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肯尼亚和中国农业资源投入与农业单产水平变化

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Changes in agricultural resource input and productivity in Kenya and China*

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Abstract: Both Kenya and China are facing great challenges in feeding their populations; this is particularly problematic in Kenya, where the population will be projected to increase by 1.4 times from 2018 to 2100. Food production has been greatly improved in China, but it still lags behind in Kenya. In this study, we systematically compared the changes in agricultural resources and crop/livestock productivity, as well as their relationships with the resource input levels and agricultural production structure, to try to provide insights into reducing food insecurity and poverty in Kenya. Our results revealed that Kenya had 2–3 times more natural resources, such as cropland, grassland, and annual precipitation, per capita than did China in the 1960s, which was similar to the daily food energy and protein supply. Currently, Kenya still has higher natural resources per capita, but has lower food security and quality when compared to China. This is due to the continued rapid increase in crop and livestock productivity regarding energy and protein production in China. From 1961 to 2017, crop protein productivity increased by 44% in Kenya, while in China it increased by 282%. Our results showed that crop and livestock productivity positively correlated with the input of fertilizers, concentrate feeds, machinery, and pesticides, as seen in China. Meanwhile, the structure of crop and livestock production also showed a large impact on the changes in productivity, such as the harvest area of vegetables/fruits to the total harvest area and the ratio of monogastric animals for livestock production. Overall, both agrochemicals and structure have strong impacts on the increase in productivity, and these could be potential options in Kenya to improve productivity due to the low input of resources into crop and livestock production.

Keywords: Kenya; China; Energy productivity; Protein productivity; Agricultural resources; Agricultural structure; Food security

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肯尼亚和中国农业资源投入与农业单产水平变化*

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摘　要: 当前, 肯尼亚和中国在生产足够粮食以保障粮食安全方面都面临着严峻的挑战。尤其是对于肯尼亚而言, 因为其 2100 年预测的人口将达到 2018 年的 1.4 倍, 且其粮食生产在过去并没有大幅度的改善。而中国近些年粮食生产能力显著提高。本文系统分析了肯尼亚和中国农业资源投入、种植业和畜牧业单产水平的历史变化, 以及农业资源投入与产量之间的关系, 为肯尼亚粮食危机和消灭贫困提供更多的理论支撑。研究结果表明, 在 20 世纪 60 年代, 肯尼亚耕地、草地和降水等自然资源人均占有量比中国高 2~3 倍, 且人均食物能量和蛋白质供应显著高于中国。当前, 肯尼亚人均资源拥有量仍高出中国约 30%, 但是其人均食品供应和粮食自给率却远低于中国平均水平。这是由于与肯尼亚相比, 中国在种植业和畜牧业长期持续的投入, 大幅度地增加了种植业和畜牧业能量或蛋白质单产水平。1961—2017 年, 中国和肯尼亚作物蛋白的平均单产分别增加 282%和 44%。中国的数据表明, 种植业和畜牧业单产水平与肥料、精饲料、机械和农药的投入具有显著正相关性; 农牧业生产结构对单产水平的变化影响也很大, 如种植业中蔬菜和水果播种面积占比, 畜牧业中单胃动物饲养占比等。总的来说, 农业资源投入和农业结构对生产力的提高都有很大的影响, 这可能是肯尼亚提高农业生产力的潜在选择。

关键词: 肯尼亚; 中国; 能量生产力; 蛋白生产力; 农业资源; 农业结构; 粮食安全

Food systems are impacted by populations, incomes, urbanization rates, demand for animal products, and pressure on natural resources, all of which are linked to food demand and security (Godfray *et al.*, 2010a; Godfray *et al.*, 2010b; Herrero *et al.*, 2010). Worldwide, agricultural production, especially of cereals, has increased due to the input of fertilizers, water, pesticides, and new crop varieties, as well as the green revolution. Hence, food shortages have been reduced (Tilman *et al.*, 2002; Qi *et al.*, 2018). Although food production has significantly increased over the past five decades, production in some countries remains low. Food security in sub-Saharan Africa is of high priority because the area is faced with food shortages, malnutrition, and dependences on food imports and aid. This is different to China, where there is only 9% of the global cropland, but this feeds around 20% of the global population (FAO, 2019a).

Agriculture production in Africa is showing a promising trend, despite lagging behind other regions of the world (Sulser *et al.*, 2015). The population of Africa is projected to increase between two and over four times by 2050 (Van Ittersum *et al.*, 2016), especially in developing countries, such as Kenya, where the population is projected to increase by 1.4 times from 2018 to 2100 (FAO, 2019a). The level of undernourishment in Africa is increasing as the prolonged decadal decrease of undernourishment in the world is ending. In Kenya, the trend has been the same from 2014 to 2018, with an increase from 25% to 29% (FAO, 2019a; FAO, 2019b).

In the last 50 years, Chinese agricultural productivity has increased tremendously, it has been possible to feed about 20% of the world's population with 9% of the world's arable land and 4% of the world's water. Crop production, especially grain production per hectare of cropland, has increased. This is unlike in Kenya, where the increase in yield has been due to the expansion of agricultural land. Livestock production in China has also increased and undergone a transition in both livestock system and structure due to an increase in demand, new technologies, and government support (Bai *et al.*, 2018; Delgado *et al.*, 1999).

