Strategies for sustainable nutrient management: Insights from a mixed natural and social science analysis of Chinese crop production systems

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Abstract [148 words]

In China intensification of agriculture has been achieved at a cost to the environment. The extension service is the leading public resource to address this but remains focused by a historic national ethos for food security, production and economic growth, whilst its administrative structure is hierarchical, slow to change and lacking in relevant functional integration. Investigation of three case study farming systems identifies how to rebalance productivity with stewardship of farm inputs and natural resources. Substance flow analyses for each case demonstrate that crop nutrient management can potentially be improved to reduce environmental risk without yield loss. Complementary stakeholder surveys and social network analyses identify barriers to change relating to the knowledge, attitudes, practices and operational constraints of farmers and extension agents, and to the structure and performance of agricultural knowledge and innovation systems. This combination of analyses offers an original synthesis of needs, planning priorities and strategies.

Key words:

diffuse pollution, nutrients, systemic approaches, extension, China

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1. Introduction

Losses of the primary macronutrients nitrogen (N) and phosphorus (P) from food production systems degrade water resources globally (Vorosmarty et al., 2010). Nutrient export from soils contributes to diffuse water pollution (Norse, 2005), and gaseous losses from inorganic fertilisers and manures also contribute to atmospheric pollution (Liu et al., 2011). For China there is accumulating evidence at plot scale (or aggregated for large areas) that inorganic fertiliser application is excessive and nutrient use efficiency is low in many farming systems (Foley et al., 2011; Ma et al., 2013a). Nationally, fertiliser use grew fourfold from 1978 to 2012 (FAOSTAT, 2015) and diffuse water pollution from agriculture (DWPA) has grown rapidly (Zhang et al., 2013; Ju et al., 2009); as evidenced by indicators of eutrophication in 80% of lakes and at least 40% of rivers (Liu and Yang, 2012), increased nutrient concentrations in groundwater and widespread soil acidification (Cui et al., 2014). In 2009, agriculture was estimated to be the source of 57% of the N and 69% of the P entering watercourses within China (MEP, 2010). Recently, Strokal et al. (2016) confirmed that inorganic fertiliser use contributes significantly to river nutrient loads. The environmental costs of all this are difficult to quantify and disaggregate from non-agricultural causes, but indicatively the aggregate costs of all water pollution may approach two percent of national GDP (SEPA and NSB, 2006; Guo, 2011).

Addressing sub-optimal management of inorganic fertilisers and manures would reduce these negative externalities and farm costs, and accord with national priorities (Garnet and Wilkes, 2014). For example, in 2015 the Ministry of Agriculture declared that annual growth in the use of inorganic fertilisers should be capped below one percent from 2015 to 2019, with zero growth from 2020 (Xu, 2015; SCMP, 2015). However, there is little evidence to date that improvements to nutrient management are being realised on a wide scale, and hence that high level policy pronouncements can be translated into action by many millions of farmers (Ma et al., 2013b). Policy needs to be informed by quantitative analyses of nutrient management within farming systems, particularly systemic analyses in which all significant nutrient flows and stocks within a system are considered (e.g. Senthilkumar et al., 2012). However, such quantification alone will not be sufficient to change the apparent inertia and economic non-rationality of excessive nutrient use on farms (Norse, 2005; Forhead, 2014; Holdaway, 2014).

The public agricultural extension system and farmer training are frequently recommended as means to change farmer behaviour in China (e.g. Guo et al., 2015; Huang et al., 2015). Yet, a combination of policies including regulation and incentives is likely to out-perform a single approach such as a fertiliser tax or farmer training alone (Weersink and Livernois, 1996; OECD, 2012). Farm advice provision is, however, important as it can facilitate compliance with regulation and adoption of improved technologies/practices and incentivised actions. Hence the functions of agricultural knowledge and innovation systems (AKIS)[1] are 'cross-cutting' and complementary and synergistic with other policy instruments.

To address this agenda this paper advances understanding of farmer behaviour in China through in-depth empirical investigation of selected farming systems representative of farming methods across large areas. For each case, systemic, quantitative analysis of nutrient management is combined with investigation of determinants of farmer attitudes and practices. The actions of, and information flows between AKIS actors need to be consistent and well-coordinated in order to delivery change and hence the structure and performance of the AKIS for each case are also holistically examined. Finally, comparative lessons are drawn from the case studies which suggest future directions for public policy for more sustainable nutrient management in Chinese agriculture.

2. Materials and methods

2.1 Case studies

Three case studies were selected to represent important crop production systems in China. With respect to their location (Figure 1) these are referred to below as "Lake Tai", "Huantai" and "Yangling". They encompass arable and protected horticultural production systems of different spatial scales, and both groundwater- and surface water-dominated systems. They also span a spectrum in terms of agrarian structure and progress of land transfer[2]. This is important because in comparison to small farms, farm management decisions in consolidated units are usually made by fewer, more professional farm managers, with relative uniformity across a cultivated area.

[Figure 1, near here]

Figure 1: Location of the case study agroecosystems in China and their dominant form of production.

The Lake Tai case study relates to a sub-catchment of the Li river and the village of Sandongqiao. The large and nearby Lake Tai is used for urban water supply and has suffered from well-publicised eutrophication, including algal blooms (e.g. Economist, 2008, 2010). This case is representative of the rice-wheat rotation that is common in southern and eastern China (Zou et al., 2005) and the major pathway for DWPA is through surface runoff. The case is also representative of medium to large scale village-based consolidated farming enterprises post land transfer.

[1] Defined as the set of organizations, institutions and actors that, through services to farmers, will exchange information and enhance farmer knowledge and skills, with the aim of enabling them to co-produce new knowledge and solutions (EU SCAR, 2012).

[2] Consolidation of small and fragmented land holdings, encouraged by government, and achieved through a range of rental and transfer arrangements (Huang et al., 2012; Smith and Siciliano, 2015).

The Huantai case study refers to a county in Shandong province. Rotational double cropping of maize and wheat is representative of farming across the North China Plain (Ha et al., 2015), and the major pathway for DWPA is pollutant leaching to groundwater. The case is also representative of small plot farming by individual farm households before land transfer[3].

The Yangling case study relates to 36 solar greenhouses in Zaixi village near the city of Yangling. Solar greenhouses are widely used[4] for the production of vegetables in central and northern China (Bomford, 2010). A variety of crops are grown over two seasons, although tomato is the most common. The major pathway for DWPA is leaching to groundwater. A farmer usually cultivates one greenhouse with a standardised area of 672 m^2 (~1 mu). This is typical for this farming sector (Gao et al., 2012), although large-scale protected horticulture also exists in some locations.

2.2 Substance flow analysis

Substance flow analyses (SFAs) were constructed to quantify the stocks and flows of N and P at an annual time step for each case study. The SFA approach uses mass balance principles to systemically identify and quantify an element from source (here entry into the case study agroecosystem), through internal stocks and flows within a defined system boundary (each case study), to the final managed or unmanaged export of an element across a system boundary (Senthilkumar et al., 2012; Cooper and Carliell-Marquet, 2013). To focus on nutrient management by farmers in important farming systems the analyses were limited to the dominant crop production for each case. Thus nutrient stocks and flows associated with food processing, other farm production or other human activity have not been considered.

Information on nutrient inputs and outputs were unique to each case and were mainly derived from existing secondary survey data and statistical datasets (Table 1), supplemented by previously published data and by primary measurements in certain cases. All losses of nutrient elements to the atmosphere and to water were estimated using previously published empirical functions (as in Bouwman et al., 2002; Stehfest and Bouwman, 2006; Velthof et al., 2009)[5].

[Table 1 near here]

Table 1: Overview of case studies in China and data sources for the substance flow analyses.

Nutrient use efficiencies (NUE) have been calculated for both N and P based on the SFAs, in order to compare the current efficiency of nutrient use across each case study. The NUE for an individual crop production system was calculated following Equation 1:

$$\left(\frac{N\ or\ P_{product\ output}}{N\ or\ P_{external\ inputs}}\right) * 100 \qquad [1]$$

Here, N or $P_{\text{product output}}$ relates to marketable output, such as grain, and N or $P_{\text{external input}}$ includes all human and natural inputs (i.e. inorganic fertiliser, manure, atmospheric

[3] An average of 0.4 hectare was recorded by our survey (details below).

[4] An area of 4.67 million hectares in 2010 (Gao et al., 2012); 4% of arable land in China (FAOSTAT, 2015).

[5] Readers may refer to the supplementary information provided for relevant data sets, functions and references.

deposition, biological N fixation and nutrients introduced via crop seeds or seedlings and irrigation), but not crop residues recycled to the soil within the system.

2.3 Socio-economic analysis

For each case study, a mixed methods approach was used comprising a farmer KAP (knowledge, attitudes and practices) survey, key informant interviews, stakeholder mapping and stakeholder workshops. The KAP survey[6] investigated current influences on nutrient management, including that exerted by the existing AKIS in each location. The population surveyed comprised farm households and in each case the person responsible for farming decisions was interviewed. For Huantai, the sample consisted of 61 respondents drawn from within the case study area. For Lake Tai and Yangling, 103 and 58 respondents were surveyed respectively, each drawn from within the case study area (Table 1) and the immediately surrounding area with the same farming system. Survey questionnaires were pre-tested and all data collection was conducted in Mandarin Chinese by experienced enumerators familiar with the locations. To investigate farmer attitudes to nutrient management and influences on their behaviour, the survey questionnaire design included use of an array of Likert items. Respondents rated their agreement with statements about nutrient management on a scale from 1 (completely disagree) to 5 (completely agree). Divergent stacked bar charts are used below to best present the data (Heiberger and Robbins, 2014). Other survey questions prompted a mixture of closed option and open responses.

Prior to and after implementation of the KAP survey, visits to the case studies were made by the research team and semi-structured interviews were conducted with key informants. These included community leaders, large farm managers and government officers. Workshops attended by farmers and township level agricultural extension officers were also held before and after the KAP survey. In Lake Tai and Huantai these workshops were also attended by city (Suzhou) and county (Huantai) level officers. These visits, interviews and workshops first provided exploratory findings regarding influences on farmer behaviour and informed the design, conduct and analysis of the KAP survey. Subsequently the SFA and KAP survey results were presented to these local stakeholders whose feedback informed the interpretation of all results.

