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Effects of Aging on Labor-Intensive Crop Production from the Perspectives of Landform and Life Cycle Labor Supply: Evidence from Chinese Apple Growers

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Abstract: The aging of the agricultural labor force is an irreversible trend that has become an important issue in China's economic transformation. Previous studies on the effects of an aging population in developing countries on agriculture mainly focused on food crops, and the conclusions were mixed. Using data for apple growers in Shaanxi Province, China, we used ordinary least squares (OLS), stochastic frontier production function (SFA), and truncated regression to investigate how rural aging affects apple production under different landform conditions. We provided evidence that (i) aging leads apple growers to use hired labor to replace family labor in the flatlands, but not in mountainous and hilly areas, due to landform constraints on the factor substitution; (ii) aging has no significant impact on mechanical inputs in either the plains or the mountains, indicating that machinery cannot effectively replace the labor force; (iii) limited by a shortage of labor quantity and quality, apple growers respond to aging by reducing agricultural inputs in mountainous and hilly areas; (iv) changes in input structure cause aging to have little influence on yield and technical efficiency in flatlands, while aging significantly reduces yield in mountainous and hilly areas; (v) there is a nonlinear relationship between aging and technical efficiency and yield; and (vi) because the overall mechanization level of China's apple industry is low, mechanical substitution for labor is not common in apple production.

Keywords: aging; factor substitution; labor-intensive; landform; mechanization

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1. Introduction

Population aging is a global issue that creates challenges for economic, political, and social trends worldwide [1]. Aging is apparent in developed countries and common in developing countries [2]. In China, people aged 65 and over increased from 7% in 2000 to 12.6% in 2019, indicating a clear aging population trend according to the Statistical Yearbook of China. With industrialization and urbanization, the rural young and middle-aged labor force continues to outflow. The rural population accounted for 39.4% of the total population in 2019, down from 63.8% in 2000. According to the Third National Agricultural Census of the National Bureau of Statistics, in 2016, the proportion of agricultural production and operation personnel aged 55 and above in China was as high as 33.6%, while in the first national agricultural census of 1996, the proportion of agricultural employees aged 51 and above in China was only 18.11%. The aging of the agricultural labor force is an irreversible trend that has become an important issue in China's economic transformation. It profoundly impacts the supply of the agricultural labor force, inputs of production factors, agricultural production efficiency, and the development of modern agriculture [3–5]. Therefore, it is necessary to study the influence mechanism of the aging rural labor force on agricultural production and provide policy suggestions to alleviate the problems caused by aging.

In recent years, the influence of the aging of the agricultural labor force on production has attracted extensive attention, but mostly it has focused on food crops, and conclusions were mixed [2,4,6,7]. Some studies argued that the aging of the agricultural labor force harms agricultural production [8,9]. Li et al. pointed out that aging reduces the physical strength of the labor force, leading to a production output decrease and aggravating the abandonment of cultivated land in the mountains [9]. However, some scholars found that the negative impact of aging on food crop production is minor because factor substitution and collective decision-making can effectively alleviate the labor supply constraints caused by the lack of physical and human capital among elderly farmers [10,11]. Hu and Zhong found that aging has no effect on the production of crops with a high degree of mechanization [12]. But is the mechanism of substituting machines for labor applicable to the production of labor-intensive economic crops, particularly when these crops are mainly grown in mountainous areas?

As a typical labor-intensive product, apples have a problem that is harder to overcome than food crops with an aging labor force: a need for significant labor investment and specialization. On the one hand, apple growers are in the workforce for the whole year. Many kinds of production links, such as blossom and fruit thinning, bagging, and bag removing, require a high level of labor. On the other hand, labor is more specialized in apple production [13], and orchard management requires scientific and reasonable production data and more elaborate control. That means apple production has higher requirements for mechanical accuracy.

More importantly, the main apple-producing areas are mountainous, hilly, plain, and tableland regions. For example, in Shaanxi, China, the most productive province, 24.03% of apple orchards were in mountainous and hilly areas, with a yield that was 14.14% of the total, increasing requirements for machinery. Therefore, the effects of aging on apple production may be heterogeneous due to the constraints of landform conditions. Through field investigation in Shaanxi Province, we found that in the plain and tableland areas with flat landforms and convenient transportation, the production decision-making and operation mode of the elderly farmers are not different from that of the young farmers. Therefore, the impact of aging on apple production seems not apparent. However, in the hills with rugged landforms and rugged roads, the production mode of the elderly farmers is extensive, and the output per hectare is generally lower than that of the young farmers. This study tries to explain the reasoning behind this aging heterogeneity effect: to alleviate reduced labor supply quality and number because of the aging problem, farmers will seek alternatives to make up for the inadequacy of their own physical and human capital, leading to different aging effects on apple production in different landform conditions.

Based on the above content, this study takes apples as an example to discuss the influence mechanism of aging on labor-intensive crop production from the perspective of landform differences and life cycle labor supply. This study examines how the aging of the agricultural labor force impacts apple production through empirical research and whether there is heterogeneity in the impact of aging on apple production's technical efficiency and yield under different landform conditions. Under this research idea, we clarify the relationship between the aging of the agricultural labor force and apple production, providing targeted suggestions for effective responses to the aging of the agricultural labor force.

The main contribution of this study to the existing literature is in two aspects. First, we contribute to a growing literature on the aging of the rural labor force in agricultural production. Studies on the aging of the rural labor force have focused on food crops [2,4,6,7,14]. Their results indicate that although farmers become more skillful as they grow older, their physical strength declines as they approach middle age [14,15]. We study the effect on cash crops, which are labor-intensive crops. Economic crops need a lot of labor investment and more specialization than food crops. Second, we also contribute to an extensive literature on induced technological innovation (e.g., [16–18]) by studying how landform and aging impact factor substitution. Aging means a rising labor price, resulting in factor substitution (using machinery to substitute labor), but landforms and crop characteristics restrict the substitution of machinery for labor.

2. Theoretical Analysis

The aging of the agricultural labor force has a "physical effect" [19], reducing labor supply in quantity and quality dimensions. On the one hand, with the growth in age, the decline in physical quality will cause an aging labor force in the family to reduce working time, reduce production, or quit the labor force. As a result, the total amount of labor in the family in apple production will decrease. On the other hand, the physical decline caused by aging will also reduce the labor quality and efficiency of farmers engaged in apple production activities. Limited by their physical strength, the elderly labor force cannot carry out physically strenuous management activities in the orchard, such as shaking the fruit under a tree.

The aging of the agricultural labor force has a "human capital effect", which mainly affects the quality of labor supply. Compared with food crops, apple planting requires more professional management [13], which requires good labor and precise fertilizer inputs. Compared with young farmers, elderly farmers lack human capital and are less receptive to new agricultural production technologies [20,21]. This is also not conducive to orchard management, such as the timing and application rates of fertilizer and pesticides. However, "life cycle labor supply" theory indicates that labor supply quality increases first and then decreases with age. Furthermore, older farmers have more experience in apple production [14]. Therefore, the influence of aging on apple production may present a nonlinear relationship.

Faced with insufficient labor supply, farmers will adjust the input structure of production from a rational perspective [10]. This study uses graphical analysis to explain aging labor's influence.

Figure 1a is an isoquant. The horizontal axis is family labor inputs; the vertical axis is other inputs. C1 is the initial resource endowment. Under the constraint, farmers can gain the largest yield at y1. E* (L_1, K_1) is the equilibrium point.

