Global Environmental Change, 23*(1), 11-27. doi: http://dx.doi.org/10.1016/j.gloenvcha.2012.10.013

Schröder, J. J., Cordell, D., Smit, A. L., & Rosemarin, R. (2010). *Sustainable Use of Phosphorus*. Report No. 357; Plant Research International, Wageningen University and Research Centre, the Netherlands, and Stockholm Environment Institute, Netherlands. Retrieved from http://ec.europa.eu/environment/natres/pdf/sustainable_use_phosphorus.pdf

Schröder, J. J., Smit, A. L., Cordell, D., & Rosemarin, A. (2011). Improved phosphorus use efficiency in agriculture: A key requirement for its sustainable use. *Chemosphere, 84*(6), 822-831. doi: http://dx.doi.org/10.1016/j.chemosphere.2011.01.065

Science Communication Unit. (2013). *Science for Environment Policy In-depth Report: Sustainable Phosphorus Use*. Report produced for the European Commission DG Environment; Science Communication Unit, University of the West of England, Bristol, UK. Retrieved from http://ec.europa.eu/science-environment-policy

Senthilkumar, K., Mollier, A., Delmas, M., Pellerin, S., & Nesme, T. (2014). Phosphorus recovery and recycling from waste: An appraisal based on a French case study. *Resources, Conservation and Recycling, 87*, 97-108. doi: http://dx.doi.org/10.1016/j.resconrec.2014.03.005

Senthilkumar, K., Nesme, T., Mollier, A., & Pellerin, S. (2012). Regional-scale phosphorus flows and budgets within France: The importance of agricultural production systems. *Nutrient Cycling in Agroecosystems, 92*(2), 145-159. doi: 10.1007/s10705-011-9478-5

Seyhan, D. (2009). Country-scale phosphorus balancing as a base for resources conservation. *Resources, Conservation and Recycling, 53*(12), 698-709. doi: http://dx.doi.org/10.1016/j.resconrec.2009.05.001

Sharpley, A. N., Weld, J. L., Beegle, D. B., Kleinman, P. J. A., Gburek, W. J., Moore, P. A., & Mullins, G. (2003). Development of phosphorus indices for nutrient management planning strategies in the United States. *Journal of Soil and Water Conservation, 58*(3), 137-152.

Sinclair Knight Merz. (2008). *Impacts of bushfires on water quality in the Gippsland Lakes: exploring options for mitigation*. Final Report: Version 3 - A report prepared for the Gippsland Lakes & Catchment Taskforce; Sinclair Knight Merz, 590 Orrong Road, PO Box 2500 Malvern, VIC 3144, Australia. Retrieved from http://www.gippslandlakes.net.au/wp-content/uploads/2012/11/R14_GLakes_Bushfires_WaterQuality_FinalReport.pdf

Smil, V. (2000). Phosphorus in the environment: Natural flows and human interferences. Annual *Review of Energy and the Environment, 25*, 53-88. doi: 10.1146/annurev.energy.25.1.53

Smit, A. L., Bindraban, P. S., Schröder, J. J., Conijn, J. G., & van der Meer, H. G. (2009). *Phosphorus in Agriculture: Global Resources, Trends and Developments*. Report to the Steering Committee Technology Assessment of the Ministry of Agriculture, Nature and Food Quality; Plant Research International, Wageningen University, Wageningen, The Netherlands. Retrieved from http://edepot.wur.nl/12571

Smit, A. L., Van Middelkoop, J. C., Van Dijk, W., Van Reuler, H., De Buck, A. J., & Van De Sanden, P. A. C. M. (2010). *A quantification of phosphorus flows in the Netherlands through agricultural production, industrial processing and households*. Plant Research International, part of Wageningen UR; Business Unit Agrosystems. P.O Box 616, 6700 AP Wageningen, The Netherlands. Retrieved from http://www.cost869.alterra.nl/Spain/Report_364_PRI.pdf

Smith, H. G., Sheridan, G. J., Lane, P. N. J., Nyman, P., & Haydon, S. (2011). Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology, 396*(1–2), 170-192. doi: http://dx.doi.org/10.1016/j.jhydrol.2010.10.043

Smith, V. H., & Schindler, D. W. (2009). Eutrophication science: where do we go from here? Trends in *Ecology & Evolution, 24*(4), 201-207. doi: http://dx.doi.org/10.1016/j.tree.2008.11.009

Sneyd, L., Legwegoh, A., & Fraser, E. G. (2013). Food riots: Media perspectives on the causes of food protest in Africa. *Food Security, 5*(4), 485-497. doi: 10.1007/s12571-013-0272-x

