Aging threatens sustainability of smallholder farming in China

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Rapidly demographic aging substantially affects socioeconomic development [1-4], presents grand challenges for food security and agricultural sustainability [5-8], which have so far not been well understood. Here, by using over 30,000 households survey across China, we show that rural population aging lowers average education level of farmers by 3% (0-11% across different provinces) and reduces farm size by 4% (2-11%) due to land transfer-out and abandonment in 2019. These changes further led to a reduction of agricultural inputs, including fertilizers and machinery, which decrease agricultural output by 4% and labor productivity by 9%. Meanwhile, fertilizer use efficiency is reduced by 3%, while increasing fertilizer-related pollutants emission to the environment. New farming models, such as cooperative farming, tend to have larger farm sizes and being operated by younger farmers, who have a higher average education level, hence reducing total labor requirement. Without policy interventions, agricultural output, labor productivity and fertilizer use efficiency would decrease by 3-16% as a consequence of population aging by 2100, compared to 2019 levels. With policy measures, such as new farming models, this decrease could be reversed and in fact an increase by approximately one-third achieved in the same time period. Our analyses suggest that population aging effects on agriculture could be effectively addressed through labor saving in large-scale new farming models, further contributing to a widespread transformation of smallholder farming to sustainable agriculture in China.

As life expectancy increases and population fertility rates decline, populations are aging at an accelerating rate globally [9]. Population aging brings grand challenges on multiple global sustainable development goals (SDGs), mainly in relation to no poverty, zero hunger, education, gender equality, decent work and economic growth, responsible consumption and production, etc [1-4, 10, 11]. Labor shortage and innovation constraints may become severe in a society with an aging population, especially in labor-intense economic sectors [3]. Policy interventions to increase birth rates seems to be largely ineffective in many countries where aging issues have been considered serious [12, 13]. Alternative strategies urgently need to be developed to achieve and maintain sustainable development paths for human society. Agriculture as a typical labor-intensive industry could be one of the sectors substantially affected by population aging, especially in countries where smallholder farming is prevalent [8, 14]. However, how aging affects agriculture and rural livelihoods has not been well researched or understood to date. This sector is facing substantial challenges in squaring the circle between maintaining food security and improving environmental protection through sustainable intensification at many levels. However, it is indispensable to identify integrated, comprehensive measures to ensure global food security, while protecting the environment and achieving rural revitalization to achieve common prosperity.

Older age groups of farmers typically have a lower education levels, are less likely to keep their agricultural skills up-to-date and embrace novel, cutting-edge methods [14-16]. Due to a consistent labor supply shortage, they can only operate small-scale farms, which leads to an increase in cropland abandonment as rural populations age [17, 18]. Meanwhile, the typical agricultural input mix and crop types (labor-intensive crops or not) are likely to shift with rural aging, reducing agricultural productivity and efficiency [5-7, 19]. These effects are usually worse in smallholder-farming-dominated countries such as China [8]. An aging society is defined as one in which more than 7% of the population is over 65 years old [20], and this ratio has doubled in rural China (Fig. 1a) in the period from 2000 to 2019. In the coming decades, China's population aging rate is predicted to accelerate [20, 21]. Thus, it is urgent and timely to address the threats of aging on agricultural production in China and also other countries and regions globally, which are facing similar issues.

Here, we explored the relationship between rural population aging (the proportion of individuals over 65 years old at household-level) and agricultural sustainability based on a panel model, using survey data from more than 30,000 rural households in China. Nine indicators overall were selected to illustrate agricultural sustainability, including farm size, farmer’s education, labor productivity, agricultural total input and output, profit-cost ratio, machine input, fertilizer input and fertilizer use efficiency (FUE). To understand the full range of effects of aging on agriculture, other variables such as transferred and abandoned cropland, pesticide and manure inputs, and technology adoption were also incorporated into the analysis. In addition, the analysis quantified the potential of new farming models, such as industrial, family and cooperative farming for contributing to addressing the threats posed by aging on a predominantly traditional smallholder farming sector. Finally, Shared Socioeconomic Pathways (SSP) scenarios of future development were used to explore options for achieving sustainable intensification of agriculture under conditions of aging rural populations.

Results and discussion

How aging threatens agriculture?

Population aging trends have been observed since the 1990s, in both urban and rural areas in China (Fig. 1). However, rural aging is more severe and happening at a more rapidly accelerating rate than that that of urban areas (Fig. 1a). The urban rate of aging increased from 6% to 11% during the period between 2000 and 2019, rural aging from 7% to 15% over the same period. The rapid aging in rural area has resulted in a substantial decline in the labor force available in the agricultural sector (Fig. 1b). Young rural laborers are attracted to non-agricultural jobs in urban areas, resulting in an imbalance of about 10% more workers in the age group from 15 to 64 being available in urban compared to rural areas. Agriculture has been the sector primarily affected by migration to urban centers as well as rural aging, with young workers becoming an increasingly scarce commodity in rural areas [6].

Using a fixed effect panel model, we found that for every one unit increase in the proportion of rural aging ratio, there is on average a 1.5-year reduction in education level of farmers (Table 1). In China, the effect of lower education levels is amplified by the rapid socioeconomic development, with more and younger people typically obtaining substantially higher education levels. Thus, regions with above-average numbers of aging households are affected by overall lower education levels compared to other regions. Meanwhile, we observe a correlation between aging and reduction in farm size with a coefficient of -0.27, demonstrating that aging farmers tend to only operate small-scale farms, and croplands are more likely to be abandoned or transferred-out to others (Table 1). Smallholder farming is currently most prevalent in regions of Central and South China, where rural aging is seen to be substantial (Fig. 1c, d).

Aging is correlated with a decrease in agricultural inputs, mainly including chemicals such as fertilizers and pesticides, and machinery and technology adoption (Table 1 and S1). This typically reduces mechanization and intensification of agriculture. Moreover, aging substantially lowers FUE by -0.13% for every one unit increase in aging. A lower FUE indicates a higher rate of fertilizer-related losses to the environment and, consequently, higher pollution. In addition, aging reduces the amount of manure input (Table S1), inhibiting the recycling of manure and aggravating environmental pollution. Consequently, agricultural output per area and labor productivity decrease substantially with aging, despite the fact that the profit-cost ratio does not vary significantly (Fig. S1). This decline in labor productivity reduces farmers' per capita income, further discouraging young people from engaging in agriculture, and in turn further exacerbates aging effects in the sector.

Aging affects agriculture both directly and indirectly as shown by a structural equation model (Fig. 2). The standardized path coefficients for the direct effects of aging on labor productivity and yield are both -0.05. This means that each standard deviation increase in aging would lead to 0.05 standard deviations of decrease in labor productivity and yield. Similarly, the direct effects of aging on fertilizer use and the FUE are -0.08 and -0.02, respectively. These direct effects are only a small share of the total effect of aging on agriculture.

More effects are factored in indirectly through farm size and education. For example, the direct effect of aging on labor productivity has a standardized path coefficient of -0.05, but the indirect effect through farm size and education is -0.08 and -0.02, respectively. It results in a net effect of -0.15 of aging on labor productivity, of which the direct effect accounts for one-third, while the indirect effect through farm size and education accounts for two-thirds (Table S2). Similarly, 29%, 33%, and 67% of the net effect of yield, fertilizer, and the FUE stem from indirect effects, respectively. This implies that multiple initiatives are needed to mitigate the consequences of rural aging, such as attracting young people to consider work in the agriculture sector, better education and training and increasing average farm size [22, 23].

Impacts on agricultural sustainability

We quantified the impact of aging on agricultural sustainability in 2019 at provincial level in China to account for the large spatial variability of aging and other related factors [24, 25]. Average education levels of farmers are lower by around 3% in rural areas (0-11% across different provinces) as a result of rural different rates of aging in predominantly urban vs. rural areas (Fig. 3 and S2). The Chongqing-Sichuan area, where aging has been accelerating since the 1990s, is the one of the most affected regions, with an education level decline of 9% (0.6 years) (Fig. 3 and S2). Provinces such as Zhejiang, Anhui, and Fujian are also affected, with a level of education 6% lower (0.4 years) on average. Lower levels in farmers' education is associated with less knowledge and adoption of technologies and scientific methods in agricultural practice, inhibiting agricultural performance and modernization. Due to a lack of knowledge and skills, aging farmers typically operate small-scale farms with outdated farming methods. As a result, aging populations are associated with average farm size reduction by 4% (2-11%) in 2019 nationally. Aging farmers tend to reduce farm size by cropland abandonment or transferring increasing amounts of farmland out to others. Approximately an additional 1 million hectares of cropland area would be expected to be abandoned in 2019 as a result of aging (Fig. S3, Table S3). The abandonment ratio is higher in hilly areas and comparatively lower in plain areas as a result of aging [18], however, the abandonment increasing rate is markedly higher in plain areas such as Shandong and Jiangsu provinces (Fig. S3). This poses a severe threat to the preservation of croplands as a key contributor to safeguarding food security.