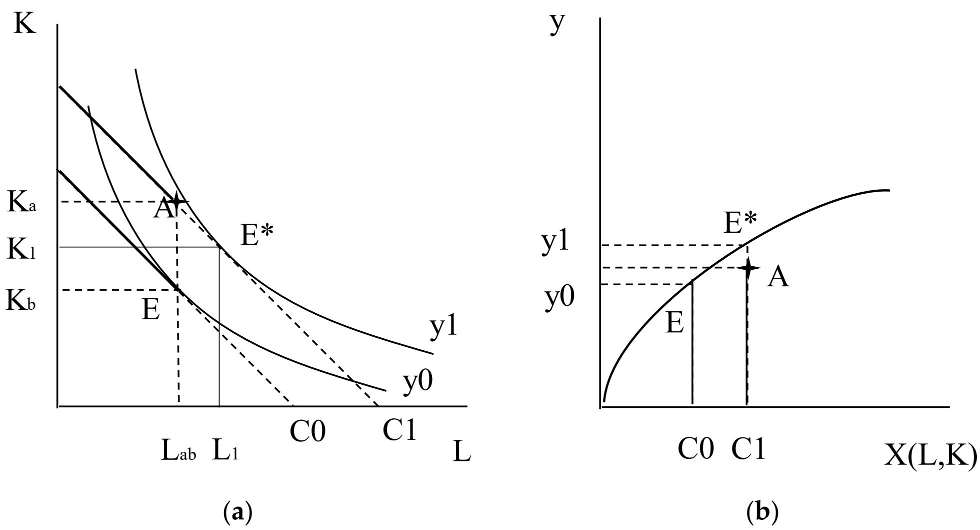

Figure 1. (**a**) Isoquant; (**b**) production technology frontier.

Figure 1b is the production technology frontier. The horizontal axis is the inputs, and the vertical axis is the output. We are assuming that all farmers are in the same production technology frontier. Above the curve is something that cannot be achieved with current technology, and the points on the curve represent the minimum input required to obtain a given output at the current level of technology or the maximum output received with a given input.

When farmers face an aging internal workforce, other inputs are overused compared to the internal aging inputs. Farmers can achieve production of point A, less than the largest yield y1. And technical efficiency is also less than optimal point E*. Farmers' first choice is to reduce other inputs to reduce the output to y0, and the technical efficiency is still at the technological frontier (E). The second choice is to increase the input that can replace self-owned labor, such as hired labor or labor-saving biological and mechanical technology. In that case, point A in Figure 1a,b moves to E* point. Therefore, farmers obtain yield y1, and the technical efficiency is still at the technological frontier (E*).

The above analysis shows that when families are aging, the realization of technological efficiency depends on whether other inputs can be reduced or effective resources can be obtained to supplement and replace family labor inputs. However, the realization of consistent yield only depends on whether effective resources can be obtained to substitute the family labor inputs.

Mechanization and hired labor are effective resources used to supplement and replace family labor. Replacing the labor force with mechanical elements is a common factor substitution for food crops. However, the overall machinery development level is lagging in labor-intensive crop production such as apples. Many key production links still lack advanced new agricultural machinery, and the mechanization degree of apple production is low [22,23], so the replacement effect of machinery on the labor force is minimal. Therefore, farmers may increase employee services to ease the labor constraint. Assuming that factor substitution is effectively realized, the labor constraints of the elderly farmers will be reduced, and there is no difference in labor endowment between the elderly and young farmers. At this time, the production decisions of the two will tend to be consistent, which is reflected in the convergence of fertilizer input decisions requiring labor assistance. However, when the labor force constraint is not effectively alleviated, the production decisions of the elderly farmers and the young farmers are different. Due to their limited physical strength, elderly farmers will reduce fertilizer inputs.

Landforms constrain the substitution effect of production factors, so the impact of aging on apple production is heterogeneous due to different landforms. Studies have found that aging has a more significant negative impact on agricultural production in mountainous areas than in lowlands [24]. Compared with flatlands, mountainous and hilly landforms significantly restrict factor replacement. In mountainous and hilly areas, landform barriers reduce the accessibility and operation convenience of agricultural machinery, and elderly farmers cannot make up the gap in labor supply between themselves and young farmers by investing more in mechanization. At the same time, employment services are more expensive in mountainous and hilly areas than in flatlands regions because of the hollowing out of local villages. As a result, older farmers, who face more significant financial constraints than younger farmers, may give up on replacing their labor inputs with employee inputs. Similarly, due to the constraints of landforms on factor substitution, aging has heterogeneous effects on fertilizer inputs under different topographies.

Faced with different labor force constraints and landform constraints, apple growers will make different combinations of factor inputs, namely, technology choices, leading to different technical efficiency levels. In flatlands, faced with labor constraints, the elderly farmers can increase inputs of abundance, such as labor, to make up for their lack of labor supply. Thus, elderly farmers can reconfigure production factors, and their technical efficiency is not far from that of young farmers. However, in mountainous and hilly areas, elderly farmers face the dual constraints of the labor force and landform conditions, and it is difficult to substitute production factors. As a result, their production input level is unbalanced, and their technical efficiency will be lower than that of young farmers.

Similarly, there is no significant difference in yield in the flatlands between older and younger farmers because substituting production factors can alleviate the labor supply constraints caused by aging. However, factor substitution is challenging in mountainous and hilly areas. Therefore, facing more substantial constraints in labor supply, the apple output of elderly farmers will be lower than that of young farmers.

Figure 2 shows this study's conceptual framework based on the above theoretical analysis.

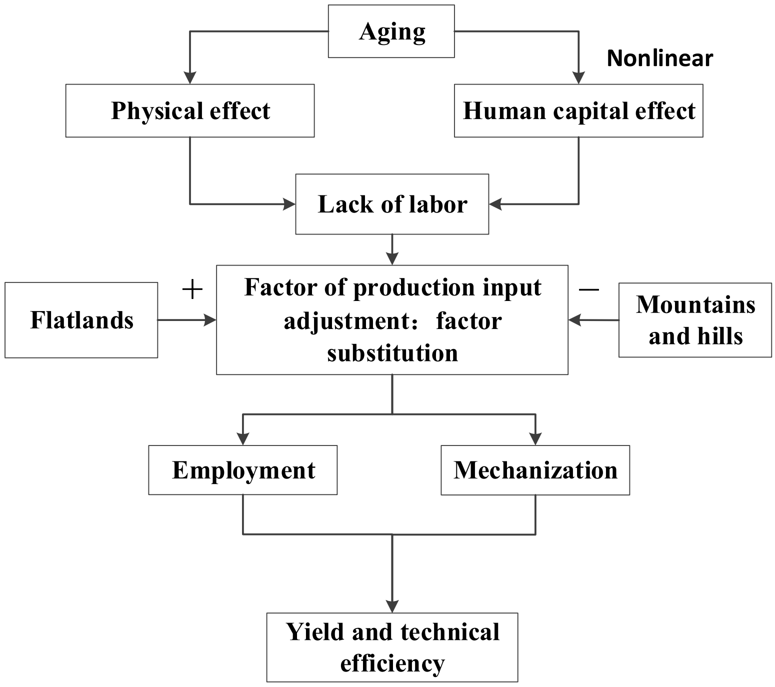

Figure 2. Conceptual framework.

3. Data and Methods

3.1. Data

The data used in this study consisted of farm-level inputs, outputs, landform conditions, aging, and control variables for apple farms from Shaanxi Province, China. Shaanxi ranks third among Chinese provinces in apple production. It is one of three provinces in the Loess Plateau (along with Shanxi and Gansu provinces) that account for about half of Chinese apple production. We collected data for three years (2017–2019) in 54 villages in four counties (Huangling, Luochuan, Pucheng, and Yanchuan) from 523 farms. Because the critical variable, landforms, are time-invariant over the three years, and some variables are missing in some samples, we used 459 effective samples for 2019 in this study.

The survey adopted a stratified random sampling method. Firstly, according to the apple industry development level and geographical location, we selected four counties in Shaanxi Province of China. Secondly, we selected 2–3 townships in each county and 4–5 villages in each township. Thirdly, 8–10 apple growers were randomly selected in each administrative village according to the ratio of large-holder farmers to small-holder farmers, about 2:8. The survey was conducted in a one-to-one structured interview.