To evaluate the AKIS for each case the key informant interviews, field visits and workshops were used to identify relevant actors in each location and characterise their interactions. Analysis for this employed Social Network Analysis (SNA) as commonly used to assess formal and informal interactions between different actors by focusing on the network of actors instead of their individual attributes or formal hierarchical structures (Scott, 1991; Wasserman and Faust, 1994; Schiffer and Hauck, 2010; Marshall and Staeheli, 2015). In a SNA each actor is represented in the network by a node and the type of relationship between nodes is represented by specific links (Schiffer and Hauck, 2010). Each case study network was analysed for indices of density and centralisation. Network density measures how many links exist within a network compared to the number of links that could theoretically exist assuming all nodes are inter-connected, and was used to assess network cohesion and coordination. The higher the density of a network the greater is the potential for collaboration between the identified actors and for joint (and hence potentially synergistic) actions (Scott, 1991; Bodin and Corona, 2009). Network centralisation measures the extent to which the network is centred on one or more key actors or links based on the number of relationships an actor or link has within the network. This provides an indication of the extent to which power

[6] Farmer KAP survey questionnaire is provides as supplementary information.

and influence is distributed in a network. The number of relationships an actor (or link) possesses is assumed to have a positive relationship with the power or influence exerted by that actor on others and the capacity of the actor to access information (although an excessive number of relationships may also constrain possibilities for action and knowledge development; Bodin and Corona, 2009). Both network density and centralisation indices are best interpreted in comparison between cases rather than in absolute terms. Network data were visualized and analysed using Visualyzer software (Visualyzer 2.0).

3. Results

3.1 Substance flow analyses: identifying opportunities for more sustainable nutrient management

The SFAs for each case study are reported in Figures 2 and 3 and system-level N and P NUEs are reported in Table 2.

[Table 2 near here]

Table 2: Comparison of nutrient use efficiencies for the case study agricultural systems.

[Figure 2 near here – whole page?]

Figure 2: Substance flow analyses detailing the flow of nutrients in kg N/ha/year for case study agricultural systems: Lake Tai (a), Huantai (b) and Yangling (c).

[Figure 3 near here – whole page?]

Figure 2: Substance flow analyses detailing the flow of nutrients in kg P/ha/year for case study agricultural systems: Lake Tai (a), Huantai (b) and Yangling (c).

For the cereal systems (Lake Tai and Huantai cases) nutrient input from inorganic fertiliser and manure[7] matches relatively closely to crop nutrient uptake. However, the SFA also accounts for the nutrient content of recycled crop residues and nutrient input from irrigation water and natural sources. This reveals substantial excesses of N (Lake Tai: 171 kg/ha/year; Huantai: 299 kg/ha/year) and P (Lake Tai: 27 kg/ha/year; Huantai: 24 kg/ha/year) compared to crop requirements for both systems (Figures 2 and 3), as also reflected in the NUE values (Table 2), particularly for N within the Huantai system.

For the protected horticultural production (Yangling) the input of nutrients from inorganic fertiliser use alone was significantly in excess of crop demand, resulting in low NUE values (Table 2). This excess was compounded by substantial inputs of N and P from use of manure. Nutrient inputs from other sources were minor in comparison, though inputs from irrigation water (57 kg N/ha/year) are relatively large in absolute terms (Figures 2 and 3). This reflects the combination of elevated N concentration within the groundwater (9.6 mg NO_3^--N L^{-1}) used for irrigation and the high volumes of irrigation water applied (595 mm per annum). Crop residues could provide a further source of nutrients but are usually removed from the greenhouses for pest control.

For all cases atmospheric losses of N are related to inputs of N from inorganic fertiliser and manure application. Consequently these losses are estimated to be greater for Huantai (123 kg N/ha/year) than Lake Tai (53 kg N/ha/year). The much higher estimate for Yangling (836 kg

[7] In the Huantai case, livestock slurry and manure was generally only applied to higher value fruit and vegetable crops and not routinely to the cereals analysed. For Lake Tai, at the time of these analyses, manure was imported to the cereal system from external suppliers.

N/ha/year) is uncertain because the input value may exceed the range for which the empirical function used is valid but actual losses must still be high (Figure 2). For both Huantai and Lake Tai, aqueous losses of N exceed atmospheric losses, and hence aggregated total losses are high for each case. For example, for Huantai the estimated aggregate losses of N (265 kg N/ha) almost match the N content of the crop output (297 kg N/ha/year).

The aqueous losses of P for Lake Tai (38 kg P/ha/year) are particularly high and are primarily driven by high soil P content (Figure 3). In this system, aqueous losses of P exceed the net balance of P at the soil surface by 10.9 kg P/ha/year. For both Huantai and Yangling similar data suggests a substantial net accumulation of P at the soil surface. High net accumulation of nutrients at the soil surface, resulting from nutrient inputs that exceed crop demand, results in significant nutrient stocks accumulating in the soils of these cases (Figures 2 and 3). For example, soil N content in the Yangling system exceeds 0.2%. For the greenhouses in this system, surface runoff and the erosion of soil nutrients are assumed not to occur because of the use of drip irrigation and the presence of physical barriers that prevent surface runoff. Thus aqueous losses are constrained to leaching beneath the root zone and are dominated by the leaching of N rather than P.

3.2 Farmer knowledge, attitudes and practices

3.2.1 Sample characteristics

The farmer KAP survey sample comprised 222 respondents. Most, 46%, declared a farmed area of 1 to 4 mu (667 to 2667m^2), 29% less than 1 mu, and 26% an area in excess of 4 mu (Table 3). Most were men (72%), aged 41 to 60 (53%); a further 41% were older and only 6% were younger (Table 3). The education level of the respondents was generally low, being to either primary level (44%), secondary level (48%) or uneducated/illiterate (9%) (Table 3).

[Table 3 near here]

Table 3: Farmer KAP survey, summary descriptive statistics by case study and whole sample (percentage values)

There are notable differences between the case studies. The Yangling sub-sample (protected horticulture) is characterised by the smallest land units - 55% of respondents cultivating one greenhouse (~1 mu) and the remainder having 2 or more greenhouses – whilst the Huantai sub-sample had the highest proportion of larger land units (> 4 mu; 53%). The age profile for Yangling respondents was younger (85% were 41 to 60 years old; 7% over 60) compared to the Lake Tai and Huantai sub-samples for which over 50% of respondents were over 60 years old (Table 3).

3.2.2 Attitudes to inorganic fertiliser application

The majority of farmer respondents in all three cases agreed with the statement *'I don't apply fertiliser as many times as is recommended, therefore when I do apply it I add an extra amount'* (Figure 4). The fertiliser recommendations referred to within this statement were those of the public extension service (supplemented and reinforced by those of university researchers in the cases of Huantai and Yangling). In contrast, the majority of farmers in each case did not agree with the statement that *'because fertiliser is cheap, I feel I can be generous with the amount I apply to my crops'* (although approximately one third of respondents from Yangling and Huantai expressed at least some agreement with this statement; Figure 4). The majority of Huantai farmers agreed with the statement that *'I don't apply fertiliser as many times as is recommended because it takes too much time/labour'* (Figure 4). In contrast, less than 25% of Lake Tai and Yangling farmers agreed that labour availability was a constraint to multiple inorganic fertiliser applications (as recommended by the extension service and universities). As noted above, Huantai respondents may cultivate a larger area than farmers in the other cases.

[Figure 4 near here]

Figure 4: Likert scale responses to attitudinal questions (percentage of farmer KAP survey respondents).

3.2.3 Influences on inorganic fertiliser application

Farmers surveyed were found to gain information on inorganic fertiliser application rates from a variety of sources (Figure 5). Neighbours and television were the most reported sources of information by Huantai and Yangling respondents. Neighbours were less significant for Lake Tai respondents who most frequently cited leaflets from the public agricultural extension service as an information source. In addition, across the three cases 45-55% of responses indicated that a respondent or family member had attended at least one fertiliser training session provided by the public extension service within the last three years. Thus although the public extension service may be the primary source of this key information, its communication to large numbers of farmers is often by indirect means.

[Figure 5 near here]

Figure 5: Sources of information on inorganic fertiliser application reported by farmers (percentage of farmer KAP survey respondents reporting the source).

A further Likert scale question revealed that for the Huantai and Yangling cases most farmers tend to apply inorganic fertiliser at the same rate as their neighbours (Figure 6), although local extension technicians, fertiliser companies and the instructions on fertiliser bags were also acknowledged as influences by approximately 50% of these respondents. The importance of the peer influence of neighbours for these cases is consistent with the observations of Rogers (2003) regarding processes for diffusion of innovation. In contrast, few Lake Tai respondents acknowledged any of these influences as important.

[Figure 6 near here]

Figure 6: Likert scale responses regarding influences on inorganic fertiliser application rates (percentage of farmer KAP survey respondents)

3.2.4 Use of soil testing

Figures 2 and 3 indicate that dependent on actual loss rates, soils in each case study accumulate nutrient stocks that could support crop production. Soil testing combined with targeted fertiliser formulations and application practices could thus help improve nutrient use efficiency in each system. The KAP survey revealed that the majority of farmer respondents in all three case studies had no experience of their soils being tested for nutrient content (soil samples had been taken at least once from the land of 25%, 39% and 43% of respondents in Lake Tai, Huantai and Yangling respectively). The practice of soil testing was investigated further through key informant interviews and stakeholder workshops. In all cases this revealed that the results of soil testing carried out on a farmer's land are not provided directly to a farmer. The data are used by the public extension service to commission supply of compound fertilisers from manufacturers for use at large spatial scales. For example, for Huantai County two fertiliser formulations were produced for use in each of the northern and southern parts of the County.

Not returning the soil test results to the farmer whose soil was tested is clearly a pragmatic and practical approach adopted for areas still farmed by large numbers of small farmers. As explained, the intention is to provide fertiliser formulations for use over large areas. A limitation of this approach is that the results of the soil tests conducted will be averaged for the area selected, and thus soils on a given farm may not be well represented. The fertiliser formulations developed may also contribute to excessive application of nutrients because a systemic analysis (such as the SFAs described above) is not carried out. Thus no account is taken of nutrients supplied by crop residues, irrigation water or natural sources. For high value crops, formulations also tend to be conservative (and thus potentially excessive in their application) in relation to any potential yield loss. This is further illustrated and discussed for the high value protected horticulture sector below. Also as noted in sections 3.2.2 and 3.2.3 above, a range of factors may influence the actual rate of fertiliser application by farmers.

3.2.6 Awareness of water quality degradation

Survey respondents were asked whether they had noticed change in local rivers, streams or lakes over their lifetime with regard to water colour, number of fish or other animals. For Lake Tai, 73% of respondents described adverse changes that included water colour and smell, and a decline in fish populations. Pollution by domestic sewage, industry and farming were perceived as causes of this. In contrast, only 28% and 9% of respondents for Huantai and Yangling respectively reported any perceived change in local water bodies, including groundwater.

