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The stocks and flows of nitrogen, phosphorus and potassium across a 30-year time series for agriculture in Huantai county, China

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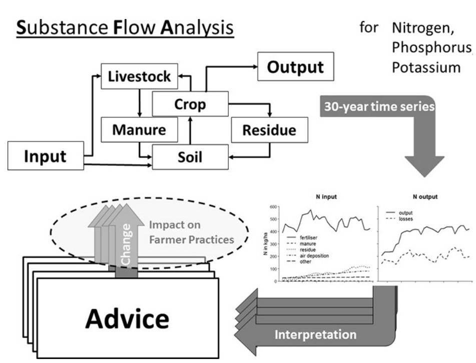
HIGHLIGHTS

- Dynamic substance flow analysis highlight nutrient imbalances.
- Revealed divergence of farm practice, fertiliser recommendations and best practice
- Specific improvements in nutrient management for different systems are required.
- Systemic analysis at county scale matches relevant decision making and policy.
- Advice can be tailored drawing from readily available information.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to improve the efficiency of nutrient use whilst also meeting projected changes in the demand for food within China, new nutrient management frameworks comprised of policy, practice and the means of delivering change are required. These frameworks should be underpinned by systemic analyses of the stocks and flows of nutrients within agricultural production. In this paper, a 30-year time series of the stocks and flows of nitrogen (N), phosphorus (P) and potassium (K) are reported for Huantai county, an exemplar area of intensive agricultural production in the North China Plain. Substance flow analyses were constructed for the major crop systems in the county across the period 1983–2014. On average across all production systems between 2010 and 2014, total annual nutrient inputs to agricultural land in Huantai county remained high at 18.1 kt N, 2.7 kt P and 7.8 kt K (696 kg N ha^{-1}; 104 kg P ha^{-1}; 300 kg K ha^{-1}). Whilst the application of inorganic fertiliser dominated these inputs, crop residues, atmospheric deposition and livestock manure represented significant, yet largely unrecognised, sources of nutrients, depending on the individual production system and the period of time. Whilst nutrient use efficiency (NUE) increased for N and P between 1983 and 2014, future improvements in NUE will require better alignment of nutrient inputs and crop demand. This is particularly true for high-value fruit and vegetable production, in which appropriate recognition of nutrient supply from sources such as manure and from soil reserves will be required to enhance NUE. Aligned with the structural organisation of the public agricultural extension service at county-scale in China, our analyses highlight key areas for the development of future

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agricultural policy and farm advice in order to rebalance the management of natural resources from a focus on production and growth towards the aims of efficiency and sustainability.

1. Introduction

China is the largest single consumer of inorganic fertilisers in the world, responsible for approximately 30% of annual global fertiliser use for each of the macronutrients: nitrogen (N), phosphate (P_2O_5 total nutrients) and potash (K_2O total nutrients) (FAOSTAT, 2014). The majority of China's demand for inorganic fertilisers is met by internal reserves or by synthesis, with the exception of potassium (K) for which China is heavily reliant on imports, to the extent that >15% of global imports of K entered China in 2014 (FAOSTAT, 2014). However, China is also recognised as a global hotspot of relatively low nutrient use efficiency within agricultural production (Foley et al., 2011; Vitousek et al., 2009). The high demand for inorganic fertilisers within China, coupled with inefficient nutrient use, exerts significant pressure on finite rock reserves (for K and phosphorus, P) and the global inorganic fertiliser markets that depend on these reserves. As high-quality rock reserves may diminish within the near future (Cordell and White, 2014; Wang et al., 2011), the pressure on fertiliser markets due to the demand exerted by China is likely to increase substantially. Further, the environmental costs associated with the production of inorganic fertilisers and with the inefficient nutrient use within agriculture, including greenhouse gas emissions, degradation of soil, freshwater and marine ecosystems and declining air quality, are likely to grow and to be particularly pronounced within China (e.g. Chen et al., 2014).

