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Skill complementarities and returns to higher education: Evidence from college enrollment expansion in China☆

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ABSTRACT

We find that the increased supply of college graduates resulting from college enrollment expansion in China increases college premiums for older cohorts and decreases college premiums for younger cohorts. This finding is inconsistent with the canonical model that assumes substitution among workers of different ages. We subsequently build a simple model that considers complementarities among workers of different ages and different skill levels. Our model predicts that the college premium of senior workers increases with the supply of young college graduates when skill is a scarce resource. The model's predictions are supported by empirical tests.

1. Introduction

In the traditional Mincer equation, the returns to education are presumed to be the same for all age groups; the assumption is that educated workers of different ages are perfect substitutes (Tinbergen, 1974, 1975). This assumption is challenged by Card and Lemieux (2001a, 2001b), who report that the college premium increases for younger workers but remains flat for older workers in the presence of a negative shock to the supply of young college graduates in the United States, United Kingdom, and Canada. These findings suggest that educated workers of different ages are imperfect substitutes.

However, imperfect substitution cannot explain the puzzling trend in the returns to education in China in a period of dramatic positive shocks to the supply of college graduates. After a long period of slow growth, college admission in China sharply increased by 40% from 1998 to 1999 (Fig. 1). In roughly a decade, from 1998 to 2009, the number of newly admitted college students in China increased by 480% (from 1.1 million to 6.4 million, as shown in Fig. 1). The overall returns to college education (Fig. 2) increased over this period despite the dramatic increase in the supply of college graduates (see also Zhang, Zhao, Park, & Song, 2005). Even more puzzling, although the college premium for younger workers (20–24 years old) has declined with expanding college enrollment, the college premium for older workers (e.g., 51–55 years old) has increased (Fig. 2), a trend that cannot be explained by the lack of substitution among skilled workers of different ages. In this paper, we also show evidence suggesting that the lower college premium

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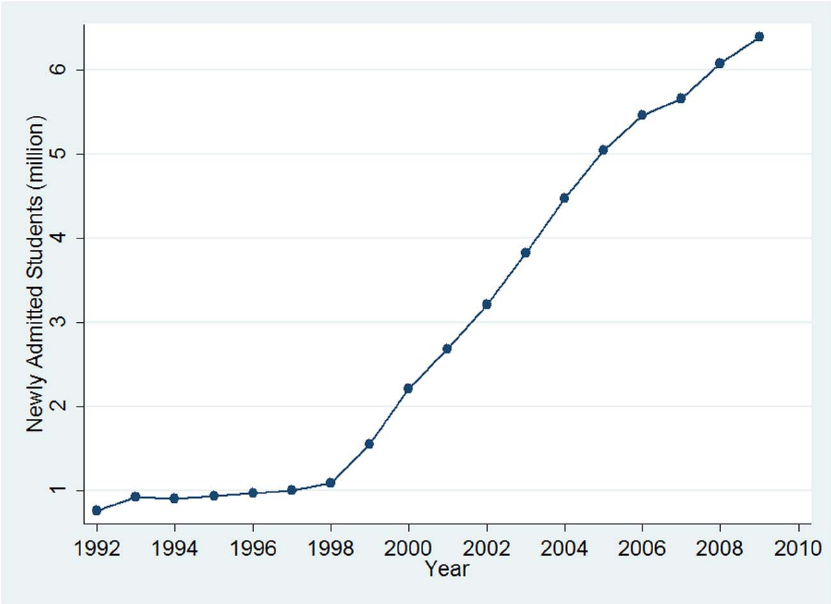

Fig. 1. Newly admitted college students in China, 1992–2009.
Source: China Education Statistical Yearbooks (1993–2010)

for younger workers cannot be explained by the possible decline of college education quality after the college enrollment expansion and that the higher college premium for older workers is not because old college-educated workers with lower wages were crowed out of the labor market by young college-educated workers after the expansion.[1]

In this study, we provide a new explanation for the diverging trends in skill premiums: we argue that skilled workers of different seniorities are complementary in production. We build a simple theoretical model based on the canonical model summarized by Acemoglu and Autor (2011).[2] In our model, workers are classified into three types: low skilled workers (without college education); young skilled workers (with college education but inexperienced); and senior skilled workers (with college education and experience). Senior skilled workers are complements to, rather than substitutes for, the first two types of workers in production. Moreover, the complementarity between senior skilled workers and young skilled workers is stronger than that between senior skilled workers and low skilled workers.[3] Our theory implies that an increase in the number of young skilled workers (relative to low skilled workers) increases the marginal product of senior skilled workers, which explains why their return to college education increases with the increasing supply of young skilled workers.

Drawing on data from the Urban Household Survey (UHS) in China, we find evidence supporting our main hypothesis, which is that the college premium of young workers decreases, whereas that of senior workers increases with the number of young skilled workers. To address endogeneity, in our analysis we use the potential college enrollment expansion, in which every province expands its enrollment in proportion to its predetermined capacity, as an instrumental variable (IV) for the number of young skilled workers. The IV estimations show that an increase in the number of young skilled workers has a positive effect on the overall college premium. However, this positive effect is mostly driven by the rising college premium for senior workers (30–60 years old). The college premium actually declines for young workers (20–24 years old). According to our estimates, an increase of one standard deviation (roughly 200 thousand) in the number of young skilled workers decreases the college premium for workers in the 20–24 age group by 5.2 percentage points. In contrast, the college premium increases by 4.5 percentage points and 6 percentage points for workers aged 30–39 and 40–60, respectively.

Our study makes several contributions to the literature. First, we extend the canonical models of college (or skill) premiums and wage inequality (Acemoglu & Autor, 2011), which treat skilled workers of different seniorities as substitutes. Unlike these models, our proposed model demonstrates that such workers are likely to be complements to each other in production. Second, although there are abundant studies that investigate the complementarities between machines (technology) and labor (Goldin & Katz, 1998; Mincer, 1989; Polgreena & Silos, 2008), we are among the first to examine the complementarities among different types of workers. The only previous study we are aware of is that of Berger (1983), who finds that young and old male workers with college degrees are

[1] We also find that there is no change in the gender composition of the older cohorts after the college expansion, meaning that the higher college premiums of the older cohorts cannot be explained by a change in the ratio of women whose college premium is higher (Rosenzweig & Zhang, 2013).

[2] Acemoglu and Autor (2011) refer to the demand–supply framework as the canonical model. The canonical model has been empirically proven not only in the United States (Davis & Haltiwanger, 1991; Goldin & Katz, 2008; Katz & Murphy, 1992; Krueger, 1991), but also in other developed nations (Fitzenberger & Kohn, 2006; Freeman & Needels, 1993; Katz, Loveman, & Blanchflower, 1995).

[3] This assumption is supported by the estimation of a translog production function with data from manufacturing firms in China, shown in Appendix A.

