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REVIEW

Towards sustainable intensification of apple production in China — Yield gaps and nutrient use efficiency in apple farming systems

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Abstract

China is in a dominant position in apple production globally with both the largest apple growing area and the largest export of fresh apple fruits. However, the annual productivity of China's apple is significantly lower than that of other dominant apple producing countries. In addition, apple production is based on excessive application of chemical fertilizers and the nutrient use efficiency (especially nitrogen) is therefore low and the nutrient emissions to the environment are high. Apple production in China is considerably contributes to farmers' incomes and is important as export product. There is an urgent need to enhance apple productivity and improve nutrient use efficiencies in intensive apple production systems in the country. These can be attained by improved understanding of production potential, yield gaps, nutrient use and best management in apple orchards. To the end, priorities in research on apple production systems and required political support are described which may lead to more sustainable and environmental-friendly intensification of apple production in China.

Keywords: apple production, China, environmental problems, nutrient use efficiency, potential yield, sustainable intensification, yield gaps

1. Introduction

Agricultural productivity in China has been rapidly improved over the past decades. However, this development has resulted in severe ecological and environmental problems (Ju *et al.* 2004, 2009; Fan *et al.* 2011; Zhang *et al.* 2011). Fertilizer applications in cash crops appear to be very high and much higher than the applications in cereal crops (Fan *et al.* 2011). Besides, the nitrogen use efficiency of cash crops in China is very low compared to that in developed countries. Such excessive applications of chemical fertilizers in combination with low nutrient use efficiencies lead to serious environmental problems due to the strong emissions of nutrients and biocides to the atmosphere, soil, ground and surface waters (Ju *et al.* 2009).

Negative influences of agriculture on the environment and ecosystems have been recognized worldwide. Sustainable intensification of crop production should lead to maximization of crop productivity with simultaneously proper management and protection of ecosystems (FAO 2014). A more practical definition of sustainable intensification is the use of the available natural resources as efficiently as possible, while minimizing the unfavorable impacts on soils, water, air and biota as much as possible (Eckert *et al.* 2000). Considering the continual increases in human pop-

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ulation and land use pressure in a country as China, there is little scope to expand the land area used for agricultural production. Hence, intensification of agricultural production systems is needed in China during the coming decades. To achieve a more sustainable and environmental-friendly type of agriculture and to protect natural ecosystems against emissions of nutrients and biocides from agriculture, the Chinese government has recently launched a number of actions to change the current agricultural developmental model which is at the cost of environment. The main objective is to improve yields and productivity of different farming systems with the same input level of agricultural chemicals.

Apple is one of the most important cash crops in China. This study gives an overview of the main problems of current apple production systems and management practices in China. These problems have to do with the low productivity of apple orchards, the poor nutrient use efficiency, and the large nutrient and other emissions to the environment. We first identified the major factors that cause these problems, and next identified the best possibilities for enhancing apple productivity and improving nutrient use efficiencies. To successfully achieve sustainable intensification of apple production systems across the country, relevant research on apple production systems and supportive agricultural policies are to be initiated. The study indicates the best possibilities for achieving sustainable apple production systems in the coming decades through closure of both the apple productivity gap and the nutrient use efficiency gap.

2. Apple production in China

Apple (*Malus domestica* Borkh.) is one of the most popular tree fruit in the world. Being the first ranking country in total growing area and export of fresh apple fruits, China has taken the predominant position in world apple industry (FAO 2016). Till 2013, the annual production of fresh apple fruits is approximately 39.7 million t and the cultivated area is 2.41 million ha, which represent 49 and 46%, respectively, of the world apple production and planting area (FAO 2016). The European Union (EU) and the United States were the 2nd and 3rd largest world producers, respectively (FAO 2016). After entry into the World Trade Organization in 2001, China's apple products have become one of the most competitive agricultural products in foreign trade (Zhai *et al.* 2008). China has been the largest apple exporter worldwide (USITC 2010). The export value and export volume of apple were approximately 0.1 billion USD and 0.86 million t, respectively in 2014 (NBSC 2016). In addition to production and export, China is one of the largest countries of apple consumption. China has a large domestic market with an annual consumption of approximately 11.28 kg per capita, which is significantly higher than the world average apple consumption (2.1 kg person^{-1} yr^{-1}) (MOA 2008).