Recent studies have indicated that agricultural productivity is related to the input into both crop and livestock systems. Additionally, a study has reviewed how high crop yields can be achieved in the short and long terms (Jaggard *et al.*, 2010). In this study, the authors assessed how changes in the yields of seventeen crops in different countries could help to increase food production through technological advances and closing yield gaps. Meanwhile, increased livestock production has been achieved through advances in science and technology, such as conventional animal breeding, modern genomic approaches, preserving rare species, and other technologies (Thornton, 2010). There have also been studies concerning the drivers and future challenges of fisheries; and how new science, policies, and intervention can help to increase fishery productivity (Garcia and Rosenberg, 2010). However, there are few studies concerning energy and protein productivity, as most studies focus on yield and how it can be increased to meet food demand.

In this paper, we aim to understand the historical changes regarding agricultural productivity in terms of energy and protein for both crop and livestock production in Kenya and China, and quantify their relationships with the input of agrochemicals and agricultural resources. This will provide insights into reducing food insecurity and poverty in Kenya.

1 Materials and methods

Data was primarily sourced from FAOSTAT from 1961 to 2017, data for annual volume of precipitation was available in intervals of five years from 1992 to 2017 for both China and Kenya (FAO, 2019a). Data obtained from this database included the land-use area, annual human population, animal numbers, crop yield and area, animal production, cereal and protein feeds; and input into agriculture, such as machinery number, total pesticides, and different forms of total fertilizer (NPK). Data retrieved from the World Bank database (World Bank, 2019) included the per capita GDP, while annual precipitation volume was derived from the AQUASTAT database of FAO. The data were entered into MS Excel 2010 (Microsoft, USA) and various calculations were performed to obtain multiple parameters, as shown in the following equations.

In this study, crop productivity refers to the average energy or protein production per hectare of cropland, as the two main functions of food for humans are to provide sufficient energy and protein.

$$P_c=\sum p_i/\sum a_i \quad (1)$$

Where, P_c is the average energy/protein production per square hectometer of cropland at the country level, expressed in kcal·hm^{-2} or kg(protein)·hm^{-2}; $\sum p_i$ is the sum of the energy or protein production of all the crop products, in kcal or kg of protein; and $\sum a_i$ is the sum of the total harvested crop area, in hm^2. In total, around eighty types of crops were considered in this study, which followed the concepts of Tilman *et al.* (2011) and Lassaletta *et al.* (2014). The energy and protein contents of different crop products were retrieved from the food balance sheet (FAO, 2019a).

Livestock productivity was expressed as the average energy or protein production per livestock standard unit (LSU), equal to a 500 kg dairy cow, and was calculated as shown below:

$$P_l=\sum p_i/\sum u_i \quad (2)$$

where, P_l is the average energy or protein production per LSU, in kcal·LSU^{-1} or kg(protein)·LSU^{-1}; $\sum p_i$ is the sum of the energy or protein produced by livestock categories in a country, in kcal or kg of protein; and $\sum u_i$ is the sum of the livestock units of each livestock category, expressed in LSU. Here, six livestock categories (pig, layer hen, broiler, beef cattle, dairy, sheep, and goat) were considered. The conversion units used for the livestock unit are as follows: dairy cow = 1 LSU, beef cow = 0.5 LSU, sheep = 0.1 LSU, goat = 0.1 LSU, pig=0.35 LSU, laying hen=0.012 LSU, and poultry=0.018 LSU (Liu *et al.*, 2017). The energy, protein content, and protein/N transfer index for each livestock product was derived from FAOSTAT.

The food self-sufficiency rate (SSR) refers to the extent to which a country can satisfy its own food production according to Thomson and Metz (1999). The SSR was calculated using equation 3. For plant products, an average of the cereals, pulses, vegetables, and fruits was used. For animal products, an average of the meat, eggs, fish, and aquatic products was used.

$$\text{SSR} = \text{production} \times 100/(\text{production}+\text{imports}-\text{exports}) \quad (3)$$

Scatter graphs were constructed using Excel to visualize the relationships between input (fertilizer, pesticides, machinery per hectare, and proportion of cultivated land) and crop energy/protein production, and between input (cereals feed and protein-rich feed) and livestock energy/protein productivity. The total consumption of cereals, feed, and protein-rich feed (oil crops) was directly derived from the food balance sheet of FAOSTAT (FAO, 2019a). All figures were generated using Excel.

2 Results and discussion

2.1 Differences in natural resources and food security

Agricultural land area, inland freshwater, and precipitation resources are the key components for agricultural and aquacultural production to supply enough food for human consumption (FAO, 2011). Kenya has higher natural resources per capita when compared to China, although there has been a dramatic decrease in Kenya over the past five decades (Fig. 1). In 1961, for example, the average cropland area per capita in Kenya was three times that of China. However, in 2017, the difference rapidly decreased to around 30% (Fig. 1a). Similar trends were also revealed for the per capita values of grassland area, inland water surface area, and the average annual volume of precipitation. The declines were mainly due to the faster population increase in Kenya when compared to China. Between 1961 and 2017, the reported human population increased by around six times in Kenya, while the increase in China was 52%, which was mainly related to the One-Child Policy (FAO, 2019a). It has been estimated that the One-Child Policy has led to 400 million fewer people in China, which accounts for 28% of the current population (Hesketh *et al.*, 2005; Jiang and Liu, 2016). As a result, cropland and grassland per capita decreased by 72% and 83% in Kenya and 38% and 23% in China, respectively (Fig. 1a–b). Additionally, both the inland waters per capita and average annual precipitation in volume per capita greatly decreased in Kenya, while there were only small changes in China (Fig. 1c–d).