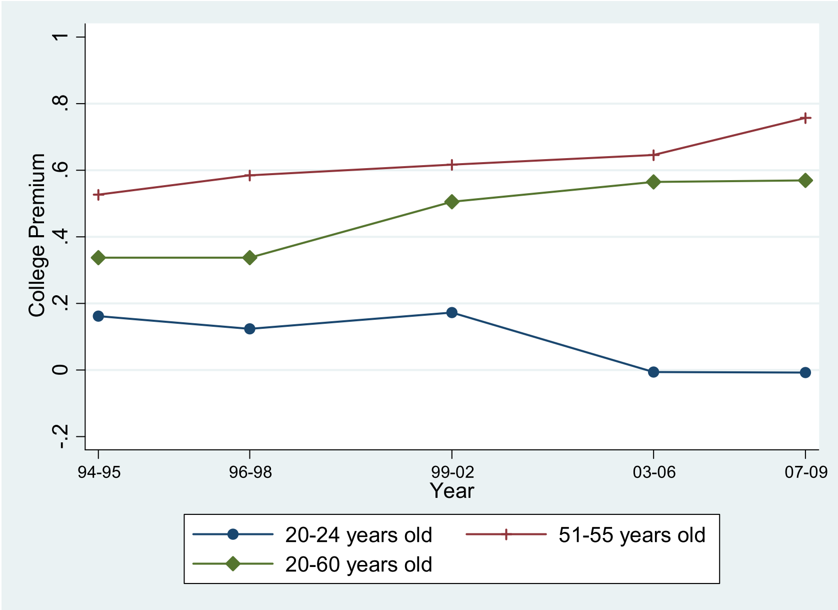

Fig. 2. Estimated college premiums for different age groups, 1994–2009.
Notes: we use the data from the UHS (1994–2009) to estimate the Mincer equations for different age groups in different periods. Specifically, we regress log earnings on a college dummy, a male dummy, age and its squared term, year dummies, and province dummies. The college premium is the regression coefficient of the college dummy.

complementary in production. In a sense, the sudden increase in the number of young college graduates in China resembles a skill-biased technological change for senior skilled workers.

Our findings suggest that education has a positive externality in the labor market.[4] The college wage premium not only depends on the average educational level of one's own and surrounding cohorts (Berger, 1985; Macunovich, 1998), but also on the skill distribution across the entire workforce. Moreover, the externality could be positive if skilled workers of different cohorts complement each other in production. The rapid expansion of college enrollment in China has been criticized for depressing wages and the wage premiums of new college graduates, but we demonstrate that not all cohorts have experienced a reduction in college premiums. In fact, we find that the older generations of college graduates have benefited from the expansion. Furthermore, the potentially steeper age-earnings profile suggests that the current young generation of college graduates may have the opportunity to catch up in earnings later in their career, if the educational level in China continues to rise.

The remainder of this paper is organized into several sections. We build a simple theoretical model and generate testable hypotheses in Section 2. We subsequently describe the empirical strategy in Section 3 and the data in Section 4. We report the empirical results in Sections 5. Section 6 discusses alternative explanations and we conclude the paper in Section 7.

2. Theoretical model

Suppose we have a general form of an aggregate production function that uses three types of workers: senior skilled workers, S, (with college education and experience), who could be managers or team leaders in a firm; young skilled workers, H, (with college education but little experience); and low skilled workers, L, (without college education). The general function can be written as

$$Y = F(S, H, L). \tag{1}$$

We assume that F is twice-continuously differentiable, strictly increasing, and strictly concave in each argument. In addition to these typical assumptions, we make the following further assumptions about complementarities between workers:

A1: $F_{12} > 0$,
A2: $F_{23} > 0$, and
A3: $F_{12} - F_{13} > 0$.

In A1–A3, $F_{12} \equiv \frac{\partial^2 Y}{\partial S \partial H}$, $F_{13} \equiv \frac{\partial^2 Y}{\partial S \partial L}$, and $F_{23} \equiv \frac{\partial^2 Y}{\partial H \partial L}$. Assumptions A1 and A2 mean that both senior skilled (managers) and low skilled (non-college) workers are complementary to young skilled (college) workers in production while assumption A3 means that young skilled workers complement the marginal product of senior skilled workers more than low skilled workers do.

[4] Acemoglu and Angrist (2001) find little evidence of positive external returns to education. Moretti (2004) provides empirical evidence for the spillover effects of human capital within cities.

There are reasons to believe that different types of workers are complementary in production (Borjas, 1983; Field, 1988; Murphy & Welch, 1992). For instance, in firms where team productions or apprenticeships prevail, workers with a higher level of education may complement the productivity of a team leader, as they have better cognitive skills and are better at following instructions. This complementarity suggests that an increase in the supply of college graduates may affect not only their own wages but also the wages of team leaders or senior workers. Assumption A3 that young skilled workers complement the marginal product of senior skilled workers more than low skilled workers do is reasonable as well, as young skilled workers have better cognitive skills or are better at following instructions than low skilled workers. In Appendix A, we provide descriptive evidence from estimation of production function to support these three assumptions.

Firms maximize profits by selecting the optimal number of workers of each type, taking wages as given. The market wages for senior skilled workers, young skilled workers, and low skilled workers are represented by w_S, w_H, and w_L, respectively. Equalizing the marginal products to wages, we can derive the labor demands S^d, H^d, and L^d as follows:

$$\frac{\partial Y}{\partial S} = F_1 = w_S, \tag{2}$$

$$\frac{\partial Y}{\partial H} = F_2 = w_H, \tag{3}$$

$$\frac{\partial Y}{\partial L} = F_3 = w_L. \tag{4}$$

Market clearing conditions define the equilibrium wages, which occur when labor demand is equal to supply. As our goal is to examine the effects of an exogenous shock to labor supply on wages, we can ignore the labor supply decisions of households and assume that labor supply is exogenously given at S^s, H^s, and L^s. Therefore, the equilibrium wages are determined by Eqs. (2) to (4), with S^d, H^d, and L^d replaced by S^s, H^s, and L^s, respectively. To simplify the notation, we hereafter use S, H, and L to represent the exogenously given labor supply and equilibrium employment levels.

We assume that the total number of young skilled workers and low skilled workers is fixed and normalized to 1, i.e., $H + L = 1$. A rise in young skilled workers, H in the theory, or college enrollment expansion in the real-world case, corresponds to a concurrent fall in the supply of low skilled workers, L, given the fixed size of the labor force.

We next examine the effects of college enrollment expansion on equilibrium wages w_S, w_H, and w_L by conducting a series of comparative static analyses. Taking the derivative of Eq. (2) with respect to H, we obtain

$$\frac{\partial w_S}{\partial H} = \frac{\partial^2 Y}{\partial S \partial H} - \frac{\partial^2 Y}{\partial S \partial L} = F_{12} - F_{13} > 0. \tag{5}$$

The effect is positive for the assumption that young skilled workers complement the productivity of senior skilled workers more than low skilled workers do. Therefore, college enrollment expansion increases the wages of senior skilled workers.

Taking the derivative of Eq. (3) with respect to H, we obtain

$$\frac{\partial w_H}{\partial H} = \frac{\partial^2 Y}{\partial H^2} - \frac{\partial^2 Y}{\partial H \partial L} = F_{22} - F_{23} < 0. \tag{6}$$

There are two effects that work toward the same conclusion. The first ($F_{22} < 0$) is the conventional supply effect: the marginal product of H declines with its own supply. The second is the cross effect: increases in the supply of young skilled workers imply a decrease in the supply of low skilled workers, which reduces the marginal product of young skilled workers, as $F_{23} > 0$. Similarly, the wages of low skilled workers should increase with the increase of young skilled workers, as

$$\frac{\partial w_L}{\partial H} = \frac{\partial^2 Y}{\partial L \partial H} - \frac{\partial^2 Y}{\partial L^2} = F_{32} - F_{33} > 0. \tag{7}$$

We subsequently examine the effects of college enrollment expansion on wage premiums. The college wage premium for young skilled workers (inexperienced college graduates) is defined as $\frac{w_H}{w_L}$. Taking its derivative with respect to H, we get

$$\frac{\partial \frac{w_H}{w_L}}{\partial H} = \frac{w_H}{w_L}\left(\frac{\frac{\partial w_H}{\partial H}}{w_H} - \frac{\frac{\partial w_L}{\partial H}}{w_L}\right) = \frac{w_H}{w_L}\left(\frac{F_{22} - F_{23}}{F_2} - \frac{F_{32} - F_{33}}{F_3}\right). \tag{8}$$

Applying Eqs. (6) and (7) gives $\frac{\partial \frac{w_H}{w_L}}{\partial H} < 0$.

