The Status and Challenges of Sustainable Intensification of Rice-Potato Systems in Southern China

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Abstract

Potato is the world's largest non-cereal crop, occupying a position critical for global food security. In China, potato is the fourth largest crop adding to food security and incomes. The large population and unremitting reductions in arable land are the most critical root causes of China's food security problems. Hence, crop yield improvements and strategies to improve land use are at the forefront of solutions to increase China's food security. Maintenance of existing land resources while increasing crop yields, avoiding soil quality degradation and wastage of water are enduring problems that have long attracted widespread attention in many research fields. This article, analyzes and discusses the status and challenges to sustainable intensification of rice-potato rotation in southern China. Three significant findings were obtained in this paper, viz. availability of about 16 million hectares of suitable land for rice-potato intensification in southern China in 2016 are reported, several conservation agricultural practices with varying intensity and higher economic benefits in rice-potato rotation than rice-fallow, which may positively effects the environment. It was concluded that agricultural intensification with potato was an economically viable avenue along with good agricultural practices that minimize adverse environmental effects.

Resumen

La papa es el cultivo no cerealero más grande del mundo, ocupando una posición crítica para la seguridad alimentaria mundial. En China, la papa es el cuarto cultivo más grande que se agrega a la seguridad alimentaria y los ingresos. La gran población y las reducciones incesantes de la tierra cultivable son las causas fundamentales más críticas de los problemas de seguridad alimentaria de China. De aquí que las mejoras en el rendimiento de los cultivos y las estrategias para mejorar el uso de la tierra están a la vanguardia de las soluciones para aumentar la seguridad alimentaria de China. El mantenimiento de los recursos de tierra existentes junto con el aumento del rendimiento de los cultivos, evitando la degradación de la calidad del suelo y el desperdicio de agua, son problemas duraderos que durante mucho tiempo han atraído la atención generalizada en muchos campos de investigación. Este artículo analiza y discute el estado y los desafíos para la intensificación sostenible de la rotación de arroz y papa en el sur de China. En este documento se obtuvieron tres hallazgos significativos, a saber, se reporta la disponibilidad de aproximadamente 16 millones de hectáreas de tierra adecuada para la intensificación del arroz y la papa en el sur de China en 2016, varias prácticas agrícolas de conservación con intensidad variable y mayores beneficios económicos en la rotación de arroz y papa que en el cultivo de arroz, lo que puede tener un efecto positivo en el medio ambiente. Se concluyó que la intensificación agrícola con papa era una vía económicamente viable junto con buenas prácticas agrícolas que minimizan los efectos ambientales adversos.

Keywords Potato · Rice-potato rotation · Sustainable intensification · Conservation agriculture · Cost–benefit analysis

Introduction

Food security is a critical and prevalent research topic globally (Lenaerts et al. 2019; Xie and Yang. 2020). Maintaining food self-sufficiency is the principle precept of China's current food security policy, which could be guaranteed if only considering the availability of cultivatable land resources

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(Fu et al. 2001; Lu et al. 2019). However, China is a densely populated country with a relatively small area of arable land. Such is the population density that China feeds almost 19% of the world's population, within its own borders, using 9% of the world's arable land (NBSPRC 2017; Shen et al. 2018). Nevertheless, due to the presence of three constraints, China's food security problems cannot be underestimated.

Firstly, the decreasing availability of arable land. Arising from China's rapid urbanization and industrialization, a loss of arable land has occurred since the 1978 market reforms and opening up to the world economy. Indeed, arable-to-urban land usage is especially prominent in China's southern provinces, where these provinces occupy a larger proportion of the available arable land (Lichtenberg and Ding 2008).

Secondly, urban-bound migration away from arable centers leads to a reduction in workforce capacity reducing the optimum number of rice harvests per year. Due to the perception that food production has a relatively low benefit, large numbers of these workers have moved to non-agricultural forms of employment leading to reduced rice planting and a decline in production (Wang et al. 2018). Consequently, the loss in agricultural workers, has resulted in large areas seeing a reduction to two harvests per year between 1990 and 2015 in former triple-cropping rice land. Similarly, double-cropping areas have observed an increase in single-cropped fields annually. This overall reduction in harvests has caused increases in land underutilization or fallow fields in the winter (Huang 2009; Jiang et al. 2019).

Thirdly, soil resources are deteriorating. The long-term continuous cropping of rice and a general lack of awareness of how to maintain soil fertility (Lu et al. 2019) in China's southern provinces has caused the deterioration the soil's physical and chemical properties. Evidence from Huang (2017) indicated that these regions' soils were severely depleted, with reduced organic matter and low soil fertility. This loss in soil fertility has contributed to a decline in productivity with the potential to undermine the sustainability of agricultural production.