Sopade, P., Hosking, B., Collins, C., Diffey, S., Fox, G., Henman, D., . . . Black, J. (2013). *Improving the efficiency of pig feed manufacturing and application of additives 4B-104*. Prepared for the Co-operative Research Centre for High Integrity Australian Pork; Pork CRC Ltd., P.O. Box 466, Willaston, South Australia 5118, Australia. Retrieved from http://porkcrc.com.au/wp-content/uploads/2013/10/4B-104-Final-Report.pdf

South Gippsland Shire Council. (2014). *Waste Water (Septic Tanks)*. South Gippsland Shire Council, 9 Smith Street (Private Bag 4), Leongatha, Victoria 3953, Australia. Retrieved from http://www.southgippsland.vic.gov.au/page/page.asp?page_Id=328

South Gippsland Water (2010). *Annual Report 2009-2010*. South Gippsland Water, 14-18 Pioneer Street, Foster VIC 3960, Australia. Retrieved from http://www.sgwater.com.au/wp-content/uploads/2014/04/2010-16815-Annual-Report-FINAL-pdf-internal-text-13-09-10.pdf

Spragg, J. (2014). *Feed Grain Supply & Demand Report 2013-14*. A report for the Feed Grain Partnership; JCS Solutions Pty Ltd, 32-34 Grantham Crescent Berwick Vic 3806, Australia. Retrieved from http://porkcrc.com.au/wp-content/uploads/2014/07/FGP-Feed-Grain-Supply-and-Demand-Report-July-2014.pdf

Suchý, P., Straková, E., Herzig, I., Steinhauser, L., Králik, G., & Zapletal, D. (2009). Chemical composition of bone tissue in broiler chickens intended for slaughter. *Czech J. Anim. Sci, 54*, 324-330.

Suh, S., & Yee, S. (2011). Phosphorus use-efficiency of agriculture and food system in the US. *Chemosphere, 84*(6), 806-813. doi: http://dx.doi.org/10.1016/j.chemosphere.2011.01.051

Sustainability Victoria (2010). *Victorian Local Government Annual Survey 2008 – 2009*. Sustainability Victoria, Level 28 Urban Workshop, 50 Lonsdale Street Melbourne Victoria 3000, Australia. Retrieved from http://www.sustainability.vic.gov.au/~/media/resources/documents/publications%20and%20research/publications/i%20-%20l/publications%20vic%20local%20government%20annual%20survey%202008%2009.pdf

Sustainability Victoria. (2011). *Victorian Local Government Annual Survey 2009–2010*. Sustainability Victoria, Level 28 Urban Workshop, 50 Lonsdale Street Melbourne Victoria 3000, Australia. Retrieved from http://www.litter.vic.gov.au/resources/documents/Victorian_Local_Government_Annual_Survey_2009-10_Report.pdf

Sustainability Victoria (2013). *Victorian Local Government Annual Survey 2010-2011*. Sustainability Victoria, Level 28 Urban Workshop, 50 Lonsdale Street Melbourne Victoria 3000, Australia. doi: https://www.google.com.au/webhp?sourceid=chrome-instant&ion=1&espv=2&ie=UTF-8#q=Victorian+Local+Government+Annual+Survey+2010-11

Sutton, M. A., Bleeker, A., Howard, C. M., Bekunda, M., Grizzetti, B., & de Vries W, e. a. (2013). *Our Nutrient World - The challenge to produce more food and energy with less pollution*. Edinburgh and Nairobi: Centre for Ecology and Hydrology (CEH) and the United Nations Environment Program (UNEP).

Tangsubkul, N., Moore, S., & Waite, T. D. (2005). Incorporating phosphorus management considerations into wastewater management practice. *Environmental Science & Policy, 8*(1), 1-15. doi: http://dx.doi.org/10.1016/j.envsci.2004.08.009

Ternouth, J. H., Davies, H. M. S., Whineray, S., & Thomas, B. J. (1980). Methods of measuring phosphorus status in sheep. *Animal Production in Australia*, 213-216. doi: http://livestocklibrary.com.au/bitstream/handle/1234/7242/Ternouth80.PDF?sequence=1

The MathWorks, Inc. (2014). *SIMULINK: Simulation and Model Based Design*. The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098, United States. Retrieved from http://www.mathworks.com.au/products/simulink/

Thronson, A., & Quigg, A. (2008). Fifty-Five Years of Fish Kills in Coastal Texas. *Estuaries and Coasts, 31*(4), 802-813. doi: 10.1007/s12237-008-9056-5