Similarly, the college wage premium for senior skilled workers (experienced college graduates) is defined as $\frac{w_S}{w_L}$. Taking its derivative with respect to H, we get

$$\frac{\partial \frac{w_S}{w_L}}{\partial H} = \frac{w_S}{w_L}\left(\frac{\frac{\partial w_S}{\partial H}}{w_S} - \frac{\frac{\partial w_L}{\partial H}}{w_L}\right) = \frac{w_S}{w_L}\left(\frac{F_{12} - F_{13}}{F_1} - \frac{F_{32} - F_{33}}{F_3}\right). \tag{9}$$

Eq. (9) shows that the sign of $\frac{\partial \frac{w_S}{w_L}}{\partial H}$ depends on the magnitudes of the percentage changes in related wages. To determine these magnitudes, we need to use a specific production function.

We consider a commonly used CES production function with the following form:

$$Y = F(S, H, L) = \left\{S^{\frac{\gamma-1}{\gamma}} + G^{\frac{\gamma-1}{\gamma}}\right\}^{\frac{\gamma}{\gamma-1}}, \tag{10}$$

where

$$G = \left[A_H H^{\frac{\sigma-1}{\sigma}} + A_L L^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

can be viewed as an intermediate good that is jointly produced by H and L. The parameters γ and σ are the elasticities of the substitutions among the various inputs. We assume that $\sigma > \gamma$, which implies that the substitutability between young skilled workers and low skilled workers is stronger than that between senior skilled workers and other workers. A_H and A_L are relative factor-augmenting technology terms with $A_H > A_L$. This implies that H type workers have a higher productivity than L type workers.

With this specific functional form, we have $w_S = F_1 = Y^{\frac{1}{\gamma}} S^{-\frac{1}{\gamma}}$, $w_H = F_2 = A_H Y^{\frac{1}{\gamma}} G^{\frac{1}{\sigma}-\frac{1}{\gamma}} H^{-\frac{1}{\sigma}}$ and $w_L = F_3 = A_L Y^{\frac{1}{\gamma}} G^{\frac{1}{\sigma}-\frac{1}{\gamma}} L^{-\frac{1}{\sigma}}$. Moreover, we have

$$F_{12} = \frac{1}{\gamma} S^{-\frac{1}{\gamma}} Y^{\frac{2-\gamma}{\gamma}} G^{\frac{1}{\sigma}-\frac{1}{\gamma}} A_H H^{-\frac{1}{\sigma}} > 0,$$

and[5]

$$F_{12} - F_{13} = \frac{1}{\gamma} S^{-\frac{1}{\gamma}} Y^{\frac{2-\gamma}{\gamma}} G^{\frac{1}{\sigma}-\frac{1}{\gamma}} \left[A_H H^{-\frac{1}{\sigma}} - A_L L^{-\frac{1}{\sigma}}\right] > 0.$$

These results suggest that the assumptions A1 ($F_{12} > 0$) and A3 ($F_{12} - F_{13} > 0$) will be satisfied, but A2 ($F_{23} > 0$) is not guaranteed, and thus we still need to impose this assumption.[6]

We next examine how an exogenous rise in H affects the wage premiums. As the college wage premium for young skilled workers can be written as

$$\frac{w_H}{w_L} = \frac{A_H}{A_L}\left(\frac{L}{H}\right)^{\frac{1}{\sigma}},$$

we have

$$\frac{\partial \frac{w_H}{w_L}}{\partial H} = -\frac{A_H}{A_L}\left(\frac{L}{H}\right)^{\frac{1}{\sigma}-1} \frac{1}{\sigma H^2} < 0. \tag{11}$$

Eq. (11) says that the college wage premium for young skilled workers declines with college enrollment expansion. We summarize this in Proposition 1.

Proposition 1. $\frac{\partial \frac{\mathrm{w_H}}{\mathrm{w_L}}}{\partial \mathrm{H}} < 0$, that is, the college enrollment expansion decreases the college wage premium for young skilled workers.

The effect on the wage premium of senior skilled workers is more complicated. The wage ratio can be expressed as $\frac{w_S}{w_L} = \alpha G^{\frac{1}{\gamma}-\frac{1}{\sigma}} L^{\frac{1}{\sigma}}$, where $\alpha \equiv S^{-\frac{1}{\gamma}}/A_L$. We can then derive

$$\frac{\partial \frac{w_S}{w_L}}{\partial H} = \frac{w_S}{w_L}\left[G^{\frac{1-\sigma}{\sigma}}\left(\frac{\sigma-\gamma}{\sigma\gamma}\right)\left(A_H H^{-\frac{1}{\sigma}} - A_L L^{-\frac{1}{\sigma}}\right) - \frac{1}{\sigma}\frac{1}{L}\right]. \tag{12}$$

Given the assumption that $\sigma > \gamma$, Eq. (12) shows that the sign of $\frac{\partial \frac{w_S}{w_L}}{\partial H}$ depends on the level of H (and that of L).

When the economy is short of young skilled workers, it is likely that $\frac{\partial \frac{w_S}{w_L}}{\partial H} > 0$, that is, college enrollment expansion increases the college wage premium for senior skilled workers. The scarcity of young skilled workers has two implications. First, when H is small and L is large, $A_H H^{-\frac{1}{\sigma}} - A_L L^{-\frac{1}{\sigma}} > 0$ holds. It actually corresponds to our earlier assumption of a higher cross productivity between S and H ($F_{12} > F_{13}$) for the general production function. Second, the scarcity of skilled workers implies that the last term on the right hand side of Eq. (12) is small and thus negligible. Proposition 2 summarizes this and the proof is given in Appendix B. Moreover, it

[5] In developing countries, it is often the case that the number of skilled workers is less than the number of unskilled workers, i.e., $H < L$. This directly leads to $F_{12} - F_{13} > 0$ as $\frac{A_H}{A_L} > 1 > \left(\frac{H}{L}\right)^{\frac{1}{\sigma}}$.

[6] To satisfy $F_{23} > 0$, we would need a small level of S, as it can be derived that $F_{23} = A_H H^{-\frac{1}{\sigma}} A_L L^{-\frac{1}{\sigma}} \frac{1}{\gamma} Y^{\frac{1}{\gamma}} G^{\frac{2}{\sigma}-\frac{1}{\gamma}-1}\left[\frac{G^{\frac{\gamma-1}{\gamma}}}{S^{\frac{\gamma-1}{\gamma}} + G^{\frac{\gamma-1}{\gamma}}} - \frac{\sigma-\gamma}{\sigma\gamma}\right]$. We think this is not an unreasonable assumption, as the number of managers or workers in high positions is always a smaller number than the number of all other employees.

shows that when $\sigma > 1$, $\frac{\partial \frac{w_S}{w_L}}{\partial H}$ is strictly monotonically decreasing in H and there exists a threshold of young skilled workers H^* such that $\frac{\partial \frac{w_S}{w_L}}{\partial H}$ is positive initially but starts to decline as H rises.[7]

Proposition 2. There exists a threshold H^* such that $\frac{\partial \frac{w_S}{w_L}}{\partial H} > 0$ for $H < H^*$ and $\frac{\partial \frac{w_S}{w_L}}{\partial H} < 0$ for $H > H^*$, that is, if young skilled workers are scarce, then the college enrollment expansion increases the college premium for senior skilled workers.

Propositions 1 and 2 lead to the following hypotheses.