Interestingly, the differences in natural resources between China and Kenya induced different trends in food energy and protein supplies. In the 1960s, both the quantity and quality of supply in Kenya were much better than those in China (Fig. 2). The average vegetal food energy and protein supply in Kenya were 1.5 times higher than those of China. Meanwhile, the food energy and protein from animal sources in Kenya were around five times higher than that of China (Fig. 2). However, the daily food energy supply in Kenya was still around the WHO recommendation of 2 500 kcal per day. Furthermore, there was inequity concerning the distribution among the rich and poor. Studies have reported that a high proportion of the population was still malnourished in Kenya in the 1960s (Brown, 1968; Mbithi and Wisner, 1973), even when Kenya was a net exporter of grains (Fig. 2). Food insecurity in China was more severe in the 1960s, and there were three years of great famine, which lead to severe and long-term damages to human health and the economy (Chen and Zhou, 2007; Wang *et al.*, 2010).

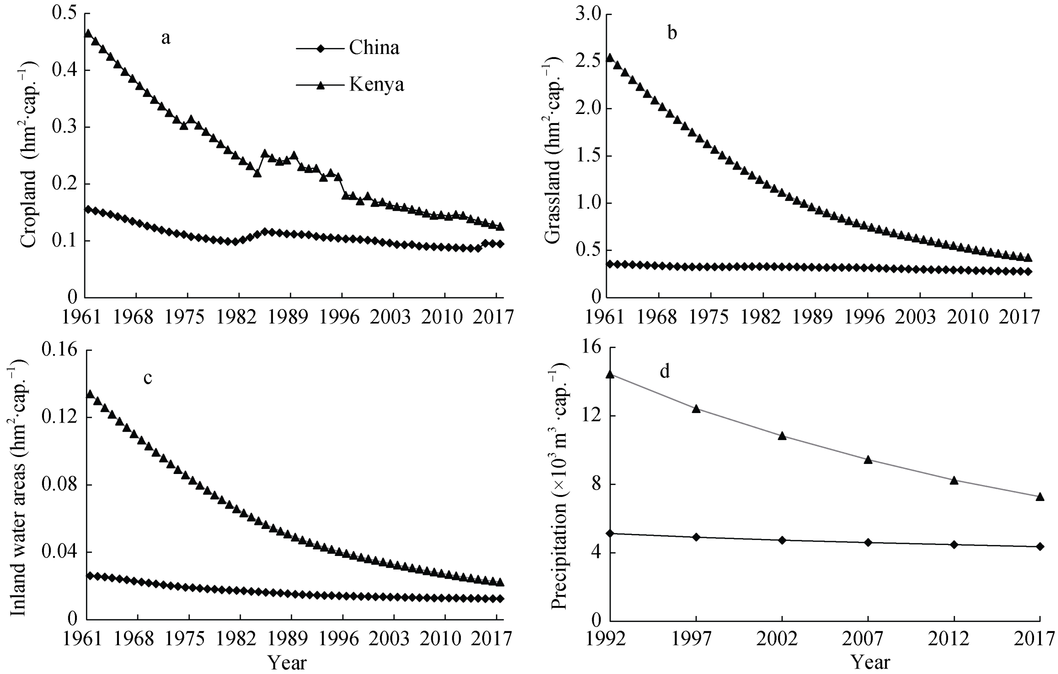

Fig. 1 Changes in natural resources from 1961 to 2017 in Kenya and China. (a) cropland area per capita, (b) grassland area per capita, (c) inland water per capita, and (d) precipitation per capita

Between the 1960s and 1980s, the daily food energy and food supply were stable in both Kenya and China. Since then, a continuously increasing trend concerning the food supply in China and a decreasing trend in Kenya have been observed. In 1983, China exceeded Kenya regarding the food energy supply, and in 1990, China exceeded Kenya regarding the food protein supply, even when Kenya's natural resources were 2 to 3 times those in China (Fig. 1). Currently, the average food energy and protein supply in China are 82% and 78% higher than those of Kenya, respectively. Meanwhile, the proportion of animal, fish, and aquaculture-sourced high-quality protein supply to total protein supply was around 45% in China, which was 59% higher than that of Kenya (Fig. 2). These factors represent significant improvements in food security and quality over the past five decades in China when compared with Kenya. Hence, the reported undernourishment has been greatly improved in China, with the current rate of the undernourished population being 8.6% (FAO, 2019a). Meanwhile, in Kenya, around 29% of the population is undernourished (FAO, 2019a), and the reported mortality rate of children less than five years is still 41.1 per 1 000 live births (WHO, 2019). This is because the current daily energy and protein supply are still below the WHO recommendations, and there is increased social inequality in Kenya, which has led to an uneven distribution of food between the rich and poor (SID, 2004).