For many Asian smallholder farmers in developing countries, potatoes have contributed to food and nutrition security, but more recently, increasingly also serve as an important source of income (Scott 2020). Per capita potato consumption in China has doubled between 2007 and 2019, from 33.6 to 65 kg, while, in 2019, production peaked to some 92 million tonnes and area planted to potato recovered to some 4.9 million ha (Scott and Suarez 2012, FAOSTAT 2021). Despite China's national plan to plant 8 million ha to potato and production of 150 million tonnes in 2015 appeared too ambitious (Scott and Suarez 2012), several factors have contributed to the observed increase. For instance, China has become increasingly urbanized and affluent, consumers have paid closer attention to healthier diets, and shifting society's consumption habits towards greater

food diversification (Chang et al. 2018; Jia et al. 2020). In parallel, higher income and increased urbanization have led to increased demand for processed potatoes (Devaux et al. 2020). Acknowledging the importance of potato for food security and incomes, the Chinese Ministry of Agriculture has promoted potato as a staple crop and issued formal guidelines to promote crop agro-industries (MOA 2016). Beyond national policies, regional industrial policies for have promoted the development of potato clusters, transforming rural areas and contributing to local economic development (Zhang and Hu, 2014). As a result, the rice-potato rotation model in southern provinces has undergone drastic development and improvement. Recent evidence shows the economic welfare enhancing impact of potato systems in southern China on employment and income creation, and alleviating poverty (Li et al. 2019; Myrick et al. 2021). Evidence of the economic welfare effects of rice-potato systems have also been documented for the Indo-Gangetic Plains (Gatto et al. 2020).

In this paper, China's capacity and potential for sustainable intensification of rice-potato agri-food systems is investigated. The following research questions for rice-potato production systems in southern China were identified:

- (1) What potential area for rice-potato rotation system is available for sustainable intensification?
- (2) What are the predicted/actual ecological and economic benefits of the rice-potato rotation system?
- (3) What are the constraints of the rice-potato rotation system?

Data in this report was gathered using various quantitative and qualitative methods, including interviewing experts, reviewing published research on rice-potato rotation systems in rice-growing regions of southern China, and analyzing the potential growth opportunities.

Background

Development and Status of Potato Production in China

The potato crop has become a significant part of the world's food system, which is increasingly due to its growing prece-dence in developing countries (Devaux et al. 2020). In 2018, the global potato planting area reached 17.6 million ha, and output reached 368 million tons (FAOSTAT 2021). Globally, approximately two billion people eat potatoes as their staple food with the bulk of people living in developing countries (Devaux et al. 2020).

Despite potatoes having been cultivated in China for more than 400 years as food and as a vegetable forage (Scott and

Table 1 Potato production and planting area in the World and China

Category	World	China	China's proportion
Potato production: 10 ⁴ t	36,817	9024.4	25%
Potato planting area: 10 ⁴ ha	1758	490.2	28%
Yield: t/ha ⁻¹	20.94	18.4	

Table 2 China's potato production from 2007 to 2018

Year	Potato production: 10 ⁴ t	Potato planting area: 10 ⁴ ha	Yield (kg/ha ⁻¹)
2007	6479.00	443.03	14,625
2008	7078.00	466.34	15,180
2009	7323.00	508.08	14,415
2010	8153.50	520.51	15,665
2011	8829.00	542.40	16,280
2012	8435.85	503.08	16,770
2013	8587.95	502.58	17,090
2014	8415.55	491.04	17,140
2015	8226.65	478.56	17,190
2016	8492.85	480.24	17,310
2017	8848.15	485.99	18,205
2018	9024.4	490.22	18,409

Suarea 2012; Long et al. 2018), in 1961, China's potato output only accounted for 4.77% of global output. However, since 1990, potato production has increased rapidly with improvements in potato breeding (Li et al. 2016), production techniques and the expansion of planting areas (Yang et al. 2017). In 2018, the planting area of fresh potatoes in China reached 4.80 million ha; potato production increasing from 45.94 million tons in 1993 to 90.24 million tons in 2018, and the planting area and output accounted for 28% and 25% of the global potato planting area and output, respectively (Table 1). Since China's Ministry of Agriculture has officially recognized potatoes as a staple food, the potatoes' harvested area in China increased steadily until 2016. However, in 2016, potato production declined slightly due to biotic and abiotic factors, as shown in Table 2. At present, China's potato industry has entered a period of prosperity due to the increased area used for planting alongside stabilizing planting scale and improving potato quality (Yang et al. 2017).

China's strategies to alleviate the food security problems, caused by increased population and decreased arable land, mainly relied on increasing crop yields and land utilization rate (Xie et al. 2010). However, mitigation of the productivity gap cannot be cushioned by continued reliance on China's three major food crops because increases in rice, wheat and corn yields have limited the potential to reduce food

security problems (Qu et al. 2005). Indeed, rice, wheat, and corn yields are already higher than the world average, with limited potential for further increases. Conversely, China's potato planting area is more extensive, but yields have been lower than the world average (Table 1). Hence, as a food security strategy component in China, the potato's potential yield increases remain to hold promise (Xie et al. 2010).