3.3 Structure and performance of agricultural knowledge and innovation systems

The social network diagrams (Figure 7) and network density and centralisation indices (Table 4) provide further insights into the factors that influence nutrient management within each case study. Farmers and village agricultural companies receive the greatest number of advice links, but supervision by public extension agents of the recommendations and actions of other farm advisors, including fertiliser companies, farmer cooperatives and village companies, and research institutes (including universities), is extremely limited. For example, in Huantai County, supervision is provided by the County Agricultural Bureau to agricultural technology transfer centres and their technicians, but rarely beyond this.

[Figure 7 near here]

Figure 7: Social network analyses for Lake Tai (a), Huantai (b), Yangling (c).

[Table 4 near here]

Table 3: Indices of network density and centralization

The network density value for Huantai suggests that 90% of all possible links between actors are present in this location for the AKIS (as defined by our actor identification). This suggests that there is good potential for collaboration and joint (potentially synergistic) actions between the actors (Scott, 1991; Bodin and Corona, 2009). Corresponding values for Lake Tai and Yangling are lower, suggesting that coordination of advice and training provision across actors is relatively weaker for these two case studies compared to Huantai. The value for network centralization is also lower in Huantai (11%) in comparison to the other cases (Yangling 49%; Lake Tai 50%). This also suggests that in Huantai the network is less centred on just a few influential actors, potentially offering greater potential for collaboration between actors than in either Lake Tai or Yangling which are characterised by more centralised networks.

Network centralization values may also be broken down according to the category of link between actors (Table 4), suggesting that supervision in particular, followed by training and advice provision, are all relatively centralized in each case study. This illustrates the top-down and hierarchical character of the AKIS in each location. Decision making in each case tends to be centred on a few public sector actors. Links for feedback and other information flows are less centralized, but it is notable that in all three cases the flow of information is from public extension agents and other advisors to farmers. Little evidence was obtained in any of the cases (from key informants and workshops) of active attempts to solicit and utilise feedback from farmers. The farmers are passive recipients of technical recommendations and other information with no formalised opportunity to feedback their priorities and needs. Hence, there appears to be relatively poor communication from lower levels (i.e. farmers and advisors at farm and village level) to the top of the hierarchy.

4. Discussion and conclusions

4.1 The need for systemic and locally specific nutrient management

The results of the SFAs (section 3.1) identify opportunities to improve the management of nutrients in three significant crop production systems in China. They are consistent with previous studies that similarly suggest that nutrient management in Chinese agriculture can be better optimised to more closely match crop nutrient requirements (e.g. Chen et al., 2014; Powlson et al., 2014; Vitousek et al., 2009). They are also consistent with a contention that systemic analyses are needed to underpin improved management. For example, the 'integrated soil–crop system management' approach, designed to optimise use of solar radiation and temperature whilst achieving greater synchrony between crop demand for nutrients and their supply from soil, environment, and applied inputs (Chen et al., 2011). Approaches such as this will facilitate transition from reliance on inorganic fertilisers towards accounting for multiple nutrient sources and the closure of nutrient loops. Failure to be systemic in approach and to improve nutrient use efficiency will continue to incur the costs of wasteful inorganic fertiliser application and risk of nutrient export to the environment.

Within this context of systemic nutrient planning and management specific recommendations can be made for the cases analysed. In all three application of inorganic fertiliser could potentially be reduced without yield loss. This is particularly true for the protected horticulture system (Yangling), consistent with other studies showing that greenhouse and other high value crop systems tend to apply fertilisers to greatest excess (Powlson et al., 2014; Lu et al., 2016). All three cases also need better accounting for the nutrient content of manures. Key informants and workshops revealed that farmers and local level extension agents value manures as soil conditioners without adequately recognising or accounting for their potential nutrient supply. Improvement could help reduce the spatial disconnection of livestock and crop production that has been driven by increasing demand for meat and dairy products and development of confined animal feeding operations that are isolated from land to which manure/slurry could be returned (Chadwick et al., 2015). Better account should also be taken of other sources of nutrients including biological N fixation, crop residues and irrigation water.

The inference from the SFA results that repeated over application of nutrients will result in accumulation of N and P within soils is also supported by other studies (e.g. Gao et al., 2012, Hartmann et al., 2014). Consequently, farmers need access to an appropriate system of soil testing, to relevant training and advice, and to an appropriate range of quality assured fertiliser formulations 'tailored' to local soil and crop requirements. Together these could enable farmers to adjust their nutrient management practices in response to soil test results. How soil test results are used is critical and farmers need to become partners who are fully engaged in an effective, evidence based recommendation and decision making regime informed by soil test data. Current soil testing and fertiliser formulation regimes operate without farmer input and at spatial scales too large to offer nutrient management plans well adapted to local factors including soil type and land use history.

4.2 Future directions for public policy for improved nutrient management

Improved and more systemic nutrient management is a challenging agenda that requires change in farmers' attitudes and practices (Hu et al., 2012; Powlson et al., 2014) and enhanced skills in farm nutrient accounting and management. Smith and Siciliano (2015) identified a nexus of factors that influence farmers' and extension agents' attitudes to use of inorganic fertiliser. These factors include a persistent national ethos to prioritise food security and maximise production, and an associated risk aversion to any potential yield loss. Survey evidence reported here suggests some association between this risk aversion and the age and education profile of farmers and their labour availability. Evidence gathered from the case studies that current training provision as a means to improve nutrient accounting and management has been largely ineffective are consistent with the findings of other researchers (e.g. Huang et al., 2012; Guo et al., 2015; Huang et al., 2015). For the cases here training by the public extension service was found to be focused on maximising productivity and extremely risk averse in the advice it provided with regard to reduced inorganic fertiliser application, especially for high-value crops.

In addition, although there is growing environmental awareness and public demand for improvements in environmental quality in China (Economist, 2014), urban atmospheric pollution and food safety concerns are foremost (Smith and Siciliano, 2015). Evidence from the farmer KAP survey, key informants and workshops revealed a lack of, or at least willingness to acknowledge, rural air and water quality concerns amongst farmers and other stakeholders. Therefore, despite the opportunities to improve nutrient management (section 4.1), and high level policy pronouncements, both farmers and the AKIS in each location lack the motivation and orientation for change. Evaluation of the structure of the AKIS in each location (section 3.3) also suggests a lack of necessary communication flows, coordination and quality control across diverse actors.

Policy recommendations must be cognisant of these constraints. Also whilst the principle of systemic nutrient management is generally applicable, this study has revealed considerable bio-physical and socio-economic variation across the three case studies. This suggests that a standardised approach to reform and improvement may be insufficient. Hence the following considers feasible changes identified for the local conditions in each case.

Land transfer has progressed furthest in the Lake Tai case. The area can be described as peri-urban and production of cereals (and other crops) is increasingly consolidated in large scale operations managed by farming companies and professional farm managers, as families that previously farmed find employment in nearby cities. However, this sits alongside a residual of small holdings and fragmented plots still cultivated independently and by an ageing and not well educated population. Both categories of farm decision maker appear resistant to reductions in inorganic fertiliser inputs, despite the majority having some awareness of potential water quality impacts. They are currently not strongly influenced in their use of inorganic fertiliser by their peers, farm advisors, fertiliser companies or the information on fertiliser bags. They may tend to apply extra inorganic fertiliser to compensate for infrequent application, but also report some sensitivity to fertiliser prices. Relatively few have experience of soil testing, and little interest in more soil testing or training was evident. For this case, a well-coordinated AKIS strategy needs to be developed locally that focuses on large farms as businesses, and which emphasizes the cost savings, water quality improvement and other environmental benefits that can be gained from more systemic nutrient management. However, such a strategy needs to be dualistic, addressing the commercial interests of farming companies and also formulating regulations, recommendations and media-based educational campaigns to reduce the risk of DWPA from residual home plots.

Cereal cultivation in Huantai remains more typical of independent small plot farming in China. The County can be described as rural and still predominantly agricultural in character. Farm decision makers are ageing and in general not well educated. The farming system is homogeneous over large areas and farmers' use of inorganic fertiliser tends to conform to the established practice of neighbours and the recommendations of local public extension. Farm size tends to be larger than in the other case studies and lack of labour contributes to infrequent and compensating over-applications of inorganic fertiliser. Awareness and concern among farmers and extension agents regarding environmental impacts is low, but this reflects, at least in part, a lack of information[8] and the hidden nature of groundwater pollution. The farming population is potentially receptive to recommendations for improved nutrient management but their options are limited by labour and knowledge constraints. An AKIS strategy for this case must emphasize cost savings from improved nutrient management, but also generate innovations including increased mechanisation and slow release fertilisers that take account of labour constraints. As for Lake Tai, the strategy must evolve into a dualistic approach as land transfer and agricultural modernisation proceeds. In the short term the need to influence the behaviour of a large number of small farmers requires innovative use of a diverse range of approaches and media, including television, supported by raising public awareness of environmental impacts. The importance of peer influence amongst farmers suggests emphasis on use of demonstration farmers and farm trials to promote diffusion from innovators and early adopters (Rogers, 2003) to the wider farming population. This recommendation is consistent with research that concludes that conventional training has only had limited short term impact on farmer behaviour with respect to fertiliser use in China (Huang et al., 2012; Guo et al., 2015; Huang et al., 2015) but that intensive training through farmers' own field trials and onsite demonstrations has potential for more persistent and long-term impact (Huang et al., 2015).

The greenhouse producers of Yangling are also potentially receptive to recommendations for improved nutrient management. The majority are in the 40 to 60 age bracket and have at least secondary level education. The area is peri-urban and well connected to markets, and the farmers can be seen as entrepreneurial and responsive to financial incentives. There is some receptiveness to both soil testing and to training. Use of fertigation is widespread and labour constraints are not binding. The practices of their peers are an important influence on

[8] It was reported in a workshop that groundwater quality monitoring is the responsibility of the Provincial Environment Department and that data is not accessible to the County Agricultural Bureau.

farmers' use of inorganic fertiliser, but they are also influenced by the commercial messages from television and fertiliser companies. During key informant interviews and workshops it was discovered that both farmers and extension agents are particularly risk averse to any potential yield reduction (not least given the high value of horticultural production). As in Huantai, awareness of environmental impacts is also of less influence and an AKIS strategy for the case is similarly challenged by the large number of producers. Thus this case also requires innovation in the use of television and other media for communication with farmers. Beyond this, cost savings can provide an incentive for improved nutrient accounting and management by producers, but must be backed by trust in scientific evidence that application rates for inorganic fertiliser and manure/slurry can be reduced without yield loss. This will require farmer managed demonstration sites at greenhouse scale, as workshops revealed that to date evidence from university-led plot based trials has failed to convince most farmers and public extension agents exposed to the results. Again it is also important to raise public awareness of environmental impacts.