The decline in farm size further leads to a reduction in the use of agricultural fixed inputs such as machinery [26]. We found that machinery inputs decreased by about 5% on average with aging, and the largest decrease was estimated at 25% found in Chongqing. In addition, aging also leads to a reduction in the use of non-fixed inputs such as chemical fertilizers, pesticide, and manure fertilizer (Table 1 and S1). Chemical fertilizer use is reduced by an average of 2% (0-8%) (Fig. 3). Total agricultural inputs are reduced by about 3% (1-9%). The decrease in agricultural inputs reduces agricultural output per area and labor productivity by 4% (2-10%) and 9% (4-22%), respectively. Even though the correlation between aging and profit-cost ratio is not significant, the reduction in farm size and education levels due to aging ultimately reduces profit-cost ratio by about 2% (1-4%). The reduction in fertilizer use did not contribute to an improvement in FUE, with aging reducing FUE by 3% (1-7%) and leading to a 3% (1-12%) increase in fertilizer-related losses to the environment (Fig. S3).

Aging in China's rural areas is likely to accelerate in the coming decades, especially in the context of urbanization due to the migration of young, working-age populations from rural to urban areas [20, 21]. This will further impact on the viability of agricultural production in areas subjected to accelerated aging [27]. The negative effects on agricultural outputs could threaten the food security of 1.4 billion people in China, and the loss in labor productivity would result in a decline in rural per capita income, compromising the attainment of the SDGs focusing on 'no poverty' and 'zero hunger'. The decline in FUE and the increase in fertilizer-related losses to the environment have the potential to further exacerbate environmental pollution and present a threat to both environmental and human health. China is already under pressure to ensure food security while also protecting the environment, so it is critical to address the negative effects of aging on agriculture.

New farming models matter

Chinese agriculture is currently dominated by smallholder farms [28]. Traditional smallholder farming emerged in the 1980s as a consequence of the introduction of the Household Contract Responsibility System (HCRS) in China [23]. The HCRS allocated cropland equally to each rural household based on family size and the quality of croplands. This resulted in small farm sizes as a status-quo across China, with a high degree of cropland fragmentation [23]. New agricultural farming models have been encouraged by Chinese government and increasingly emerging since 2010s, mainly including family, cooperative and industrial farming, to improve overall agricultural performance [29, 30]. Family farming is still by rural households, but with larger farm size, compared to traditional smallholders' farming. Cooperative farming is characterized by shared agricultural equipment, such as machinery, across several families with much larger farm size. Industrial farms are large-scale agricultural enterprises targeting marketing and sales with large scales and professional production to maximize profits. Also, young farmers with higher education levels are drawn to these new farming models. Here, we considered these three models together as new farming models.

New farming models was observed to have better performance than that of traditional smallholder farming in several aspects in 2019 (Fig. 4). Compared to traditional farming, aging ratio in new farming was 33% lower, with 64% higher in education level and 20% larger in farm size. In other words, new farming models attract younger farmers to participate in agricultural practices who have a higher education level and capability to operate large-scale farming. The total input and machinery input were 41% and 68% higher in the new farming, respectively, therefore, the output per area and labor productivity increased by 24% and 29% in the new farming, respectively, although the profit-cost ratio was slightly changed. Furthermore, despite fertilizer input was slightly higher in new farming, there is no statistically significant difference compared to the traditional smallholder farming (Fig. 4, Table S4). On the contrary, new farming had a 4% higher FUE than smallholder farmers in 2019, suggesting less environmental pollution in new farming.

The reason why new farming models have better agricultural performance than traditional smallholder farming is mainly because it has younger farmers with higher education level. These younger farmers also have the opportunities to realize higher incomes by working in non-agricultural sectors in cities, which means they face substantial opportunity costs if they decide to engage in farming. To offset the opportunity cost, these farmers have to increase their income by increasing farm size and improving farm management. In contrast, older farmers in traditional farming do not have such opportunities and are thus not prone to respond to incentives. Thus, we can see a shift in agricultural input mix as well as an increase in output and labor productivity under new farming models. Furthermore, as these new farming farmers are younger and well educated, they are more likely to have scientific knowledge and embrace new technologies [15], resulting in increased mechanization and FUE, contributing to agricultural modernization and long-term sustainability.

Mitigation pathways

To quantitatively assess future trends of aging and its impacts, we accounted for demographic change in Shared Socioeconomic Pathways (SSPs) scenarios [31]. SSP1 (Taking the green road), SSP2 (Middle of Road), SSP3 (A rocky road) and SSP4 (A road divided) are included in this analysis [32]. SSP5 (Taking the highway) is excluded due to having a similar population structure to SSP1. Among these scenarios, SSP1 includes the world's most pronounced population aging, with more than 60% of the world's population over the age of 65 by 2100 (Fig. S4). Total population first increases in the coming decades and then starts to decrease by the 2060s. Even with high urbanization rates and economic growth under the green development path, high levels of aging would exert substantial negative impacts on socioeconomic development and agricultural production. SSP4 comprises the smallest rate of aging, with only 24% of over 65s in 2100. However, in this scenario, the global population rises to 12.7 billion by 2100, with an urbanization rate of under 60% and a severe slowdown in economic growth.

Despite the different assumptions for future development paths, the aging trend continues to rise in all scenarios (Fig. S4). We found that for China, the abandonment ratio of croplands would increase from 5% in 2020 to 15-47% by 2100 nationally due to aging, while average farm size would decrease by 5-16% (0.04-0.11 ha), and education levels would fall by 8-28% (0.6-2 years) (Fig. 5, S5 and S6). Meanwhile, agricultural performance would decline, with machinery and fertilizer inputs decreasing by 3-5% and 1-5% by 2100, respectively. The overall input per area would reduce by 1-2% as well, leading to a decrease in output and profit-cost ratio by 3-5% and 3-13%, respectively. Labor productivity is projected to decrease by about 7-14%, from an $7.2 per labor hour in 2020 to $5.2-6.6 in 2100. In addition, FUE would decrease by 5-16%, and fertilizer loss increase by 3-5%. Without interventions, food security challenges and environmental degradation would pose substantial threats to ecosystem and human health and well-being.

Fortunately, the decline in agricultural performance caused by aging can be reversed by promoting an increasing uptake of new farming models. With new farming models, average farm size would increase by 11-22% from 2020 to 2100, accompanied by an improvement in the average education level. This would lead to a 14-15% increase in total inputs, a 13-46% increase in mechanization and a 4-5% decrease in fertilizer use. As a result, output and labor productivity would increase by 12-14% and 57-72%, respectively, FUE improve by 12-25% and fertilizer loss be reduced by 4-7%. New farming models could mitigate impacts of aging on agriculture, resulting in a substantial improvement in agricultural sustainability for China. In addition, new farming models would accelerate the transformation of the agricultural sector from traditional smallholder farming to large-scale sustainable agriculture.

Social co-benefits

The implementation of new farming may present a cost-effective solution for China, especially considering the dual challenges of maintaining food security and protecting the environment [24]. This strategy would also lead to additional social co-benefits, not limited to agriculture.

The proportion of the population engaged in agricultural production has continued to fall over time, while the proportion of people employed in non-agricultural sectors has continued to rise (Fig. S7). In China, young people tend to move to cities, leaving older people in rural areas maintaining an involvement in agriculture. But most rural young people do not settle in city, continue to support rural families and eventually return to the countryside. As a result, agriculture is no longer the primary source of income for rural households. In 2019, income derived from agricultural activities accounted for just 23% of rural household income (Fig. S7). This essentially implies that farmers do not rely on agriculture any more and agricultural vitality is diminishing.