Besides the potential for yield increases, other agronomical characteristics favor potato as a food security crop. Agonomically, potatoes are highly adaptable, resistant to soil infertility and yield more food more rapidly on less land than any other major crop (Devaux et al. 2020). Compared with other major crops, potatoes can produce more nutritious food under less land area, harsher climate, and more arid conditions (Luo 2015). Indeed, the portion that can be consumed by humans is as high as 85% (Jin et al. 2003). Therefore, potatoes are widely planted in China's various ecological regions, especially in the impoverished western regions and remote mountainous areas. These positive attributes have played an essential role in alleviating China's food security pressure and eliminating regional poverty (Jin et al. 2003; Luo et al. 2005; Qu et al. 2005).

Patterns of China's Rice-Potato Rotation Systems

Since ancient times, Chinese agriculture has had an established tradition of intensive farming and management practices (Liu 2000). With an emphasis on increasing land utilization, this practice is referred to as cultivated land intensification. Multi-cropping of cultivated land is one of the most straightforward measures to extend cultivated land use in terms of time and space (He et al. 2016). Rice-potato rotation systems began to develop in Guangdong Province in the 1980s, mainly as a commercial spinoff to supply potatoes for Hong Kong. However, over time it gradually developed and spread to its current scale to include winter cropping areas in Guangdong, Fujian, Guangxi, and now the largest scale in low-altitude southern Yunnan. At present, about 40% of cultivated land in China has multiple cropping modes (Yan et al. 2005), and 1/4 of the food produced comes from increases in the multi-cropping index (MCI)¹ of cultivated land (Tong 1998). China mainly used crop rotation, row intercropping and relay intercropping to increase farmed land's MCI (Wen 2015). Paddy rice with subsequent dry-crop (i.e., non-paddy rice) rotation² was one of the most dominant crop rotation methods utilized in southern China

¹ Multiple cropping index (MCI): Multiple cropping index refers to the period of time (usually 1 year) average number of crops planted on the same plot of arable land, that is, the average number of crops grown on arable land during the year.

² Paddy rice and dry crop rotation: The planting methods of rice and dry crops are sequentially rotated in the same field.

Fig. 1 Main rotation pattern with rice in the south of China

(Jiang et al. 2019). It refers to planting rice and other 'dry' crops at different periods within a single year (i.e., a single growing season) on the same field (Sun et al. 2019). This crop rotation is conducive to improving land-use efficiency, improving soil physical and chemical properties, increasing crop yields, and ensuring sustainable farmland development (Sun et al. 2019). In this way, traditional paddy-rice cropping is often followed by dry cropping of wheat, rapeseed or green manure (Fig. 1), despite minimal economic benefit (Wang et al. 2019). The southern rice areas have predominantly adopted single-crop rice or a continuous 'fallow-rice-rice' cropping model (Liu and Jiang 2019). However, the 'rice-potato' cropping pattern has been widely adopted in southern winter potato planting areas in recent years (Fig. 1). This rice-potato cropping method can increase the MCI of land, increase farmers' incomes, and make full use of winter fallow fields (Jiang et al. 2019).

In the 12 rice-growing provinces of southern China, typically from late-maturing rice (150–170 days)³ and middle-maturing rice (120–150 days)² harvest to the second year of rice planting, about 16 million ha rice fields are fallow (commonly referred to as winter fallow fields) (Table 4). Conditions such as temperature, light, water and fallow field soil temperature in winter and the additional 150 days of resting are conducive to winter potato production. According to Xie et al. (2010), where the potato was introduced in rotation with winter fallow paddy fields in 2006, higher yields and economic benefits of potato resulted. These trials took place across all 12 rice-growing provinces in southern

China, with a total planting area of 642,500 ha. However, the potato planting area of winter fallow rice fields across the 12 provinces only accounted for a mere 3.93% of the total winter fallow rice fields (Xie et al. 2010). Since this planting method does not compete with rice for land, the rice-potato rotation model has excellent development potential in these areas. Indicators from Yunnan Province illustrate the potential for rapid adoption of the rice-potato model (DARAYP 2018). Between 2010 and 2017, the potato planting area (fall and winter) increased by 41.4%. This figure represents an increase in land area from 153,000 ha to 217,000 ha.