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences, 108*(50), 20260-20264. doi: 10.1073/pnas.1116437108

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., . . . Swackhamer, D. (2001). Forecasting Agriculturally Driven Global Environmental Change. *Science, 292*(5515), 281-284. doi: 10.1126/science.1057544

Topping, A. (2008, April 21). Food crisis threatens security, says UN chief. *The Guardian*. Retrieved from http://www.theguardian.com/environment/2008/apr/21/food.unitednations (accessed: 12.07.2013)

UN. (2000). *United Nations Millennium Declaration*. Millennium Summit, held in United Nations Headquarters in New York, 6-8 September. Retrieved from http://www.unsceb.org/content/un-millennium-declaration (accessed: 12.10.2013)

UN. (2010). *Keeping the promise: a forward-looking review to promote an agreed action agenda to achieve the Millennium Development Goals by 2015*. Report of the Secretary General of United Nations, issued pursuant to General Assembly resolution 64/184 (February 12, 2010), United Nations, Rome, Italy. Retrieved from http://www.un.org/ga/search/view_doc.asp?symbol=A/64/665

UN. (2011). *World Population Prospects: The 2010 Revision*. Volume I: Comprehensive Tables; Department of Economic and Social Affairs, Population Division, United Nations, New York, USA. Retrieved from http://esa.un.org/wpp/Documentation/pdf/WPP2010_Volume-I_Comprehensive-Tables.pdf

UNEP. (2011). *Emerging issues in our global environment*. UNEP Year Book- 2011; United Nations Environment Programme, Nairobi, Kenya. Retrieved from http://www.unep.org/yearbook/2011

US EPA. (2011). *Moving Forward on Gulf Hypoxia: Annual Report 2011*. Mississippi River Gulf of Mexico Watershed Nutrient Task Force , U.S. Environmental Protection Agency, 1200 Pennsylvania Avenue, NW, Washington, DC 20460, USA. Retrieved from http://water.epa.gov/type/watersheds/named/msbasin/upload/Hypoxia_Task_Force_Annual_Report_2011.pdf

USDA. (2013). *USDA National Nutrient Database for Standard Reference*. Release 26; U.S. Department of Agriculture, Agricultural Research Service; Nutrient Data Laboratory, BLDG. 005 ROOM 105 BARC-WEST Beltsville, MD 20705, USA. Retrieved from http://www.ars.usda.gov/Services/docs.htm?docid=24936

USGS. (2003). *Mineral commodity summaries 2003*. U.S. Geological Survey (USGS), USA, 199 p. Retrieved from http://minerals.usgs.gov/minerals/pubs/mcs/2003/mcs2003.pdf

USGS. (2009). *Mineral commodity summaries 2009*. U.S. Geological Survey (USGS), USA, 195 p. Retrieved from http://minerals.usgs.gov/minerals/pubs/mcs/2009/mcs2009.pdf

USGS. (2010). *Mineral commodity summaries 2010*. U.S. Geological Survey (USGS), USA, 193 p. Retrieved from http://minerals.usgs.gov/minerals/pubs/mcs/2010/mcs2010.pdf

USGS. (2011). *Mineral commodity summaries 2011*. U.S. Geological Survey (USGS), USA, 198 p. Retrieved from http://minerals.usgs.gov/minerals/pubs/mcs/2011/mcs2011.pdf

USGS. (2012). *Mineral commodity summaries 2012*. U.S. Geological Survey (USGS), USA, 198 p. Retrieved from http://minerals.usgs.gov/minerals/pubs/mcs/2012/mcs2012.pdf

USGS. (2013). *Mineral commodity summaries 2013*. U.S. Geological Survey (USGS), USA, 198 p. Retrieved from http://minerals.usgs.gov/minerals/pubs/mcs/2013/mcs2013.pdf

USGS. (2013a). *The effects of urbanization on water quality: Phosphorus*. The USGS Water Science School; U.S. Geological Survey (USGS), USA. Retrieved from http://water.usgs.gov/edu/phosphorus.html (accessed: 09.11.2013)

USGS. (2014). *Mineral commodity summaries*. Phosphate Rock Statistics and Information. U.S. Geological Survey (USGS), USA. Retrieved from http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/ (accessed: 17.12.2014)

Vaccari, D. A. (2009). Phosphorus: A Looming Crisis. *Scientific American, 300,* 54-59. doi: 10.1038/scientificamerican0609-54

Vaccari, D. A. (2011). Sustainability and the phosphorus cycle: inputs, outputs, material flow, and engineering. *Environmental Engineer: Applied Research & Practice, 12,* 1-11.