Apple production ranks the first in fruit industry in China in terms of growing area. Shandong, Liaoning, Hebei, and Henan provinces in the Bohai Bay area and Shaanxi, Shanxi, and Gansu provinces in the Loess Plateau area are the major apple growing provinces in China. The total production in 2014 in the above provinces were 9.29, 2.47, 3.45, 4.41, 9.88, 4.17, and 2.97 million t, respectively (NBSC 2016). Fuji (*Malue domestica Borkh*., *cv.* Fuji) is the dominant commercial cultivar produced which constitutes approximately 60% of total apple cultivated in the country (FAO 1999). Other important cultivars include Starkrimson (*Malue domestica Borkh*., *cv.* Starkrimson), Jonagold (*Malue domestica Borkh*., *cv.* Jonagold), Golden Delicious (*Malue domestica Borkh*., *cv.* Golden Delicious) and Gala (*Malue domestica Borkh*., *cv.* Gala).

Apples are produced in widely varying locations across the country, but are mostly concentrated in the Bohai Bay area and the Loess Plateau area (Liu and Fan *et al.* 2012) (Fig. 1). The two areas account for 80% of growing area and 90% of production in the country. In the Loess Plateau and Bohai Bay regions, most apples orchards are operated by smallholders (e.g., more than 75% farmers owned small piece of land less than 0.3 ha in the Loess Plateau region and more than 40% of apple orchards were below 7 ha in the Bohai region) and are cultivated with low levels of mechanization and standardization (Liu *et al.* 2002; Zhai *et al.* 2008). For smallholder farmers, apple is the major income source. The development of the apple production and industry in the region has contributed considerably to the local economy and employment (Fan and Hu 2005; Zhang *et al.* 2012). There is an urgent need to increase production and export revenues and to improve farmers' livelihoods. Instead of expansion of the apple production area, more focus should be given on improving the productivity and

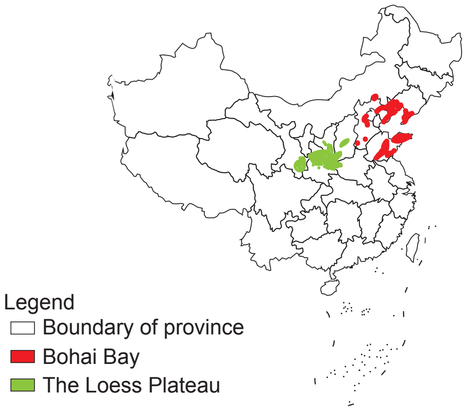

Fig. 1 Major apple production regions in China (the central area indicates the Loess Plateau region and the northeast area indicates Bohai Bay region, MOA 2008).

production efficiency, increasing fruit quality and improving the industrial chain, to strengthen China's competitiveness on the international markets.

3. Yield gaps and major production constraints

3.1. Apple yields and farming systems in China

The production of apple fruits increased remarkably in the past few decades, with a relatively gentle increase from 1980 (2.38 million t) to 1990 (4.33 million t) and a rapid growth in the following two decades (Fig. 2-A) (FAO 2016). On the other hand, the growing areas of apple trees declined from 2.95 million ha (1995) to 1.89 million ha (2005) (Fig. 2-A). This implies a dramatic increase in apple yield per unit land area (Fig. 2-B). In spite of the continuously increasing yields, the current average apple yields under farmer practices in China remained low compared with that in other dominant apple production countries, such as New Zealand, the United States, Brazil, Chili and some EU countries (e.g., France and Italy), where the annual yields ranged between 20 to 50 t ha^{-1} yr^{-1} (Fig. 3) (USITC 2010; FAO 2016).

It has been widely recognized that due to the favourable climate conditions and soil properties, the major apple production regions of China have great potential for attaining relatively high apple yields compared to those in other regions of the world. However, the average annual apple yield in these Chinese regions (17.96 t ha^{-1}), although it was higher than the average yield in China (16.46 t ha^{-1}) and in the world (15.49 t ha^{-1} on average), was significantly lower compared to the average yield in the other dominant apple growing countries, such as the United States (27.85 t ha^{-1}), France (43.98 t ha^{-1}), Germany (25.40 t ha^{-1}) and Italy (40.11 t ha^{-1}) (FAO 2016). Based on on-farm investigations in the major apple growing regions in the Loess Plateau, more than 50% of the surveyed farms attained yields less than 22.5 t ha^{-1}. The proportion of the farms that attained over 45 t ha^{-1} yield was less than 8% (Liu *et al.* 2002).