The level of food insecurity was exasperated in Kenya when the self-sufficiency rates of crop production and demand were considered, since Kenya currently needs to import around 10% of its grain consumption. China was more self-sufficient in grains but imported a huge amount of non-grain feed resources from the global market, such as soybean (*Glycine max*), barley (*Hordeum vulgare*), and sorghum (*Sorghum bicolor*) (FAO, 2019a). Recently, China has also become a leading importer of beef, pork, and milk products, due to an outbreak of African swine fever. Each year, Kenya receives around 68 thousand tons of food aid, which helps to alleviate the severe undernourishment. In 2018, Kenya received the equivalent of 89 million US$ from developed countries (USAID, 2019).

2.2 Differences in crop and livestock productivity

The contradicting results of higher natural resources per capita but a lower food supply in Kenya compared to China were mainly related to the significant differences in crop and livestock productivity. In 1961, crop energy and protein productivity per hectare of cropland for both countries had small differences. However, in 2017, the differences were significantly increased, with productivity in China being around three times that of Kenya (Fig. 3). Crop protein productivity from 1961 to 2017 increased by 44% in Kenya, while in China it increased by 282%. Additionally, from 1961 to 2017, crop energy productivity for Kenya and China rose by 35% and 323%, respectively (Fig. 3a–b). Meanwhile, similar trends were observed for livestock production (Fig. 3c–d). However, a considerable decrease in livestock productivity in Kenya after 2005 was observed, which is mainly related to the 2005–2006 drought that affected most ruminant livestock (Nkedianye *et al.*, 2011).

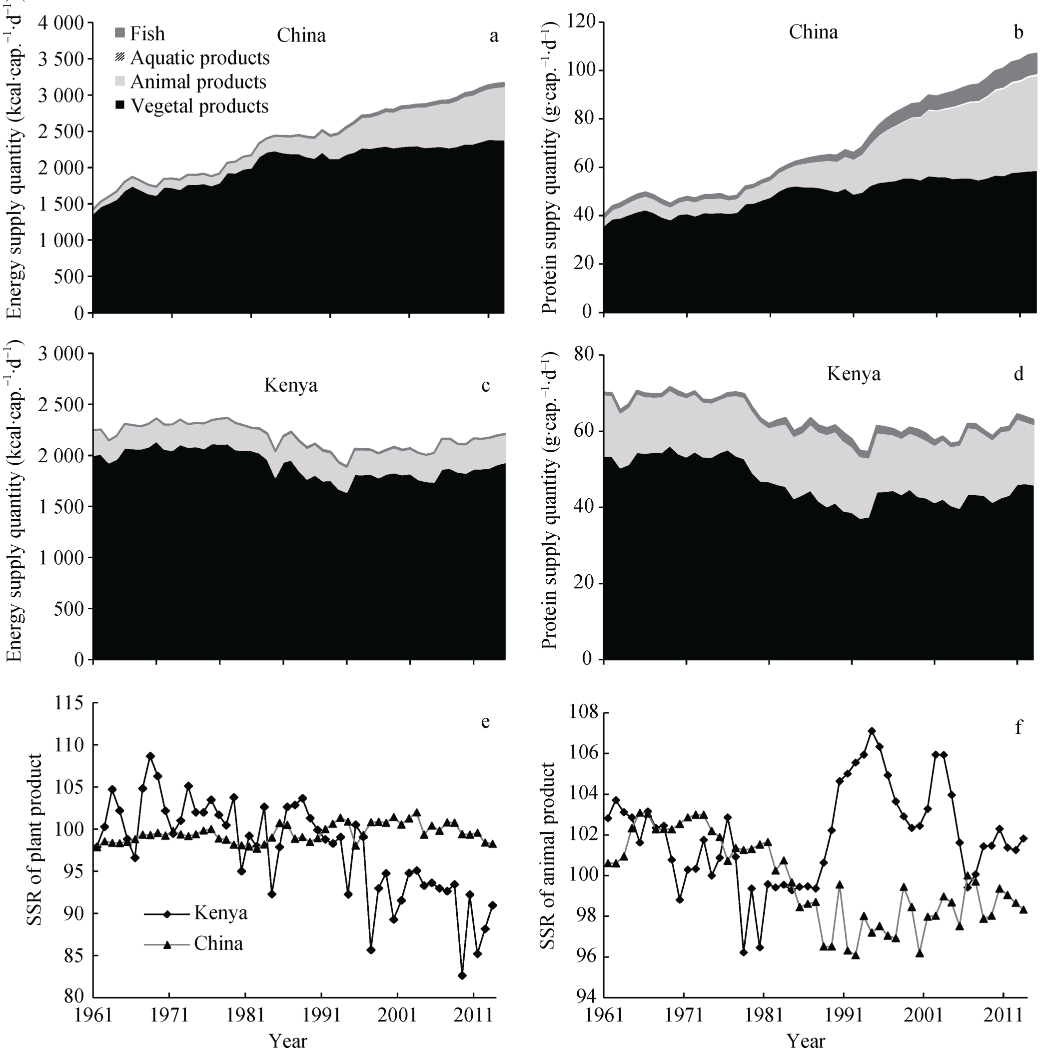

Fig. 2 Food consumption trends in terms of protein, energy, and food self-sufficiency rates in Kenya and China. (a and c) food energy supply, (b and d) protein supply, and (e and f) food self-sufficiency rate of plant and animal products. The self-sufficiency rate (SSR) refers to the extent to which a country can satisfy its own food production according to the FAO (1999).