Thus for all three cases farm advice should emphasize resource use efficiency, profit maximisation and environmental protection alongside the goal of high productivity. It should increasingly address farms as businesses, looking beyond yields to the objectives of the farming family or farming company, and to the management of costs, labour use, crop residues and animal wastes, and environmental impacts. To achieve this farmer participation and feedback must increasingly inform research and extension agendas. A leading example is provided by the need to address labour constraints in the Huantai case through mechanisation and slow release fertiliser formulations well matched to local conditions. This will need two-way dialogue and information exchange (as also concluded by Huang et al., 2015).

Also for all three cases the rapid progress of land transfer and the growing diversity of farm types and scale are of great importance. Farmer advice and training modes should become more differentiated by farm size, management type and cropping system. Similarly a diversity of communication and training methods need to be employed, matched to the needs and access of different farmer types and also targeting wider public awareness of environmental quality. The number of small and ageing farmers is a great challenge now, but farm regulation, training and advice provision will become more achievable and cost effective as the number of farms reduces, their size and commercial orientation increases, and younger professional farm managers emerge.

Further challenges are presented by the growing diversification of advice and technology provision by agro-enterprises, input suppliers, supply chains and producer organisations (noting that these commercial actors may have limited incentive to prioritise resource use efficiency and sustainability). The planning and implementation of local nutrient management strategies well-tailored to farming systems, farm characteristics and catchment conditions need to be seen as 'public goods', production of which should be coordinated by the public extension system in partnership with universities and research institutes and local government. Provision of advice to farmers then needs to be coordinated and consistent with the agreed nutrient management strategy for a defined farm type, cropping system and area even if that advice is delivered via multiple public and private sector pathways. Closer inter-agency working, with improved communication and data sharing at all levels, are required to develop the new ethos and overcome barriers to coordination created by functional divisions and specialisations (Smith and Siciliano, 2015). Farmer associations, cooperatives and leading agro-enterprises should be assisted and utilised as demonstrations of best practice.

Stakeholder mapping and SNAs (section 3.3) suggest that the actors and linkages necessary for these AKIS strategies are, in the main, in place. However, they also suggest that there is a need to relax centralised control by the hierarchical public extension service to facilitate innovation and the diverse communication mechanisms necessary to reach and change the behaviour of large numbers of increasingly heterogeneous producers. The public extension service must then seek to develop roles for coordination and quality control, aiming to ensure validity and consistency of information and recommendations provided to farmers by diverse actors, and reducing the possibility of contradictory, insufficiently systemic and untrusted nutrient management guidance being provided. Effective communication and coordination between actors will be essential for this.

It can be concluded that the public agricultural extension system is currently not well oriented towards this agenda (see also: Alex et al., 2004; Jia et al., 2015). Yet alternative feasible approaches for mitigation of the negative environmental externalities of excessive nutrient applications in farming are few[9], and the extension service remains the key public resource available for mitigation of DWPA. As considerable technical knowledge and capacity does exist in the extension service, it is important in the short to medium term to keep qualified extension employees and utilise their expertise (Jia et al., 2015) whilst embarking on the investment in reorientation, re-training, and institutional capacity necessary for the oversight, coordination and quality assurance of the systemic nutrient management and pluralist AKIS developments envisaged here. Further research, not least for a greater diversity of case study locations in China, is needed to support and take forward this agenda; and catchment-based pilot projects employing action research could usefully test and refine approaches.

Acknowledgements

[insert text here – see title page]

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[9] Measures such as enforceable regulations, farmer incentive schemes, or taxation of inorganic fertilisers face greater practical, economic and political constraints (Smith and Siciliano 2015; Smith et al. forthcoming).

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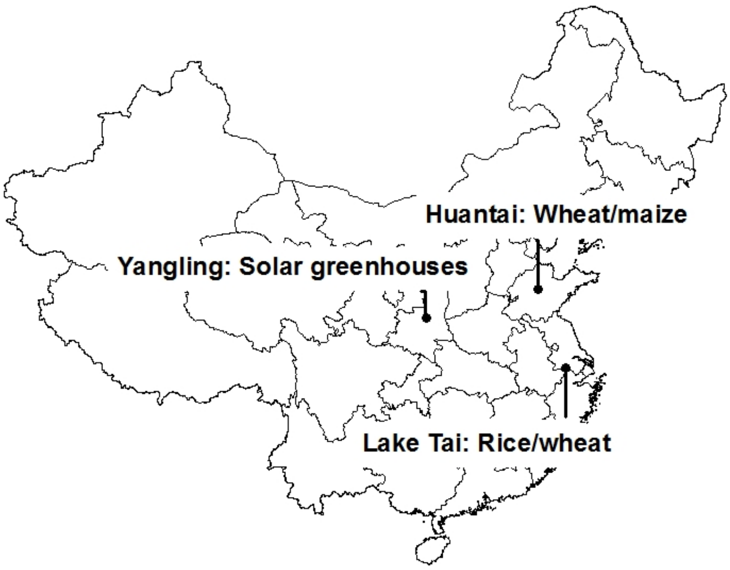

Figure 1: Location of the case study agroecosystems in China and their dominant form of production.

Table 1: Overview of case studies in China and data sources for the substance flow analyses.

Site name	Location	Agricultural system	Data source
Lake Tai	Village demonstration site, sub-catchment of the Li river, Jiangsu Province	Rice, wheat; 80 ha	Interview with farm manager for the year 2012
Huantai	*Huantai County, Shandong Province*	*Maize, wheat; 52000 ha*	*County statistical data from Agricultural Yearbook (5 year average 2007 – 2011)*
Yangling	Zaixi village, Yangling, Weihe river plain, Shaanxi province	Vegetables grown in greenhouses; 3 ha	Farmer surveys carried out in 2014

Table 2: Comparison of nutrient use efficiencies for the case study agricultural systems.

Case study	N-NUE	P-NUE	Year
Lake Tai	62	70	2012
Huantai	49	68	2007 - 2011
Yangling	32	10	2014

(The NUE figures are derived from the data reported in Figures 2 and 3, based on Equation 1).

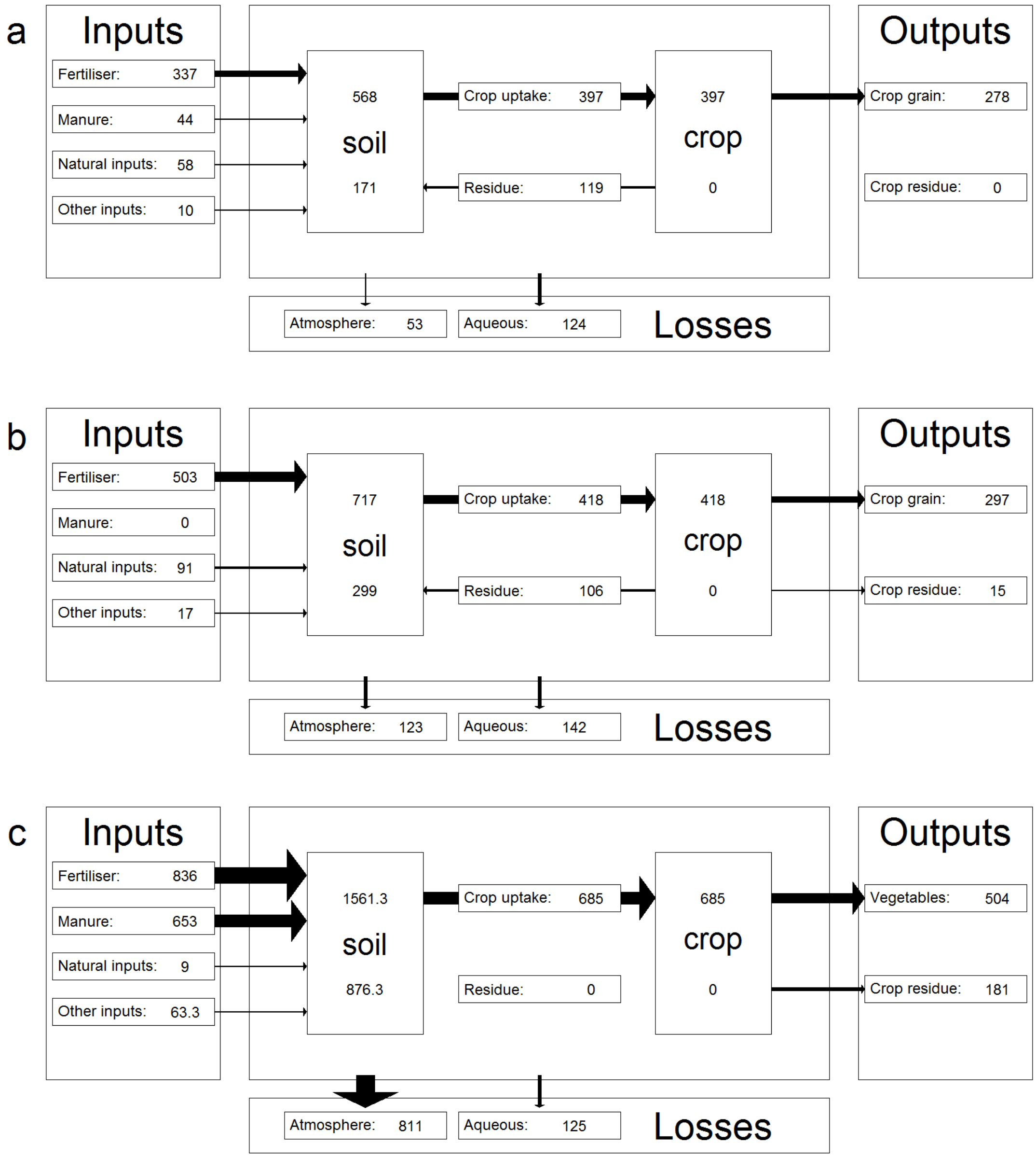

Figure 2: Substance Flow Analyses detailing the flow of nutrients in kg N/ha/year for case study agricultural systems: Lake Tai (a), Huantai (b) and Yangling (c). The compartments comprise all nutrients that are imported into the system (Inputs), exported out of the system (Outputs), lost out of the system (Losses) as well as flows within the agricultural system. Some inputs and losses have been aggregated for clarity and include the following: Inputs: 'Natural inputs' – atmospheric deposition and biological N fixation; "Other inputs" – irrigation and nutrients contained in seeds; Losses: "Atmospheric" – Gaseous N losses via ammonia, nitrous oxide, nitric oxide, and dinitrogen; "Aqueous" – losses via runoff, erosion and leaching. The agricultural system is represented by the "soil" to which the nutrients are added and "crop" that take the nutrients up (numbers above text 'soil' and 'crop' are the total input, numbers below are the balance (input-output, not considering losses)). The figure of zero beneath the "crop" box reflects no net accumulation or loss of crop biomass on an annual timescale, because all crop material is either exported across a system boundary as residue or food product, or is returned to soil as crop residue. Arrow widths are proportional to quantities of N.