The poor management practices in apple production systems in the Loess Plateau and Bohai Bay regions constraint farmers from gaining high productivity. Irrigation systems are poor in most regions of the Loess Plateau and apple growth depends largely on rainfall (Fan and Hu 2005; Li *et al.* 2010). Deep tillage is performed and soils are limed (if applicable) prior to planting to improve soil conditions in hilly regions. Top dressing (with chemical fertilizers) is performed over the growing seasons primarily before bud break, before or after flowering and during fruit enlarging period (FAO 1999). Mulching (with 10–20 cm straw or plastic film) is a common practice in apple orchards in the region that is effective for weed control but rather labour-intensive and costly (FAO 1999). Apple trees are often cultivated in rows at a density of approximately 1 000 trees per ha or less. The most common training system is the modified central leader system. Pruning, thinning and training are performed each year by hand, which require a lot of labour inputs (USDA 2013).

3.2. Yield gaps and major production constraints

The maximum production level of a crop, such as an apple orchard, can be derived by evaluating the potential yield under irrigated conditions or the water limited yield under rainfed condition. The potential yield of a particular crop (Y_p) is the yield that can be obtained with sufficient supply of water and nutrients, and optimal crop management and protection, and is determined only by the genetic characteristics of the crop and the environmental conditions, such as radiation level and temperatures in the region (Van Ittersum

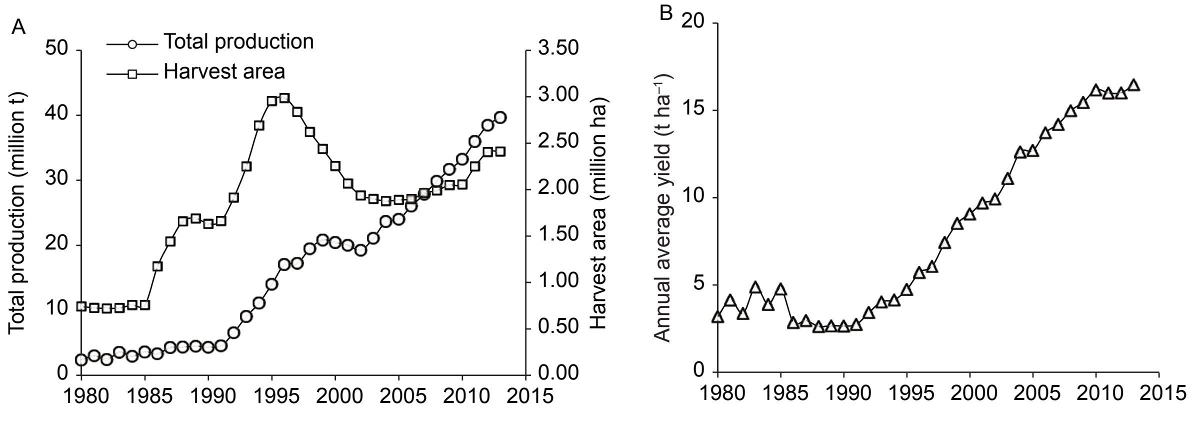

Fig. 2 Changes in Chinese apple production over the past few decades in total production and growing area (A) and productivity (B). Data source: FAO (2016).

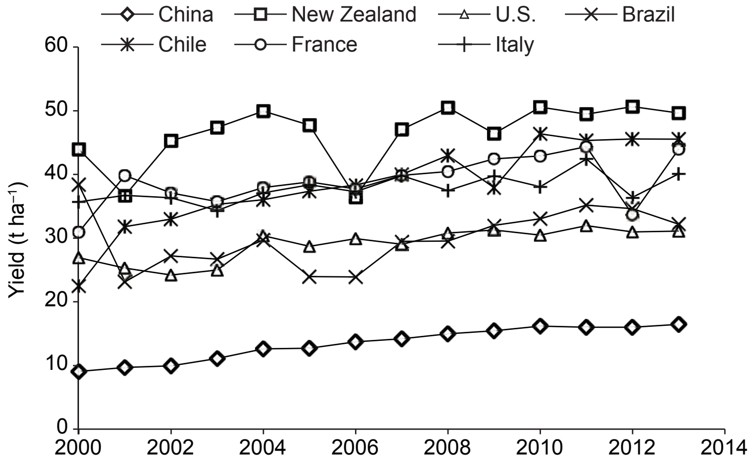

Fig. 3 Fresh apple yields in China and other apple growing countries over 2000–2013. Data source: FAO (2016).