The main content of the dataset was as follows. First, the overall production and operation situation included basic information on family members, farmland operations, agricultural production, and organic fertilizer price subsidies from 2017 to 2019. Second, data were collected on a farm's biggest apple orchard plot, including apple production inputs and output from 2017 to 2019. The reason for selecting the largest apple orchard plot was that there are differences in soil quality, fertility, climate, and other physical characteristics in different plots, and apple growers apply different inputs to the different apple orchard plots [25].

3.1.1. Dependent Variables

(1) Yield

This variable referred to the current year (2019) output value of apples harvested by farmers per hectare (CNY/ha). Apples are cash crops, and the unit price of apples of different varieties and fruit diameters varies greatly. Therefore, the physical yield (kg/ha) cannot fully reflect the output level of farmers, so the monetary yield was adopted as a dependent variable in this study.

(2) Machine quantity

This variable referred to the amount of mechanical power that farmers put into apple production throughout the year and was weighted by the time it takes to complete one hectare of the orchard, using the following equation:

$$mp = \text{mechanical\_power} \times time$$

(3) Machine cost

Machine cost was measured by the cost (CNY/hectare) that farmers incurred in the whole apple production process in the current year.

(4) Hired labor

Hired labor was measured by the time (hour/hectare) and cost (CNY/hectare) that farmers invested in the whole apple production process in the current year.

(5) Technical efficiency

This variable was calculated using a stochastic frontier production function estimation method, and reflected the gap between the actual output level and the theoretically possible, maximum output level.

3.1.2. Key Explanatory Variables

(1) Aging

In this study, the average age of the apple production labor force in the current year represented the aging degree of the agricultural labor force in the family.

(2) Landform

The landform of Shaanxi province is high in the north and south, low in the middle, with plateaus, mountains, plains, basins, and other landscapes. This study divided landforms into flatlands (landform = 0), including the large tableland and plain regions; and mountainous and hilly areas (landform = 1), including hills, residual tableland, and mountainous and river valley regions.

3.1.3. Other Variables

(1) Control variables for apple yield

Various production factors are crucial to agricultural production, especially for cash crops like apples. This study selected the seven most common production factors in the current year. They included cost of hired labor (CNY/ha), cost of chemical fertilizer (CNY/ha), cost of commercial organic fertilizer (CNY/ha), cost of pesticides (CNY/ha), cost of machinery (CNY/ha), and land area (ha). Control variables included dummy variables for the stage of the apple production cycle (high = 1; low = 0) and for whether or not a natural disaster occurred in the current year (yes = 1; no = 0).

(2) Control variables for factor inputs

Control variables in this section included the prices of some factors of production, including the average price of hired labor, chemical fertilizer, commercial organic fertilizer, and pesticides in the current year. The apple price last year was also included in the control variables. Other control variables were all in the current year, including (i) Part-time, the number of people engaged in part-time work in the current year; (ii) Apple_sum, the number of people who worked in apple production in the current year; (iii) Production cycle stage, as apple production tends to be cyclical because older plants have an alternate bearing problem, when yields are high one year, they tend to be low the next; and (iv) Natural disaster, whether or not there was a natural disaster in the current year.

(3) Control variables for technical efficiency

Control variables in this section were all in the current year, including the individual characteristics of sex (the sex of the decision makers) and technology training (years of decision makers attending fertilizer technology training). Family characteristics were also included in the control variables, including social capital (whether or not there were party members and/or villagers' representatives in the family). Farmer production characteristics were also included in the control variables, including apple percent (the ratio of apple labor to total labor in the current year), land fragmentation (the ratio of planting scale to the number of plots in the current year), natural disaster (disaster or not in the current year), planting density (how many trees per hectare), soil testing formula (whether to adopt soil testing formula), and did farmers know the NPK content of the land. Table 1 shows the definitions and summary statistics of variables.

Table 1. Definitions and summary statistics of variables.

Variable	Definition (Unit)	Mean	SD	Max	Min
Yield	Value of apple yield (CNY/hectare)	79,163	60,206	404	413,250
Family labor expense	Cost of family labor (CNY/hectare)	62,174	50,376	4243	538,433
Machinery quantity	Machinery power (kilowatts/hectare)	3002	4474	0	42,596
Machinery expense	Cost of machinery (CNY/hectare)	1904	2542	0	26,133
Hours of employment	(hours/hectare)	1722	1550	259	19,880
Employment expenses	Cost of employment (CNY/hectare)	16,462	18,474	0	108,320
Commercial organic fertilizer materials expenses	Cost of commercial organic fertilizer materials (CNY/hectare)	7165	6582	0	53,460
Chemical fertilizer materials expenses	Cost of chemical fertilizer (CNY/hectare)	15,529	15,535	0	138,798
Pesticide expenses	Cost of pesticide (CNY/hectare)	338.0	301.2	14	3640
Other inputs expenses	Cost of other inputs (CNY/hectare)	596.4	607.3	0	7615
Aging	Average apple production labor age	52.87	8.262	32	80.50
Landform	Mountains and hills = 1; flatlands = 0	0.390	0.488	0	1
P_labor	Price of hired labor in the current year (CNY/hour)	15.750	4.720	8.364	51.75
P_organic fertilizer	Price of commercial organic fertilizer materials in the current year (CNY/kg)	1.636	0.942	0	13.50
P_ chemical fertilizer	Price of chemical fertilizer materials in the current year (CNY/kg)	4.182	3.166	0.230	40
P_pesticide	Price of pesticide in the current year (CNY/kg)	733.4	600.0	30	6825
Last price	Apple prices last year	4.464	2.145	0.250	16.02
Part-time	The number of people engaged in part-time work in the current year	0.514	0.799	0	6
Apple_sum	The number of people who worked in apple production in the current year	2.000	0.557	1	6
Area_large	The area of the biggest apple orchard in the current year (hectare)	0.349	0.167	0.0667	1.333
Sex	The sex of the decision makers	0.941	0.236	0	1
Technology training	Years of decision makers attending fertilizer technology training	1.161	1.875	0	20
Social capital	Party members and/or villagers' representatives (Yes = 1; No = 0)	0.377	0.485	0	1
Apple percent	The ratio of apple labor to total labor	0.822	0.234	0.200	1
Land fragmentation	The ratio of planting scale to the number of plots	0.294	0.166	0.0667	1.767
Natural disaster	Disaster or not in the current year (Yes = 1; No = 0)	0.590	0.492	0	1
Planting density	How many trees per hectare	46.09	15.13	16	150
Soil testing formula	Whether to adopt soil testing formula in the current year (Yes = 1; No = 0)	0.240	0.427	0	1
NPK content of the land	Did farmers know the NPK content of the land in the current year (Yes = 1; No = 0)	0.0414	0.199	0	1
Production cycle stage	Stage of apple production cycle in the current year (high = 1; low = 0)	0.821	0.383	0	1

3.2. Econometric Model to Examine the Influence of Aging and Landform on Inputs

To verify whether the mechanism of factor substitution is effective, we used ordinary least squares (OLS) regression to analyze the influence of aging on the factor input of apple machinery and employment. We used OLS because the factor input variables were treated logarithmically, for which it is easy to satisfy the normality [26]. Equations (1) and (2) are as follows:

$$\begin{aligned} lnF_{iz} = \theta + \theta_1 aging_i + \theta_2 lnP\_labor_i + \theta_3 lnP\_chem_i + \theta_4 lnP\_organic_i \\ + \theta_5 lnP\_pest_i + \theta_6 lnlastprice_i + \theta_7 parttime_i \\ + \theta_8 applenum_i + \tau_i \end{aligned} \tag{1}$$

$$\begin{aligned} lnF_{iz} = \theta + \theta'_1 aging_i + \theta''_1 aging_i\hat{}2 + \theta'_2 lnP\_labor_i + \theta'_3 lnP\_chem_i \\ + \theta'_4 lnP\_organic_i + \theta'_5 lnP\_pest_i + \theta'_6 lnlastprice_i \\ + \theta'_7 parttime_i + \theta'_8 applenum_i + \tau_i \end{aligned} \tag{2}$$

where F_{iz} represents the input of production factors, and z represents machinery input per hectare and employee input per hectare. We ran these regressions separately on each input. $aging_i$ represents the aging degree of the agricultural labor force, using the average age of the family agricultural labor force. We also added a squared term of aging in Equation (2). P_labor_i represents the current labor price, P_chem_i represents the current chemical fertilizer input price, $P\_organic_i$ represents the current organic fertilizer input price, P_pest_i represents the pesticide input price in the current year, $lnlastprice_i$ represents the average price of apples in the previous year, $parttime_i$ represents the number of apples in the household, and $applenum_i$ represents the number of apples in the household.