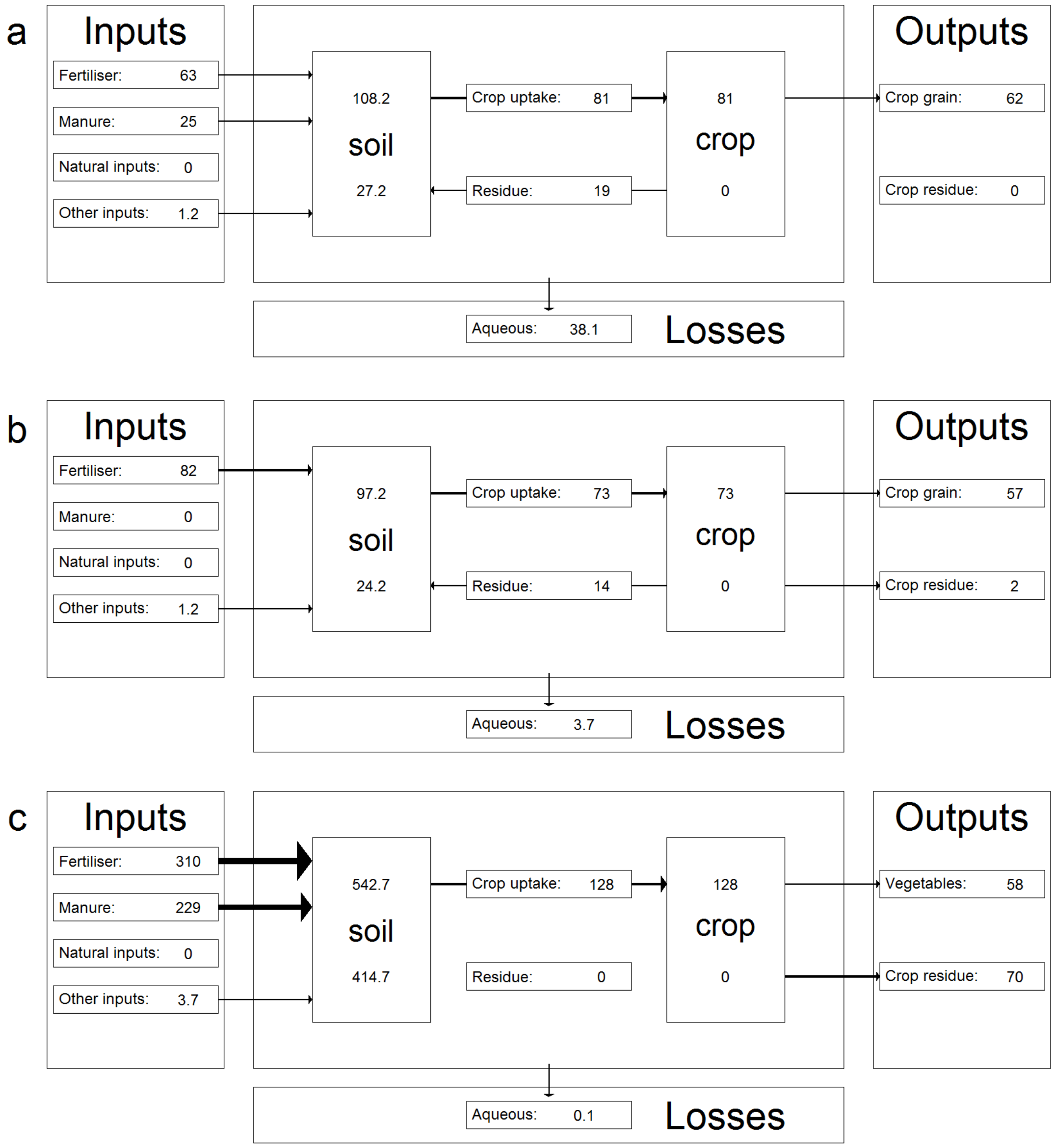

Figure 3: Substance Flow Analyses detailing the flow of nutrients in kg P/ha/year for case study agricultural systems: Lake Tai (a), Huantai (b) and Yangling (c). The compartments comprise all nutrients that are imported into the system (Inputs), exported out of the system (Outputs), lost out of the system (Losses) as well as flows within the agricultural system. Some inputs and losses have been aggregated for clarity and include the following: Inputs: 'Natural inputs' – atmospheric deposition and biological N fixation; "Other inputs" – irrigation and nutrients contained in seeds; Losses: "Aqueous" – losses via runoff, erosion and leaching. The agricultural system is represented by the "soil" to which the nutrients are added and "crop" that take the nutrients up (numbers above text 'soil' and 'crop' are the total input, numbers below are the balance (input-output, not considering losses)). The figure of zero beneath the "crop" box reflects no net accumulation or loss of crop biomass on an annual timescale, because all crop material is either exported across a system boundary as residue or food product, or is returned to soil as crop residue. Arrow widths are proportional to quantities of P.

Table 3: Farmer KAP survey, summary descriptive statistics by case study and whole sample (percentage values)

	a) Farm size (mu) (1mu = 667m^2)			**b) Gender**	**c) Respondent age, years**			**d) Education level**
	0 to 1	**1 to 4**	**> 4**	**Male**	**<41**	**41 to 60**	**61+**	**Primary/ Secondary**
Lake Tai	30.0	51.5	18.5	81.6	6.8	38.8	54.4	55.3/42.8
Huantai	1.6	45.9	52.5	54.1	3.3	45.9	50.8	44.3/29.5
Yangling	55.2	34.5	10.3	72.4	8.6	84.5	6.9	20.7/77.6
Whole sample	28.8	45.5	25.7	71.6	6.3	52.7	41	43.7/47.8

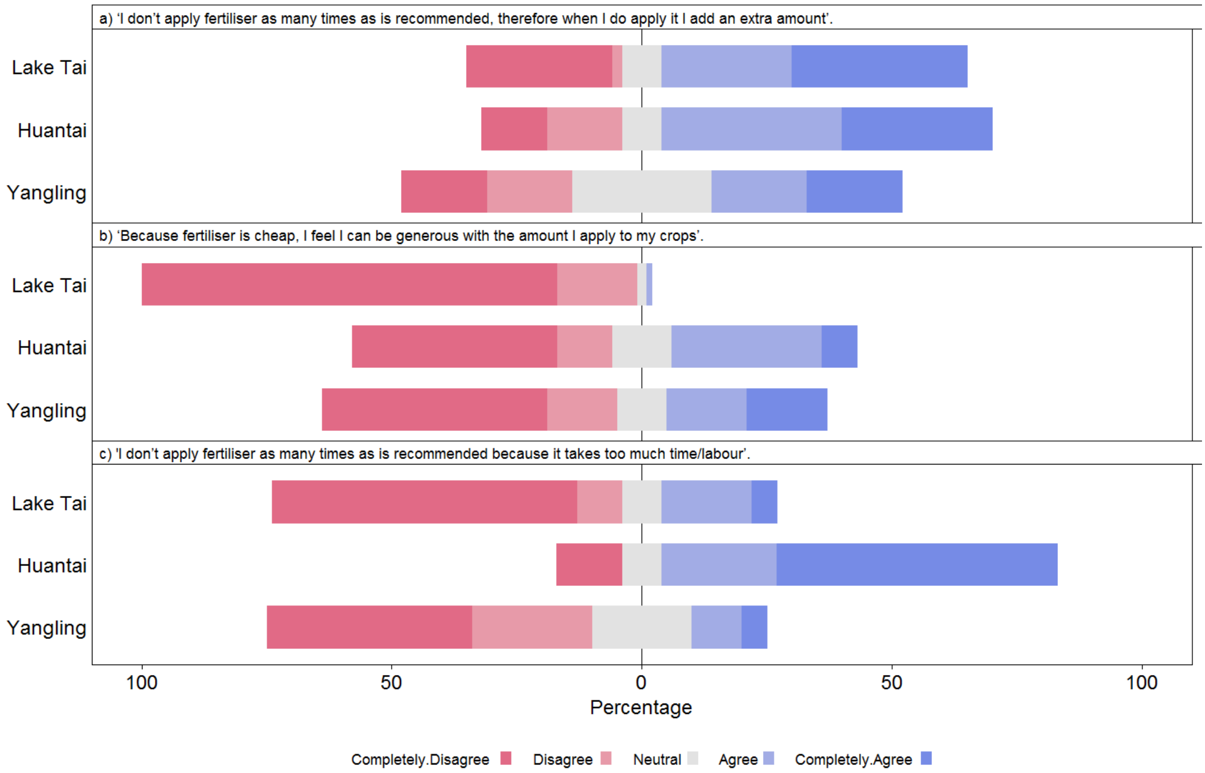

Figure 4: Likert scale responses to attitudinal questions (percentage of farmer KAP survey respondents).

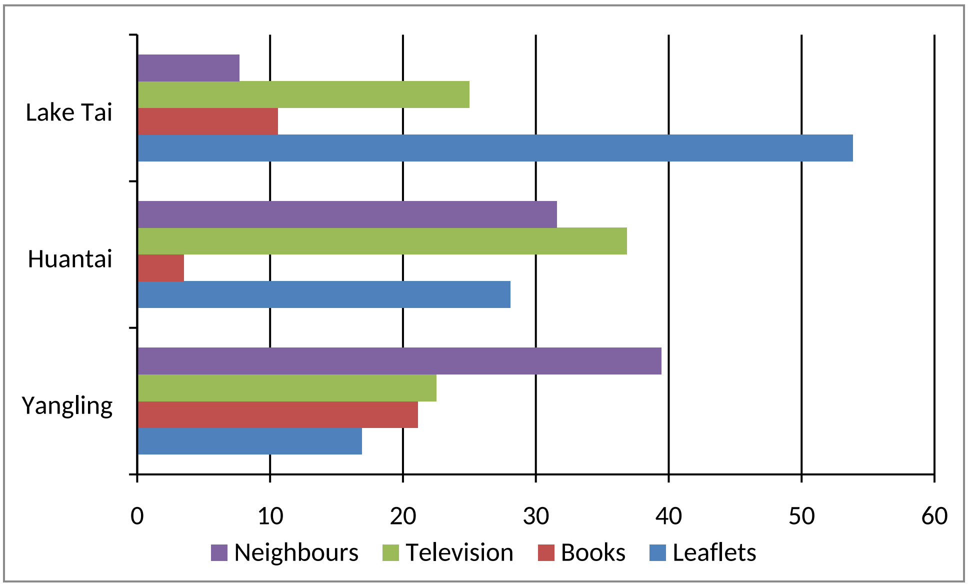

Figure 5: Sources of information on inorganic fertiliser application reported by farmers (percentage of farmer KAP survey respondents reporting the source).