et al. 2013). On the other hand, yields are often limited by water and nutrient availability (yield limiting factors), and also by the damage of pests and diseases (yield reducing factors), so that the actual yield becomes much lower than the potential value. Therefore, the variations in yield level for the same crop in different regions and under different managements are mainly associated with crop genotypes, the prevailing environmental conditions and management practices of the farmers. The crop yield gap is defined as the difference between the potential yield or water limited yield and the actual yield obtained by farmers (Van Ittersum *et al.* 2013), which is to be explained from the genotype-management-environment characteristics.

It is clear that there is large a gap between the current apple yields in China and those in other apple growing countries, yet the theoretically achievable yield of apple orchards in China is not yet derived and thus unclear. However, it can be assumed that differences exist between the potential apple yield level in China and that in other apple production countries due to differences in tree varieties (e.g., productivity and the length of the growth period) and environmental conditions (mainly, radiation level, temperatures and the length of the frost free period). Besides, compared to China, these countries produce apples in more modernized production systems with high intensity management and advanced storage, packing and marketing systems (O'Rourke 2001, 2002; USITC 2010). Therefore, the large difference in average apple yield with that in China could also be associated with many yield limiting factors (i.e., availability of water and nutrients) and yield reducing factors (i.e., damages and losses by pest and diseases) and their interactions. The major constraints to apple production in China are perceived to be inferior tree varieties, poor soil properties (e.g., low soil nitrogen and organic matter contents) (Zhang L *et al.* 2013; Zhang L N *et al.* 2013) and poor management practices (e.g., high plant density, low light penetration and unbalanced nutrient applications, FAO 1999; Zhao *et al.* 2002; Zhang *et al.* 2010). Further, adverse climate conditions such as low rainfall availability, erratic rainfall distribution, especially when occurring in the periods of fruit expansion and flower bud differentiation (FAO 1999; Zhao *et al.* 2002; Li *et al.* 2011), and low spring temperatures (USDA 2013), are major factors that may limit apple yield levels.

4. Nutrient management, nutrient use efficiency and environmental risks of apple farming systems

4.1. Nutrient management in the apple farming system

In order to achieve high apple yields, apple production in China often depends on large amounts of external inputs (especially, high levels of inorganic nitrogen fertilizers). It is widely recognized that it is not cost-effective to apply large amounts of fertilizers, since crop yield responses to the last part of a high nutrient application become almost nil, when the yield has almost attained the theoretically highest level. However, fertilizers are easily available for most smallholders and the costs are low compared to those of other inputs (e.g., irrigation). In addition, farmers are mainly focused on ensuring the regular production level and maintaining a good apple quality across the years. Because farmers lack a diagnostic tool for leaf nutrient estimation, particularly smallholder farmers apply fertilizers based on their empirical knowledge. For instance, the N fertilizer application in apple orchards of Changwu County, Shaanxi Province, ranged between 500 and 1 000 kg ha^{-1} yr^{-1}, which was significantly higher than the N applications in annual cropping (150–170 kg ha^{-1} yr^{-1})(Fan *et al.* 2004).

The average N application rate in the major apple production area of China was between 400 and 600 kg ha^{-1} yr^{-1} (Peng and Jiang 2006), which was much higher than that in other apple growing countries. For example, the recommended fertilizer inputs for apple orchards in the Netherlands are about 100 kg N ha^{-1} minus the N supply from the soil (Reuler *et al.* 2013), the recommended N application is 88–176 kg ha^{-1} yr^{-1} in Canada for young dwarf apple trees (Neilsen and Neilsen 2002), and the recommended N and K_2O amounts are respectively, 0–50 and 0–120 kg ha^{-1} yr^{-1} in Santa Catarina and Rio Grande do Sul States in Brazil (Nava and Dechen 2009).

In addition, the nutrient inputs in apple orchards in China consist mainly of chemical fertilizers and the N-P-K inputs are often unbalanced. The recommended fertilization rate according to researchers and local extension services for major apple production areas of Shaanxi Province is 150–300 kg N ha^{-1}, 150–250 kg P_2O_5 ha^{-1} and 90–195 kg K_2O ha^{-1} in chemical fertilizers and 30–60 t organic fertilizer ha^{-1}. This amount of organic fertilisers contains roughly 180–360 kg N ha^{-1}, 120–240 kg P_2O_5 ha^{-1} and 130–260 kg K_2O ha^{-1} (as based on nutrient concentrations in different types of organic material from SPQTSB 2014) and is needed to maintain annual yields between 15 and 30 t of apples per ha (Liu *et al.* 2002).