Based on Equation (1), we added landforms to discuss the heterogeneity of aging on apple production factors input under different landform conditions:

$$\begin{aligned} lnF_{iz} = \alpha + \alpha_1 aging_i + \alpha_2 landform_i + \alpha_3 c\_aging_i \times landform_i \\ + \alpha_4 lnP\_labor_i + \alpha_5 lnPchem_i + \alpha_6 lnP\_organic_i \\ + \alpha_7 lnP\_pest_i + \alpha_8 lnoutput_i + \alpha_9 parttime_i + \alpha_{10} applenum_i \\ + \epsilon_i \end{aligned} \tag{3}$$

where $landform_i$ is the landform dummy variable, $landform_i = 0$ represents flatland areas, and $landform_i = 1$ represents mountainous and hilly areas. The aging and landform interaction term $c\_aging_i \times landform_i$ was introduced to capture the impact of aging on the output value of apples under landform constraints.

3.3. Econometric Model of Aging's Impact on Technical Efficiency and Yield

This study used a stochastic frontier production function (SFA) proposed by Aigner et al. [27] and Meeusen and van Den Broeck [28] to measure the technical efficiency of apple production, which reflects the gap between the actual output level and the theoretical maximum output. We adopted a Cobb–Douglas (C-D) production function as a model form, as follows:

$$\begin{aligned} lnQ_i = \omega + \omega_1 lnlabor_i + \omega_2 lnchem_i + \omega_3 lnpest_i + \omega_4 lnmach_i \\ + \omega_5 lnland_i + v_i - u_i \end{aligned} \tag{4}$$

where v_i accounts for measurement errors and other sources of non-systematic statistical noise, and u_i is a non-negative random variable that represents technical inefficiency. The literature has used a variety of distributions for u_i, including the half-normal [27], exponential [28], truncated normal [29], and gamma [30]. This study tried the truncated normal, half-normal, and exponential distributions, as discussed below. $labor_i$ indicates the average amount of labor work per hectare, $chem_i$ indicates the average amount of fertilizer input per hectare, $lnpest_i$ indicates the average amount of pesticide input per hectare, $mach_i$ indicates the average amount of machinery input per acre, and $land_i$ indicates the area under cultivation.

Technical efficiency, defined as the ratio of observed output to maximum feasible output, was derived from Equation (5):

$$TE_i = exp(-u_i) \tag{5}$$

This study explored the effect of aging and landform on farm-level technical efficiency using Equations (6) and (7). Considering that the values of technical efficiency range from 0 to 1, we used the truncated regression to analyze the influence of aging on it. The error terms in a truncated regression model have a truncated normal distribution, which is used to model truncated data [31].

$$TE_i = \delta + \delta_1 aging_i + \mu \cdot X_i + \varepsilon_i \tag{6}$$

$$TE_i = \delta' + \delta_1' aging_i + \delta_1'' aging_i\hat{}2 + \mu \cdot X_i + \varepsilon_i \tag{7}$$

where X_i are control variables including the personal characteristics of decision makers, household characteristics, production characteristics, and disaster or not for farm i. Based on Equation (6), the decentralized aging and landform interaction term $c\_aging_i \times landform_i$ was added in Equation (8), exploring the heterogeneous effects of aging on technical efficiency under different landform conditions:

$$\begin{aligned} TE_i = {} & \varphi + \varphi_1 aging_i + \varphi_2 landform_{ii} + \varphi_3 c\_aging_i \times landform_i + \mu \cdot X_i \\ & + \varepsilon_i \end{aligned} \tag{8}$$

Based on the theoretical analysis, aging has an impact on yield. So, we estimated the effect of agricultural aging on yield by applying OLS. Considering that the impact of the planting scale on yield is likely to be nonlinear [32], the square term of the planting area was added to Equations (9) and (10).

$$\begin{aligned} lnQ_i = {} & \beta + \beta_1 aging_i + \beta_2 lnlabor_i + \beta_3 lnchem_i + \beta_4 lnpest_i + \beta_5 lnmach_i \\ & + \beta_6 lnland_i + \beta_7 (lnland_i)\hat{}2 + \mu_i \end{aligned} \tag{9}$$

$$\begin{aligned} lnQ_i = {} & \beta' + \beta_1' aging_i + \beta_1'' aging_i\hat{}2 + \beta_2' lnlabor_i + \beta_3' lnchem_i + \beta_4' lnpest_i \\ & + \beta_5' lnmach_i + \beta_6' lnland_i + \beta_7' (lnland_i)\hat{}2 + \mu_i \end{aligned} \tag{10}$$

Based on Equation (9), we added the interaction term between aging and landform in Equation (11) to analyze the heterogeneous influence of landform on apple yield caused by aging:

$$\begin{aligned} lnQ_i = {} & \gamma + \gamma_1 aging_i + \gamma_2 landform_i + \gamma_3 c\_aging_i \times landform_i + \gamma_4 lnlabor_i \\ & + \gamma_5 lnchem_i + \gamma_6 lnpest_i + \gamma_7 lnmach_i + \gamma_8 lnland_i \\ & + \gamma_9 (lnland_i)\hat{}2 + \varepsilon_i \end{aligned} \tag{11}$$

The symbols have the same meaning as above.

4. Effects of Aging on Factor Substitution

4.1. Replacing the Aging Labor Force with Machinery under Different Landform Conditions

To examine the substitution effect of machinery on labor, we conducted a regression analysis of the impact of the aging agricultural labor force on the input of mechanical factors and the ratio of machinery to work.

Columns (1), (2), and (3) in Table 2 report the effect of the aging on the amount of machinery input (kw/hectare), and columns (4), (5), and (6) report the effect of aging on the cost of machinery input (CNY/hectare). The results showed that aging had no significant effect on machinery input in flatland, both in kw/ha and CNY/hectare. That indicates that apple growers do not choose to increase mechanical input to compensate for the decline in the quantity and quality of family labor. On the contrary, some studies have concluded that aging promotes agricultural mechanization in food production [33]. Furthermore, the interaction terms between aging and landform had a significant negative effect on these two explained variables, showing that, in mountainous and hilly areas, if the average age increased by one year, the amount of machinery (kw/ha) decreased by 4.53% and machinery input (CNY/ha) decreased by 5.32%. This indicates that landform restricts the substitution of machinery for labor.

Table 2. Effects of aging on machinery input in different landform conditions.