These large differences in agricultural productivity partly explain the relatively lower natural resources but higher food energy and protein supply in China. However, the differences in daily food energy and protein supply between China and Kenya were relatively smaller than the differences in agricultural productivity, since Kenya only has 30% more cropland area per capita than does China. The higher livestock production in China (Bai *et al.*, 2018), which consumes a higher proportion of domestically produced feeds, such as maize (*Zea mays*), soybean, and wheat (*Triticum aestivum*), explains the relatively small differences in daily food energy and protein supply between China and Kenya.

2.3 Relationship between resource input and crop productivity

There are many possible reasons for the large differences in agricultural productivity between China and Kenya, such as the climate, soil nutrient level, crop species, and crop production structure (Tittonell *et al.*, 2007; Huang *et al.*, 1999). However, we argue that the main differences might stem from the level of resource input in agricultural production, such as fertilizers and pesticides, especially in China (Zhang *et al.*, 2011). Fertilizer, pesticide, and machinery inputs in China are all significantly and positively correlated to crop energy and protein productivity (Fig. 4a–c).

The input of nitrogen (N) fertilizer was positively correlated to crop energy and protein production, even though many reports have shown the presence of N over-fertilization in China (Vitousek *et al.*, 2009; Ju *et al.*, 2009). However, there were lower crop productivity responses to phosphorus (P) and potassium (K) fertilizer inputs when the P and K input rates reached 50 $kg(P_2O_5)\cdot hm^{-2}$ and 40 $kg(K_2O)\cdot hm^{-2}$, respectively (Figs. 4, 5). Although there are still positive responses to fertilizer input and crop productivity, scientists and policymakers in China have recommended that fertilizer input be reduced, as fertilizers have been over-applied, which has led to severe air, water, and soil pollution (Liu *et al.*, 2013; Guo *et al.*, 2010; Yu *et al.*, 2019). Similarly, the Chinese central government

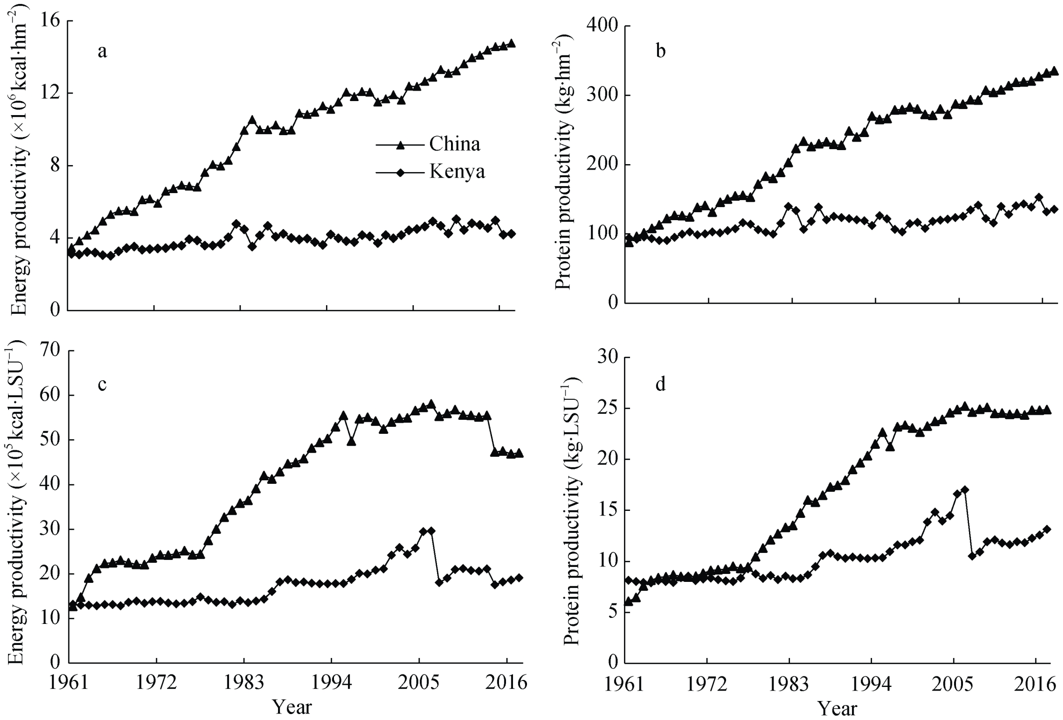

Fig. 3 Changes in (a and b) crop and (c and d) livestock productivity regarding energy and protein in Kenya and China

initiated a campaign for the reduction of pesticide use in 2015 (MOA, 2019).

In Kenya, the input of fertilizers, pesticides, and machinery is low when compared with China, which partly explains the lower crop productivity. Resource inputs into agriculture play a vital role in agricultural productivity (Vitousek *et al.*, 2009; Dobermann and Cassman, 2005; Tittonell and Giller, 2013). A study has shown that agricultural inputs in sub-Saharan Africa are low, which is associated with the low agricultural yield (Sheahan and Barrett, 2017). Fertilizer application is related to the output of crops, as seen in maize experimental studies carried out in Kenya (Li *et al.*, 2018; Mucheru-Muna *et al.*, 2014). However, the responses in different agro-ecological zones vary. Therefore, the fixed fertilizer recommendations limit the yields of different crops (Smaling *et al.*, 1992; Zingore *et al.*, 2007).