The increasing number of young people leaving to seek employment in cities may have additional socio-economic impacts, e.g. contributing to a rising mortality rate of rural elderlies and children in recent years [33, 34]. The mortality rate of the elderly over 65 years old in rural areas due to accidents, mental illness and suicide is much higher than that in urban areas (Fig. S8). That is mainly because elderly who are left behind in rural areas face additional risks of living alone [33]. Furthermore, the mortality rate of children less than 14 years old in rural areas are often greater than for urban locations (Fig. S9). Aside from variations in medical care provision, the greater prevalence of accidental mortality among rural compared to urban children can also be attributed to the neglect of children left behind due to their young parents moving to cities [35, 36].

However, new farming models can reinvigorate agriculture and improve rural income levels, promoting rural revitalization and common prosperity. Meanwhile, it contributes to the return of young people to their rural villages and hometowns, resolving the issue of elderly and children being left behind on their own and sustaining rural communities. These additional benefits are intertwined with agricultural sustainability, contributing to attaining multiple SDGs.

Policy changes and feasibility

Adverse impacts of population aging would – without policy interventions - be unavoidable in the future, and in particular the impacts on agriculture and rural communities require urgent attention [37]. Mitigating these adverse impacts is a great challenge, but also presents a tremendous opportunity, which requires multiple stakeholders' efforts. Increasing fertility policy is an important measure with long-term benefits to address aging issues despite it may bring challenges on feeding more people. It can directly stimulate childbirth, reduce demographic aging and mitigate its adverse impacts. Under the family planning strategy in China, a couple was restricted to have only one child on average before 2016 [13]. In recent years, the government has authorized the second and third children to each couple to increase birthrate. Meanwhile, social security measures including maternity subsidies, insurance and maternity leave have been improved gradually. However, changes of fertility policy may not substantially reverse the population aging according to the experiences in other developed countries/regions such as Japan and European Union. Other policies and measures are still required to complement the interventions on aging.

Policy changes on *Hukou* and land tenure systems would make the implementation of new farming models feasible, benefiting the controls on adverse impacts of population aging. The smallholder aging issues are mainly due to the unique Chinese household registration system that divides the Chinese population into two categories: rural and urban, allocating lands and other public resources based on the *Hukou* status of residents [28]. The growing urbanization in recent years has resulted in young rural people migrating to cities to engage in non-agricultural sectors, leaving the elderly in rural areas. Rural elders are unable to move to cities because they are unable to access urban social services such as pension and medical care under the restriction of *Hukou* system. The large rural aging population inhibits the extension of new farming models. Thus, new policies are needed to move rural aging population to urban areas and exchange their rural resources (mainly croplands and homesteads) for urban social services, especially the elderly whose children have moved to urban areas. It has been reported that the Jiangsu governments have compensated farmers who give up croplands and migrate to cities with a cash transfer equal to five times their annual income as social security [29]. This effectively encourages rural-to-urban migration of aging people. Meanwhile, croplands of these migrating aging farmers can be integrated for large-scale farming and their homesteads can also be reclaimed for farming [38]. It is estimated that the reclaimed lands due to rural-to-urban migration under urbanization could increase the cropland area by 4.1% by 2050 nationally, approximately 5.8 million hectares [39]. And average farm size can increase from less 0.6 ha to over 16 ha through land consolidation in some regions [40], benefiting the implementation of new farming models. Reforming *Hukou* and land tenure systems to achieve such changes is an effective pathway for the new farming models [30].

Given the experiences in Jiangsu Providence, it should be feasible for the reform of rural communities through reallocation of lands and other public resources to increase their use efficiencies. Over 40,000 hectares of homesteads have been reclaimed during past decade, suggests that it is not only feasible but also happening in practice [39]. These released croplands could be integrated for large-scale new farming, which normally have much higher cost-efficiencies than that in smallholders (Fig. 4). Similarly, urban areas have higher efficiency on the supply of non-agricultural services such as health care and education, and the rural-to-urban migration would benefit the increase of labor productivity through training and better health care. Therefore, it should be cost-effective to compensate rural-to-urban migrated farmers [29]. This strategy would bring in multiple social benefits that far outweigh its cost. Increasing cropland area through both homesteads reclamation and decreasing the abandonment benefit food security that is the top priority of national strategy. Improving rural income under new farming models encourages return of young people, promoting rural revitalization and sustainable rural communities. The cost of land consolidation can also be recovered in the following decades, despite a large number of one-time inputs [40]. When the environmental and human health benefits are considered, the reforming cost should be much lower than the benefits. Chinese central government has already issued a policy of giving 'Priority to Development of Agriculture, Rural Areas and Farmers' in early 2019 to accelerate the construction of large-scale high-standard croplands. These ongoing changes suggest that reforming Chinese agriculture to address the threats of rural population aging on the sustainability of smallholder farming is not only important but also feasible.

Methods

Data sources. We used data from the China Rural Household Panel Survey (CRHPS) database, which includes the Chinese Family Database of Zhejiang University, and data of the China Household Finance Survey conducted by the Survey and Research Center for China Household Finance at the Southwestern University of Finance and Economics, China. From this database, rural household level data concerning age, education, income, farm size and agricultural inputs and outputs in 2015, 2017, and 2019 was obtained for statistical analysis, resulting in about 33,058 observations after being screened. This database is openly available at http://ssec.zju.edu.cn/dataset/CRHPS/.

The province and country-level population aging and rural aging data was derived from the China Population & Employment Statistics Yearbook (available at https://data.cnki.net/yearbook/Single/N2021020056). County-level population aging data in 2020 shown in Fig.1c is taken from the Sixth National Census in 2010 (available at http://www.stats.gov.cn/tjsj/pcsj/rkpc/6rp/indexch.htm) and weighted by province-level aging data for the year 2020 from the Seventh National Census (available at http://www.stats.gov.cn/tjsj/tjgb/rkpcgb/qgrkpcgb/). County-level farm size data in Fig.1d is from the statistics of the Second National Pollution Census (non-public database), which is averaged by investigated household farm size.

We obtained future population data across all age groups based on the Shared Socioeconomic Pathways (SSP) database hosted by the IIASA Energy Program (https://tntcat.iiasa.ac.at/SspDb). In this paper, scenario SSP5 was not considered as its population change is in line with that of scenario SSP1.

Statistical analysis. CRHPS data allowed estimating the relationships between population aging and agricultural performance. Aging ratio, the proportion of people 65 years and older in rural households, was adopted as an indicator to demonstrate population aging at household-level. Adult farmer's ratio, defined as the proportion of people over 15 but less 64 years old in rural households, was also considered to demonstrate age groups. Nine different indicators were determined to illustrate agricultural sustainability, including farm size (ha), education (yr), labor productivity ($\$ \ hr^{-1}$), total agricultural input ($\$ \ ha^{-1}$), output ($\$ \ ha^{-1}$), profit-cost ratio, machine input ($\$ \ ha^{-1}$), fertilizer input ($\$ \ ha^{-1}$) and fertilizer use efficiency (FUE). Other variables concerning transferred-out cropland, abandoned cropland, pesticide, pesticide use efficiency, manure and technology adoption were also incorporated to demonstrate agricultural performance changes under population aging. The detailed interpretation of these indicators is documented in Supplementary Information.

To explore the relationships between population aging and agricultural sustainability, we first used a fixed effect panel (FEP) regression model to conduct the longitudinal analysis, while controlling for confounding factors such as crop type, plot numbers, regional and year effect. We estimated the following equation using data on households from 2015, 2017 and 2019:

$$Agriculture_{it} = \alpha + \beta \cdot Aging_{it} + \gamma \cdot Education_{it} + \delta \cdot Farmsize_{it} + \sum_m \theta_m \cdot p_{mit} + \varepsilon_{it} + \sigma_k \tag{1}$$

where subscript *i, k* and *t* denote household, county and time, respectively. $Agriculture_{it}$ refers to the agricultural sustainability indicators and other inputs and outputs on household level. $Aging$ refers to the proportion of people ≥ 65 years in rural households. $Education$ refers to average years of education of family members aged 15 and over. $Farmsize$ is the logarithm of total cultivated area covering all crops. p_m is control variable including adult farmer's ratio, income ratio from non-agricultural sectors, crop type, plot numbers, county-level regional effect and year effect. α is a constant, ε_{it} and σ_k are error items. $\beta, \gamma, \delta \ and \ \theta$ are coefficients that need to be estimated. The detailed results are listed in Table 1 and S1.