	Log of Machine Quantity (kw/hectare)			**Log of Machine Cost (CNY/hectare)**		
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Aging	−0.00982 (0.0106)	0.0560 (0.106)	0.00310 (0.00944)	−0.0168 (0.0149)	0.0445 (0.132)	0.00354 (0.0172)
Aging squared		−0.000630 (0.00104)			−0.000586 (0.00126)	
Landform			−0.411 ** (0.171)			0.109 (0.201)
Aging_center × landform			−0.0453 ** (0.0224)			−0.0532 * (0.0283)
ln(P_organic fertilizer)	−0.359 (0.272)	−0.360 (0.272)	−0.0689 (0.264)	−0.630 * (0.379)	−0.631 * (0.379)	−0.479 (0.382)
ln(P_chemical fertilizer)	0.523 *** (0.178)	0.524 *** (0.178)	0.784 *** (0.169)	0.412 * (0.247)	0.413 * (0.248)	0.658 *** (0.232)
ln(P_pesticide)	0.199 (0.149)	0.203 (0.151)	0.211 (0.150)	0.199 (0.198)	0.203 (0.199)	0.172 (0.191)
ln(last price)	0.0975 (0.191)	0.0882 (0.191)	0.0124 (0.165)	−0.0320 (0.217)	−0.0407 (0.214)	−0.0518 (0.213)
Part-time	0.0262 (0.0846)	0.0201 (0.0848)	0.0594 (0.0902)	−0.0988 (0.126)	−0.105 (0.126)	−0.0164 (0.134)
Apple_sum	0.388 *** (0.130)	0.391 *** (0.130)	0.479 *** (0.129)	0.284 (0.175)	0.287 (0.176)	0.226 (0.176)
Production cycle stage	−0.101 (0.204)	−0.122 (0.202)	−0.142 (0.189)	−0.0757 (0.268)	−0.0946 (0.269)	−0.128 (0.267)
Natural disaster	0.177 (0.150)	0.183 (0.152)	0.159 (0.148)	−0.237 (0.212)	−0.230 (0.214)	0.182 (0.209)
Town fixed effect	Yes	Yes	No	Yes	Yes	No
Constant	4.382 *** (1.094)	2.711 (2.974)	3.683 *** (1.084)	3.539 ** (1.583)	1.984 (3.824)	4.339 ** (1.699)
Observations	459	459	459	459	459	459
F statistic	6.17 ***	5.92 ***	6.09 ***	2.72 ***	2.61 ***	1.80 *
R-squared	0.208	0.210	0.138	0.120	0.120	0.037

Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The local apple industry is not mechanized enough to replace labor effectively. The level of mechanization in fertilization, pesticides, and plowing is higher than other links in apple production. However, in these three links, apple growers' investment in machinery tends to be homogenized. Most use semi-self-made small machinery, which requires manual production, and the mechanization degree is low. And other essential production links such as blossom and fruit thinning, bagging, bag removing, and harvesting require fine and detailed work; mechanization cannot be achieved, and the work requires significant labor to complete. Therefore, the factor substitution effect of machinery on the labor force in apple production is minimal, which means that elderly apple growers cannot fill the lack of labor force with mechanical inputs.

4.2. Replacing the Aging Labor Force with Employment under Different Landform Conditions

When mechanical substitution for family labor fails in labor-intensive apple production, substitution with other labor is considered. Elderly apple growers can replace their labor supply by purchasing the services of hired workers. However, due to landform constraints, the elderly apple growers in mountainous and hilly areas face higher labor prices and capital constraints, which results in the heterogeneous impact of aging in different landforms. The results are shown in Table 3.

Table 3. Effects of aging on employment input in different landform conditions.

	Log of Hours of Employment (hour/hectare)			Log of Employment Expenses (CNY/hectare)		
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Aging	0.00336 (0.00392)	0.00369 (0.0390)	0.00894* (0.00507)	0.0149 (0.0246)	0.0161 (0.0246)	0.0650 ** (0.0287)
Aging squared		−0.000412 (0.000303)			−0.00147 (0.00181)	
Landform			−0.220 *** (0.0645)			−1.154 *** (0.403)
Aging_center × landform			−0.0147 ** (0.00705)			−0.177 *** (0.0461)
ln (P_ organic fertilizer)	0.0349 (0.106)	0.0343 (0.106)	0.116 (0.0966)	−0.385 (0.678)	−0.387 (0.679)	0.735 (0.782)
ln (P_ chemical fertilizer)	0.189 ** (0.0890)	0.189 ** (0.0881)	0.202 ** (0.0843)	0.896 ** (0.408)	0.899 ** (0.405)	1.612 *** (0.403)
ln (P_pesticide)	0.0826 * (0.0498)	0.0849 * (0.0502)	0.0988 ** (0.0497)	0.255 (0.341)	0.263 (0.342)	0.341 (0.340)
ln (Last price)	0.143 * (0.0798)	0.137 * (0.0797)	0.160 ** (0.0728)	1.233 ** (0.479)	1.211 ** (0.479)	0.985 ** (0.450)
Part-time	0.0741 ** (0.0366)	0.0701 * (0.0368)	0.0906 ** (0.0356)	0.293 (0.215)	0.279 (0.217)	0.437 ** (0.216)
Apple_sum	−0.0278 (0.0594)	−0.0259 (0.0597)	−0.0272 (0.0574)	0.0350 (0.291)	0.0420 (0.291)	0.346 (0.291)
Production cycle stage	0.180 ** (0.0797)	0.167 ** (0.0799)	0.218 *** (0.0740)	0.742 (0.508)	0.695 (0.511)	1.034 ** (0.511)
Natural disaster	0.0697 (0.0766)	0.0742 (0.0765)	0.133 ** (0.0669)	0.0955 (0.426)	0.111 (0.424)	0.147 (0.382)
Town fixed effect	Yes	Yes	No	Yes	Yes	No
Constant	5.601 *** (0.500)	4.508 *** (0.983)	5.272 *** (0.510)	0.192 (3.046)	−3.705 (5.864)	−4.283 (2.890)
Observations	459	459	459	459	459	459
F statistic	5.37 ***	5.16 ***	7.28 ***	7.48 ***	7.34 ***	7.91 ***
R-squared	0.151	0.154	0.119	0.236	0.237	0.154

Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The estimation results of columns (2) and (4) were based on columns (1) and (3), adding landforms and interaction terms between landforms and aging. The results showed that aging significantly affected employee input per hectare in flatland, indicating that if the average age increased by one year, employment quantity (hour/ha) increased by 0.89% and employment expenses (CNY/hectare) increased by 6.50%. Liao et al. (2019) also found that some counties have the coupling mode of "increasing rural aging and labor employing quantity" [34]. In contrast, in mountainous and hilly areas, if the average age increased by one year, employment quantity (hour/ha) decreased by 0.58% and employment expenses (CNY/hectare) decreased by 11.20%.

Elderly apple growers alleviate the insufficient family labor force caused by aging by increasing hired labor. However, landform conditions restrict factor substitution, which leads to the heterogeneous impact of aging on labor-intensive apple production under different landform conditions. Flatlands have convenient transportation and relatively abundant labor resources. When their labor supply is insufficient, elderly apple growers actively seek employees to replace family labor, thus filling the gap between themselves and young apple growers. However, elderly apple growers face higher employee prices and capital constraints in mountainous and hilly areas due to landform constraints. Their endowment level is not enough to support them in investing in employees to maintain output. Therefore, elderly apple growers in mountainous and hilly areas will reduce employee inputs. In conclusion, elderly apple growers replace their labor force with employment inputs to maintain normal production. The landform constraints make the difficulty of factor substitution different, so aging has a heterogeneous impact on employment input in flatlands and mountains.

4.3. Robustness Checks

To increase the reliability and stability of the research results, we replaced the aging index with the age of the apple production decision makers in the household for robustness checks. Results are shown in Table 4. The results showed that with the increase in age, apple growers, faced with the labor supply shortage caused by aging, will increase the input of hired labor in the flatlands and reduce the input of hired labor in the mountains and hills, which is consistent with the above results.

Table 4. Robustness checks for the effects of aging on factor substitution.