4.2. Nutrient cycling in apple orchards

Compared with cereal crops, the apple farming system could be more sustainable due to the relatively low nutrient removal in the yield, high nutrient recycling (e.g., through decomposition of fallen leaves) and retention in the system (e.g., through nutrient storage in woody part of the tree) (Wu *et al.* 2008). The nutrient uptake and removal by apple trees (through harvest and pruning) is relatively low compared to other types of farmlands. For a typical high-density apple orchard, a total amount of 25–60 kg ha^{-1} N is removed annually (by fruits harvest, falling leaves and pruning) for different tree varieties (Neilsen and Neilsen 2002). It can be assumed that the nutrient removal will be much lower in low density and low productivity orchard. Due to the relatively low rooting densities (especially those with dwarf rootstocks such as M.9), fruit trees are inefficient in their use of N fertilizer (Neilsen and Neilsen 2002). The typical N recovery efficiency of applied fertiliser N on apple trees is approximately 20% (Weinbaum *et al.* 1992) which is remarkably low compared to that on croplands (55%) and grasslands (70%) (Peng *et al.* 2003).

Like in many deciduous tree crops, the growth and yields of apple trees are dependent on nutrient accumulation in the trees over multiple seasons (Wünsche and Lakso 2000). The annual retention of N in the woody part of the tree is approximately 50% of the total N taken up by the trees (Neilsen *et al.* 2001). The nutrient uptake by apple trees to attain a high yield of 90 t ha^{-1} was estimated at 120 kg N, 46 kg P_2O_5 and 241 kg K_2O ha^{-1} yr^{-1} in 14-yr-old "Golden Delicious" apple orchard with tree density of 500 trees ha^{-1} (Neilsen *et al.* 2003). The net uptake of N by fruit trees (by subtracting the N return *via* decomposition of fallen leaves and wooden residues from the total N uptake by trees) is even less (i.e., at most 40 kg ha^{-1} yr^{-1}, Peng *et al.* 2003).

Ecologically sound fertilizer application recommendations can be developed based on the amount of annual removal of nutrients from apple orchards (Weinbaum *et al.* 1992; Ernani *et al.* 2008; Peng *et al.* 2003). In this way, the annual N requirements for a high density (3300 trees ha^{-1}) "Gala/M.9" apple orchard was estimated at 20, 34.4 and 40 kg N ha^{-1}, respectively, the second, third and sixth established year to attain an apple yield of 4.9 (2 yr), 18.8 (3 yr) and 43 t ha^{-1} (4 yr) (Neilsen and Neilsen 2002). For comparison, the fertilizer amounts applied to attain a yield of 37 t ha^{-1} for Fuji apple cultivated under experimental conditions in Heyang County in the Loess Plateau were 330 kg N, 220 kg P_2O_5 and 240 kg K_2O per ha (Zhao *et al.* 2014). For comparison, the amounts of applied fertilizer are much lower (i.e., 80 kg N, 57 kg P_2O_5 and 120 kg K_2O per ha, respectively) under experimental conditions in the Po Valley, Northern Italy to attain the same yield level (Malaguti *et al.* 2002).

4.3. Environmental risks of apple production in China

The excessive fertilizer N applications have resulted in great concern about the environmental risks of apple production systems in the Loess Plateau (Liu *et al.* 2002; Ju *et al.* 2004, 2006; Fan and Hu 2005; Zhang *et al.* 2010; Wang *et al.* 2011; Gao *et al.* 2012). The environmentally safe fertilizer N rate to avoid N accumulation and leaching is less than 200 kg N ha^{-1} yr^{-1} (Liu *et al.* 2002). The excessive applications of N fertilizers in the Loess Plateau region have led to severe nitrate-N accumulation in the soil profile of apple orchards (Fan *et al.* 2004). For instance, the N accumulation was about 265 kg N ha^{-1} in a 400-cm deep soil profile under a 5-yr-old apple orchard in Weibei dry land of the Loess Plateau, which was significantly higher than the N accumulation in the nearby high-yield arable land (approximately 118 kg N ha^{-1}) (Fan *et al.* 2004). The amount of accumulated N appears to increase in both amount and depth over the years (Huang *et al.* 2001; Fan and Hu 2005).

