Agricultural Systems 161 (2018) 42–60

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

# A multi-year phosphorus flow analysis of a key agricultural region in Australia to identify options for sustainable management

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## ABSTRACT

This paper presents a comprehensive substance flow analysis (SFA) of phosphorus (P) for a six-year period (2008–13) in Gippsland, a key agricultural region of Australia with high economic and environmental significance. The analysis has revealed that around 71% (10,904 t) of the mean annual total inflow of P was stored in this region. This finding is different from other published regional scale SFAs, where more than 50% of the P in annual total inflow eventually left the region. Per capita P inflow in Gippsland is also found substantially higher compared to available SFAs. In Gippsland, the annual inflow of P primarily occurred as commercial fertilizer (66% or 10,263 t) and livestock feed (29% or 4443 t), and the outflow mainly occurred as livestock products (94% or 4181 t); while the majority (66% or 7218 t) of the P storage occurred in soils of the livestock farming area. A comparative analysis of the magnitude of P flow in different subsystems indicates that more than 80% of the annual total inflow, outflow, and storage of P in this region is associated with the livestock (mainly dairy and meat cattle) farming subsystem. For the Gippsland region as a whole and almost all subsystems, significant annual variations in the magnitudes of P inflow, outflow, storage and internal flow have been observed. Between 2008 and 2013, both the annual total inflow (mainly as commercial fertilizer) and the annual total storage (mainly in soils) of P in this region showed a substantial decrease (41% and 54% of the 2008 level, respectively), while the annual total outflow (mainly as livestock and crop products) remained nearly the same, indicating an improvement towards sustainable P management. Despite such a positive sign, there is still adequate room for improvement. This analysis indicates that over the study period, about 65,424 t P were accumulated (mainly as soil storage) that is approximately six times the mean annual P inflow as commercial fertilizer in this region; while approximately 3241 t P lost as soil erosion and runoff, indicating substantial adverse economic and environmental implications. Based on the findings of the current analysis, this paper outlines a wide range of policy and management interventions to reduce the downstream loss of P and other nutrients as well as the region's dependency on imported commercial fertilizers and grain based feed. This paper also presents new criteria for data quality analysis and a set of P concentration data of various materials that could be readily utilized in future SFAs of P at any geographical scale. This paper suggests that considering the inter-annual variations in P flow as assessed in this SFA, future research should focus on identifying the influence of socio-environmental, technological and political factors on the magnitude P flow in Gippsland.

## 1. Introduction

Phosphorus (P) is a non-substitutable, non-renewable and geographically restricted but essential resource for food production. The significance of sustainable management of P for global food security as well as for the protection of aquatic ecosystems is well addressed in numerous published literature (i.e. Cordell et al., 2009; Childers et al., 2011; UNEP, 2011; Elser, 2012; Ulrich and Schnug, 2013; Wyant et al., 2013; Scholz et al., 2014; Withers et al., 2015; Chowdhury et al., 2017; Metson et al., 2017). In order to formulate effective policy and strategic decisions for securing sustainable management of the global P resource, there is need for a thorough understanding of the nature and magnitude of P flow in various systems at different geographical scales (Chowdhury et al., 2014). In recent years, the substance flow analysis (SFA) method (Brunner and Rechberger, 2004) has been extensively utilized for quantitative analysis of the flow of P in diverse systems (Cordell et al., 2012; Chowdhury et al., 2014; Chowdhury and Chakraborty, 2016). Such

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https://doi.org/10.1016/j.agsy.2017.12.005
Received 9 December 2016; Received in revised form 12 December 2017; Accepted 15 December 2017

analyses have provided an understanding of the nature and magnitude of P wastage from various systems, and thus, allowed to determine the potential for decreasing P loss and increasing P recovery and reuse (Chowdhury et al., 2014).

Reviews on recent SFAs of P at various geographical and temporal scales (Chowdhury et al., 2014; Chowdhury and Chakraborty, 2016) revealed that despite its significance in terms of the magnitude of P flow and storage, the regional scale (i.e. an agricultural region within a country) has received limited attention with respect to multi-year analysis. This indicates that there is a significant knowledge gap regarding the inter-annual variations in P flow at this scale. An understanding of the dynamic nature of annual P flow over multiple years at the regional scale may provide a basis for evaluating the influence of various socio-economic, cultural, environmental, technology, management, and policy factors for making well-informed, appropriate and long-term decisions for sustainable P management. Although several multi-year P flow analyses with such purpose have already been performed at various geographical scales (Neset et al., 2010; Ma et al., 2012, 2013, 2014; Roy et al., 2014; Jiang and Yuan, 2015; Wu et al., 2015, 2016; Keil et al., 2017), these studies are limited to only a few countries (mostly China). Therefore, in order to secure sustainable management of the global P resource, similar multi-year analyses should be conducted for other countries, particularly focusing on the agricultural production system at the regional scale. Here, we present a detailed multi-year SFA of P of an important agricultural region (Gippsland) in Australia to examine the inter-annual variations in P flow. Based on this analysis, we identify priority areas for improving P management, and suggest necessary management strategies and directions for future research to secure sustainable P management in this region. Thus far, we are aware of only one city scale (Tangsubkul et al., 2005) and one national scale (Cordell et al., 2013) published SFAs of P (both for a single year) in Australia; therefore, in this study, we report the first comprehensive multi-year regional scale SFA of P in Australia.