	Log of Machine Quantity (kw/hectare)	Log of Machine Cost (CNY/hectare)	Log of Hours of Employment (hour/hectare)	Log of Employment Expenses (CNY/hectare)
Variables	**(1)**	**(2)**	**(3)**	**(4)**
Aging	−0.00857	−0.00792	0.00857 *	0.0553 **
	(0.00869)	(0.0173)	(0.00517)	(0.0277)
Landform	−0.468 ***	0.0218	−0.239 ***	−1.397 ***
	(0.163)	(0.199)	(0.0629)	(0.398)
Aging_center × landform	−0.0316	−0.0243	−0.0122 *	−0.146 ***
	(0.0203)	(0.0282)	(0.00714)	(0.0436)
Observations	459	459	459	459
R-squared	0.140	0.031	0.118	0.143

Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5. Effects of Aging on Technical Efficiency and Yield

5.1. Effects of Aging on Technical Efficiency under Different Landform Conditions

This study used various models to estimate the technical efficiency, as the distributions of u_i have different assumptions, including half-normal [27], exponential [28], truncated normal [29], or gamma [30]. The production function estimation results are presented in Table A1. Table 5 shows the estimated effects of aging on technical efficiency based on truncated regression, with and without considering landform and age squared.

The results in columns (2), (5), and (8) showed that there was a nonlinear relationship between average age and technical efficiency, with efficiency initially increasing and then declining beginning at an average age of about 50, similar to other studies [2,35].

The results in columns (3) and (9) showed that in the mountainous and hilly areas, aging had a significant negative impact on technical efficiency, but this finding was not robust to the assumed distribution of u_i, since it was not statistically significant in column (6). If the average age increased by one year, technical efficiency decreased by 0.46% in mountainous and hilly areas, which was statistically significant. This means that, in mountainous and hilly areas, elderly apple growers may reduce other inputs so that technical efficiency does not decline too much.

Figure 3 shows the relationship between average age and technical efficiency in different landforms using local linear regression fitting. Technical efficiency in flatlands remained stable with a slight variation range with the aging of the agricultural labor force. Technical efficiency rose slowly before the average age of 42 and then slowly descended. However, in mountainous and hilly areas, technical efficiency showed a downward trend as the average age increased, and it declined dramatically after the average age reached about 70. This result intuitively illustrated the heterogeneity of aging's impacts on technical efficiency under different landform conditions.

Table 5. Estimated determinants of technical efficiency.

	Technical Efficiency								
	Truncated Normal			Half-Normal			Exponential		
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
Aging	−0.000863	0.0182 *	−0.000654	−0.000878	0.0165	−0.00120	−0.000863	0.0182 *	−0.000652
	(0.00118)	(0.0110)	(0.00147)	(0.00121)	(0.0113)	(0.00150)	(0.00118)	(0.0110)	(0.00146)
Aging squared		−0.000181*			−0.000166			−0.000181 *	
		(0.000103)			(0.000107)			(0.000103)	
Landform			−0.0731 ***			−0.0632 ***			−0.0731 ***
			(0.0217)			(0.0223)			(0.0217)
Aging_center × landform			−0.00463 *			−0.00303			−0.00464 *
			(0.00273)			(0.00266)			(0.00273)
Sex	−0.0302	−0.0289	0.00644	−0.0276	−0.0266	0.0111	−0.0302	−0.0289	0.00642
	(0.0410)	(0.0410)	(0.0378)	(0.0429)	(0.0428)	(0.0397)	(0.0410)	(0.0410)	(0.0378)
Technology training	0.00919 **	0.00980 **	0.0127 ***	0.00894 **	0.00956 **	0.0122 ***	0.00919 **	0.00980 **	0.0127 ***
	(0.00446)	(0.00435)	(0.00482)	(0.00451)	(0.00449)	(0.00473)	(0.00446)	(0.00435)	(0.00482)
Social capital	0.0332 *	0.0325 *	0.0230	0.0245	0.0238	0.0149	0.0332 *	0.0325 *	0.0231
	(0.0181)	(0.0179)	(0.0192)	(0.0189)	(0.0188)	(0.0196)	(0.0181)	(0.0179)	(0.0192)
Apple percent	0.0192	0.0375	0.0268	0.0216	0.0374	0.0305	0.0192	0.0375	0.0268
	(0.0396)	(0.0409)	(0.0419)	(0.0418)	(0.0431)	(0.0431)	(0.0396)	(0.0409)	(0.0419)
Land fragmentation	−0.00137	0.000579	−0.0342	-1.55×10^{-5}	0.00134	−0.0343	−0.00139	0.000559	−0.0342
	(0.0537)	(0.0537)	(0.0571)	(0.0549)	(0.0550)	(0.0577)	(0.0537)	(0.0537)	(0.0571)
Natural disaster	−0.0691 ***	−0.0667 ***	−0.0708 ***	−0.0749 ***	−0.0727 ***	−0.0708 ***	−0.0691 ***	−0.0667 ***	−0.0707 ***
	(0.0209)	(0.0207)	(0.0191)	(0.0221)	(0.0219)	(0.0198)	(0.0209)	(0.0207)	(0.0191)
Planting density	−0.000633	−0.000729	−0.00177 **	−0.000332	−0.000411	−0.00173 **	−0.000634	−0.000729	−0.00177 **
	(0.000911)	(0.000915)	(0.000732)	(0.000917)	(0.000920)	(0.000757)	(0.000911)	(0.000915)	(0.000732)
Soil testing formula	0.0354	0.0342	0.0137	0.0387	0.0374	0.0169	0.0354	0.0341	0.0137
	(0.0227)	(0.0225)	(0.0236)	(0.0237)	(0.0235)	(0.0245)	(0.0227)	(0.0225)	(0.0236)
NPK content of the land	−0.0244	−0.0280	0.0104	−0.0116	−0.0150	0.0240	−0.0244	−0.0281	0.0104
	(0.0456)	(0.0442)	(0.0464)	(0.0458)	(0.0447)	(0.0479)	(0.0456)	(0.0442)	(0.0464)
Town fixed effect	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Constant	0.667 ***	0.166	0.747 ***	0.507 ***	0.0533	0.635 ***	0.668 ***	0.166	0.748 ***
	(0.0995)	(0.301)	(0.0981)	(0.105)	(0.310)	(0.104)	(0.0994)	(0.301)	(0.0981)
Observations	459	459	459	459	459	459	459	459	459
Wald chi2	117.74 ***	121.15 ***	55.76 ***	113.70 ***	116.85 ***	50.12 ***	117.72 ***	121.13 ***	55.76 ***
R-squared	0.247	0.253	0.121	0.216	0.220	0.101	0.247	0.253	0.121

Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

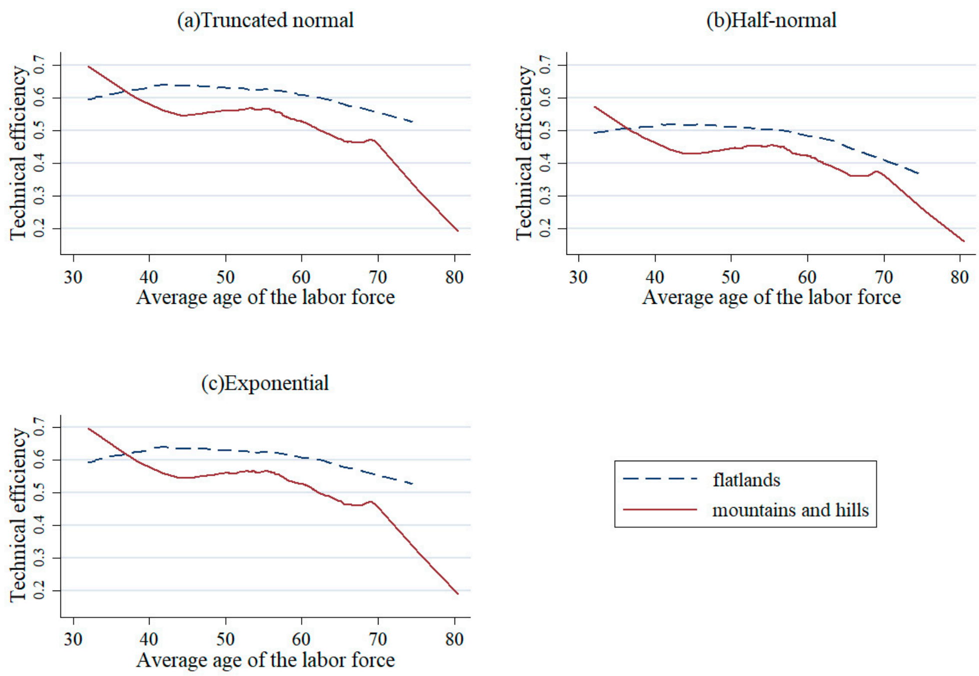

Figure 3. The relationship between aging and technical efficiency in different landform conditions.