Given too many zeros in variables of variables of transfer-out cropland, abandoned cropland, machine input and owned, and manure fertilizer input, we also used a Tobit regression model to validate the relationship between these variables and aging. We estimated the following equation using data on households in 2015, 2017 and 2019:

$$y_{it}^{*} = \alpha + \beta \cdot Aging_{it} + \gamma \cdot Education_{it} + \delta \cdot Farmsize_{it} + \sum_n \varphi_n q_{n,it} + \varepsilon_{it} \quad (2)$$

where subscript *i* and *t* denote household and time, respectively. y_{jt}^{*} refers to latent variables including transfer-out cropland, abandoned cropland, machine input and owned, and manure fertilizer input in each household. Latent variables can be observed when over 0, truncated at 0 when the value is equal to 0 or less 0. $Aging$ refers to the proportion of people over 65 years old in rural households. $Education$ refers to average years of education of family members aged 15 and over. $Farmsize$ is the logarithm of total cultivated area covering all crops. q_n is control variable including adult farmer's ratio, income ratio from non-agricultural sectors, crop type, plot numbers, city-level regional effect and year effect. α is a constant and ε_{it} is the error item. $\beta, \gamma, \delta\ and\ \varphi$ are coefficients that need to be estimated. Farm size was removed in explaining variables in the equation with explained variable of transfer-out and abandoned cropland considering multi-collinearity. The results are listed in Table 1 and S1.

The latent variable is expressed in terms of the observed variable y_{it}^{*} in the following form:

$$\begin{cases} y_{it} = y_{it}^{*} & if\ y_{it}^{*} > 0 \\ y_{it} = 0 & if\ y_{it}^{*} \leq 0 \end{cases} \quad (3)$$

Besides, a Logit regression model was adopted as technology adoption (Tech) is a binary variable. This model is formulated as follows based on household-level data from 2015, 2017 and 2019:

$$Logit\{P_{it}(\mathrm{Tech}_{it} = 1)\} = \alpha + \beta_1 \cdot Age_{it} + \beta_2 \cdot Age_{it}^{2} + \gamma \cdot Education_{it} + \delta \cdot Farmsize_{it} + \sum_n \varphi_n q_{n,it} + \varepsilon_{it} \quad (4)$$

where subscript *i* and *t* denotes household and time, respectively. P_{it} is the probability of the occurrence of Tech (Tech_{it}=1: event occurs; Tech_{it}=0: event does not occur). Age refers to the log-transformed age of the head of the investigated household. $Education$ refers to education years of the head of the investigated household. $Farmsize$ is the logarithm of total cultivated area covering all crops. q_n is control variable including income ratio from non-agricultural sectors, crop type, plot numbers, city-level regional effect and year effect. α is a constant and ε_{it} is the error item. $\beta, \gamma, \delta\ and\ \varphi$ are coefficients that need to be estimated. The results are listed in Table S1.

To test the difference of agricultural performance of traditional and new farming model under aging, a binary variable indicating the occurrence of new farming (NF_{it}) (NF_{it}=1: event occurs; NF=0: event does not occur) was introduced based on Eq. (1) and (2). The equations are expressed in the following forms:

$$Agriculture_{it} = \alpha + \omega \cdot \mathrm{NF}_{it} + \beta \cdot Aging_{it} + \gamma \cdot Education_{it} + \delta \cdot Farmsize_{it} + \sum_m \theta_m \cdot p_{mit} + \varepsilon_{it} + \sigma_k \quad (5)$$

$$y_{it}^{*} = \alpha + \omega \cdot \mathrm{NF}_{it} + \beta \cdot Aging_{it} + \gamma \cdot Education_{it} + \delta \cdot Farmsize_{it} + \sum_n \varphi_n q_{n,it} + \varepsilon_{it} \quad (6)$$

$\omega, \beta, \gamma, \delta, \theta\ and\ \varphi$ are coefficients that need to be estimated. Related results are listed in Table S4. Note that as new farming is not widely prompted in China, new farming data is limited. Thus, we consider that when the variable NF with *p<0.05* in Table S4, there is a significant difference.

Meanwhile, we replaced aging ratio with the age of the head of the investigated household and average education years with the head's education for a robustness check. The results of this robustness check are detailed in Table S1 and S5.

We then used a structural equation model (SEM) to understand the direct and indirect effects of aging on agriculture [41]. Considering the multi-collinearity of agricultural indicators, such as output with labor productivity, fertilizer input with total input, only some of typical indicators were selected. Also, we excluded variables with nonlinear relationships with aging (e.g. machine input) to deduce comparable standardized path coefficients. Income ratio from non-agricultural sectors and the ratio of cash crops area to total cultivated area were controlled when doing SEM analysis. In this model, the goodness-of-fit statistics are reasonable based on CRHPS data in 2019: non-normed fit index (NNFI) > 0.90, comparative fit index (CFI) > 0.90, root mean square error (RMSE) < 0.05, and standardized root mean square residual (SRMR) < 0.05. Using the results from the SEM, the direct and indirect effects of aging with standardized path coefficients are shown in Fig.2.

Summary statistics for main variables used in statistical regression analysis are listed in Table S7. We did all statistical analysis in Stata12.0 software.

Impact of aging on agricultural sustainability. We assume that the population age distribution remains at the 1990 level to represent no aging. Province-level population data for 1990 from the China Population & Employment Statistics Yearbook was introduced after weighting by the difference between this data and CRHPS to reduce the error caused by variations in data stemming from different databases. Then province-level population data was downscaled to household-level proportionally. Finally, aging and adult farmer's ratio without aging are deduced. We assume that other variables remain the same and calculated the predicted value of agriculture without aging on each household based on coefficients estimated in Eq. (1). For household *i*, the predicted without aging is calculated as follows:

$$Y_{ijt}^{Predicted\ Without\ Aging} = \exp\left(Ln\ Y_{ijt}^{Observed} + Ln\ Y_{ijt}^{Without\ Aging} - Ln\ Y_{ijt}^{With\ Aging}\right) \tag{7}$$

where the subscript *i, j* and *t* denote household, explained variable and year, respectively. Y_j includes farm size, output, input, labor productivity, fertilization and FUE. $Y_{ijt}^{Observed}$ refers to the observed value of each household. $Y_{ijt}^{Without\ Aging}$ is the deduced value based on estimated coefficients in Eq. (1) using the aging and adult farmer's ratio data in 1990. $Y_{ijt}^{With\ Aging}$ is the deduced value using the observed aging and adult farmer's ratio (age over 15 but less than 64) data from CRHPS. For explained variables without log-transformed such as education and profit-cost ratio, the predicted is calculated as follows:

$$Y_{ijt}^{Predicted\ Without\ Aging} = Y_{ijt}^{Observed} + Y_{ijt}^{Without\ Aging} - Y_{ijt}^{With\ Aging} \tag{8}$$

Y_j includes education and profit-cost ratio.

For some variables with nonlinear relationship with aging, the following equation was adopted to calculate the impact of aging based on Eq. (2):

$$Impact_{ijt} = \beta \cdot \Delta Aging_{ijt} + \gamma \cdot \Delta Education_{ijt} + \delta \cdot \Delta Farmsize_{ijt} + \varphi_1 \cdot \Delta Adult_{ijt} \tag{9}$$

where the subscript *i, j* and *t* denote household, explained variable and year, respectively. Δ refers to the value difference with and without aging. Y_j includes abandoned cropland and machine input. $Adult_{ijt}$ refers to adult farmer's ratio in rural household. Then the predicted value on each household without aging was calculated:

$$Y_{ijt}^{Predicted\ Without\ Aging} = Y_{ijt}^{Observed} - Impact_{ijt} \tag{10}$$

Note that we first derived the predicted education without aging. Then abandoned cropland area was derived based on predicted education as it is one of the explanatory variables. Farm size was derived based on predicted education and considering abandoned cropland changes. The remaining variables were finally calculated based on predicted education and farm size.