Sustainable and Intensive Development of Agriculture in China

Globally, the intensification of agriculture and parallel increases in land utilization are some of the most notable changes in agriculture in the 20th Century (Matson et al. 1997; Li et al. 2004; Wang and Wang 2004). In many countries in the past 60 to 70 years, agriculture has transitioned from extensive to intensive management methods. This global trend in intensification is particularly prominent in China's agricultural sector (Xiang and Tang 2005). Agricultural intensification requires relatively high inputs (capital, labor, and technology) per unit of land area to achieve higher output and efficiency (Liu 2000). However, sustained intensification in agriculture is achievable if its impact on agroecology is limited (Ni 2018). Tilman et al. (2011) pointed out that enhancing nutrient use efficiency and reducing land reclamation are developmental pathways for sustainable agricultural intensification. Sustainable agricultural intensification focuses on the impacts and integrated benefits of ecological, economic, and social systems simultaneously. Sustainable intensification should realize food security in parallel with ecosystem conservation and farm household

³ Middle rice and late rice: in China, rice can be divided into early rice, middle rice and late rice according to seeding, growth and maturity. In general, the growing period of early rice is 90–120 days, the middle rice is 120–150 days, and the late rice is 150–170 days.

livelihood improvement (Garnett et al. 2013; Garibaldi et al. 2017). Rockstrom et al. (2017) proposed sustainable agricultural intensification within an operational framework of agricultural development, increased agricultural productivity and socio-ecological resilience geared towards protecting agro-ecologies. Given China's large population and food insecurity threat, it needed to follow a path that is both high-yielding, quality-focused and efficient (i.e., intensive) while maintaining existing resources and the environment (i.e., sustainable) (Liu and Ren 1993). Thus, in short, the sustainable intensification of Chinese agriculture has been based on high yield, efficiency, quality and low resource consumption to achieve continuous productivity growth, sustained use and conservation of agriculture, natural resources, improved soil fertility and an improved rural ecological environment (Yu et al. 1999).

Materials and Methods

Reviewing the Publicly Available Literature

Publicly available literature was reviewed to achieve the research objectives of this article. Information was mainly sourced from relevant documents archived under the CNKI (China National Knowledge Infrastructure, <https://cnki.net/index/>), including changes in the rice planting area of southern China, the paddy-dry rotation methodology, and the effects of these rotation methods on the soil. The benefits of rotation systems on the soil focused on improvements in the soil's physical and chemical properties, increases in microbial content, and fertilizer savings. At the same time, documents were collected in relation to the development potential of potato cultivation in China, and research literature on sustainable intensification, among other areas. The relevant documents are summarized in Supplementary Table 1.

Data Sourcing and Processing

The planting area and output data of food crops (including rice and potato) were derived from agricultural statistics for China, between 2007 and 2017. The yield per unit area was obtained by using yield data for grain crops and area sown. Since available statistics only correspond to Mainland China, data for Taiwan, Hong Kong and Macau were not considered in this study. Furthermore, in published national statistics, potato planting in Beijing, Tianjin, Shanghai, Jiangsu, Shandong, and Henan were included in the vegetable area instead of grain-related areas. Hence, this study also included data related to potatoes in these areas. Estimates of the potato and rice planting areas and production changes data from 12 provinces in southern China from 2007 to 2017, and

Table 3 The number of interviewees by profession

Profession	Number of interviewees
Breeder	8
Agronomist	4
Potato pathologist	11
Farmer	1
Agricultural economist	1
Entrepreneurs	5
Total	30

individually for Yunnan, Sichuan and Guangdong in 2017 were performed using Microsoft Excel. These estimates also included calculating the ratio of total planting area to yield from available data.

Key Information Interview

Expert opinions in our research area were used to understand first-hand information and experiences. In this study, experts in potato research were consulted, which included breeders, agronomists, agricultural economists, and potato pathologists (Table 3). To better understand potato cultivation in relevant provinces, experts were interviewed in Guangdong, Sichuan and Yunnan. These interviews provided a profound understanding of the rice and dry crop rotation methods in these three provinces and the sustainable intensification in cultivation methods of rice and potato rotation.

Study Area

We selected the Provinces of Guangdong, Yunnan, and Sichuan as objects for this study. There were three prominent reasons for choosing these three provinces for this study: firstly, in 2017, their combined potato planting area accounted for about 30% of the country's total cropping area (Fig. 2), otherwise accounting for about 26% of the annual output (Fig. 3). Accordingly, these quantities illustrated the importance of potatoes in these areas. Secondly, all three provinces performed winter potato cropping. The main winter potato planting regions are Dehong, Puer and Lincang in Yunnan province, Chengdu and Liangshan in Sichuan province, Shanwei and Huizhou in Guangdong province. Winter cropping was primarily observed in Guangdong Province, where winter potatoes utilize 85% of the area, and 15% were spring potatoes. Lastly, the rice-rice-potato rotation system is very mature in Guangdong Province, and Yunnan Province had become the country's largest winter potato production area since 2017, indicating that the potato industry in this region

Fig. 2 Proportion of potato planting area in Yunnan, Sichuan and Guangdong provinces to the total potato planting area in China

Fig. 3 Proportion of potato production in Yunnan, Sichuan and Guangdong provinces to the total potato production in China

Map 1 Four major potato cultivation regions in China. *Source* Wang et al. 2011

developed very rapidly. These provinces underpin the predominant trend in southern China and provided the opportunity to compare the planting areas and typical agronomic norms between each region.