Hypothesis 1. *The college premium for young skilled workers decreases with college expansion.*

Hypothesis 2. *The college premium for senior skilled workers increases with college expansion when skill (college education) is scarce in the labor market.*

We draw on Chinese data to test these hypotheses. Hypotheses 1 and 2 imply that the effect of college expansion on the average wage premium is ambiguous. Two offsetting effects exist. First, the college premium for senior skilled workers will increase. However, the college premium for young skilled workers will decline. When the positive effect dominates, the average effect will be positive; in other words, an increase in the supply of college graduates will increase the college wage premium.

3. Empirical strategy

We test our hypotheses by estimating the following model for workers in different age groups:

$$\ln w_{ipt} = \alpha_0 + \alpha_1 College_{ipt} + \alpha_2 Young\ Skilled_{pt} + \alpha_3 College_{ipt} \times Young\ Skilled_{pt} + \alpha_4 Young\ Population_{pt} + X_{ipt}\beta + \mu_p + \nu_t + \mu_p \times t + \varepsilon_{ipt}. \tag{13}$$

$\ln w_{ipt}$ is the log of annual earnings for individual i in province p in year t. $College_{ipt}$ is a dummy variable that equals 1 for individuals with a college degree. $Young\ Skilled_{pt}$ is the number of college graduates aged 20–24 in province p in year t. The coefficient on the interaction of $College_{ipt}$ and $Young\ Skilled_{pt}$, α_3, captures the effect of the supply of young skilled workers on the college premium. Considering that provinces having larger young population might have more young skilled workers, we control for $Young\ Population_{pt}$ (i.e. 20–24 years old individuals) in the regression. X_{ipt} is a vector of variables including a male dummy, age, and age squared. We also control for province fixed effects (μ_p), year fixed effects (ν_t), and province-specific time trends ($\mu_p \times t$). ε_{ipt} is an error term with a zero mean. The standard errors are clustered at the province level to account for the correlation of individuals within the same province.[8]

Our theoretical model suggests that the college premium for senior skilled workers will increase with the number of young skilled workers, whereas the premium for young skilled workers will decline. This suggests that $\alpha_3 > 0$ for the senior cohorts, whereas $\alpha_3 < 0$ for the young cohorts. For the full sample, the two effects offset each other; therefore, the sign of α_3 is ambiguous.

Consistent OLS estimates of α_3 (and α_2) require that there should be no unobserved shocks to earnings that co-vary with the supply of young college-educated workers. One important unobserved determinant of earnings is a change in demand for skilled labor. If the unobserved demand for young skilled labor is correlated with its contemporary supply, then the OLS estimator will be inconsistent.

The college enrollment expansion that began in 1999 significantly increased the supply of college graduates in subsequent years; this provides an opportunity to deal with the endogeneity problem. The expansion of higher education reflects the aspiration of the Chinese government to achieve mass higher education. Before 1997, the gross enrollment rate of higher education was consistently below 7%, significantly lower than the typical 15% criterion for mass higher education. A general consensus among researchers and policymakers was that China should expand its higher education system to meet the long-term need for social and economic development.

A concrete plan for college expansion was proposed in 1998 by Min Tang, the former chief economist of the Asian Development Bank Mission in China. The Chinese government followed his advice and decided to expand college enrollment in June 1999, one month before that year's college entrance examination. The enrollment of college freshmen from 1998 to 2009 grew by an average of 17% annually, increasing from one million in 1998 to seven million in 2009. Consequently, the total number of newly admitted regular undergraduate students increased from 6 million in 1998 to 20 million in 2009. At the same time, the gross enrollment rate of higher education increased from 9.8% to 21%. To absorb the enrollment increase, existing colleges set up multiple campuses and additional new colleges were established.

[7] The implication of $\sigma > 1$ is that the percentage change in the ratio of young skilled workers and low skilled workers employed by firms will be higher than the percentage change in the marginal rate of technical substitution (or percentage change in relative wages). It does not invalidate our earlier complementarity assumptions ($F_{12} > 0, F_{23} > 0$). Moreover, the purpose of this parameter specification is to derive the result of $\frac{\partial \frac{w_S}{w_L}}{\partial H} < 0$ for large values of H. As $\frac{\partial \frac{w_S}{w_L}}{\partial H}$ is always infinity when evaluated at $H = 0$, there always exists a threshold such that $\frac{\partial \frac{w_S}{w_L}}{\partial H} > 0$ for small value of H even when $\sigma \le 1$.

[8] The standard error clustered over provinces could be biased since we only have 9 provinces. For the sake of statistical inference, we also use the method of wild bootstrap proposed by Cameron, Gelbach, and Miller (2008) to calculate the empirical P-values (using STATA code "cgmwildboot"). The significance levels are quite similar. We do not report these P-values in the paper but they are available upon request.

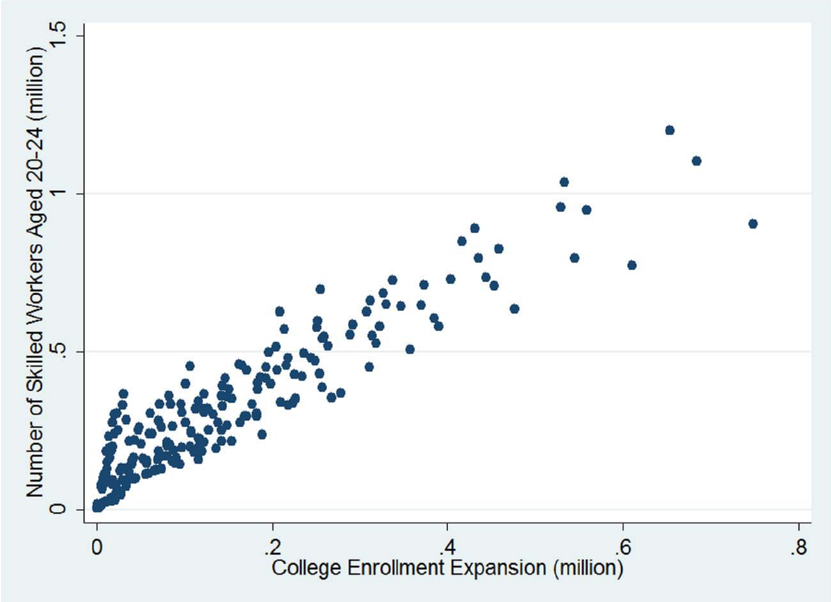

Fig. 3. Correlation between college enrollment expansion and young skilled workers (2003–2009).
Notes: college enrollment expansion is the sum of potential enrollment expansion from six years previously until four years previously for each province in each year in the 2003 to 2009 period. The potential enrollment expansion is the product of the deviation of actual national enrollment from its pre-1999 linear time trend and the provincial share of national enrollment in 1998.

A shortcoming of directly using actual college enrollment expansion as an IV is that each province may have also considered expected increases in the demand for skilled labor when it set its level of expansion. Therefore, we use potential college enrollment expansion to construct the IV. The potential college enrollment expansion of province p in year s is calculated as

$$\text{Potential Expansion}_{ps} = \text{Total Expansion}_{s} \times \text{Enrollment Share}_{p,1998} \tag{14}$$

where Total Expansion$_s$ is the deviation of actual national enrollment from its pre-1999 linear time trend in year s, and Enrollment Share$_{p,1998}$ is the provincial share of national enrollment in 1998. Unlike the actual college enrollment expansion in a province, which may partially reflect the anticipated future demand for skills, the potential college enrollment expansion is determined only by a province's latent enrollment capacity, in which case every province expands its college enrollment in proportion to this pre-determined capacity. In other words, the actual college enrollment expansion would be equal to its potential level only if every province expanded its college enrollment merely as a response to the national policy.