When the household-level predicted value in 2019 was calculated, the provincial predicted means including input, output, machine and fertilization were averaged after weighted by the total cultivated area on province-level. The rest were arithmetic averages.

Scenario analysis. We based our analysis of future socio-economic development on the SSP scenarios to determine the impact of population aging on agricultural sustainability. We obtained population age data (2015-2100) from the SSP database. We undertook a comparison between the population age data for 2015 in the SSP and CRHPS databases, and weighted aging and adult farmer's ratio by their difference to reduce the error. Then country-level population data was downscaled to household level proportionally. Then the aging and adult farmer's ratio data of the SSP scenarios for the period between 2020 and 2100 were calculated for each household. Finally, the predicted values ($Y_{ijt}^{Predicted\ SSP}$) of nine agricultural sustainability indicators and abandoned cropland under future aging were calculated based on Eqns. (7), (8), (9) and (10) under the hypothesis that other variables remain stable at 2019 levels. The equations are expressed in the following forms:

$$Y_{ijt}^{Predicted\ SSP} = \exp\left(Ln\ Y_{ij,2019}^{Observed} + Ln\ Y_{ijt}^{SSP} - Ln\ Y_{ij,2019}^{With\ Aging}\right) \tag{11}$$

$$Y_{ijt}^{Predicted\ SSP} = Y_{ij,2019}^{Observed} + Y_{ijt}^{SSP} - Y_{ij,2019}^{With\ Aging} \tag{12}$$

$$Impact_{ijt} = \beta \cdot \Delta Aging_{ijt} + \gamma \cdot \Delta Education_{ijt} + \delta \cdot \Delta Farmsize_{ijt} + \varphi_1 \cdot \Delta Adult_{ijt} \tag{13}$$

$$Y_{ijt}^{Predicted\ SSP} = Y_{ijt}^{Observed} - Impact_{ijt} \tag{14}$$

Δ in Eq. (13) refers to the value difference between year 2019 and year *t*.

To improve agricultural performance and estimate the effectiveness of mitigating negative impacts of future population aging, we assume that new farming models will be promoted as a key element of future agricultural sector development. Based on the relative sector share of the new farming models, which is 2% in 2019, we hypothesize that its coverage will increase by about 1.2% annually, reaching 100% by 2100. For household *i*, the predicted value of nine agricultural sustainability indicators and abandoned cropland under new farming is calculated as follows:

$$Y_{ijt}^{Predicted\ NF} = \exp\left(Ln\ Y_{ijt}^{Predicted\ SSP} + \rho_j \cdot Coverage_t\right) \tag{15}$$

where the subscript *i, j* and *t* denote household, explained variable and year, respectively. Y_j includes farm size, output, input, labor productivity, fertilization and FUE. $Y_{ijt}^{Predicted\ NF}$ is the predicted value new farming (NF) models. $Y_{ijt}^{Predicted\ SSP}$ is the predicted value under SSP scenarios. ρ_j refers to estimated coefficients of new farming responding to explained variable *j*. The results of these estimated coefficients are detailed in Table S4. $Coverage_t$ means the assuming coverage of new farming in year *t*.

For explained variables without log-transformed, the predict is calculated as follows:

$$Y_{ijt}^{Predicted\ NF} = Y_{ijt}^{Predicted\ \text{Under}\ SSP} + \rho_j \cdot Coverage_t \quad (16)$$

Y_j includes education and profit-cost ratio, abandoned cropland and machine input.

Note that we first derived the predicted education under SSP scenarios. Then abandoned cropland was derived based on predicted education as it is one of the explanatory variables. Farm size was derived based on predicted education and considering abandoned cropland changes. The remaining variables were finally calculated based on predicted education and farm size.

Country-level mean values of each year including input, output, machine and fertilization were averaged after weighting by the total cultivated area across the whole country. The rest were arithmetic averages.

References:

1. Harper, S. Economic and social implications of aging societies. *Science* **346**, 587-595 (2014).
2. Chen, C., Goldman, D.P., Zissimopoulos, J. & Rowe, J.W. Multidimensional comparison of countries' adaptation to societal aging. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 9169-9174 (2018).
3. Bloom, D.E., *et al*. Macroeconomic implications of population ageing and selected policy responses. *Lancet* **385**, 649-657 (2015).
4. Yu, B., Wei, Y., Kei, G. & Matsuoka, Y. Future scenarios for energy consumption and carbon emissions due to demographic transitions in Chinese households. *Nat. Energy* **3**, 109-118 (2018).
5. Li, M. & Sicular, T. Aging of the labor force and technical efficiency in crop production: Evidence from Liaoning province, China. *China Agric. Econ. Rev.* **5**, 342-359 (2013).
6. Ji, Y., Hu, X., Zhu, J. & Zhong, F. Demographic change and its impact on farmers' field production decisions. *China Econ. Rev.* **43**, 64-71 (2017).
7. Apipoonyanon, C., *et al*. Socio-economic and environmental barriers to increased agricultural production: New evidence from central Thailand. *Outlook Agric.* **50**, 178-187 (2021).
8. Rigg, J., Phongsiri, M., Promphakping, B., Salamanca, A. & Sripun, M. Who will tend the farm? Interrogating the ageing Asian farmer. *The Journal of peasant studies* **47**, 306-325 (2020).
9. Lutz, W., Sanderson, W. & Scherbov, S. The coming acceleration of global population ageing. *Nature* **451**, 716-719 (2008).
10. Yang, J., *et al*. Projecting heat-related excess mortality under climate change scenarios in China. *Nat. Commun.* **12**, 1039 (2021).
11. Chen, X., Huang, B. & Li, S. Population ageing and inequality: Evidence from China. *World Econ.* **41**, 1976-2000 (2018).
12. Zhang, X., Guo, F. & Zhai, Z. China's Demographic Future Under the New Two-

Child Policy. *Popul. Res. Policy Rev.* **38**, 537-563 (2019).

13. Zeng, Y. & Hesketh, T. The effects of China's universal two-child policy. *Lancet* **388**, 1930-1938 (2016).
14. Satola, L. Problems of the aging of the farmers' population in small farms in Poland. *Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development* **19**, 305-310 (2019).
15. Cutler, J., *et al*. Ageing is associated with disrupted reinforcement learning whilst learning to help others is preserved. *Nat. Commun.* **12**, 4440 (2021).
16. Huang, X., Lu, Q., Wang, L., Cui, M. & Yang, F. Does aging and off-farm employment hinder farmers' adoption behavior of soil and water conservation technology in the Loess Plateau? *Int. J. Clim. Chang. Strateg. Manag.* **12**, 92-107 (2020).
17. Min, S., Waibel, H. & Huang, J. Smallholder participation in the land rental market in a mountainous region of Southern China: Impact of population aging, land tenure security and ethnicity. *Land Use Pol.* **68**, 625-637 (2017).
18. Li, S., *et al*. An estimation of the extent of cropland abandonment in mountainous regions of China. *Land Degrad. Dev.* **29**, 1327-1342 (2018).
19. Jansuwan, P. & Zander, K.K. What to do with the farmland? Coping with ageing in rural Thailand. *J. Rural Stud.* **81**, 37-46 (2021).
20. Peng, X. China's demographic history and future challenges. *Science* **333**, 581-587 (2011).
21. Chen, R., Xu, P., Song, P., Wang, M. & He, J. China has faster pace than Japan in population aging in next 25 years. *Biosci Trends* **13**, 287-291 (2019).
22. Usman, M., Sawaya, A., Igarashi, M., Gayman, J.J. & Dixit, R. Strained agricultural farming under the stress of youths' career selection tendencies: a case study from Hokkaido (Japan). *Hum. Soc. Sci. Commun.* **8**, 19 (2021).
23. Ren, C., *et al*. The impact of farm size on agricultural sustainability. *J. Clean Prod.* **220**, 357-367 (2019).
24. Liao, L., Long, H., Gao, X. & Ma, E. Effects of land use transitions and rural aging on agricultural production in China's farming area: A perspective from changing labor employing quantity in the planting industry. *Land Use Pol.* **88**, 104152 (2019).
25. Wu, Song & Yu. Spatial Differences in China's Population Aging and Influencing Factors: The Perspectives of Spatial Dependence and Spatial Heterogeneity. *Sustainability (Basel, Switzerland)* **11**, 5959 (2019).
26. Ren, C., *et al*. Fertilizer overuse in Chinese smallholders due to lack of fixed inputs. *J. Environ. Manage.* **293**, 112913 (2021).
27. Liu, X., *et al*. The impact of urbanization and aging on food security in developing countries: The view from Northwest China. *J. Clean Prod.* **292**, 126067 (2021).
28. Wu, Y., *et al*. Policy distortions, farm size, and the overuse of agricultural chemicals in China. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 7010-7015 (2018).
29. Yu, Y., Hu, Y., Gu, B., Reis, S. & Yang, L. Reforming smallholder farms to mitigate agricultural pollution. *Environ. Sci. Pollut. Res.* (2021).
30. Fang, D. & Guo, Y. Induced Agricultural Production Organizations under the Transition of Rural Land Market: Evidence from China. *Agriculture* **11**, 881 (2021).
31. Guo, Ding, Zhong, Cheng & Huang. Predicting the Future Chinese Population using Shared Socioeconomic Pathways, the Sixth National Population Census, and a PDE Model. *Sustainability (Basel, Switzerland)* **11**, 3686 (2019).
32. O Neill, B.C., *et al*. The roads ahead: Narratives for shared socioeconomic