Vaccari, D. A., Mew, M., Scholz, R. W., Van Kauwenbergh, S. J., & Wellmer, F. W. (2014). Exploration: What reserves and resources?. In R. W. Scholz, A. H. Roy, F. S. Brand, D. T. Hellums & A. E. Ulrich (Eds.), *Sustainable phosphorus management: a global transdisciplinary roadmap* (pp. 129-151). Berlin: Springer.

Vaccari, D. A., & Strigul, N. (2011). Extrapolating phosphorus production to estimate resource reserves. *Chemosphere, 84*(6), 792-797. doi: http://dx.doi.org/10.1016/j.chemosphere.2011.01.052

Van Kauwenbergh, S. J. (2010). *World Phosphate Reserves and Resources*. International Fertilizer Development Centre (IFDC), P.O. Box 2040, Muscle Shoals, Alabama 35662, USA. Retrieved from http://pdf.usaid.gov/pdf_docs/PNADW835.pdf

Van Kauwenbergh, S. J., Stewart, M., & Mikkelsen, R. (2013). World Reserves of Phosphate Rock-a Dynamic and Unfolding Story. *Better Crops, 97*, 18-20. doi: http://www.ifdc.org/World-Reserves-of-Phosphate-Rock-a-Dynamic-and-Unf.pdf/

Van Vuuren, D. P., Bouwman, A. F., & Beusen, A. H. W. (2010). Phosphorus demand for the 1970–2100 period: A scenario analysis of resource depletion. *Global Environmental Change, 20*(3), 428-439. doi: http://dx.doi.org/10.1016/j.gloenvcha.2010.04.004

Vaquer-Sunyer, R., & Duarte, C. M. (2008). Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences, 105*(40), 15452-15457. doi: 10.1073/pnas.0803833105

Varley, P. F., Callan, J. J., & O'Doherty, J. V. (2010). Effect of phosphorus level and phytase inclusion on the performance, bone mineral concentration, apparent nutrient digestibility, and on mineral and nitrogen utilisation in finisher pigs. *Irish Journal of Agricultural and Food Research, 49*, 141-152.

Ventana Systems, Inc. (2014). *Vensim*. Ventana Systems, Inc., 60 Jacob Gates Road, Harvard, MA 01451, USA. Retrieved from http://vensim.com/

Vidal, J. (2008, August 13). Soaring fertiliser prices threaten world's poorest farmers. *The Guardian*. Retrieved from http://www.theguardian.com/environment/2008/aug/12/biofuels.food (accessed: 31.07.2013)

Vienna University of Technology. (2012). *Stan2web*. Vienna University of Technology, Karlsplatz 13/226, Vienna 1040, Austria. Retrieved from http://www.stan2web.net/

Villalba, G., Liu, Y., Schröder, H., & Ayres, R. U. (2008). Global Phosphorus Flows in the Industrial Economy from a Production Perspective. *Journal of Industrial Ecology, 12*(4), 557-569. doi: 10.1111/j.1530-9290.2008.00050.x

Vinneras, B. (2002). *Possibilities for Sustainable Nutrient Recycling by Faecal Separation Combined with Urine Diversion*. Doctoral thesis; Swedish University of Agricultural Sciences, Uppsala, Sweden. Retrieved from http://pub.epsilon.slu.se/332/1/Agraria_353.pdf

Vinneras, B., Palmquist, H., Balmer, P., & Jonsson, H. (2006). The characteristics of household wastewater and biodegradable solid waste-A proposal for new Swedish design values. *Urban Water Journal, 3*, 3-11. doi: 10.1080/15730620600578629

Voet, E. V. D. (2002). Substance flow analysis methodology. In R. U. Ayres & L. W. Ayres (Eds.), *A Handbook of Industrial Ecology* (pp. 91-101). Northampton, USA: Edward Elgar Publishing Limited.

Vonlanthen, P., Bittner, D., Hudson, A. G., Young, K. A., Muller, R., Lundsgaard-Hansen, B., . . . Seehausen, O. (2012). Eutrophication causes speciation reversal in whitefish adaptive radiations. *Nature, 482,* 357-362. doi: 10.1038/nature10824

Watts, P. J., McGahan, E. J., Bonner, S. L., & Wiedemann, S. G. (2011). *Feedlot Mass Balance and Greenhouse Gas Emissions - A Literature Review*. Meat & Livestock Australia, Locked Bag 991, NORTH SYDNEY NSW 2059, Australia. Retrieved from http://www.mla.com.au/Research-and-development/Final-report-details?projectid=15176