Responding to these challenges requires new frameworks comprised of policy, practice and the means of delivering change, in order to improve the efficiency of inorganic fertiliser use (Bellarby et al., 2015), whilst also meeting projected increases in the demand for food within China (Zhang et al., 2011). These frameworks should emerge from systemic understanding of the stocks and flows of nutrients within agriculture. In this context, substance flow analyses (SFAs) can be used to quantify the stocks and flows of a substance (in this case, individual nutrient elements) within a defined spatial unit and across different sectors within that spatial unit (Cooper and Carliell-Marquet, 2013; Senthilkumar et al., 2012). Previous SFAs within China have examined nutrient stocks and flows at country-level (Hou et al., 2013; Ma et al., 2010), at province-level (Ma et al., 2012; Sheldrick et al., 2003) and at the level of individual farm systems (Gao et al., 2012; Hartmann et al., 2014). These analyses reveal substantial regional differences in nutrient management within agriculture, largely reflecting differences between climatic regions and the resulting dominant production systems. In general terms, nutrient use efficiency (NUE) is greater in arable crop production systems than in vegetable and fruit production in China, whilst vegetable and fruit production demonstrate higher NUE than animal production systems (Ma et al., 2012). Enhancing NUE within animal husbandry in China is recognised as a particular challenge, due to increasing disconnection between concentrated animal production facilities and land to which animal manure can be returned (Bai et al., 2013; Chadwick et al., 2015).

However, the majority of SFAs to date have either examined only one nutrient element (usually N or P), or N and P in combination (Cooper and Carliell-Marquet, 2013; Ma et al., 2012; Senthilkumar et al., 2012). Little research has examined the third macronutrient, K, in combination with N and P (Sheldrick et al., 2003; Zhen et al., 2006), despite the fact that an imbalanced supply of the macronutrients N, P and K can adversely impact crop yield and decrease NUE (Dai et al., 2013). Further, the majority of SFAs have only focused on data from a single year, providing a snapshot of nutrient stocks and flows for a given spatial unit (Chowdhury et al., 2014). However, such snapshots do not capture longer-term trajectories of change in nutrient stocks and flows within a system, as driven by natural processes, such as variation in rainfall or temperature regimes, by management practices, such as crop rotations, by policies, such as variation in trade tariffs, farm input and fertiliser industry subsidies (Li et al., 2013; Sun et al., 2012), or by regulation, such as the ban on the burning of crop straw in China from 2008 (Miao et al., 2011). The use of longer time series of data to construct SFAs would help to avoid the risks associated with basing policy and practice on short-term analyses that may not accurately account for longer-term changes in nutrient management within a system (Sheldrick et al., 2003).

Our previous research suggests that the county-scale is a key spatial unit at which to consider the potential for change in nutrient management practices within China, particularly for largely rural counties in which the management of nutrients in agriculture is clearly important (Smith and Siciliano, 2015). The county-scale is especially relevant in China because of the corresponding structural organisation of the public agricultural extension service. Key decisions regarding agricultural policies and farm advice provision are made for county-wide execution by the County Agricultural Bureau, which has considerable autonomy with regard to such policies and advice (Bellarby et al., 2017; Smith and Siciliano, 2015). For example, the bureau is responsible for undertaking soil nutrient surveys and for the provision of fertiliser recommendations based on the resulting information. These recommendations are often applied county-wide, and form the basis for compound fertiliser formulations sourced from manufacturers for county-wide distribution. In the current paper, we report a county-level analysis of nutrient use within agricultural production systems in China, based on SFAs for the macronutrients N, P and K using a time series of data that spans 32 years from 1983 to 2014. The objectives of these analyses were: i) to quantify changes in N, P and K stocks and flows within individual production systems at county-scale in China over a 30-year timescale; ii) to interpret drivers of the observed changes in nutrient management over this timescale; and iii) to consider the ways in which analysis of historical patterns of nutrient use in agriculture can inform future policy and practice seeking more sustainable stewardship of N, P and K resources.

2. Materials and methods

2.1. System boundary and design of the substance flow analyses

Substance flow analyses were constructed for Huantai county in Shandong Province, China (Fig. 1). Huantai county covers approximately 520 km^2 with a total farmed area of 354 km^2 (68%) in 1980. Agricultural production in the county is primarily an intensive rotational double cropping area of summer maize and winter wheat, typical of agriculture within the North China Plain (Ha et al., 2015). Crop production relies heavily on irrigation with groundwater (Chen et al., 2010; Liu et al., 2005). Other arable crops (cotton, peanut, potato, soybean and sweet potato), vegetable, fruit (apple, apricot, Chinese date, grape, hawthorn, peach and pear), as well as livestock, are produced in the county. In this paper, other arable crops, vegetable, fruit, and livestock are each considered as individual production systems (Fig. 2). Approximately 250,000 of the county's 493,000 population are engaged in farming (Huantai Agricultural Bureau, 2014).

The SFA approach uses mass balance principles to systemically identify and quantify an element from source (here, input into one of the production systems within Huantai county), through internal stocks and flows within the defined system boundary, to the final managed