pathways describing world futures in the 21st century. *Glob. Environ. Change* **42**, 169-180 (2017).

33. Zhou, L., Wang, G., Jia, C. & Ma, Z. Being left-behind, mental disorder, and elderly suicide in rural China: a case–control psychological autopsy study. *Psychol. Med.* **49**, 458-464 (2019).
34. Steptoe, A., Shankar, A., Demakakos, P. & Wardle, J. Social isolation, loneliness, and all-cause mortality in older men and women. *Proc. Natl. Acad. Sci. U. S. A.* **110**, 5797-5801 (2013).
35. Zhao, F. & Yu, G. Parental Migration and Rural Left-Behind Children's Mental Health in China: A Meta-Analysis Based on Mental Health Test. *J. Child Fam. Stud.* **25**, 3462-3472 (2016).
36. Li, Q., Liu, G. & Zang, W. The health of left-behind children in rural China. *China Econ. Rev* **36**, 367-376 (2015).
37. O'Meara, P. The ageing farming workforce and the health and sustainability of agricultural communities: A narrative review. *Aust. J. Rural Health* **27**, 281-289 (2019).
38. Gu, B., Zhang, X., Bai, X., Fu, B. & Chen, D. Four steps to food security for swelling cities. *Nature* **566**, 31-33 (2019).
39. Wang, S.*, et al*. Urbanization can benefit agricultural production with large-scale farming in China. *Nat. Food* **2**, 183-191 (2021).
40. Duan, J.*, et al*. Consolidation of agricultural land can contribute to agricultural sustainability in China. *Nat. Food* (2021).
41. Garland, G.*, et al*. Crop cover is more important than rotational diversity for soil multifunctionality and cereal yields in European cropping systems. *Nat. Food* **2**, 28-37 (2021).

Data availability

Data supporting the findings of this study are available within the article and its supplementary information files.

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Author contributions

B.G. designed the study. C.R. conducted the research. B.G. and C.R. wrote the first draft of the paper, S.R. revised the paper. C.W., Y.G., Y.D., S.S., and W.L. processed the raw data. X.Z. and J.X. contributed to the discussion of the paper.

Declaration of competing interest

All authors have no conflicts of interest to report.

Table 1 Fixed effect panel models determining the effect of aging on agricultural sustainability

	Farm size and Education				Cost and Benefit				Fertilizer and Machinery			
	Ln Farm size (ha)	Education (yr)	Transfer -out	Abandoned (ha)	Ln Output (\$ ha^{-1})	Ln Input (\$ ha^{-1})	Profit-cost ratio	Ln LP (\$ hr^{-1})	Ln Fertilization (\$ ha^{-1})	Ln FUE	Machine input (\$ ha^{-1})	Machine owned (\$ ha^{-1})
Aging	-0.27***	-1.54***	0.76***	0.19**	-0.32***	-0.30***	-0.03	-0.37***	-0.23***	-0.13***	-112***	-919***
Ln Farm size (ha)					-0.14***	-0.20***	0.13***	0.61***	-0.28***	0.10***	-25.2***	464***
Education (yr)	0.01***		0.04	-0.01	0.03***	0.01***	0.03***	0.03***	-0.003	0.04***	12.8***	55.0***
County	Yes	Yes			Yes	Yes	Yes	Yes	Yes	Yes		
City			Yes	Yes							Yes	Yes
N	16767	16767	16137	12304	16767	15602	15460	16247	15447	15292	16542	16593
Adjust R^2	0.51	0.29			0.26	0.20	0.08	0.41	0.21	0.13		
Model	FEP	FEP	Tobit	Tobit	FEP	FEP	FEP	FEP	FEP	FEP	Tobit	Tobit

$^{*}p < 0.05$, $^{**}p < 0.01$, *and* $^{***}p < 0.005$. LP, Labor productivity. FUE, Fertilizer use efficiency. FEP, Fixed effect panel. Farm size is the total cultivated area covering all crops. Education refers to average years of education of family members aged 15 and over. Transfer-out are the ratio of transferred-out cropland area to the current total cropland area. Abandoned indicates the area of abandoned cropland by farmers. Profit-cost ratio means the ratio of difference between agricultural income and input to the input. Labor productivity (LP) indicates agricultural output per working hour of labor. Fertilizer use efficiency (FUE) is the ratio of agricultural output to fertilizer input, measuring fertilizer contribution and reflecting its loss. Machine input is total machine cost including machinery rent and depreciation to total cultivated area. Machine owned means original value of agricultural machinery the household owned per area. Aging refers to the proportion of people over 65 years old in rural households. County and city mean county-level or city-level regional effect is controlled, respectively. Adult farmer's ratio, income ratio from non-agricultural sectors, crop type, plot numbers and year effect have been controlled in all regression equations.

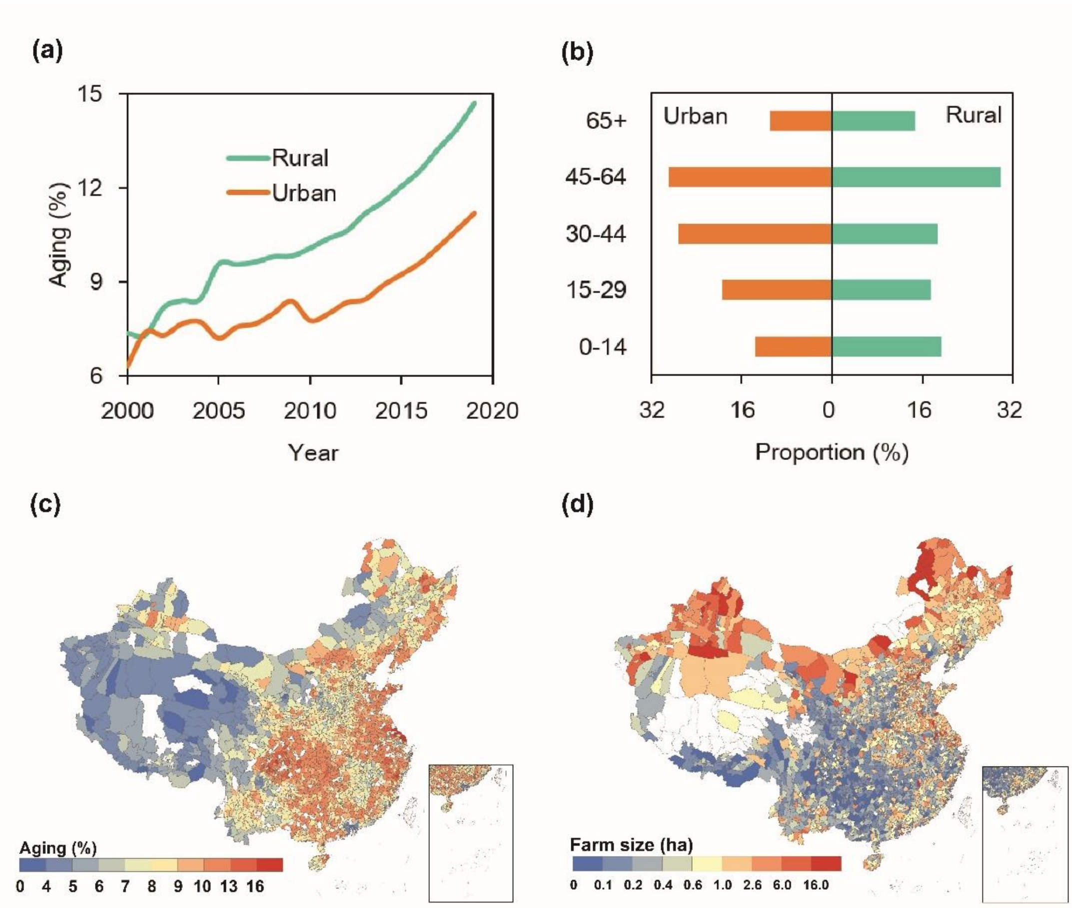

Fig. 1 Population aging and farm size in China. (a) Aging trend in rural and urban China from 2000 to 2019; (b) Age stages in rural and urban China in 2019; (c) County-level aging in 2020; (d) Farm size in 2017. Aging in (a) and (c) refers to the proportion of people over 65 years old on country and county-level, respectively. It is calculated by the number of people over 65 years old to the total population.