In recent years, Sichuan Province has ranked first in terms of potato area and output in China. Potatoes in Sichuan Province are planted at different altitudes and, consequently, divided into spring, fall and winter cropping zones. Although potato planting in Yunnan Province is like that of Sichuan Province, differences in latitude and altitude result in different planting times and cultivation practices. Finally, these three provinces have developed suitable local cultivation techniques for potato planting. Sustainable intensification has developed rapidly with the preferential support of national policies, and each has specific characteristics in the rice-potato rotation system.

Southern China is dominated by tropical and subtropical monsoon climates, with hot and rainy summers and mild winters with little rain. The annual precipitation is above 800 mm, and the winter temperatures above 0 degrees centigrade. The terrain is complex and variable, including plains, hills, basins, and mountains. This area accounts for about 25% of the country's land area and about 2.4 million square kilometers. The potato cultivation system in China is roughly divided into four climatic regions (Map 1): the temperate north (Zone I), the Central Plains (Zone II), the winter cropping area (Zone III) of the south and the mixed cropping area (Zone IV) of the southwest which has the potential to adopt a rice-potato rotation pattern. The provinces under study are distributed across the southern winter cropping area and the southwest mixed cropping area.

Results and Discussion

Paddy Rice-Upland Crop Rotation System in Selected Southern Provinces

Through interviews with experts on potato cultivation and detailed reviews of available literature on paddy-dry rotations, the southern region contained approximately 16 million ha of fallow rice fields in winter. On one hand, the large number of fallow fields was because of rural labor shortages and high labor costs. On the other hand, because these paddy rice fields had a relatively poor soil water holding capacity, when fields were drained in preparation for dryland crops in the winter, due to low levels of organic matter and low temperatures, the soil may become hard with a poor condition unsuitable for planting. This unsuitability for multi-cropping is especially prevalent in the southwestern mixed cropping area (Zone IV), where mountainous terrain and small rain-fed field sizes inhibit water management (i.e., irrigation and drainage) possible in other regions. Simultaneously, water resources are scarce in these provinces, irrigation is inadequate, and irrigation facilities are insufficient that is mainly a problem during the dry-cropping period (Wu and Jiang 2014). Winter is also a dry season in the south of China, low precipitation can lead to reduced potato yields, thus affecting farmers' income. At the same time, cost of water-saving irrigation facilities is very high because most winter potato is grown on small and scattered plots. These factors are limiting the development of rice and potato crop rotation system in winter crop areas (Wu and Jiang 2014). The current measures proposed by the Chinese government to transform low- and medium-yielding fields can only be achieved when the government invests in appropriate infrastructure, including water-saving irrigation systems.

The survey also found that the proportion of rice-potato rotations to the total proportion of potato acreage in each province differed significantly between the southern winter crop zone and the southwestern mixed crop zone. The proportion of winter potatoes planted in the southern winter crop area ranged from 88 to 100%, while the proportion of winter potatoes planted in the southwestern mixed cropping area ranged from 4 to 40% (Table 4). The main reasons leading to this difference were the geography and climate variance between the winter crop area and the southwestern mixed crop area. The winter crop areas like Guangdong Province were mainly composed of hills, the annual rainfall being 1000–3000 mm, and the frost-free duration being more than 300 days. These elements provide favorable conditions for planting potatoes in winter. The southwestern mixed crop area mainly consisted of mountains, so the temperature and rainfall were significantly different in low and high altitudes.

Table 4 Potato cultivation in fallow paddy fields in some provinces in southern China in 2016

Province	Fallow rice land (10 ⁴ ha)	Potato planting area (10 ⁴ ha)	Potato planting area in the rice fields (10 ⁴ ha)	Percentage of potato area in the rice fields	Percentage of potato area planted in rice fields to total potato area
Zhejiang	53.43	7.09	5.0	9.36%	70.52%
Anhui	239.78	0.69	—	—	—
Fujian	51.00	8.42	8.06	15.8%	95.7%
Jiangxi	222.54	1.47	1.3	0.5%	88.4%
Hubei	219.41	25.15	—	—	—
Hunan	279.05	8.16	—	—	—
Guangdong	95.19	4.66	4.66	4.8%	100%
Guangxi	99.09	6.56	6.56	6.6%	100%
Chongqing	65.89	37.18	6.7	10.2%	18.0%
Sichuan	187.49	80.7	30.9	16.5%	38.3%
Guizhou	70.05	73.17	15.2	9.56%	9.16%
Yunnan	83.15	55.78	5.6	6.7%	10.0%
Total	1666.08	309.03			

(1) Fallow rice fields are the total of the middle-rice fields and late-rice fields, and rice fields data is sourced from the China Agriculture Statistical Report (2016); (2) Potato planting areas in the different province were investigated or were sourced from statistical data in 2016

Table 5 Conservation agriculture practice adopted in Yunnan, Sichuan and Guangdong