As it takes four years to graduate from college, and the normal age of a college graduate is 22, most skilled workers between 20 and 24 years old in the current year have entered college four to six years ago; accordingly, we define our IV, Expansion$_{pt}$, as the sum of potential college enrollment expansion,

$$\text{Expansion}_{pt} = \sum_{s=t-6}^{t-4} \text{Potential Expansion}_{ps}. \tag{15}$$

Fig. 3 plots the number of young skilled workers against the variable "Expansion," which we have just defined. There seems to be a strong positive correlation between these two variables. By using Expansion$_{pt}$ as the instrument, we leverage the abrupt policy change that led to a huge increase in the supply of young college-educated workers, while excluding the variation in provincial college expansion that may be related to demand factors.

4. Data

Our main analysis uses the UHS data collected by the National Bureau of Statistics (NBS) of China. The UHS covers all of the provinces in China and uses probabilistic sampling and a stratified multistage method to select households. The UHS is a pooled cross-sectional data set in which one-third of the sample is replaced each year, and the entire sample is changed every three years. The survey collects demographic and income information on every family member. We have access to data for nine provinces over the 1994 to 2009 period.[9] The mean values and trends of the most important variables in our sample are similar to those in the national sample. All of the individuals aged between 20 and 60 who have positive earnings are retained for analysis. Our final sample consists

[9] Our sample includes Beijing, Liaoning, Zhejiang, Anhui, Hubei, Guangdong, Sichuan, Shaanxi, and Gansu.

Table 1
Summary statistics of the UHS sample and provincial variables.

Panel A: individual characteristics

	Full sample	Aged 20–24	Aged 25–29	Aged 30–39	Aged 40–60
Annual earnings (yuan)	7213.586	4236.165	6606.932	7538.455	7379.835
	(7494.968)	(3814.979)	(6171.077)	(7601.231)	(7784.443)
College	0.312	0.350	0.471	0.381	0.249
	(0.463)	(0.477)	(0.499)	(0.486)	(0.432)
Male	0.533	0.472	0.471	0.484	0.572
	(0.499)	(0.499)	(0.499)	(0.500)	(0.495)
Age	40.947	22.510	27.054	35.018	47.589
	(9.321)	(1.338)	(1.412)	(2.817)	(5.322)
Observations	286,267	13,339	24,639	84,387	163,902

Panel B: yearly provincial variables

Young Skilled (million)	0.289
	(0.186)
Young Population (million)	3.798
	(2.074)
Expansion (million)	0.077
	(0.124)
GDP (billion yuan)	303.347
	(282.285)
Export (billion yuan)	109.646
	(226.414)
FDI (billion yuan)	12.492
	(16.111)
Scarcity	0.691
	(0.146)
Observations	144

Notes: standard deviations are shown in parentheses. College is a dummy variable that equals 1 if the worker has a college degree, and 0 otherwise. Young Skilled is the number of college-educated workers aged 20–24 years. Expansion is the deviation of actual national enrollment four years previously from its pre-1999 linear time trend, multiplied by the provincial share of national enrollment in 1998. Scarcity is the fraction of workers aged 20–24 years without a college degree.

of 286,267 individuals.

In addition to the UHS data, we obtain provincial-level data from several statistical yearbooks and 2000 population census. Specifically, the size of college enrollment at the provincial level is derived from the Educational Statistics Yearbook of China. The provincial GDP and export values are obtained from the official website of the NBS. The value of foreign direct investment is derived from the China Compendium of Statistics 1949–2008. The annual number of young skilled workers and young population in each province is derived from the 2000 population census.

Table 1 presents the summary statistics of the sample. Panel A shows the individual characteristics. For the entire sample (column 1), the average annual earnings are 7214 yuan. About 31% of the individuals have a college degree, and 53% are male. The average age is 41 years. We also report the means for different age groups (20–24, 25–29, 30–39, and 40–60). In general, younger groups have lower earnings, fewer men, and more college graduates. Panel B displays the provincial variables. On average, there are 0.289 million young skilled workers (i.e., workers with college degrees and between 20 and 24 years old). The potential college enrollment expansion is 0.077 million.

5. Empirical results

In this section, we estimate Eq. (13) and examine the effect of an increasing supply of young college graduates on college premiums. We first present the ordinary least squares (OLS) results, which serve as a benchmark. To test our two hypotheses, we then compare the effects on young and old workers. Finally, we test Hypothesis 2 by examining the scarcity of young skilled workers.

Table 2
OLS estimates of the effects of the supply of young skilled workers on college premiums in urban China.

	Dependent variable: ln(annual income)					
	Full sample	Full sample	Aged 20–24	Aged 25–29	Aged 30–39	Aged 40–60
	(1)	(2)	(3)	(4)	(5)	(6)
College	0.520***	0.463***	0.125	0.382***	0.439***	0.524***
	(0.020)	(0.021)	(0.073)	(0.036)	(0.014)	(0.032)
Young Skilled (million)		0.357**	0.360	0.563*	0.339**	0.332
		(0.117)	(0.236)	(0.247)	(0.110)	(0.193)
College × Young Skilled		0.158**	− 0.148	0.064	0.156**	0.158*
		(0.055)	(0.131)	(0.095)	(0.056)	(0.080)
Male	0.387***	0.388***	0.050*	0.162***	0.294***	0.495***
	(0.024)	(0.024)	(0.025)	(0.028)	(0.026)	(0.029)
Age	0.144***	0.144***	0.369	0.089	0.110***	0.215***
	(0.007)	(0.007)	(0.220)	(0.137)	(0.028)	(0.017)
Age squared	− 0.002***	− 0.002***	− 0.005	− 0.001	− 0.001***	− 0.002***
	(0.000)	(0.000)	(0.005)	(0.003)	(0.000)	(0.000)
Young Population (million)		0.019**	0.025	0.003	− 0.001	0.036***
		(0.006)	(0.021)	(0.015)	(0.009)	(0.008)
Constant	5.049***	4.905***	2.159	5.765**	5.730***	3.066***
	(0.125)	(0.151)	(2.411)	(1.782)	(0.500)	(0.415)
Observations	286,267	286,267	13,339	24,639	84,387	163,902
R-squared	0.348	0.348	0.272	0.412	0.414	0.319

Notes: standard errors, clustered over province, are shown in parentheses. Province dummies, year dummies, and province-specific time trends are controlled in all of the regressions. College is a dummy variable that equals 1 if the worker has a college degree, and 0 otherwise. Young Skilled is the number of college-educated workers aged 20–24 years.

* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.

5.1. OLS estimates using the full sample

Before testing our hypotheses, we first report the OLS estimation results using the full sample, which can be benchmarked to previous findings in the literature. In the first column of Table 2, we report estimates of the standard Mincer equation, i.e., without considering the effect of the supply shock. The estimated college premium is 52% for the full sample, which is comparable to the estimates in previous studies (Li, Liu, & Zhang, 2012; Zhang et al., 2005).[10]

We then allow the college wage premium to vary with the supply of young skilled workers by estimating Eq. (13). As shown in column 2 of Table 2, the coefficient on the interaction term of college dummy and the number of young skilled workers in the labor market is positive and significant at the 5% level. This means that an increasing supply of young college graduates actually increases the average college premium for the full sample. We next test whether this positive effect is due to differences between young and old workers.

5.2. OLS estimates: young vs. old workers

We next test our hypotheses by separately estimating the effect of an increasing supply of young skilled workers on college premiums for different age groups, i.e., the 20–24, 25–29, 30–39, and 40–60 age groups. According to our hypotheses, an increase in the supply of young skilled workers should depress their own skill wage premiums but increase those of senior skilled workers.