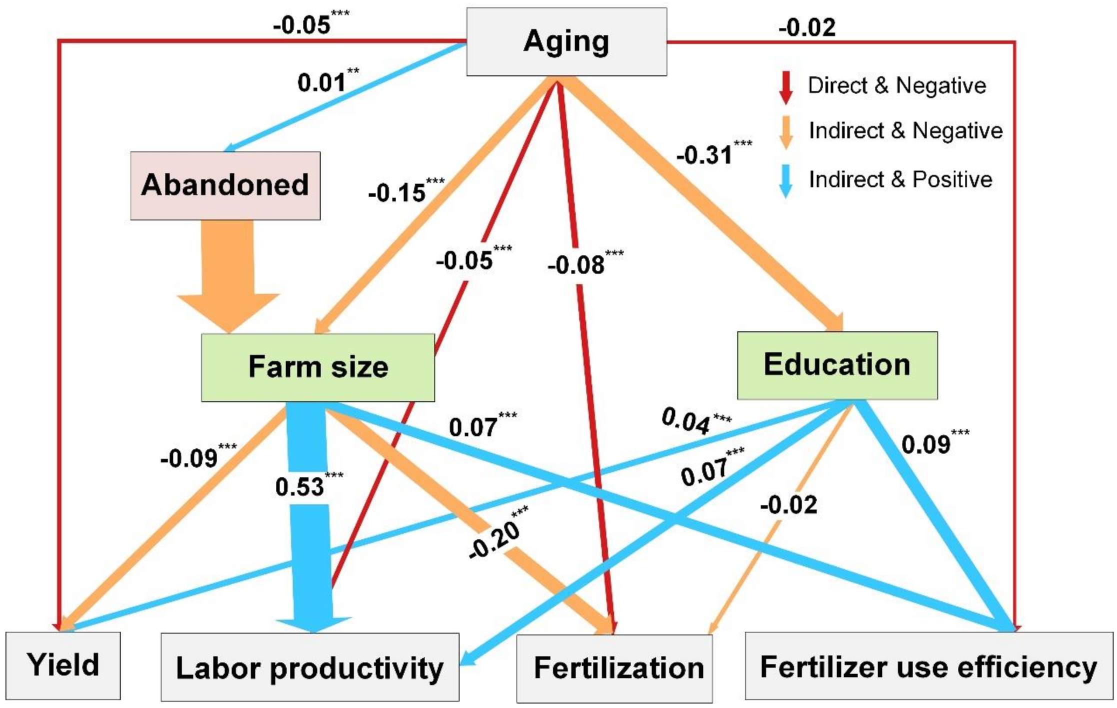

Fig. 2 Structural equation model of aging impacts on agricultural sustainability. *$^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.005$.* The numbers adjacent to the lines are the standardized path coefficients, which means how much standard deviation changes in dependent variable if each of the independent variable changes by one standard deviation. The blue and red lines represent positive and negative effects, respectively. Dark and light red indicate the direct and indirect negative effects of aging on agriculture, respectively. The line width is proportional to the strength of the standardized path coefficient. Variables in this figure except aging, abandoned cropland and education have been log-transformed. It is worth noting that the path coefficient between aging and abandoned cropland was not incorporated in this structural equation model considering the nonlinear relationship between these two variables. The coefficient of "0.01" between aging and abandoned cropland means the abandoned cropland area increase when aging ratio increase by one unit averagely. Then the abandoned cropland squarely decreases household-level farm size.

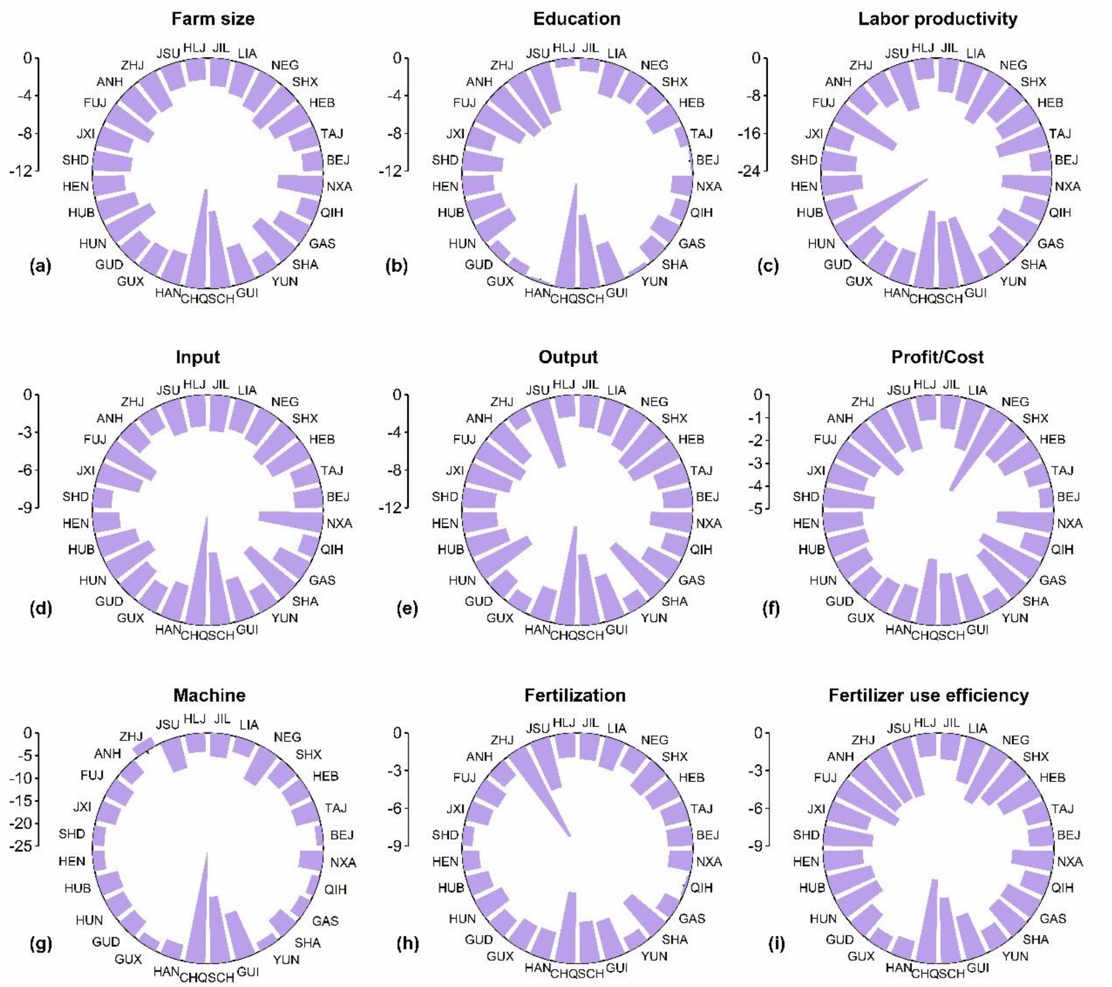

Fig. 3 Impact of aging on agricultural sustainability across China's provinces in 2019. (a) Farm size; (b) Education; (c) Labor productivity; (d) Total agricultural input; (e) Agricultural output; (f) Profit-cost ratio; (g) Machine input; (h) Fertilization; (i) Fertilizer use efficiency. It is calculated by determining the difference between the predicted values without aging and the observed values with aging divided by the observed value on province-level, and the result is carried out in percentage terms. Acronyms for 31 provinces, autonomous regions, and municipalities directly under the Central Government are listed in Table S6. Shanghai, Tibet and Xinjiang aren't depicted due to data limitation.