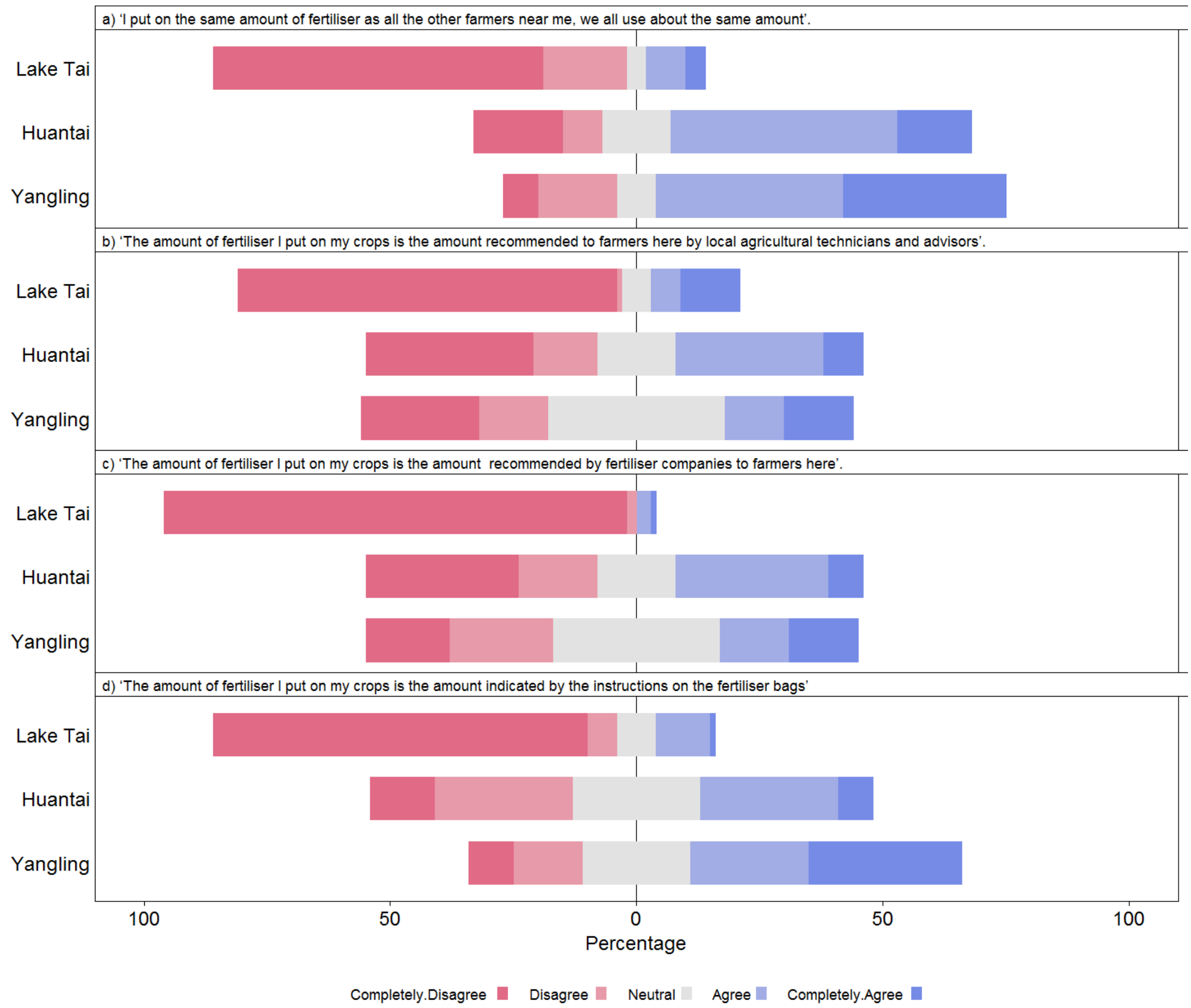

Figure 6: Likert scale responses regarding influences on inorganic fertiliser application rates (percentage of farmer KAP survey respondents)

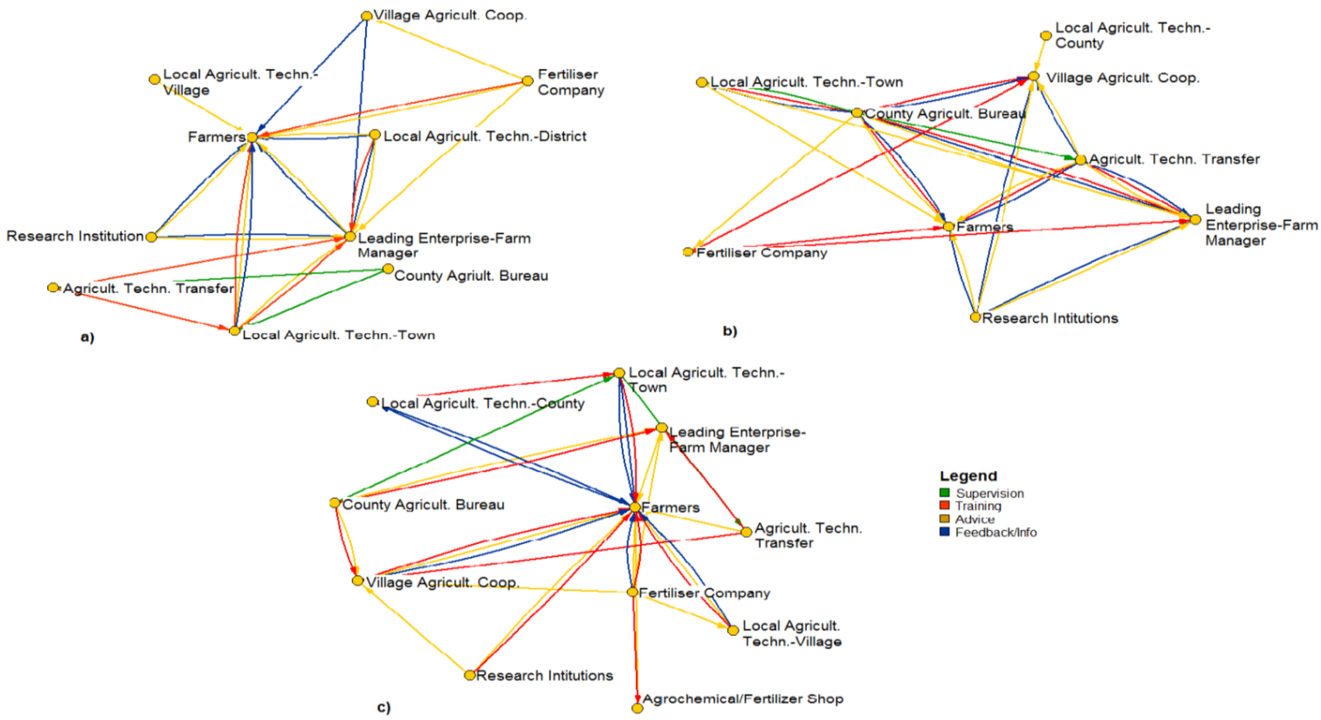

Figure 7: Social network analyses for Lake Tai (a), Huantai (b), Yangling (c). Interactions between actors are represented by the following links: feedback\information flows (feedback flows from farmers and farm managers to extension agents and general information flows about available technologies and options), technical advice (specific recommendations on fertiliser use or other technologies derived from soil testing and experimental trials), formal organised training sessions for farmers, and supervision (monitoring and authorisation from higher levels of government to lower levels).

Table 4: Indices of network density and centralization
(Density: the ratio of the number of observed links to the maximum possible. Centralization: the extent to which the network is centred on one or more key actors and links.)

		Density	Centralization
Lake Tai	**Whole network**	**60%**	**50%**
	Advice	24%	81%
	Feedback/info	18%	70%
	Training	13%	90%
	Supervision	4%	100%
Huantai	**Whole network**	**90%**	**11%**
	Advice	33%	86%
	Feedback/info	28%	73%
	Training	25%	80%
	Supervision	6%	100%
Yangling	**Whole network**	**60%**	**49%**
	Advice	24%	82%
	Feedback/info	13%	80%
	Training	20%	98%
	Supervision	4%	100%

Supplementary Information 1 - Data used for substance flow analyses to calculate input, output and internal flows.

Table S1: Nutrient contents based on fresh weight of an item.

Group	Item	%N	%P	Case study	Source
Cereal	Maize grain	1.47	0.32	Huantai	1
	Maize straw	0.87	0.13	Huantai	1
	Rice grain	1.3	0.36	Lake Tai	2, 3
	Rice straw	0.91	0.1	Lake Tai	2, 3
	Wheat grain	2.25	0.41	Lake Tai	2, 3
	Wheat grain	2.16	0.37	Huantai	1
	Wheat straw	0.62	0.1	Lake Tai	2, 3
	Wheat straw	0.62	0.07	Huantai	1
Fruit and vegetables	Tomato crop	0.31	0.031	Yangling	4
	Tomato residue	1.83	0.71	Yangling	5
	Cowpea crop	1.21	0.16	Yangling	6
	Cowpea residue	2.02	0.48	Yangling	5
	Cucumber crop	0.21	0.044	Yangling	4
	Cucumber residue	2.75	0.69	Yangling	5
	Strawberry crop	0.11	0.02	Yangling	6
	Strawberry residue	1.64	0.86	Yangling	5
	Muskmelon crop	0.09	0.015	Yangling	6
	Muskmelon residue	3.34	0.81	Yangling	5
	Water melon crop	0.25	0.039	Yangling	4
	Water melon residue	2.47	0.46	Yangling	5
Input	Irrigation water	0.183	0.007	Lake Tai	7
	Irrigation water	0.96	0.05	Yangling	8, 9
	Mixed commercial manure	2.33	1.34	Lake Tai	7
	Monopotassium phosphate		22.1	Lake Tai	7
	Urea	46.4		Lake Tai	7

[1]NATESC, 1999; [2]Ma et al., 2011; [3]Ma et al., 2008; [4]Gao et al., 2012; [5]Zhou (personal communication); [6]http://nutritiondata.self.com; [7]Lai (personal communication); [8]Yuan et al., 2010; [9] Zhang and Fang, 2006.

Table S2: Inputs and outputs in Lake Tai.