The accumulated mineral N in apple orchards is partly taken up by apple trees and the excess amounts of N are lost to the air or leached (Fig. 4). Excessive use of fertilizers has resulted in large emissions of N to the air by ammonia volatilization and denitrification (Cui *et al.* 2014). Whereas the possibility of accumulated N to leach to the deep groundwater is limited (Fan *et al.* 2004), N leaching to surface water occurs in areas with shallow ground water. Excessive amounts of N resulted here in water contamination and eutrophication by leaching and/or run-off from sloping fields (Huang *et al.* 2001; Fan and Hu 2005). Furthermore, the unbalanced and continuous applications of large amounts of the same type of fertilizer has not improved the soil fertility (Wu *et al.* 2008), but has rather enhanced the depletion of other important soil nutrients (e.g., Ca, Mg, Zn and some micro-nutrients) and sometimes generated chemical soil problems, such as soil salinity (Agegnehu *et al.* 2014). The excessive application of fertilizers in the apple orchards of China has therefore led to severe soil degradation problems and water pollution (Huang *et al.* 2001; Fan *et al.* 2004).

5. Conclusion and recommendations

5.1. Possibilities for closing yields gaps and improving nutrient use efficiency

We can define three production levels in apple orchards, such as (a) current apple yields with current farming practices in China, (b) 80% of experimental yield level in China, and (c) 80% of the optimal experimental yields in other countries which have similar environmental conditions. For each level, the required management practises to attain the yield increases and the major production constraints are described (Table 1). Compared to farmer's practices, yields can be improved by 14–18% with improved management practices (i.e., grass and plastic mulching and better fertilizer application methods) (Li *et al.* 2010). The potential yield of Fuji apple produced in the Loess Plateau region of China, which is approximately 37 t ha^{-1} based on experiments with improved management practices (Zhao *et al.* 2014), is in the same range as the yields attained in other apple producing countries with more advanced techniques in experiential fields, e.g., in Po Valley, Northern Italy (Malaguti *et al.* 2002). Hence, China has the potential as many other countries to attain high apple yields with a good product quality (i.e., large size, good colour and high sugar content) and with "pollution-free" fruits in the future. For instance, the Loess Plateau area of China has suitable climate conditions (e.g., high solar radiation intensity; low humidity; warm days and cool nights and a long growing season), good soils (i.e., deep, fertile and well-drained soils) and a good location (i.e., away from industrial areas) for apple production (Zhao *et al.* 2002; Fan and Hu 2005). In addition, due to the large rural population in China, labour is abundantly available and even sufficiently during the periods with peak labour demand (e.g., at harvest) (Lu *et al.* 2004). The market share of apples produced in China may increase in the future due to the cheap and reliable labour and the relatively low market price (Yang *et al.* 2013).

To achieve sustainable and environmental-friendly apple production systems, it is essential to close the nutrient cycle as much as possible, to reduce nutrient emissions from apple orchards to the environment. Today, there are large differences between the theoretical nutrient demands (i.e., particularly N) of apple orchards and the actual fertilizer N applications in apple orchards at current yield levels in China. This indicates excessive N supplies in current systems com-

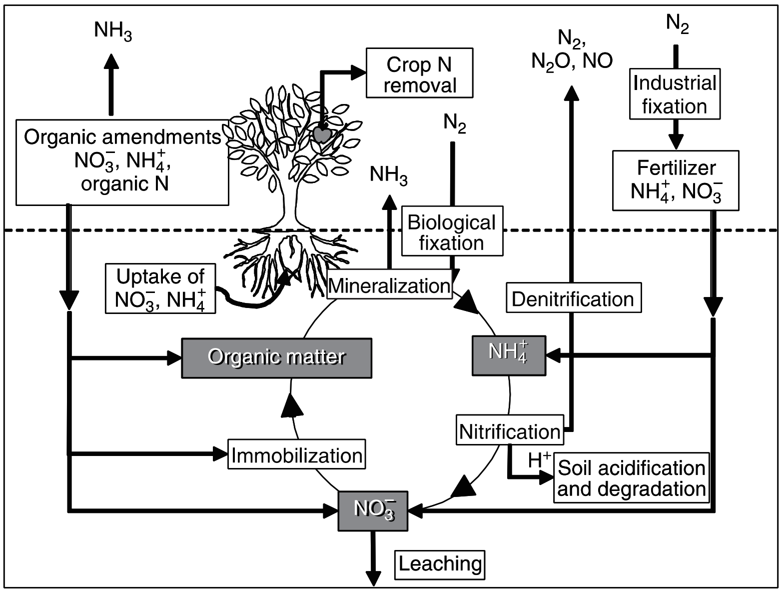

Fig. 4 The N balance in a typical apple orchard. Source: Neilsen *et al.* (2003).