The results reported in columns 3–6 of Table 2 indeed show that the supply of young skilled workers has varying effects on the college premiums of different age groups. The coefficient on the interaction term between the college dummy and the number of young skilled workers is negative for the 20–24 age group; this is consistent with Hypothesis 1, which suggests that the college wage premium for young workers decreases with the supply of young skilled labor, although the effect is not precisely estimated. The coefficient on the interaction term becomes positive for the 25–29 group, and positive and statistically significant for the two more senior age groups (30–39 and 40–60). These estimates are consistent with Hypothesis 2, which states that the college premiums for senior workers increase with the supply of young skilled workers. The significant estimates for the senior groups suggest that a one standard deviation increase in young skilled workers (200 thousand) increases the college premium for individuals aged 30–60 years by about three percentage points.

[10] Li et al. (2012) use the Chinese Twins Survey and estimate that the return to college education in China is 35.7%–40.0% in 2002; Zhang et al. (2005) use the UHS data and find that returns to college versus high school and primary school are 32.1% and 60.5%, respectively, in 1998.

Table 3
IV Estimates of the effects of the supply of young skilled workers on college premiums in urban China.

	Dependent variable: ln(annual earnings)				
	Full sample	Aged 20–24	Aged 25–29	Aged 30–39	Aged 40–60
	(1)	(2)	(3)	(4)	(5)
College	0.425***	0.164**	0.370***	0.413***	0.474***
	(0.025)	(0.069)	(0.037)	(0.015)	(0.037)
Young Skilled (million)	0.370**	0.438	0.115	0.374***	0.407
	(0.185)	(0.282)	(0.244)	(0.080)	(0.324)
College × Young Skilled	0.263***	− 0.264**	0.098	0.228***	0.296***
	(0.078)	(0.107)	(0.108)	(0.063)	(0.110)
Male	0.388***	0.049**	0.163***	0.295***	0.495***
	(0.023)	(0.023)	(0.026)	(0.024)	(0.027)
Age	0.144***	0.364*	0.085	0.110***	0.214***
	(0.006)	(0.210)	(0.131)	(0.027)	(0.016)
Age squared	− 0.002***	− 0.005	− 0.001	− 0.001***	− 0.002***
	(0.000)	(0.005)	(0.002)	(0.000)	(0.000)
Young Population (million)	0.019***	0.025	0.005	− 0.001	0.034***
	(0.007)	(0.020)	(0.022)	(0.009)	(0.010)
Observations	286,267	13,339	24,639	84,387	163,902
R-squared	0.348	0.272	0.411	0.414	0.319
Cragg-Donald Statistics	220,000	10,648	19,071	69,840	120,000

Notes: standard errors, clustered over province, are shown in parentheses. Province dummies, year dummies, and province-specific time trends are controlled in all of the regressions. College is a dummy variable that equals 1 if the worker has a college degree, and 0 otherwise. Young Skilled is the number of college-educated workers aged 20–24 years. Expansion and its interaction with the college dummy are used as the IVs for Young Skilled and its interaction with the college dummy.

* Significant at 10%.

** Significant at 5%.

*** Significant at 1%.

5.3. IV estimates

To account for possible endogeneity in the supply of young skilled workers, we next turn to the IV estimates. Specifically, we use *Expansion* (and its interaction with the college dummy) defined in Section 4, as the instrument for the supply of young skilled workers (and its interaction with the college dummy).

The IV estimates,[11] which are displayed in Table 3,[12] exhibit a very similar pattern to the OLS estimates. For the full sample (column 1), the coefficient of the interaction of the supply of young skilled workers and the college dummy is positive and significant at the 1% level. More importantly, the results for different age groups are consistent with our hypotheses. For the youngest age group (20–24), the coefficient of the interaction term is negative and significant, suggesting that the supply of young college-educated workers can have a negative effect on the college premium of young college graduates. The point estimate suggests that an increase of one standard deviation in the supply of young skilled labor decreases the college premium for workers aged 20–24 by 5.2 percentage points. For workers aged 25–29, however, the coefficient of the interaction term is positive but not statistically significant. For workers aged 30–39 and 40–60, the coefficients of the interaction term are both positive and significant at the 1% level. According to our estimates, a one standard deviation increase in the supply of young skilled labor increases the college premium for workers in the 30–39 and 40–60 age groups by 4.5 and 6 percentage points, respectively. Taken together, the findings of the IV estimation for different age groups support Hypotheses 1 and 2.

The IV estimation requires that the instrument should not affect the dependent variable, i.e., earnings, through channels other than the endogenous variable. In our case, the variation in the IV (i.e., potential college enrollment expansion at the province level) comes from two sources: the cross-province variation in college enrollment relative to national total enrollment in 1998 and the abrupt increase in total enrollment nationwide after 1999 due to the policy change. If the 1998 provincial enrollment ratio correlates with future demand for skilled labor in the province, then our IV estimates will be inconsistent.

To address this concern, we directly test whether our IV is correlated with demand factors. Specifically, we regress both four-year-lagged expansion and current expansion on the demand factors, in the expectation that college expansion is correlated with neither current nor future demand factors. The regression results reported in Table 4 show that our instrumental variable, "Expansion", is not correlated with provincial-level demand factors such as GDP, FDI, or export.

[11] The first stage results are displayed in Appendix Table 3.

[12] The associated Cragg-Donald Statistics, shown in the last row of Table 4, far exceed the conventional critical values for the Stock-Yogo weak identification test (Stock & Yogo, 2005). The detailed estimation results of the first stage regressions are shown in Appendix Table 2.

Table 4
Correlation between college enrollment expansion and the demand factors.

	Dependent variables					
	Expansion (four-year-lagged)			Expansion (current year)		
	(1)	(2)	(3)	(4)	(5)	(6)
ln(GDP)	0.022*	− 0.001**	− 0.012***	− 0.009	− 0.012	− 0.015
	(0.124)	(0.106)	(0.111)	(0.020)	(0.020)	(0.021)
ln(FDI)		− 0.002	− 0.001		− 0.001	− 0.001
		(0.010)	(0.010)		(0.001)	(0.001)
ln(export)			0.015			0.002
			(0.027)			(0.004)
Observations	496	489	486	496	489	486
R-squared	0.920	0.925	0.926	0.989	0.991	0.991

Notes: standard errors, clustered over province, are shown in parentheses. In all of the regressions, year dummies, provincial dummies, and province-specific time trends are included.
* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.

Table 5
Instrument variable estimates of effects of the supply of young skilled workers by scarcity of skilled workers.

	Dependent variable: ln(annual earnings)			
	Aged 20–24	Aged 25–29	Aged 30–39	Aged 40–60
	(1)	(2)	(3)	(4)
College	− 0.167	0.551***	1.039***	0.923***
	(0.222)	(0.146)	(0.118)	(0.096)
Young Skilled (million)	0.830**	− 0.408	0.791***	0.283
	(0.370)	(0.500)	(0.264)	(0.579)
Scarcity	0.676	− 0.635**	0.200	− 0.188
	(0.449)	(0.263)	(0.170)	(0.260)
College × Young Skilled	0.084	− 0.846*	− 1.195***	− 0.520
	(0.528)	(0.469)	(0.266)	(0.323)
Scarcity × College	0.446	− 0.482	− 1.077***	− 0.732***
	(0.375)	(0.336)	(0.214)	(0.196)
Scarcity × Young Skilled	− 1.509*	1.416	− 0.417	0.598
	(0.839)	(0.893)	(0.714)	(0.821)
Scarcity × College × Young Skilled	− 0.228	2.346*	2.677***	1.351
	(1.085)	(1.214)	(0.744)	(0.839)
Male	0.049**	0.163***	0.297***	0.497***
	(0.024)	(0.026)	(0.024)	(0.028)
Age	0.353*	0.091	0.113***	0.215***
	(0.213)	(0.127)	(0.029)	(0.016)
Age squared	− 0.005	− 0.001	− 0.001***	− 0.002***
	(0.005)	(0.002)	(0.000)	(0.000)
Young Population	0.019	0.013	− 0.001	0.038***
	(0.018)	(0.016)	(0.013)	(0.014)
Observations	13,339	24,639	84,387	163,902
R-squared	0.273	0.411	0.415	0.319

Notes: standard errors, clustered over province, are shown in parentheses. In all of the regressions, year dummies, provincial dummies, and province-specific time trends are included. College is a dummy variable that equals 1 if the worker has a college degree, and 0 otherwise. Young Skilled is the number of college graduates aged 20–24 years old in each province and each year. Scarcity is the one-year-lagged percentage of worker without a college degree in those aged 20–24 years old. Expansion and its interactions with other variables are used as the IVs for Young Skilled and its interactions with the other variables.
* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.