SI (sustainable intensification) practice	Yunnan		Sichuan		Guangdong	
	+/-	Adoption rate of farmers	+/-	Adoption rate of farmers	+/-	Adoption rate of farmers
Integrated late blight management	+	86%	+	50%	+	> 90%
Plastic film mulching	+	43%	+	50%	+	> 90%
Water and fertilizer integration	+	1.4%	—	0%	—	0%
Mechanization	+	57%	+	10%	+	> 90%
Soil testing and formula fertilization	+	No data	+	50%	+	80%
Zero tillage	—	0%	+	No data	—	0%
Drip irrigation	+	1.4%	—	0%	+	No data

+ : means to use these measures; —: means not to use

These conditions have a significant influence on crop planting in the southwestern mix crop area. For instance, Sichuan winter potatoes accounted for about 4%. The low proportion was due to Sichuan Province being the country's largest winter rapeseed cultivation area and many rice fields being used for rapeseed cultivation (MOA 2020). Yunnan's proportion was high due to the economic benefits of winter potatoes being very high. For instance, in Dehong, Mangshi, Honghe, Jianshui and Kaiyuan in southern Yunnan, many farmers planted winter potatoes using the so-called "1-1-3-9 method". That is planting 1 mu (45 t/ha⁻¹), for 100 days, with a yield of 3000 kg and an approximate revenue of CNY 9000 (USD 138.9) (DARAYP 2018). Especially in Dehong, potato yields gradually increased to an average of 47 t/ha⁻¹ (Li et al. 2019). Due to the better prices for potatoes than other winter crops such as tobacco, the farmer has more motivation to plant potatoes. Consequently, increases

in winter potatoes in Yunnan Province have been swift, becoming the largest winter potato planting area in China (DARAYP 2018).

Conservation Agriculture Practices in the Process of Rice-Potato Rotation

As shown in Table 5, in the rice-potato rotation systems in the three provinces investigated, the leading conservation agricultural practice in potato planting included integrated late blight management, mechanization, plastic film mulching and soil testing and formula fertilization technology. The late blight integrated management is the principal measure taken in potato planting in southern China. It was found that farmers' adoption rate in Sichuan Province was 50%, lower than Yunnan Province and Guangdong Province. The overriding reason was that farmers in Sichuan Province planted

potato just for their own household consumption rather than to sell, so they did not spend much on integrated late blight management. The high adoption rate of potato as a winter crop in Guangdong and Yunnan was due to the 'farmers' reliance on agricultural revenues earned from the winter season. Intentions to maximize agricultural production obliged farmers to spend more on farm management and inputs. Plastic film mulching was the primary cultivation measure adopted for winter potato planting (Shan and Han 2015; Mo et al. 2017).

Table 5 also shows that the adoption rates of farmers in Yunnan and Sichuan were almost half of Guangdong. The reason for this difference was that regional geography (Zone IV) limited the use of the mechanization necessary for plastic-mulching. Likewise, the southwestern mix crop area's geography had the same impact on the adoption of mechanization. This impact was due to mountainous agro-ecology, leading to small disparate fields. Soil testing and formula fertilization was a quick and accurate method to determine the relative acidity of the soil (pH) and the level of several essential nutrients (phosphorus, potassium, calcium, magnesium, sodium, sulfur, manganese, copper, and zinc) as a guide to farmer fertilization (Duan 2018; Bradley and Deanna. 2019). The Chinese Ministry of Agriculture has promoted the technology in recent years (Zhu et al. 2016), resulting in the increased adoption rate of technology by farmers. The practices of water and fertilizer integration and drip irrigation were barely present in the three provinces. It was understood that the irrigation facilities' cost was high and cumbersome for field-based production as evidenced by the expert's opinions. Also, recently high winter and spring rainfall in the southern regions resulted in farmers not adopting the practice. The zero-tillage technique was not practiced in Yunnan and Guangdong because paddy fields were not suitable for direct planting. Such practices resulted in tubers rotting before emergence.

Benefit Analysis of the Rice-Potato Rotation System

Economic Benefit Analysis of the Rice-Potato Rotation

The economic benefits of rice-potato rotation mainly referred to the increase in the rotation's production and profitability, closely related to farmers' incomes. This survey found that in contrast to the rice-fallow system, the rice-potato rotation system increased profitability by 266% (Table 6). Compared to the rice-fallow system, rice yields and thus outputs are lower in the rice-potato system. Despite the apparent loss in production, this phenomenon appeared to be due to the duration that a rice variety's crop takes to reach harvest. For instance, in the rice-potato rotation system, farmers plant the early maturing rice to ensure the required growth period for the succeeding potato crop, but in the rice-fallow system,

Table 6 Inputs, outputs, benefits and profitability in rice-potato and rice-fallow system

Item	Rice-potato		Rice-fallow	Percentage
	Rice	Potato	Rice	
Yield (kg/ha ⁻¹)	9000	33,000	11,250	273%
Output (CNY/ha ⁻¹)	22,500	75,000	27,000	
Input (CNY/ha ⁻¹)	9000	22,500	9000	
Benefit (CN/ha ⁻¹)	13,500	52,500	18,000	266%

a farmer can plant middle or late-maturing rice varieties resulting in greater rice yield. However, some early maturing rice varieties that fit into rice-potato systems may only result in a small yield reduction compared to medium or late maturing varieties (Hong et al., 2020). Transplanting rice, as practiced in the Indo-Gangetic Plains, could be another farming practice to maintain yields (Gatto et al., 2020). In this case, production increases compared to a scenario where the period after rice is left fallow.