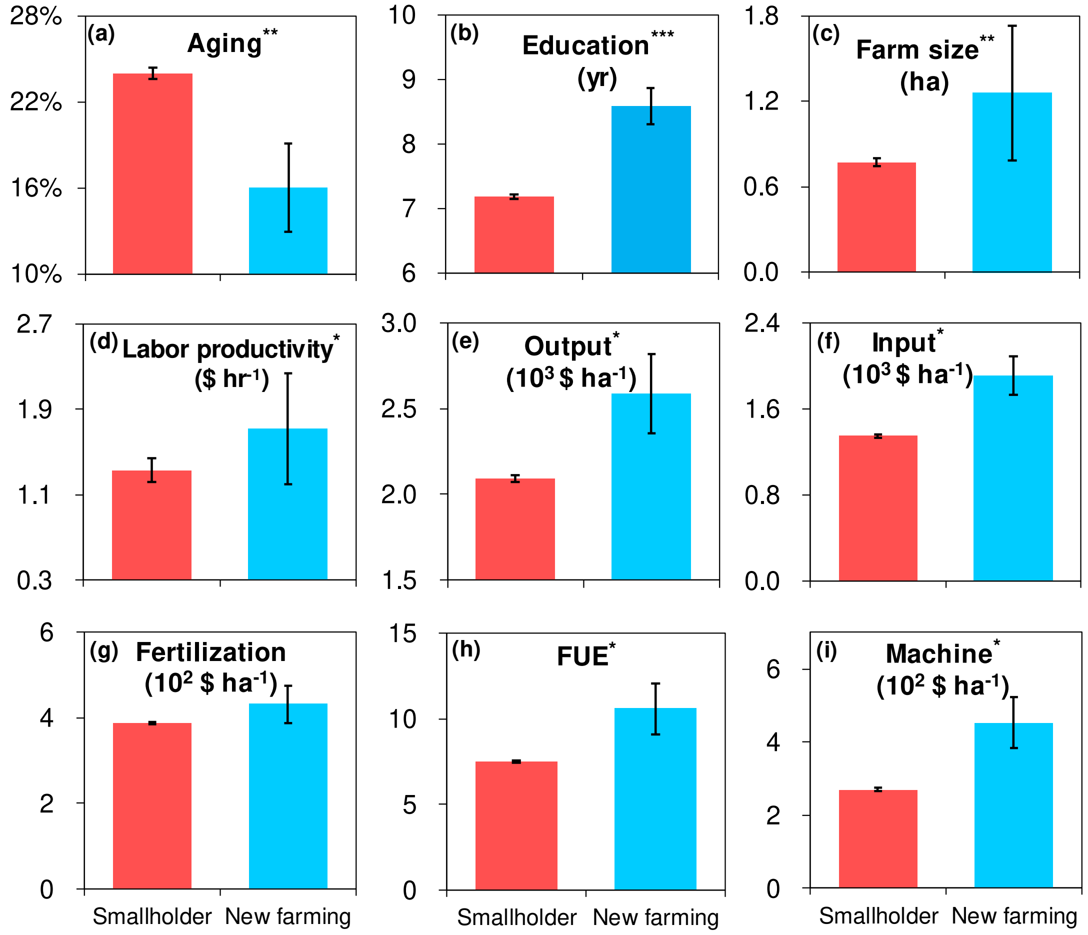

Fig. 4 Comparison of smallholder and new farming models on agricultural sustainability in 2019. (a) Aging farmer's ratio; (b) Education; (c) Farm size; (d) Labor productivity; (e) Agricultural output; (f) Total agricultural input; (g) Fertilization; (h) Fertilizer use efficiency (FUE); (i) Machine input. $^{*}p < 0.05$, $^{**}p < 0.01$, *and* $^{***}p < 0.005$, which indicates the significant difference level between smallholder and new farming responding to indicators of agricultural sustainability. Error bars refer to standard errors. The statistical results are in Table S4.

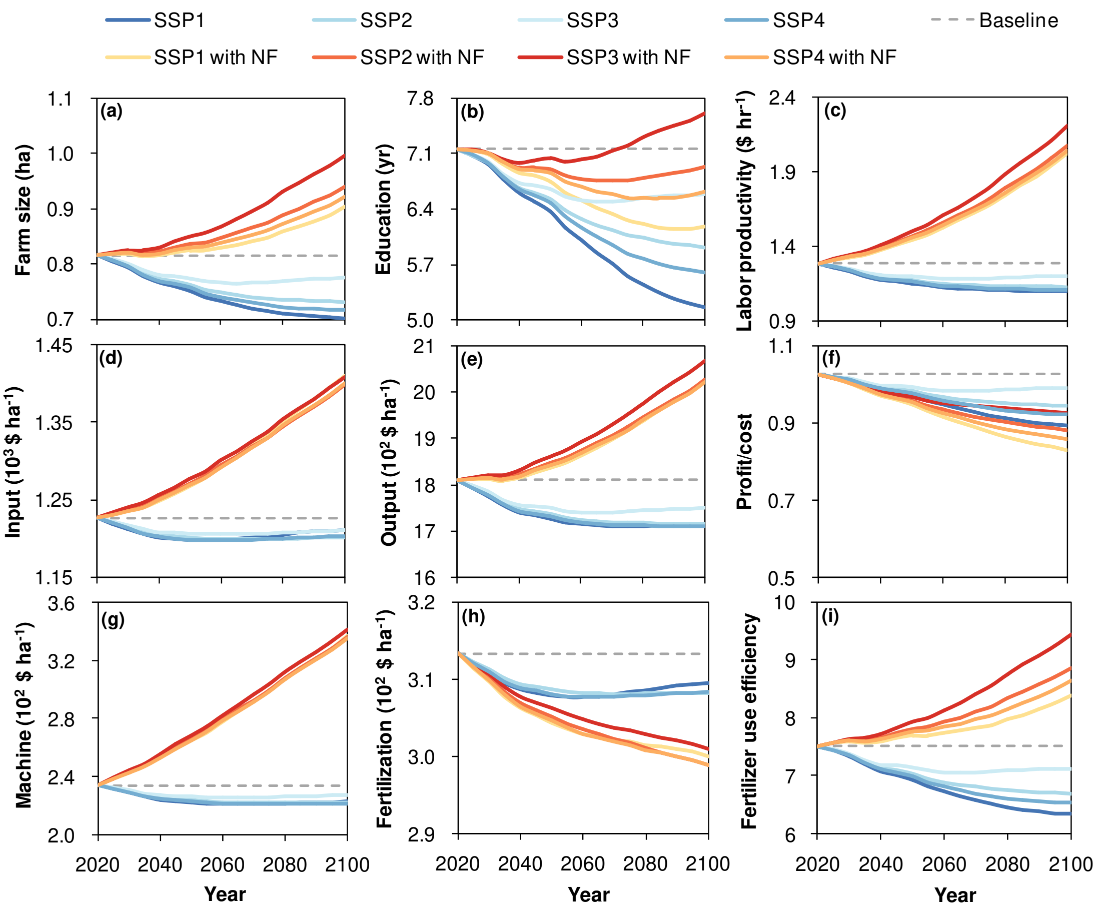

Fig. 5 Future agricultural sustainability changes due to aging under SSP scenarios by 2100. (a) Farm size; (b) Education; (c) Labor productivity; (d) Total agricultural input; (e) Agricultural output; (f) Profit-cost ratio; (g) Machine input; (h) Fertilization; (i) Fertilizer use efficiency. The Baseline assumed no changes in the future. SSP1-4 refers to Shared Socioeconomic Pathways (SSPs) scenarios. NF, New farming. The changes of input, output, machine and fertilization are all weighted with the total cultivated area.

Supplementary Files

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- SupplementaryInformation.docx