pared to the actual net N uptake by the apple orchards. With better nutrient management practices (e.g., more time- and site-specific applications of fertilizer nutrients, and adapting the total fertilizer amount to the target yield and its nutrient demand), the N use efficiency can be improved dramatically (Zhang *et al.* 2011). Further, by applying fertigation through a drip irrigation system, the N use efficiency of apple trees could be improved dramatically (Table 1). In these ways, it is possible to close yield gaps, reduce N inputs and reduce nutrient emissions to the environment in apple orchards.

5.2. Required research to support improvements in apple farming systems

Over the past few decades, the priorities in research projects and government policies on apple production were focused on the improvement of tree productivity and product quality. This was important to enhance the net incomes and living standards of apple producers in China. The major improvement strategies included the replacement of low productivity cultivars by superior cultivars and by early-mature cultivars (MOA 2008). However, less attention has been given to the potentially attainable yields and the yield gaps of apple orchards in China. Additionally, it is still unclear what are the specific factors with respect to genotype, management, and environment, and their interactions, that currently limit apple yields in smallholder farming of China. More research is needed to estimate the yield gaps of apple orchards. This will lead to the identification of the most important production constraints that limit current apple yields and that should be overcome by implementing improved management practices. Recognizing the most important production constraints in conjunction with socio-economic limitations may provide guidelines to close the yield gap and to improve land use efficiency (Van Ittersum *et al.* 2013). The yield gap research should consist of farmers' participatory research, field experiments and model analyses (Affholder *et al.* 2013). In combination, this research work may result in more knowledge about the best opportunities and approaches towards a sustainable intensification of apple farming systems in China.

To better understand the required nutrient uptake by apple trees and the required fertilizer nutrient application for a certain yield increase, research should focus on the nutrient use efficiencies (defined as the increase in crop yield per unit of fertilizer input, Vanlauwe *et al.* 2011) of apple orchards in the different regions in China, both with current and improved management practices. Nutrient use efficiency is influenced by various biotic (e.g., cultivar, pests and diseases) and abiotic factors (e.g., soil properties, water availability, and soil and land management). The main factors that affect nutrient use efficiency are also the primary factors that influence the yield level (Tittonell *et al.* 2008). To be able to improve nutrient use efficiency, the differences between farming systems, landscape, socio-economic and environmental conditions are to be considered. For example, the nutrient use efficiency of apple orchards might vary between apple varieties, environmental conditions (i.e., climate and soil type), and farming systems (e.g., high or low level of fertilizer application; high or low labour use; intercrop or monocropping; high or low apple density). For example, in apple orchards with a long history of excessive fertilizer applications, the N use efficiency will remain low over a long period due to the large historical nutrient inputs and the unbalanced N-P-K applications. On the other hand, in orchards with low nutrient inputs in the past, nutrient use efficiency could be either high or low depending mainly on the current fertiliser application (e.g., site specific application or not), the indigenous soil fertility, the water supply during the growth period, and soil properties (e.g., water holding

Table 1 Apple yield levels and N use efficiencies in three different production systems

Production system	Yield (t ha^{-1})	N use efficiency (%)	Main aspects of the required management	Main production constraints
Current farming practices	16.46$^{1)}$	3.75$^{2)}$	Current variety+Current management practices	Less productive variety, sensitivity to diseases, poor management
Experiments in China	30$^{3)}$	14.74$^{3)}$	Idem+Formula fertilization+ Better tillage+Mulching+ Suitable pruning	Low mechanization, no effective irrigation systems
Experiments in other comparable countries	30$^{4)}$	22.3$^{5)}$	Idem+Fertigation	No limitations

1) Current apple farming yield is the average yield across the country (FAO 2016).

2) The N use efficiency of farmers' practices was derived from Li (2010).