Similarly, findings for intensified systems with potato have been documented by Qiu et al. (2015) who found that rice-potato rotations had higher economic benefits than the rice-rapeseeds rotation when analyzing the economic benefits. Unlike rice-rapeseed rotations, in rice-potato crop rotation systems, potato cultivation does not prevent earlier rice planting.

Li et al. (2016) also pointed out that under the "potato-rice-rice" model in Guangdong Province, fertilization can be reduced by 80% compared to the control. After harvesting potatoes, early and late double-cropping rice are planted, allowing for a significant reduction in fertilization applications. Similar economic benefits were also observed in other parts of Asia where rice-potato systems are prominent (Gatto et al. 2020).

Ecological Benefit Analysis of Rice-Potato Rotation From Reviewed Literature

Intensification of agriculture results in higher input-use and, by default, negatively affects the environment, such as soil and water quality. However, input-use efficiency can be increased in rice-potato systems as both crops jointly require fewer inputs than both crops individually. The ecological benefits of rice and dry rotation refer to the impact on soil structure (Cui 2018), soil fertility (Liu and Jiang 2019), soil quality (Sun et al. 2019), the entire ecological environment and agricultural ecosystem after a particular farming system model is implemented or promoted (Wang et al. 2002; Liu and Jiang 2019). It is further implicated in the larger issue of sustainable development. Field experiments showed that paddy rice and dry rotation can improve the physical and chemical properties of the soil (Wang et al.

2003), accelerate the renewal of organic matter, increase the permeability of the soil, and facilitate the effectiveness of soil nutrients. Yu (2010) analyzed the soil nutrients in the rice-potato rotation system. Yu's results showed that in this type of rotation system, after the potato is harvested, the quantity of organic matter, total nitrogen, total phosphorus, alkali hydrolyzed nitrogen, available phosphorus, and available potassium increased by 3.39 g/kg^{-1} , 0.159 g/kg^{-1} , 0.029 g/kg^{-1} , 15.2 mg/kg^{-1} , 17.2 mg/kg^{-1} , 42.6 mg/kg^{-1} compared with rice-fallow. Wang et al. (2009) showed that the residues of the roots of different winter crops such as winter potatoes provide a relatively large amount of organic carbon source for the growth of microorganisms during rice growth and improved the activity of soil microorganisms. Zhang et al. (2009) also showed that different winter crops such as potato, ryegrass, milk vetch and rapeseed all increased the soil microbial activity, carbon and nitrogen content of paddy fields.

Wang et al. (2002) showed that the total weed coverage of the late rice field in the second year of the paddy and dry rotation was 80% less than that of the continuous late-rice field. Other studies also showed that aquatic and xerophytic weeds of the paddy-dry rotation, grass weeds such as oat grass in wheat fields and dodder seeds in the dry rotation with legumes had been effectively controlled. South China Agricultural University (2014) developed a method of planting potatoes in winter fallow rice fields that can effectively control the damage of *Ampullaria gigas* to early rice in the coming year. Xie et al. (2010) also indicated some soil and seed-borne diseases of potatoes in a rice-potato rotation, such as bacterial wilt, ring rot and scab disease (Wu et al. 2020), can be eliminated or significantly reduced after one or two rounds of flooding the paddy field. In summary, the rice-potato rotation can have positive ecological benefits within an agricultural ecosystem. Not only is the input-use efficiency increased, rotation contributes to improving soil health by increasing the utilization rate of the soil, thus reducing soil-borne diseases.

Constraints of the Rice-Potato Rotation System in Southern China From Reviewed Literature

In the rice-potato rotation system, several general factors affected rice-potato cultivation. First, despite the limited availability of arable land in China, urbanization continues to advance. A large amount of agricultural land has already been occupied. However, the total area of arable land in China was only 130 million ha, and the per capita arable land area was only 0.09 ha per person (Jiao 2018), the stability of agricultural production has been seriously affected. Among all the arable land in China, there are no restrictions on the necessary conditions for paddy and dry rotation. However, only 39% of the arable land with irrigation facilities was of

relatively good quality. The remaining 60% of the arable land was affected by various restrictive factors. This non-arable land quality was relatively low, so these lands cannot be used for rice and dry crop rotation (Wu and Jiang 2014).