The results concerning pesticide use align with the findings of a study conducted on maize and beans in the Kenyan highlands, where the use of herbicides also resulted in a higher yield (Kibata *et al.*, 2002). Agriculture mechanization in Sub-Saharan Africa is low in both land preparation and harvesting, which results in low productivity. Human power is predominantly used in Kenya, followed by that of draught animals, and a smaller percentage use tractors for land preparation, unlike in China (Ashburner and Kienzle, 2011; Sims and Kienzle, 2006). Interestingly, there was always a positive relationship between crop productivity and resource inputs in Kenya, as there was a steady increase in crop productivity, while the use of fertilizers increased through the liberalization of the fertilizer market (Olwande *et al.*, 2009). However, there were frequent drought and flood issues in Kenya, which halted the increases in crop productivity (Gichere *et al.*, 2013).

2.4 Relationship between resource input and livestock productivity

Similarly, the productivity of livestock in terms of energy is related to inputs into livestock production. In China, cereal and protein feeds are correlated with energy and protein production. However, in Kenya, they are not correlated due to the low input, purpose of livestock, and type of livestock category (Fig. 6a–d). The type of feeds used in livestock production depends upon the kinds of livestock systems, agricultural structures, and livestock purposes (Bai *et al.*, 2018). Clearly, there is a positive correlation between the input of cereals and protein-rich feed with livestock production, both in terms of energy and protein productivity in China.

Many studies have attributed the significant increase in livestock production in China to the recently developed feed industry (Gale, 2015), because the cereal and soybean-cake based diets were rich in high quality energy and protein. Importantly, both energy and protein were balanced for the growth of animals, especially for monogastric animals. However, no strong correlations between feed input and livestock productivity was found in Kenya when compared with China. This may be partially related to the higher indigenous ruminant animal production in Kenya, where most were less efficient in using concentrated feeds as they relied on the local lower quality roughages and grasses to provide energy and protein for maintenance,

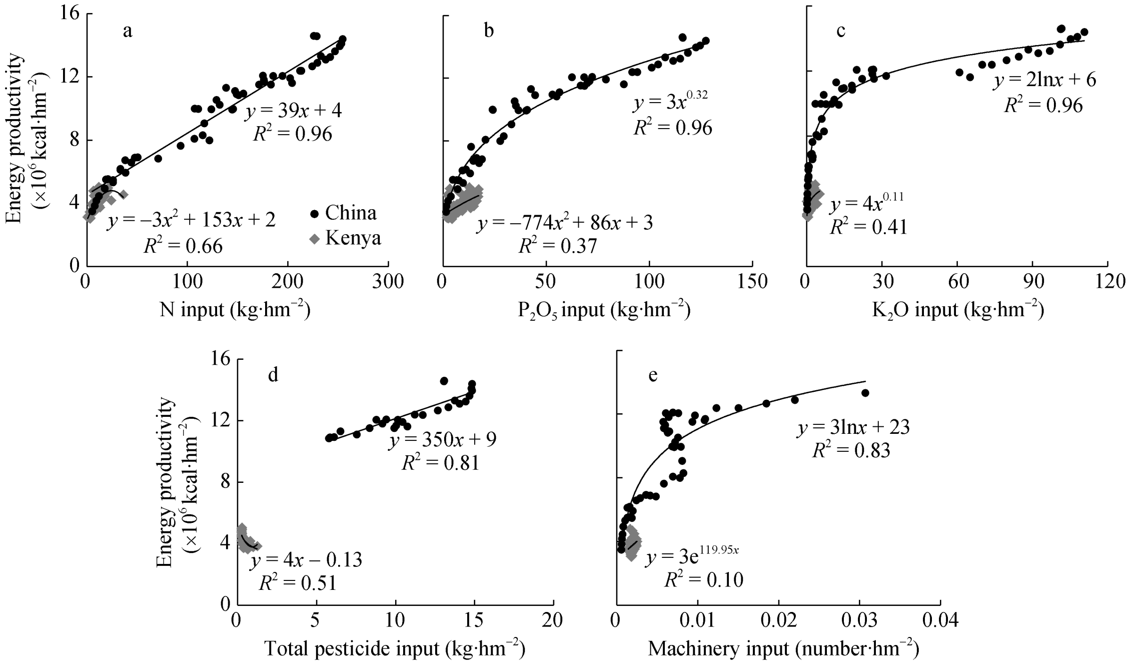

Fig. 4 Relationships of the energy production with agrochemical inputs of (a) nitrogen (N), (b) phosphorus (P_2O_5), and (c) potash (K_2O) fertilizers, as well as the (d) total pesticide and (e) total machinery (total agricultural tractors and combine harvesters in use)