5.4. *Scarcity of college graduates*

A condition for Hypothesis 2 is a scarcity of college graduates in the labor force. We argue that the college premium for senior workers increases with college expansion in a labor market where college graduates are scarce. We construct a new variable, *Scarcity*, which is the fraction of workers between the ages of 20 and 24 without a college education in the labor force in a given province in

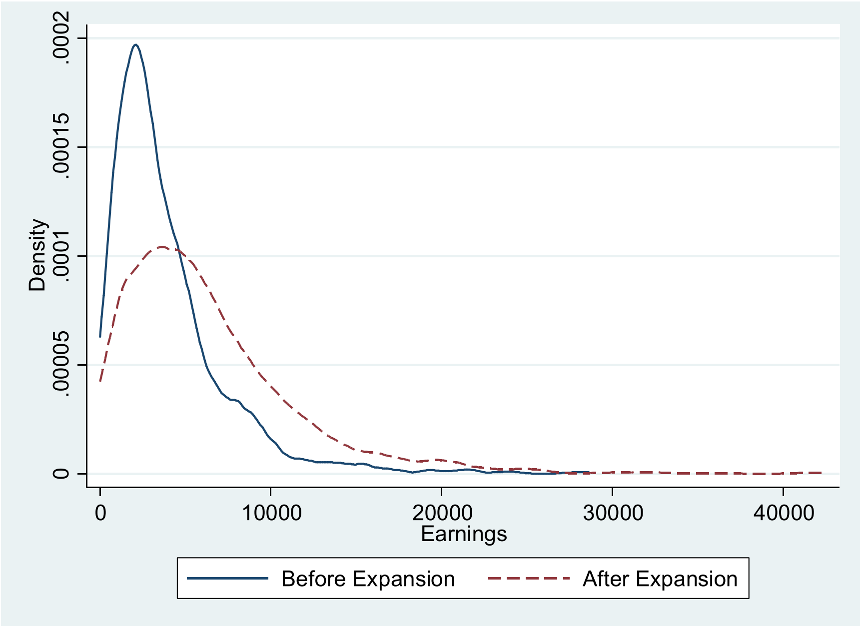

Fig. 4. Distribution of earnings for young skilled workers (20–24 years old).
Source: China Urban Household Survey (1994–2009)

the previous year. We then add to the regressions (using subsamples stratified by age) a triple interaction term of scarcity, the college dummy, and the number of young skilled workers. All of the relevant double interaction terms are also included in the regressions.

The IV estimation results reported in Table 5 indicate that the college premium of senior workers increases with the number of young skilled workers when college educated workers are scarce in the labor force. For the youngest age group, the coefficient on the triple interaction is negative, but not statistically significant at conventional levels. For all three older age groups, the coefficients on the triple interactions are positive and significant, confirming the idea that the college premium of senior workers increases with the supply of young skilled workers when college educated workers are scarce in the market.

6. Alternative explanations

There could be other explanations which account for the diverging college premiums. One possibility is that the college enrollment expansion could lead to a decline in college education quality which would cause the decrease of wages for young skilled workers who graduated from college after the college enrollment expansion. Another possibility lies in that the dramatic increase of young college graduates might crow out those older college-educated workers in the labor market. Older workers with lower wages are more likely to exit the labor market such that workers remaining in the labor mark are those having higher wages. We investigate whether these concerns are valid in this section.

Since we do not have direct measurement of education quality, we therefore compare the wage distribution of young college-educated workers before and after the college enrollment expansion. If the college education quality decreased after the expansion and drove down the wages of young college graduates, we should see a leftward shift of the wage distribution after the expansion. Fig. 4 shows that there is no leftward shift. In contrast, the average wage level of young skilled workers after the reform (about 6270 yuan) is even higher than that before the reform (about 3867 yuan). It suggests that the possible decline of college education quality is not the reason driving our main results. However, one caveat we need to bear in mind is that, without a good measurement of college quality, our results presented here can only be considered as suggestive.

We then estimate the effect of the number of young college-educated workers on the employment status of the older college-educated workers. Table 6 shows the results. In this table, the outcome variable is an indicator for having earnings. Column 1 shows the result using individuals aged 25–60 years and columns 2–4 are for individuals aged 25–29, 30–39 and 40–60, respectively. We use expansion as an IV for the number of young skilled workers. As shown in the table, none of the coefficients of the young skilled workers is significant. It suggests that there is no evidence for the existence of crowing-out effects of young skilled workers on older skilled workers.

Table 6
IV estimates of the effects of the supply of young skilled workers on employment of senior college workers.

	Dependent variable: dummy for having positive income			
	Aged 25–60	Aged 25–29	Aged 30–39	Aged 40–60
	(1)	(2)	(3)	(4)
Young Skilled (million)	− 0.006	0.096	− 0.032	− 0.010
	(0.031)	(0.136)	(0.031)	(0.040)
Male	0.043***	− 0.021***	0.016***	0.088***
	(0.004)	(0.006)	(0.004)	(0.006)
Age	0.061***	0.417***	0.018**	0.131***
	(0.004)	(0.085)	(0.009)	(0.007)
Age squared	− 0.001***	− 0.007***	− 0.000*	− 0.001***
	(0.000)	(0.002)	(0.000)	(0.000)
Young Population (million)	− 0.002	0.003	− 0.003**	− 0.003
	(0.002)	(0.008)	(0.002)	(0.003)
Constant	− 0.155*	− 5.136***	0.651***	− 1.861***
	(0.082)	(1.144)	(0.157)	(0.142)
Observations	89,663	13,087	32,862	43,714
R-squared	0.111	0.053	0.012	0.173

Notes: standard errors, clustered over province, are shown in parentheses. Province dummies, year dummies, and province-specific time trends are controlled in all of the regressions. College is a dummy variable that equals 1 if the worker has a college degree, and 0 otherwise. Young Skilled is the number of college-educated workers aged 20–24 years. Expansion is used as the IV for Young Skilled.

* Significant at 10%.

** Significant at 5%.

*** Significant at 1%.

7. Conclusions

This study is motivated by the observation that the college premium has continued to increase even after a substantial increase in the supply of college-educated workers in China. In roughly a decade, the number of students admitted to college every year has grown almost five-fold in China. The unprecedented college expansion has dramatically increased the supply of college graduates in the Chinese labor market. Surprisingly, the returns to college education have slightly increased after the recent rapid expansion of college enrollment. Specifically, the college premium for younger workers has decreased, whereas that of older workers has increased over the same period.

We construct a simple model that incorporates complementarity among workers with different skill levels and ages. Our theoretical framework suggests that an increase in the number of young skilled workers will increase the marginal product of senior skilled workers. This outcome explains why the average college premium increases with an increase in the supply of young skilled workers.