## 2. Methods of analysis

The SFA method, that applies the mass-balance principle to quantitatively assess the flow of substance within a system defined in space and time (Brunner and Rechberger, 2004), has been utilized for the present multi-year analysis of regional scale P flow. To perform this analysis, a multi-year SFA model was developed in the MATLAB/Simulink® software platform (The MathWorks, Inc., 2014). This model accounts for, both structurally and operationally, all the necessary P flows and storage associated with all key systems, subsystems, processes or components, and associated interactions at the regional scale. Based on the given input of material mass flow and P concentration data, in an annual time step, this model calculates P flows and storage over multiple years. The detailed procedure of model development, and model application for analysing multi-year P flow has been published in Chowdhury et al. (2016). In this paper, 'P inflow' refers to the mass flow of P (elemental) that enters into a system/subsystem through a particular material in a given time, and 'P outflow' refers to the mass flow of P that leaves a system/subsystem through a particular material in a given time. 'P storage' is the difference between the mass of total inflow (sum of all inflows) and total outflow (sum of all outflows) of P relating to a particular system/subsystem in a given time. In this section, we mainly focus on the procedure of data collection, the quality assessment of the data, and the various assumptions used in case of missing data and information.

### 2.1. *Description of the study area and rationale for selection*

Gippsland, a mostly intensive agricultural region of Australia, has been chosen for the current SFA as it is predominantly a food-producing region with areas of significant ecological value, and it has a unique combination of well-defined land use systems including substantial urban areas. Geographically, it 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. 1). It covers a total area of 41,557 sq. km, with an estimated resident population of 263,858 (ABS, 2014) residing mainly in the urban and peri-urban areas of its six local government administrative zones i.e. Bass Coast, Baw Baw, East Gippsland, Latrobe, South Gippsland and Wellington. Approximately 33% of the total area of the Gippsland region is occupied by production forestry, 28% by agricultural lands (mainly grazing based livestock farming) and 28% by conservation and natural environment (ABARES, 2014). The environment and climate of Gippsland are favourable for natural resource based industries.

Gippsland's economy is mainly based on natural resources and agricultural commodities. It comprises more than 1400 dairy farms that produce over 2 billion litres of milk annually, accounting for around 21% of Australia's milk production (GippsDairy, 2015). It also contributes about 25% of the total beef production and 14% of the total fruit and vegetable production of Victoria (according to ABS, 2016, among all states, Victoria is the second highest contributor to Australian GDP, with approximately 23% or AUD 373,624 million in 2016). Additionally, Gippsland accounts for around 29% of the agricultural, forestry and fishing exports of Victoria (Victorian Government, 2014). There are more than 6500 farms in Gippsland, together producing about AUD 1.3 billion of agricultural products each year (DEPI, 2014). In order to sustain its agricultural production and associated economic outputs, Gippsland requires significant quantities of imported commercial phosphate fertilizers (i.e. 38,400 t Single Super Phosphate in 2013 according to ABS, 2014a) at significant cost. The lakes and adjacent wetlands in Gippsland, which constitute approximately 600 sq. km, are of intrinsic ecological and economic value (GLMAC, 2013) and several instances of P induced pollution have been reported (Cottingham et al., 2006; Ladson and Tilleard, 2006; Holland and Cook, 2009). Connolly and Hylands (2009) estimated a direct economic loss of AUD 18.2 million to the tourism industry from a blue green algal bloom in the Gippsland Lakes in 2008. Given all these circumstances, there are clearly significant economic and environmental benefits of reducing the region's dependency on imported P fertilizers and P induced water pollution through sustainable P management.

### 2.2. *Selection of system boundary and temporal scale*

The geographic boundary of the region analysed (Fig. 1) corresponds with the Australian Bureau of Statistics region Latrobe-Gippsland (ABS, 2015). The subsystems considered for the current analysis include crop farming, livestock farming, forest, household and urban, waste management, and water bodies. The boundaries of these subsystems are determined based on the areas dedicated to relevant land use and industries as well as the associated activities, processes and flows of materials. This region does not have any mineral fertilizer industry and relies entirely on imported phosphatic fertilizers. The 2008–13 period has been selected as the temporal scale for current SFA because of better data availability in these years. The analysis of P flow has been carried out in an annual time step.