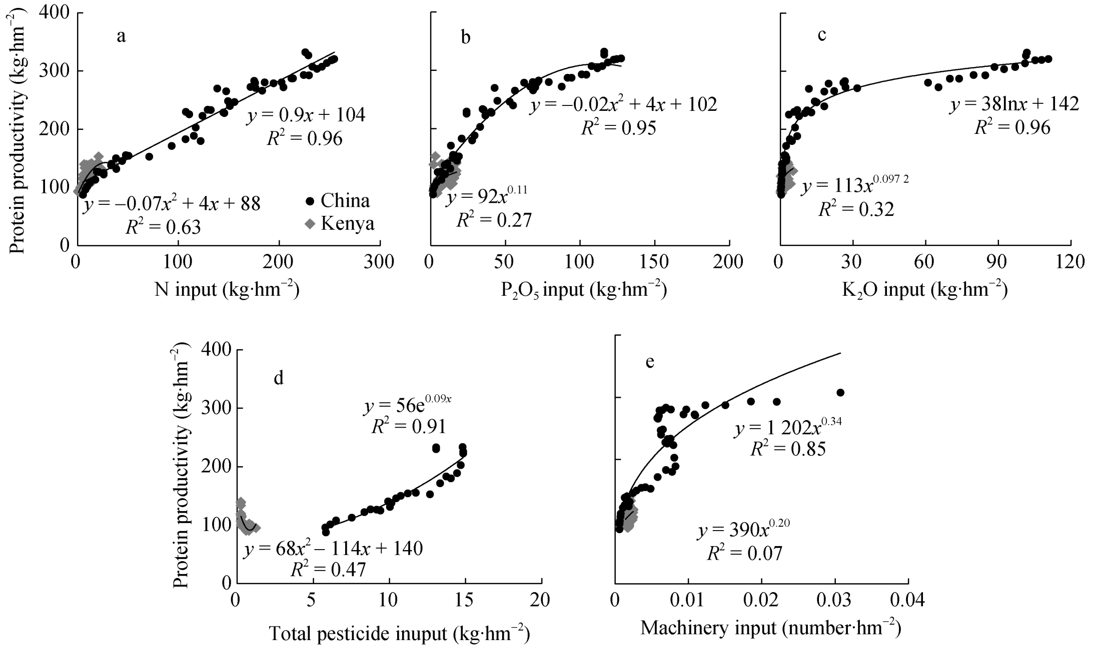

Fig. 5 Relationships of protein production with agrochemical inputs of (a) nitrogen (N), (b) phosphorus (P_2O_5), and (c) potash (K_2O) fertilizers, as well as the (d) total pesticide and (e) total machinery (total agricultural tractors and combine harvesters in use)

growth, and reproduction (Herrero *et al.*, 2010).

2.5 Relationship between agricultural production structure and productivity

The changes in productivity may also link to the agricultural production structure, as different types of crops differ in their energy and protein contents. There were positive correlations between the ratio of the cultivated area of vegetables and fruits to the total cropland area and crop productivity in both China and Kenya (Fig. 7a–b), although the vegetable and fruit products were not rich in energy or protein. This is probably due to the rapid increase in grain production. For example, between 1961 and 2017 the yield of maize, rice (*Oryza sativa*), and wheat in China increased by five, three, and ten times, respectively (FAO, 2019a), which was much higher than the increases in crop energy and protein productivity during the same period. This, together with the even greater

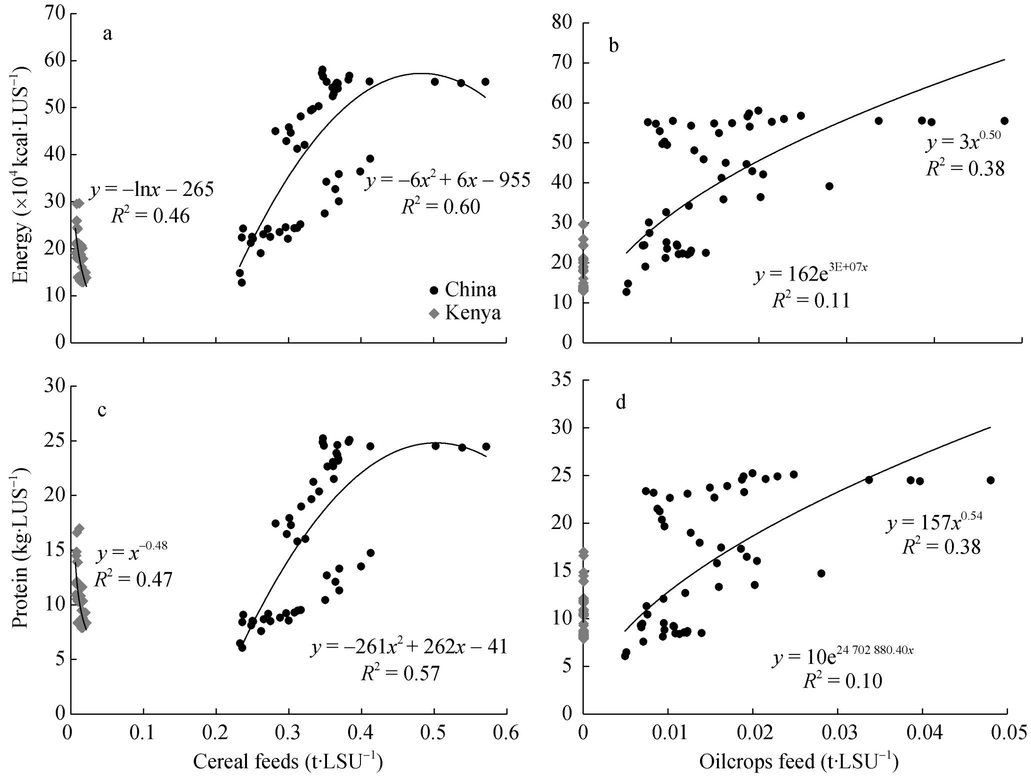

Fig. 6　Relationships of (a and b) energy production and (c and d) protein production with (a and c) cereal feeds from cereal crops, and (b and d) protein feeds from oil crops