5.2. Effects of Aging on Yield under Different Landform Conditions

Table 6 presents the results for apple yield based on ordinary least squares (OLS) regressions of aging and landforms on the yield with and without considering landform and age squared. The form is a Cobb–Douglas (C-D) production function.

Table 6. Estimated determinants of yield for apple production.

	Log of Yield (CNY/hectare)					
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Aging	−0.0274 *** (0.00540)	0.150 *** (0.0480)	−0.00405 (0.00455)	0.0700 * (0.0377)	0.00259 (0.00615)	−0.00214 (0.00574)
Aging squared		−0.00170 *** (0.000455)		−0.000708 ** (0.000358)		
Landform					−0.170 (0.141)	−0.225 *** (0.0860)
Aging_center × landform					−0.0258 ** (0.0101)	−0.0177 * (0.00964)
ln(Family labor expense)			−0.0620 (0.0587)	−0.0698 (0.0586)		0.0278 (0.0585)
ln(Hired labor expense)			0.0386 *** (0.00982)	0.0381 *** (0.00979)		0.0404 *** (0.0102)
ln(Chemical fertilizer expense)			0.00201 (0.0252)	0.000534 (0.0251)		0.0357 (0.0257)
ln(Organic fertilizer expense)			−0.0111 (0.0176)	−0.0130 (0.0176)		0.0226 (0.0177)
ln(Machinery expense)			0.0180 (0.0165)	0.0174 (0.0165)		0.0151 (0.0171)
ln(Pesticide expense)			−0.0332 (0.0585)	−0.0295 (0.0583)		−0.0112 (0.0611)
ln(Other expenses)			0.285 *** (0.0393)	0.281 *** (0.0392)		0.289 *** (0.0404)
ln(Area_large)			0.453 (1.176)	0.312 (1.175)		0.845 (1.225)
ln(Area_large) × ln(Area_large)			−0.0652 (1.597)	0.104 (1.594)		−0.380 (1.698)
Production cycle stage			0.214 ** (0.0937)	0.192 ** (0.0941)		0.405 *** (0.0977)
Natural Disaster			−0.243 *** (0.0824)	−0.233 *** (0.0823)		−0.252 *** (0.0789)
Town fixed effect	Yes	Yes	Yes	Yes	No	No
Constant	12.39 *** (0.289)	7.846 *** (1.252)	9.637 *** (0.825)	7.903 *** (1.202)	10.76 *** (0.357)	7.882 *** (0.860)
Observations	459	459	459	459	459	459
F statistic	25.84 ***	20.22 ***	18.16 ***	17.68 ***	17.89 ***	20.58 ***
R-squared	0.054	0.081	0.490	0.494	0.361	0.394

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The column (4) results in Table 6 added age squared based on column (3), indicating a nonlinear relationship between average age and yield with a decline beginning at average age 49.

The column (6) results in Table 6 added landforms and interaction terms between landforms and aging based on column (3). Again, the aging variable had no impact on the yield, indicating that, in the flatlands, aging did not affect the yield. However, the interaction term between aging and landform was significantly negative, meaning that, in the mountainous and hilly areas, if the average age increased by one year, yield decreased by 1.77%.

The estimated mean partial output elasticities in Table 6 were consistent with Table A1. The family labor expense was not significant, while the hired labor expense significantly impacted the yield. Apple is a labor-intensive crop, and multiple production links require a large labor input. The increase in labor input by apple growers can improve yield (CNY/ha), similar to the research conclusion of [20]. Chemical fertilizer materials positively affected yield at a significance level of 1%, but this result was not stable. Pesticide inputs had no significant impact on yield (CNY/ha) because pesticides are often an afterthought once pest infestation has already occurred, at which point the application of pesticides can only stop further yield loss. The effect of mechanical input on yield was not statistically significant, consistent with Table 2. Large-scale mechanization cannot be realized in labor-intensive apple production in China. Apple growers generally use semi-homemade small machinery, which requires manual fertilizing and spraying assistance. The penetration rate of such advanced machinery as a rotary cultivator is shallow, and the promotion effect of mechanical input on yield is minimal. Furthermore, hired labor and chemical fertilizer are the main driving forces of output growth in apple production. Other inputs positively impacted yield, consistent with the conclusion of the early study [36], indicating that irrigation and other inputs increased yield (CNY/ha).

Figure 4 shows the relationship between average age and yield in different landforms using local linear regression fitting. The results showed that yield (CNY/hectare) in flatlands rose slowly before the average age of 42 and then descended. However, yield (CNY/hectare) showed a downward trend in mountainous and hilly areas as average age increased, and it declined dramatically after the average age reached about 57. This result intuitively illustrated the heterogeneity of aging's impacts on yield (CNY/hectare) under different landform conditions.

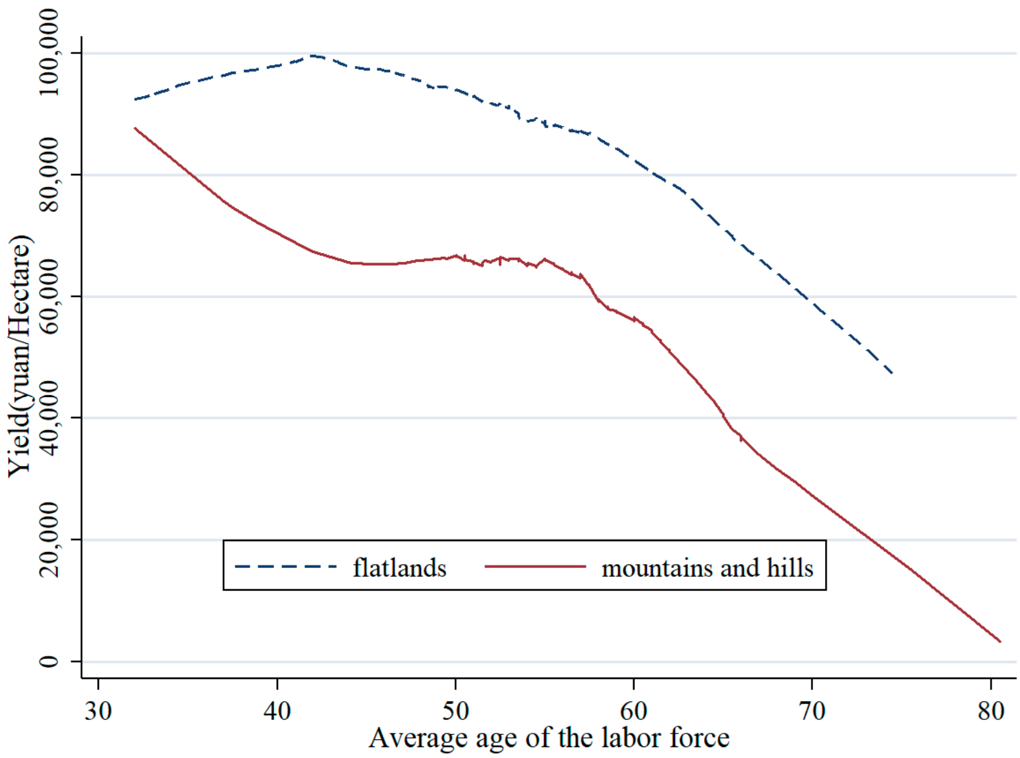

Figure 4. The relationship between aging and yield in different landform conditions.