Item	Type	Amount	Unit
Urea on wheat	Input	190	Kg product/ha
Monopotassium phosphate on wheat	Input	140	Kg product/ha
Atmospheric deposition	Input	27.9	Kg N/ha
Biological fixation	Input	30	Kg N/ha
Mixed commercial manure (pig and chicken) on wheat	Input	1000	Kg manure/ha
Urea on rice	Input	540	Kg product/ha
Monopotassium phosphate on rice	Input	145	Kg product/ha
Mixed commercial manure (pig and chicken) on rice	Input	900	Kg manure/ha
Irrigation water	Input	2680000	L water/ha
Irrigation water N	Input	1.83	Mg N/L
Irrigation water P	Input	0.073	Mg P/L
Seed rate wheat	Input	150	Kg seeds/ha
Seed rate rice	Input	135	Kg seeds/ha
Residue wheat	SC[a]	8.1	T residue/ha
Residue rice	SC[a]	7.6	T residue/ha
Yield of wheat	Output	7.2	t grain/ha
Yield of rice	Output	9	t grain/ha

[a]SC: System cycling, cereal residue is incorporated into the field

Table S3: Data for cropland within Huantai county based on a 5 year average (2007 – 2011)

Item	Type	Amount	Unit
Land area	Cropland	23723	ha
N	Input	503	Kg N/ha
P	Input	82	Kg P/ha
Irrigation water	Input	14	Kg N/ha
Total N from Seeds	Input	3	Kg N/ha
Total P from Seeds	Input	1	Kg P/ha
Wheat	Output	178598	T grain
Maize	Output	217185	T grain
Proportion of wheat straw returned	SC[a]	90	%
Proportion of maize straw returned	SC[a]	86	%
Wheat: straw/grain mass ratio		1.04	
Maize: straw/grain mass ratio		0.91	

[a] SC: System Cycling

Table S4: Average inputs to greenhouses in Yangling and total area.

Item	Type	Amount	Unit
Greenhouse area		2.4192	Ha
Fertiliser application – N	Input	836.1	Kg N/ha
Fertiliser application – P	Input	309.8	Kg P/ha
Manure application – N	Input	653	Kg N/ha
Manure application – P	Input	228.7	Kg P/ha
Amount of irrigation water	Input	5954702	L water/ha
Irrigation water –Nitrate-N only	Input	9.6[a]	Mg N/L
Irrigation water –P	Input	0.5[b]	Mg P /L

[a]Yuan et al., 2010; [b]Zhang et al., 2006.

Table S5: Greenhouse outputs.

Vegetable	Area cropped in ha[a]	Amount of residue in t DM/ha[b]	Vegetable yield in t fresh weight/ha[b]
Tomatoes	2.8896	5.54	108.16
Cowpea	0.1344	6.91	30.21
Cucumber	0.7392	1.93	88.93
Strawberry	0.4032	5.23	11.25
Muskmelon	0.0672	1.51	22.50
Watermelon	0.6048	3.33	37.50

[a] this considers the area available for both seasons, meaning that it is twice the area available in one season

[b] yields are given for one crop in one season, because the effect of double cropping is already considered in the area under cultivation for an individual crop.

Table S6: Input of nutrients in kg/ha via transplanted seedlings (Wim Voogt, personal communication) and derived average input into greenhouses of Yangling.

Vegetable	N in kg/ha	P in kg/ha	Area occupied in %
Tomatoes	7.14	0.78	60
Cucumber	5.04	0.62	15
Average nutrient input[a]	6.3	0.72	

[a] the nutrient values for cucumber were used for the remaining 25% of the cultivated area of the greenhouses, because over 60% of this area are within the same family.

Table S7: Nitrogen deposition and biological N fixation rates for the case studies in which no experimental measurements were available.

Case study	N deposition rates in kg N/ha	N fixation rates in kg N/ha
Huantai	76[1]	5[3]
Yangling	4[2]	5[3]

[1]He et al., 2007; [2]Liang et al., 2014; [3]Bouwman et al., 2005.

Calculation of atmospheric losses

For P, it was assumed that no gaseous losses occur. Empirical models with a series of factors were used for the calculation of losses of ammonia (NH_3) (Bouwman et al., 2002) and the nitrogenous greenhouse gases, nitrous oxide (N_2O) and nitric oxide (NO) (Stehfest and Bouwman, 2006). The amount of nitrogen gas (N_2) lost was estimated via the ratio of N_2 to N_2O produced during denitrification using the freely available spreadsheet model SimDen (http://agro.au.dk/en/research/sektioner/soil-fertility/fpv/simden/).

Table S8 provides an overview of the factor class used in the published functions for each of the five case study catchments.

Table S8: Factor classes for the calculation of atmospheric N losses according to Bouwman et al., (2002); Stehfest and Bouwman, (2006) and SimDen.

	Factor	Lake Tai	Huantai	Yangling
NH_4	**Fertiliser type**	Urea, manure	Urea, compound fertiliser	Ammonium phosphates, urea, compound fertiliser, manure
	Croptype	Other crop, Wetland rice	Other crop	Other crop
	pH	5.5-7.3	7.3 - 8.5	7.3 – 8.5
	CEC	16 – 24	16 - 24	24-32
	Climate[a]	Temperate	Temperate	Temperate
	Application method	Broadcast or incorporated then flooded	Broadcast	Incorporated or applied in solution[b]
N_2O	**SOC**	1 – 3	1 - 3	1-3
	pH	5.5 - 7.3	7.3 - 8.5	7.3 – 8.5
	Texture	Medium	Medium	Medium
	Climate[a]	Temperate continental	Temperate continental	Temperate continental
	crop type	Cereals Wetland rice	Cereals	Other crop
NO	**Soil N content**	0.05 - 0.2	0.05-0.2	>0.2
	Climate[a]	Temperate continental	Temperate continental	Temperate continental
N_2	**Soil type**	Sandy loam (26% clay)	Clay loam	Clay loam
	SOM/precipitation	High	High	High

[a]see

Table S9 for an explanation of climate thresholds; [b]all manure is incorporated along with 15% of the fertiliser, 85% of the fertiliser is applied in solution

Table S9: Thermal climate classification units taken from Fischer et al., (1996).

Division	Subdivision	Characteristics
Tropics		monthly T_{mean}> 18 °C
Subtropics	Summer rainfall	monthly T_{mean}> 5 °C and at least one month T_{mean}<18 °C rainfall mainly in summer
	Winter rainfall	As above, but rainfall mainly in winter
Temperate	Oceanic	4 or more months T_{mean}> 10 °C and at least one month T_{mean}< 5 °C Difference in T_{mean} between warmest and coldest month ☒20 °C
	Continental	As above, but difference in T_{mean} between warmest and coldest month >20 °C
Boreal	Oceanic	Less than 4 months with T_{mean}> 10 °C and at least one month T_{mean}< 5 °C Difference in T_{mean} between warmest and coldest month ☒20 °C
	Continental	As above, but difference in T_{mean} between warmest and coldest month >20 °C
Polar/Arctic		Monthly T_{mean}< 10 °C

Aqueous losses – Erosion, runoff and leaching

Losses via runoff and leaching have been determined using the empirical model developed for N (Velthof et al., 2009), which has been extended to include erosion by Ma et al. (2010). The algorithms for the calculation of runoff and erosion are considered to be the same for N and P, which are related to fertiliser application rates and soil nutrient content, respectively. However, leaching of P is expected to be much lower compared to N. Therefore, the literature factor of 0.1 kg P/ha/year, as reported by Némery et al., (2005), is used throughout for P loss via leaching.

The approach of Velthof et al. (2009) requires information regarding ranges of slope, land use, soil type, soil and rooting depth, clay and carbon content, temperature and precipitation surplus that are reasonably widely available. The precipitation surplus was assumed to be at the lowest precipitation surplus applied. Table 10 reports the factor classes applied to each case study. It was assumed that runoff and erosion was zero for the greenhouses in the Yangling case study, because the soil is contained within the greenhouse walls.

Table 10: Factor classes used for the calculation of aqueous losses based on Velthof et al. (2009) and Ma et al. (2010).

	Factor	Lake Tai	Huantai	Yangling
Leaching	**Soil type**	Loamy (26% clay)	Loamy	Loamy
	Land use	Other	Other	Other
	Minimum of other factors	Precipitation < 50mm	Precipitation < 50mm	Precipitation < 50mm
Runoff	**Slope in %**	0-8	0-8	
	Land use	Other	Other	
	Minimum of other factors	Precipitation < 50mm	Precipitation < 50mm	
Erosion	**Slope in %**	0-8	0-8	
	Precipitation surplus	< 50mm	< 50mm	
	Minimum of other factors	Clay content 18 - 34%	Clay content 18 - 34%	

Note: the grey shading represents the assumption that no losses occur. In this case, runoff and erosion are assumed to be zero for the greenhouses as the soil is contained within the greenhouse walls.

Input, output, internal flows and losses

Table S11: Nutrient flow in N/P kg/ha.

	Huantai		Lake Tai		Yangling	
	N	P	N	P	N	P
Fertiliser	503	82	337	63	836	310
Manure	0	0	44	25	653	229
Atmospheric deposition	76	0	28	0	4	0
N fixation	15	0	30	0	5	0
Irrigation	14	0.2	5	0.2	57	3
Seed	3	1	5	1	6.3	0.7
Residue returned	106	14	119	19	0	0
Total input	**717**	**97.2**	**568**	**108.2**	**1561.3**	**542.7**
Crop uptake	418	73	397	81	685	128
Soil balance	299	24.2	171	27.2	876.3	414.7
Crop grain output	297	57	278	62	504	58
Residue exported	15	2	0	0	181	70
NH_3	71		30		216	
N_2O	6		3		32	
NO	4		1		305	
N_2	42		19		258	
Total atmospheric losses	**123**		**53**		**811**	
Leaching	79	0.1	25	0.1	125	0.1
Runoff	13	2	10	2	0	0
Erosion	50	1.6	89	36	0	0
Total aqueous losses	**142**	**3.7**	**124**	**38.1**	**125**	**0.1**

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Supplementary information – Farmer KAP Survey

SCREENING QUESTION

SURVEY RESPONDENT MUST BE THE **MAIN DECISION MAKER** REGARDING FERTILISER APPLICATION RATES FOR THE FARM OR GREENHOUSE
(Check that this is the case before proceeding with selection of respondent and interview).

SURVEY ADMINISTRATION DETAILS

Interviewer's name

Write in: ________________________________

Name of community where interview taking place

Write in: ________________________________

Date of interview

Write in: _______ / _______ / _________

A). RESPONDENT PROFILE

Respondent's name

Write in: ________________________________

Respondent's age

Write in: ________________________________

Respondent's gender (tick correct option):

Male
Female

Respondent's Village

Write in: ________________________________

Main occupation of the respondent

Farmer
Other (write in): ________________________________

Is the respondent the head of the household?

Yes
No

Does anyone else in the family other than the respondent make decisions regarding how their land is managed?

Yes
No

If Yes, who?
Write in: ________________________________

Number of family members involved in working the land unit (including respondent):

1
2
3
4
5
6
More than 6

Who are the other family members working the land unit? (tick all options that apply):

Spouse
Son
Daughter
Grandson
Grand daughter
Other family members (specify): ____________________

What level of education establishment has the respondent attended?