3) Experimental yield data and N use efficiency were derived from Li (2010). The average fertilization rates applied in experiments were: $N:P_2O_5:K_2O=1:0.59:1.04$.

4) Experimental yield of Fuji apple in Northern Italy. Data were derived from Malaguti *et al.* (2002). The average fertilization rates in the experiment were: $N:P_2O_5:K_2O=1:0.71:1.5$.

5) N use efficiency of young apple trees (4 yr) in fertigation systems (N was introduced to the irrigation system at a rate of 35 kg N ha^{-1}). Data were derived from Neilsen *et al.* (2001).

capacity which affects the degree of nutrient leaching).

Despite the large number of studies on improved fertilizer application techniques in apple production systems, little quantitative information is available on nutrient use efficiency and its explaining factors in apple orchards in China. To achieve higher nutrient use efficiencies and reduce the nutrient surpluses and emissions, it is critical to understand responses of apple orchards to fertilizer applications, taking into account the differences in production systems and regions. Given the fact that water availability, temperature and radiation are in general sufficient to match the growth requirements of apple orchards in the Loess Plateau region of China, soil properties and management practices play the more important roles in a sufficient supply and optimal recovery of nutrients. Research should be conducted to establish the nutrient use efficiencies in apple orchards in regions over China with different soil properties and management practices, and to identify and close the gaps between theoretical nutrient requirements and the actual nutrient inputs in apple farming systems at current and potential yield levels in the different apple production regions over China.

5.3. Required policies to support adoption of improved management practices

To enhance the productivity of apple farming systems and to improve China's apple industry, policies are required to financially support apple production and marketing systems. For example, more mechanization in apple production is to be required. Irrigation facilities and transportation infrastructures are strongly needed especially in the Loess Plateau region. Organic fertilizers are helpful in enhancing apple yield, by improving nutrient use efficiency and improving soil quality (Tagliavini *et al.* 1996; Reganold *et al.* 2001; Cui *et al.* 2014; Zhao *et al.* 2014). Subsidies for organic fertilizer recycling and usage are needed to encourage the application of organic fertilizers on apple orchards. In addition, the development of post-harvest facilities does not keep up with the continually increasing production and export. The storage capacity of China's apple is only 20% of the total production, whereas 60–80% of total production is cold-stored after harvest with controlled atmosphere or specific facilities in developed countries (MOA 2008). Greater efforts must be exerted to enhance the usage of cold storage facilities, to prolong the life of apples and increase their availability during the summer month.

Chemical fertilizer prices continue to increase and large applications of fertilisers may contribute to increasing apple production costs and decreasing competitiveness of China's apples worldwide. The high and long-term application of chemical fertilizers is associated with a heavy burden on the environment. In addition, the high level of chemical inputs also generates concern of the food safety of Chinese apples and apple products. A number of pollution-free production standards need to be promoted to restrict the application of chemical fertilizers, pesticides and plant growth regulator, to enhance the fruit quality and environmental security, and to match the standards of importing countries. Meanwhile, associated policies should be initiated to arrange the implementations of those standards. The linkage between agriculture extensions and research institutes should be enhanced to track and identify the environmental problems in apple farming systems and in the apple production chain. To cope with these production and environmental problems, specific strategies should be developed to find local solutions.

Constraints to increasing the yields and nutrient use efficiencies are likely to be farm and region specific. Therefore, the improvements in management and applied technologies should be site-specific with respect to soil, landscape and climate, and should consider the specific types of apple orchards and farms (e.g., smallholder *vs.* large-scale farming systems; resource endowed *vs.* resource poor farms). These improved management practices should also consider the capacity of farmers to implement such improvements and to cope with constraints, such as the availability of inputs, machinery, and labor, the level of knowledge and expertise of the farmer, etc. The implementation of such improved management practices should be supported by agricultural extension systems and other agricultural services. The knowledge about such new techniques and management practices could be broadcasted by radio and TV programmes, and by consulting websites with information with smart phones and computers.

The profitability of implementing improved management practices and technologies should be evaluated to ensure their economic efficiency. Such financial evaluation should consider the total production cost and gross and net margins for apple farming systems with different types of apples, with current and improved management practises, and in different regions. An important aspect of apple farming systems is the labour demand, as fruit production is in certain periods as particularly the harvest, very labour-intensive. Hence, the net margins of apple farmers are strongly related with labour requirements and labour cost, which are to be considered in such a financial evaluation.

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