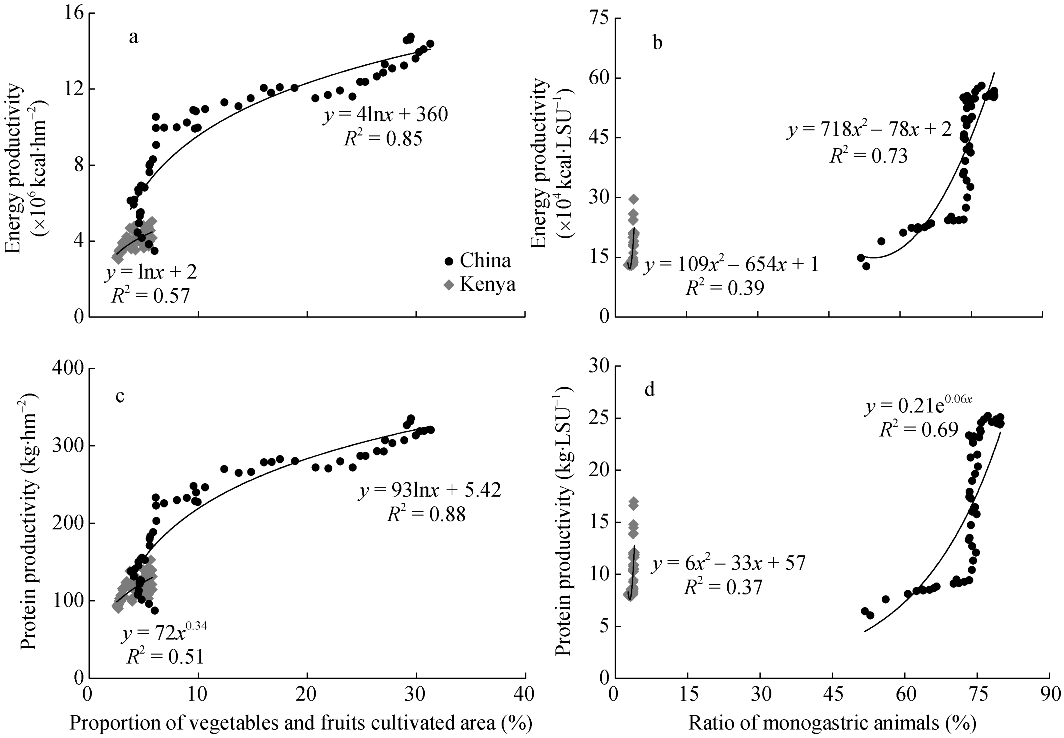

Fig. 7　Relationships of energy (a and b) and protein (c and d) productivity with the proportion of (a and c) cultivated area of vegetables and fruits and (b and d) ratio of monogastric animals

increase in yield for vegetables and fruits per hectare, has compensated for the overall decrease in crop energy/protein productivity. There were also positive correlations between the monogastric animal ratios with livestock productivity, especially in China. This is because monogastric animals are more efficient in meat production per livestock unit than ruminant animals, such as beef cattle. The higher production of monogastric animals, especially pig production, was the main reason for the rapid growth of livestock productivity in China (Bai *et al.*, 2014; Bai *et al.*, 2018).

2.6 Implications and recommendations for future research

According to the results, agricultural productivity in Kenya could follow the same path as China, by achieving increased food production and reduced food insecurity. Productivity in China from 1961 to around 1970 used low inputs with low yields, which is the same as the current situation in Kenya. From the late 1980s, the productivity of China changed due to high inputs and agricultural intensification, which resulted in high yields. However, the high input has led to a low resource use efficiency, resulting in environmental losses. Agricultural production in Kenya could be increased through the right recommendations and higher resource use efficiencies. As soils in Africa are depleted, there is a need to replenish the soil nutrients using fertilizers and other sources of nutrients, to increase the food production per capita (Sanchez, 2002).

Kenya has a large potential resource for both fisheries and aquaculture production due to the inland and marine waters, despite this, the consumption and production trends of these resources are low. Fish production could contribute to food nutrition and security in Kenya. Therefore, there is a need to improve fishery productivity. This could be attained through financial support, improved breeds, and good governances/policies, which will help to reduce post-harvest losses through cold chain management, promoting sustainable fisheries and aquaculture growth, and facilitating trade.

3 Conclusion

Protein and energy productivity in Kenya and China showed different trends, which resulted in differences in food supply and demand. Changes in productivity have impacts on consumption, food self-sufficiency, and food insecurity, hence the need to increase productivity sustainably. Despite the decline in natural resources per capita, food productivity can be attained, as has been seen in China, which has fewer resources but has been able to increase productivity to three times that of Kenya. As revealed in the results, productivity in different countries is related to the input amounts, use of agrochemicals, machinery per hectare of cropland, and the ratio of monogastric animals. Therefore, to achieve agricultural productivity and food security in Kenya, correct recommendations of agrochemical inputs and machinery should be adopted, thus increasing resource use efficiency. In addition, policies and investments from both private and public sectors should be implemented.

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