Weaver, D., & Wong, M. F. (2011). Scope to improve phosphorus (P) management and balance efficiency of crop and pasture soils with contrasting P status and buffering indices. *Plant and Soil, 349*(1-2), 37-54. doi: 10.1007/s11104-011-0996-3

Weber, M. A., Tidwell, V. C., & Thacher, J. A. (2010). Dynamic physical and economic modelling of riparian restoration options. *Environmental Modelling & Software, 25*(12), 1825-1836. doi: http://dx.doi.org/10.1016/j.envsoft.2010.05.017

Wellstead, J. (2012, November 29). The future of phosphate is in Morocco. *Potash Investing News*. Retrieved from http://potashinvestingnews.com/6590-future-phosphate-morocco-ocp-fertilizer-production-flsmidth-agrium-potashcorp.html (accessed: 15.07.2013)

White, S., Cordell, D., & Moore, D. (2010). *Securing a sustainable phosphorus future for Australia: implications of global phosphorus scarcity and possible solutions*. Review prepared by the Institute for Sustainable Futures, for CSIRO Sustainable Agriculture Flagship, Australia.

Williams, P. G., Droulez, V., Levy, G., & Stobaus, T. (2007). *Composition of Australian red meat 2002*. 3. Nutrient profile, Food Australia, 59, 331-341. Retrieved from http://ro.uow.edu.au/cgi/viewcontent.cgi?article=1050&context=hbspapers

Winter, J. G., Dillon, P. J., Futter, M. N., Nicholls, K. H., Scheider, W. A., & Scott, L. D. (2002). Total Phosphorus Budgets and Nitrogen Loads: Lake Simcoe, Ontario (1990 to 1998). *Journal of Great Lakes Research, 28*(3), 301-314. doi: http://dx.doi.org/10.1016/S0380-1330(02)70586-8

Wu, H., Yuan, Z., Zhang, L., & Bi, J. (2012). Eutrophication mitigation strategies: perspectives from the quantification of phosphorus flows in socioeconomic system of Feixi, Central China. *Journal of Cleaner Production, 23*(1), 122-137. doi: http://dx.doi.org/10.1016/j.jclepro.2011.10.019

Wu, H., Yuan, Z., Zhang, Y., Gao, L., & Liu, S. (2014). Life-cycle phosphorus use efficiency of the farming system in Anhui Province, Central China. *Resources, Conservation and Recycling, 83,* 1-14. doi: http://dx.doi.org/10.1016/j.resconrec.2013.12.002

Wu, H., Yuan, Z., Zhang, Y., Gao, L., Liu, S., & Geng, Y. (2014a). Data uncertainties in anthropogenic phosphorus flow analysis of lake watershed. *Journal of Cleaner Production, 69,* 74-82. doi: http://dx.doi.org/10.1016/j.jclepro.2014.01.043

Wyant, K. A., Corman, J. R., & Elser, J. J. (2013). *Phosphorus, food and our future*. Oxford: Oxford University Press.

Xu, H., Paerl, H. W., Qin, B., Zhu, G., & Gaoa, G. (2010). Nitrogen and phosphorus inputs control phytoplankton growth in eutrophic Lake Taihu, China. *Limnology and Oceanography, 55*(1), 420-432. doi: 10.4319/lo.2010.55.1.0420

Yuan, Z., Sun, L., Bi, J., Wu, H., & Zhang, L. (2011). Phosphorus flow analysis of the socioeconomic ecosystem of Shucheng County, China. *Ecological Applications, 21*(7), 2822-2832. doi: 10.1890/10-1409.1

Yuan, Z., Liu, X., Wu, H., Zhang, L., & Bi, J. (2011a). Anthropogenic phosphorus flow analysis of Lujiang County, Anhui Province, Central China. *Ecological Modelling*, *222*(8), 1534-1543. doi: http://dx.doi.org/10.1016/j.ecolmodel.2011.01.016

Yuan, Z., Shi, J., Wu, H., Zhang, L., & Bi, J. (2011b). Understanding the anthropogenic phosphorus pathway with substance flow analysis at the city level. *Journal of Environmental Management, 92*(8), 2021-2028. doi: http://dx.doi.org/10.1016/j.jenvman.2011.03.025

Zhao, W., Ren, H., & Rotter, V. S. (2011). A system dynamics model for evaluating the alternative of type in construction and demolition waste recycling center – The case of Chongqing, China. *Resources, Conservation and Recycling*, *55*(11), 933-944. doi: http://dx.doi.org/10.1016/j.resconrec.2011.04.011