Primary (up to x years)
Secondary (up to x years)
Post Secondary School Further Education (i.e vocational training)
Post secondary School Higher Education (i.e University Degree
Other (specify): ___________________________________

Hukou registration of the respondent?

Rural
Urban
None

What types of crops are grown on the respondent's land unit? (Write list):

____
____
____
____
____

How much land does the respondent have control over?

Write land area in mu: _________________________________

B). INFLUENCES ON THE AMOUNT OF FERTILISERS APPLIED

Q1. ASK ALL RESPONDENTS
I'm going to read out a list of comments about fertiliser application rates. For each comment, please could you say whether you agree or disagree. Please use a scale of 1 to 5 where 5 means you completely agree and 1 means you completely disagree

INTERVIEWER: READ OUT ALL STATEMENTS AND MARK EACH FOR SCALE OF 1 TO 5.

(a) 'The amount of fertiliser I put on my crops is the amount my father always used to put on his crops'

(b) 'I put on the same amount of fertiliser as all the other farmers near me, we all use about the same amount'

(c)'The amount of fertiliser I put on my crops is the amount recommended to farmers here by local agricultural technicians and advisors'

(d) 'The amount of fertiliser I put on my crops is the amount recommended by fertiliser companies to farmers here'

(e) 'The amount of fertiliser I put on my crops is the amount indicated by the instructions on the fertiliser bags'

(f) 'I base my fertiliser applications on the levels provided by technical advice but I also add an extra amount of fertiliser just to make sure I am applying enough'

(g) 'Because fertiliser is cheap, I feel I can be generous with the amount I apply to my crops'

(h) 'I don't apply fertiliser as many times as is recommended, therefore when I do apply it I add an extra amount'

(i) I don't apply fertiliser as many times as is recommended because it takes too much time/labour'

Q2. IF RESPONDENT AGREES WITH STATEMENT (f) AT Q1 [i.e. score of 4 or 5] ASK THE FOLLOWING:
Why do you have concerns that the recommended amount of fertiliser for your crops is not enough?

____
____
____

C). SOIL TESTS UNDERTAKEN

Q3. ASK ALL RESPONDENTS
Do you ever have tests carried out on your land to see how much nutrient (N,P,K) is already in the soil?

Yes
No

Q4. IF YES AT Q3 (if not at Q3 go to Q7)
Approximately how often are these tests undertaken?

INTERVIEWER: READ OUT AND TICK ONE OPTION ONLY

More frequently than every year
Every Year
Every 3 Years
Every 5 Years
Less often than every 5 Years

Q5. IF YES AT Q3
Who is involved in carrying out these tests?

INTERVIEWER: READ OUT AND TICK ALL OPTIONS THAT APPLY

Yourself
Farming co-operative
Agricultural Technician (Village Level)
Agricultural Technician (Town Level)
Agricultural Technician (Regional Level)
Fertiliser company
University Staff
Other (specify) ____________________

Q6. IF YES AT Q3
Do you adapt your fertiliser application rates on the basis of these tests to avoid applying too little or too much fertiliser?

INTERVIEWER: READ OUT AND TICK ONE OPTION ONLY

Yes – always
Yes - sometimes
No

Q7. ASK ALL RESPONDENTS
I'm going to read out a list of comments about soil testing. For each comment, please could you say whether you agree or disagree. Please use a scale of 1 to 5 where 5 means you completely agree and 1 means you completely disagree

INTERVIEWER: READ OUT ALL STATEMENTS AND MARK EACH FOR SCALE OF 1 TO 5.

(a) 'I understand the benefits of soil testing for managing use of fertiliser for my crops'

(b) 'I like the idea of having the soil tested regularly on my land'

(c) 'I know who to go to to get information about soil testing'

Q8. IF RESPONDENT AGREES WITH STATEMENT (b) AT Q7 (Score 4, 5), ASK:
Who would you trust most to carry out soil tests on your farm?

INTERVIEWER: READ OUT AND TICK ONE OPTION ONLY

Farming co-operative
Agricultural Technician (Village Level)
Agricultural Technician (Town Level)
Agricultural Technician (Regional Level)
Fertiliser company
University Staff
Other (specify) ____________________

D). FERTILISER TRAINING (INFORMATION) RECEIVED

Q9. ASK ALL RESPONDENTS
Have yourself or anyone in your family attended a face-to-face training session on fertiliser application in the last 3 years?

Yes – Respondent
Yes – Other family member
No

(if answer to Q9 is no, go to Q13; if yes ask Q10-12)

Q10. If other family member at Q9, who attended this face-to-face training?

Spouse
Son
Daughter
Grandson
Grand daughter
Other family members (specify): ____________________

Q11. Approximately how many hours have you (or other family member) spent attending fertiliser application training in the last 3 years? (tick cell that applies):

	< 5hrs	5-10hrs	11-20hrs	21-30hrs	31-40 hrs	Over 40 hrs
Respondent						
Spouse						
Son						
Daughter						
Grandson						
Grand daughter						
Other family member 1 (specify_________________)						
Other family member 2 (specify_________________)						

Q12. Who provided the face-to-face training you (or other family member) received?

INTERVIEWER: READ OUT AND TICK ALL OPTIONS THAT APPLY

Farming co-operative
Agricultural Technician (Village Level)
Agricultural Technician (Town Level)
Agricultural Technician (Province Level)
Fertiliser company
University Staff
Other (specify) ____________________

Q13. ASK ALL RESPONDENTS
Do you get any information about fertiliser application rates from any of the following?

INTERVIEWER: READ OUT AND TICK ALL OPTIONS THAT APPLY

Leaflets
Books
Television
Neighbours
None of the above

E). INTERACTION WITH AGRICULTURAL EXTENSION

Q14. ASK ALL RESPONDENTS
How often have you received verbal advice on fertiliser use from each of the following in the last 3 years?

INTERVIEWER: READ OUT AND TICK ONE CELL FOR EACH ROW

	Once	Twice	Three times	Four times	Five times	More than five times	Never
Agricultural Technician (Village Level)							
Agricultural Technician (Town Level)							
Agricultural Technician (Regional Level)							
Fertiliser company							
University staff							
Marketing Association							
Other (specify) ______________________							

Q15. ASK ALL RESPONDENTS (EXCEPT THOSE RECEIVING NO ADVICE AT Q14)
I'm going to read out a comment other people have made about using advice on fertiliser applications. Please could you say whether you agree or disagree. Please use a scale of 1 to 5 where 5 means you completely agree and 1 means you completely disagree

INTERVIEWER: READ OUT ALL STATEMENTS AND MARK EACH FOR SCALE OF 1 TO 5.

(a) 'I have found the advice to be good and I continue to follow it'

(b) 'I followed the advice for one season only and then went back to my original practice'

(c) 'The advice I received was given in a way I could not easily understand'

(d) 'I understood the advice but did not follow it because I did not think it was right for my land'

Q16. ASK ALL RESPONDENTS
If you have a problem with a crop which you suspect might be a nutrient related problem who would you prefer to go to for advice?

INTERVIEWER: READ OUT AND TICK ONE OPTION ONLY

A neighbour
A relative
Farming co-operative
Agricultural Technician (Village Level)
Agricultural Technician (Town Level)
Agricultural Technician (Province Level)
Fertiliser company
University Staff
Other (specify) ____________________

F). AWARENESS OF ENVIRONMENTAL IMPACT

Q17. ASK ALL RESPONDENTS
Have you noticed any changes in your local rivers, streams or lakes over your lifetime regarding the colour of the water or the number of fish or other animals that live in or near the water?

Yes
No

Q18. IF YES AT Q17
What changes have you noticed?

1.___________________________________

2. __________________________________

3. __________________________________

4. __________________________________

5. __________________________________

Q19. FOR EACH CHANGE NOTED AT Q18
Which of the following do you think might have caused these changes?
INTERVIEWER: READ OUT AND TICK ALL OPTIONS THAT APPLY

	Changes recorded in at Q18				
	1.	2.	3.	4.	5.
Domestic sewage					
Other activities of householders					
Activities of farmers					
Activities of industries other than farming					
Other causes (specify) ______________					

Q20. IF 'ACTIVITIES OF FARMERS' MENTIONED AT Q19
Which farming activities do you think have caused these changes?

____

____

____

G). FARM LABOUR AVAILABILITY

Q21. ASK ALL RESPONDENTS
How many hours on average each week during the most labour-intensive farming activities, such as planting, weeding, harvesting, etc does each person in your household spend working on your land unit?

INTERVIEWER: REFER BACK TO LIST GENERATED AT PROFILE SECTION

INTERVIEWER: READ OUT AND TICK CELLS THAT APPLY FOR EACH FAMILY MEMBER

	< 5hrs	5-10hrs	11-20hrs	.21-30hrs.	31-40 hrs	Over 40 hrs	None
Respondent							
Spouse							
Son							
Daughter							
Grandson							
Grand daughter							
Other family member 1 (specify)							
Other 2 (specify)							

Q22. FOR EACH FAMILY MEMBER MENTIONED AT Q21
Does this family member also work in another job in your village or in a town or city?

	Yes	No
Spouse		
Son		
Daughter		
Grandson		
Grand daughter		
Other family member 1 (specify)		
Other family member 2 (specify)		

Q23. Does your family provide enough labour to management your farm?

Yes
No

H). FUTURE SCENARIOS

Q24. ASK ALL RESPONDENTS
Which of the following best describes how you use your land?

INTERVIEWER: READ OUT AND TICK ONE OPTION ONLY

To grow crops for consumption by your family
To grow crops for consumption by your family but also to sell
To grow crops for sale only
Other (specify)___________________

Q25. ASK ALL RESPONDENTS
Would you like to stop farming your land yourself if you had a choice?

Yes
No

Q26. ASK IF NO AT Q25 (if yes at Q25 go to Q27)
Why do you say this?

____
____
____

Q27. ASK IF YES AT Q25
Which one of the following options would be best for you?

INTERVIEWER: READ OUT AND TICK ONE OPTION ONLY

(a) To rent out the land to a farming company or larger farmer but still work on the land as a farm worker
(b) To rent out the land to a farming company or larger farmer and go to work in another job in the town or the city
(c) To rent out the land to a farming company or large farmer and retire

THANK YOU AND CLOSE

Strategies for sustainable nutrient management: insights from a mixed natural and social science analysis of Chinese crop production systems

Highlights

nutrient substance flow analyses for three agricultural systems in China

excessive nutrient input in each system risks soil, air and water quality impacts

soil nutrient stocks represent an under-exploited resource

potential to rebalance productivity with stewardship of natural resources exists

there is need to re-orient agricultural knowledge and innovation systems (AKIS)