5.3. Robustness Checks

To increase the reliability and stability of the research results, we replaced the aging index with the age of the apple production decision makers in the household for robustness checks. The results in columns (1), (3), (5), and (7) of Table 7 indicated that technical efficiency and yield had a nonlinear relationship with aging. The results in column (8) showed that aging did not affect yield in flatlands but had a negative impact on yield in mountainous areas. These results were basically consistent with the previous findings about technical efficiency.

Table 7. Robustness checks for the effects of aging on technical efficiency and yield.

	Technical Efficiency						Log of Yield (CNY/hectare)	
	Truncated Normal		Half-Normal		Exponential			
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Aging	−0.00346 ***	−0.00113	−0.00332 ***	−0.00187	−0.00346 ***	−0.00113	−0.00719 *	0.000923
	(0.00121)	(0.00145)	(0.00121)	(0.00145)	(0.00121)	(0.00145)	(0.00430)	(0.00542)
Aging squared	−0.000235 **		−0.000235 **		−0.000235 **		−0.000608 *	
	(0.000109)		(0.000107)		(0.000109)		(0.000334)	
Landform		−0.0801 ***		−0.0682 ***		−0.0801 ***		−0.389 ***
		(0.0212)		(0.0220)		(0.0212)		(0.129)
Aging_center × landform		−0.00363		−0.00157		−0.00364		−0.0183 **
		(0.00243)		(0.00239)		(0.00243)		(0.00844)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	459	459	459	459	459	459	459	459
R-squared							0.495	0.506

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

6. Discussion

A caveat for our results is that the aging variable is potentially endogenous if older farmers exit apple production at different rates than younger farmers. For example, older farmers with health problems may be more likely to quit apple production. That would diminish the measured effect of aging because the older farmers who remain in apple production are in better health, causing aging to have a greater negative impact on agricultural production than in our estimates.

These results help us understand how landform and aging affect factor substitution. Aging incentivizes apple growers to use hired labor to replace elderly family labor, but landform conditions significantly constrain this substitution. Machinery is not an effective substitute for labor in labor-intensive cash crops, such as apples. The overall mechanical level of China's apple industry is low, and many key production links lack advanced, economical, and practical new agricultural machinery and tools [23]. Taking the ditching fertilizer machine as an example, larger horsepower machines are of limited use in mountainous landforms. At the same time, the price of high-horsepower machinery is high, and most apple growers cannot afford it. Small types of fertilizer machinery still require manual fertilizing and backfilling, resulting in low efficiency and no time savings.

However, the United States is also a major producer of apples, and the mechanical level of apple production there is higher than that in China, which is realized by the use of harvesting machinery. For example, apple harvest and in-field presorting machines can combine the field presorting and harvesting functions of apples. As a result, it can save the cost of post-harvest treatment and storage, reduce the problems of post-harvest pests and diseases, better manage the inventory, and improve harvesting productivity [37]. Therefore, as compared to the United States, China's agricultural machinery level lags behind.

It is worth discussing why the current state of mechanical apple production in China is low compared to the situation with food crops. First, apple production has more planting links than food crops, and needs more labor and specialization. That means apple production needs more detailed and specialized machinery. Second, almost all food crops are planted in flatlands. But, in Shaanxi, 24.03% of apple orchards were in mountainous and hilly areas, with a yield that was 14.14% of the total. Third, compared to other apple-production countries, China's proportion of processing apples is smaller. Harvesting machinery is more viable for processing apples than table apples, because minor bruises caused by a harvesting machine do not matter much.

7. Conclusions and Suggestions

In this study, we provided evidence that (i) aging induces apple growers to use hired labor to replace family labor in the flatlands, but not in mountainous and hilly areas due to landform constraints on factor substitution; (ii) aging has no significant impact on mechanical inputs in either plains or mountains, and machinery cannot effectively replace the labor force in apple production; (iii) limited by a lack of labor quantity and quality, apple growers will reduce material inputs in mountainous and hilly areas; (iv) changes in input structure result in aging having little influence on yield and technical efficiency in flatlands, while aging negatively affects apple production in mountainous and hilly areas; and (v) there is a nonlinear relationship between average age and technical efficiency, and between average age and yield.

Given the above research conclusions, this study puts forward the following suggestions:

First, agricultural machinery in apple production should be improved and innovated, and agricultural machinery subsidy policies should be improved, accompanied by increased technical training for farmers and market-based methods to attract young people into agricultural production. The research and development of modern agricultural machinery should be vigorously supported, such as automatic fertilizer and picking machines, so that apple planting gradually moves away from labor-intensive production. At the same time, the existing machinery purchase subsidy policy should be further deepened and improved, and the scope and intensity of new agricultural machinery subsidies should be increased. Second, the development of social services related to apple production should be encouraged. At present, social services mainly focus on food crops, while apple-related services are rare. The local government should actively promote the construction of the apple social service market to alleviate the labor supply problem caused by aging. Apple growers can purchase social services to obtain professional human services, modern agricultural machinery, and new production technologies to complete part of their apple production and improve technical efficiency. Third, there is a need to improve infrastructure. The level of agricultural infrastructure construction in mountainous and hilly areas of China still restricts agricultural development, and strengthening infrastructure construction is an important measure to accelerate agricultural modernization. Fourth, targeted apple technical training and on-site guidance should be carried out. For apple growers, especially elderly apple growers, regular training can be carried out on new apple production technologies such as applying organic fertilizer instead of chemical fertilizer, improved seed technology, and the "fruit–livestock–marsh" ecological cycle agriculture model.

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Appendix A

Table A1 presents the production function estimation results.

Table A1. Production function estimation results.

Variables	Truncated Normal (1)	Half-Normal (2)	Exponential (3)
ln(Family labor expense)	0.0492	0.0216	0.0492
	(0.0532)	(0.0559)	(0.0532)
ln(Hired labor expense)	0.0408 ***	0.0432 ***	0.0408 ***
	(0.00906)	(0.00920)	(0.00906)
ln(Chemical fertilizer expense)	0.0768 ***	0.0802 ***	0.0768 ***
	(0.0211)	(0.0213)	(0.0211)
ln(Organic fertilizer expense)	0.0230	0.0226	0.0230
	(0.0160)	(0.0161)	(0.0160)
ln(Machinery expense)	0.0102	0.0126	0.0102
	(0.0154)	(0.0159)	(0.0154)
ln(Pesticide expense)	0.0540	0.0377	0.0541
	(0.0578)	(0.0585)	(0.0578)
ln(other expenses)	0.203 ***	0.206 ***	0.203 ***
	(0.0413)	(0.0419)	(0.0413)
lnarea_large	0.897 ***	0.747 **	0.898 ***
	(0.324)	(0.338)	(0.324)
Constant	7.982 ***	8.589 ***	7.980 ***
	(0.725)	(0.743)	(0.725)
Mu	−873.2		
	(2056)		
Usigma	6.297 ***	0.222	−0.955 ***
	(2.351)	(0.144)	(0.192)
Vsigma	−1.344 ***	−1.634 ***	−1.343 ***
	(0.151)	(0.223)	(0.150)
Observations	459	459	459

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$.

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