Another inhibitory factor was limited access to water resources. The major problem facing rice-potato rotation was water scarcity. 90% of water resources in Asia were used for agricultural production, and rice irrigation water accounted for 50% of the total agricultural water consumption (Bouman 2001). In China, nearly 70% of water resources were used for agricultural production, and rice irrigation accounted for 65% of total agricultural water consumption (Si et al. 2000). Winter was typically a dry season in the south of China, where rainfall was low, and rainfall cannot meet potato growth and development needs. Hence, irrigation was necessary to obtain high yields for potato tubers with a moisture content of about 75% to 80%. Therefore, the water crisis was a critical factor restricting adoption of rice and dry crops' rotation (Wu and Jiang 2014).

Third, high-yielding and early maturing varieties that are also resistant to biotic and abiotic stressors were not readily available. In 2015, between 15 and 20% of the area was planted to early/medium-maturing varieties (Gatto et al. 2018). Breeding for resistance/tolerance and earliness are key traits to make potatoes fit in rice-potato systems, to not affect spring sowing, and provide economic viability.

Fourth, the supplies of virus-free seed potatoes was one of the main restricting factors of the high yield of potatoes in the winter cropping areas. Most southern provinces in China have high temperatures and heavy rainfall in the summer. Virus vectors and sources of potato viruses are numerous and complex, which leads to rapid degradation of potato varieties and ultimately affects the yield and quality of commercial potatoes. Therefore, virus-free seed potatoes are generally transported from the north of China. However, recently, the high-altitude areas of the mixed cropping area of the southwest have also begun to produce virus-free seed potatoes, which means that seed potatoes grown in the winter cropping area may also be derived from the mixed cropping area.

Add to these factors the small land sizes and limited access to in- and output markets (Scott and Suarez 2012). While potato production may be more profitable compared with other crops, such as rapeseed, the mentioned factors, combined or individually, pose serious constraints to adoption of sustainably intensified rice-potato systems.

Conclusions

This article summarized the status and challenges of sustainable intensification of rice-potato rotation in southern China. It mainly analyzed the sustainable intensification method

adopted in the rice-potato rotation system and the adoption rate of farmers in the selected provinces while analyzing the economic benefits under the rice-potato rotation mode. Using reviewed literature, the ecological benefits and constraints of rice-potato rotation were also analyzed.

The rice-potato rotation system was emphasized for higher economical profitability, which significantly motivated farmers to plant potatoes in winter. This article also showed that conservation agriculture practices have a diverse adoption rate among farmers across the three provinces. Generally, the adoption rate of farmers in Guangdong Province is much higher than in Yunnan Province and Sichuan Province. The significant reasons are due to the differences in geographic environment and climate. From the literature review, we found that rice-potato rotations can protect the environment and save agricultural production costs, enabling the agricultural production system to develop in a sustainable way. Due to the multiple advantages of potato planting and higher planting benefits, rice-potato rotation increased in the south of China.

However, some rice-potato rotation constraints included arable land, water resources, and access to quality seed potatoes. To solve the limitation of arable land and water resource, the Ministry of Agriculture of China issued the "Agricultural Resources and Ecological Environmental Protection Project Plan (2016–2020)" in 2017 (MOA 2017), proposing to transform low- and medium-yield fields, which was predicted to improve agricultural production conditions, the ecological environment, and increase land outputs. In southwestern regions such as Yunnan and Sichuan Province, the problem of seed potatoes has now begun to strengthen seed potato production capacity in middle and high altitude areas to provide high-quality seed potatoes for low altitude winter cropping areas.

This article presented a primary investigation into the merits of the rice-potato crop rotations to intensify production and potential revenues of farmers. Our sources of information relied on publicly available reports and individual interviews. To develop a more comprehensive picture of the three southern provinces, more interviews, field surveys, agronomic plot-level data, and household surveys are required.

This research has limitations. The primary data source used for this research were key informant interviews with a sample size of 30. We acknowledge that the small number may lead to biased estimates of the rice-potato systems' potential. Including more experts, or using quantitative data collected through representative farmer samples accompanied by remote sensing data, is an important avenue of future research.

In conclusion, there are large areas of winter fallow fields in southern China that can be used to grow winter potatoes. While our study mainly focuses on the economic and

agronomic potential of rice-potato systems in China, there are several constraints to production and uptake, as Scott and Suarez (2012) summarize: technical (such as poor quality seed and limited genetic base for breeding), natural (such as depleting water tables and higher temperatures exacerbated by climate change), institutional (such as land tenure and related small land sizes of about 1 ha constraining farmers to benefit from economies of scale). Providing an estimate of the potential area suitable for rice-potato cultivation that included those additional constraints would be worthwhile and an important area of future research.

Also, access to affordable quality seed and improved varieties that fit rice-potato systems will be important factors to make the cropping system successful. If successful, these measures can ensure the sustainable development of the rice-potato rotation system. As such, increasing potato planting in winter fallow rice fields can significantly contribute to China's food security and increase farmers' income in southern rice fields.

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