The main hypotheses derived from our model are evaluated using the household survey data from China. Using the time and spatial variation in college expansion, we determine that the sudden increase in the supply of young college graduates exhibits an overall positive effect on the returns to college education in China. The positive effect is mostly attributed to the increase in college premiums for senior workers (aged 25–60 years); in fact, the college premium decreases for young workers (aged 20–24 years). Our findings provide empirical evidence of the complementarity among workers disaggregated by age and education and of the externalities of education across different cohorts.

These findings suggest that education has externalities that should be considered in policy evaluations. Although growth in the number of young college graduates may reduce the college premium for this group, it increases the college premium for senior workers. Consequently, the average college premium for the entire workforce has actually increased; that is, the overall effect of college expansion is positive in terms of the earnings of college graduates in the labor market. This indicates that college expansion improves productivity and should be continued as long as young college graduates can be compensated either through redistribution, such as subsidized education, or faster wage growth.

Appendix A. Labor complementarity in production

In this appendix, we provide some suggestive evidence for the complementarities among different types of workers in production. The biggest difficulty in testing worker complementarity in production lies in data limitations, as conventional firm-level datasets do not include detailed information about the number of employees by education, age, or position. The only Chinese dataset we are aware of that includes such information is a 5% random sample drawn from the Census of Industrial Firms of China in 1995, conducted by the National Bureau of Statistics of China. The dataset contains 18,000 firms and has information on output, total assets, and the number of employees by position and by education level; this allows us to test the complementarity hypotheses. However, one caveat is that we only have one year of data, which makes it impossible to use the methods proposed by Olley and Pakes (1996) and Levinsohn and Petrin (2003) to deal with the endogeneity problem in the estimation of the production function. Given the limitations of the cross-sectional data, our results can only be considered as suggestive evidence for the existence of complementarities among different types of workers.

We test whether workers of different types are complementary in production by estimating the following translog production function:

$$\begin{aligned}\ln Y_{ijp} &= \alpha_0 + \alpha_1 \ln(s_{ijp}) + \alpha_2 \ln(h_{ijp}) + \alpha_3 \ln(l_{ijp}) + \alpha_4 \ln(k_{ijp}) \\ &+ \alpha_{54apitalegen\ due\ to\ the\ space\ limit\ but\ available\ from\ authors\ upon\ request, 3-4), and\ 2004\ (columns\ 5-6).its\ due\ to\ the} \ln(s_{ijp}) \times ln(h_{ijp}) \\ &+ \alpha_6 \ln(s_{ijp}) \times ln(l_{ijp}) + \alpha_7 \ln(h_{ijp}) \times ln(l_{ijp}) + \alpha_8 \ln(s_{ijp}) \times ln(k_{ijp}) + \alpha_9 \ln(h_{ijp}) \times ln(k_{ijp}) + \alpha_{10} \ln(l_{ijp}) \times ln(k_{ijp}) \\ &+ \alpha_{11} [ln(s_{ijp})]^2 + \alpha_{12} [ln(h_{ijp})]^2 + \alpha_{13} [ln(l_{ijp})]^2 + \alpha_{14} [ln(k_{ijp})]^2 + \theta_j + \mu_p + \varepsilon_{ijp}. \end{aligned} \tag{16}$$

Y_{ijp} represents the total output of firm i in industry j in province p. s_{ijp} indicates the number of managers in the firm. h_{ijp} and l_{ijp} represent the number of workers with and without a college degree, respectively.[13] k_{ijp} represents capital and is measured by total assets. We also control for industry dummies, θ_j, and province dummies, μ_p. ε_{ijp} is the error term with a zero mean. The model is estimated by OLS, with standard errors calculated by clustering over the province-industry level.[14]

The regression results reported in Appendix Table 2 indicate that different types of workers are indeed complementary in production. The coefficient on the interaction of managers and college workers (both in logs) is positive and significant at the 1% level, suggesting that the marginal product of managers increases with the number of workers with a college degree. In other words, workers with a college degree are complementary to managers in production. The coefficient on the interaction of college workers and non-college workers is also positive and significant at the 5% level (column 2 where both province and industry dummies are controlled), suggesting that these two types of workers are also complementary to each other in production. However, the coefficient on the interaction of managers and non-college workers is statistically insignificant, suggesting that they are not complementary.

In summary, these descriptive regression results show that both senior skilled (managers) and low skilled (non-college) workers are complementary to young skilled (college) workers in production; and young skilled workers complement the marginal product of senior skilled workers more than low skilled workers do. This latter result is reasonable, as young skilled workers have better cognitive skills or are better at following instructions than low skilled workers.

Appendix B. Proof for Proposition 2

Proof: Plugging the expression of G into Eq. (13), we obtain $\frac{\partial \frac{w_S}{w_L}}{\partial H} = \frac{1}{\sigma L}\frac{w_S}{w_L}\left[\frac{\frac{\sigma-\gamma}{\gamma}\frac{A_H}{A_L}\left(\frac{H}{L}\right)^{-\frac{1}{\sigma}} - \frac{A_H}{A_L}\left(\frac{H}{L}\right)^{\frac{\sigma-1}{\sigma}} - \frac{\sigma}{\gamma}}{\frac{A_H}{A_L}\left(\frac{H}{L}\right)^{\frac{\sigma-1}{\sigma}}+1}\right]$. Let $g\left(\frac{H}{L}\right) \equiv \frac{\sigma-\gamma}{\gamma}\frac{A_H}{A_L}\left(\frac{H}{L}\right)^{-\frac{1}{\sigma}} - \frac{A_H}{A_L}\left(\frac{H}{L}\right)^{\frac{\sigma-1}{\sigma}} - \frac{\sigma}{\gamma}$, so that the sign of $\frac{\partial \frac{w_S}{w_L}}{\partial H}$ is equivalent to the sign of $g\left(\frac{H}{L}\right)$.

We first have

$$\lim_{\frac{H}{L}\to 0} g\left(\frac{H}{L}\right) = \infty - 0 - \frac{\sigma}{\gamma} = \infty\ ,$$

$$\lim_{\frac{H}{L}\to \infty} g\left(\frac{H}{L}\right) = 0 - \infty - \frac{\sigma}{\gamma} = -\infty\ .$$

We then have

$$g'(.) = -\frac{\sigma-\gamma}{\sigma\gamma}\frac{A_H}{A_L}\left(\frac{H}{L}\right)^{-\frac{1}{\sigma}-1} - \frac{\sigma-1}{\sigma}\frac{A_H}{A_L}\left(\frac{H}{L}\right)^{-\frac{1}{\sigma}} < 0.$$

The above formulation means that there exists one and only one threshold $\left(\frac{H}{L}\right)^*$ such that $g(h) > 0$ for $h \in \left[0, \left(\frac{H}{L}\right)^*\right)$ and $g(h) < 0$ for $h > \left(\frac{H}{L}\right)^*$. This further indicates that $\frac{\partial \frac{w_S}{w_L}}{\partial H} > 0$ for $H < H^*$ and < 0 for $H > H^*$. **Q.E.D.**

[13] We make the assumption that all managers are senior skilled workers; therefore, the number of young skilled workers is the number of employees with college degrees minus the number of managers.

[14] The summary statistics of variables used in the production function are shown in Appendix Table 1.

Appendix C. Appendix C

Appendix Table 1
Summary statistics of the 1995 Census of Industrial Firms of China.

	Observations	Mean	Standard deviation
Total output (million yuan)	17,974	133.022	648.717
Managers	17,974	932.071	306.192
College workers	17,974	706.812	158.880
Non-college workers	17,974	5096.430	1684.683
Capital (million yuan)	17,974	367.560	551.045

Appendix Table 2
Production function estimated using the 1995 Census of Industrial Firms of China.

Dependent variable: ln(total output)	(1)	(2)
ln(managers)	1.252***	1.148***
	(0.172)	(0.162)
ln(college workers)	− 0.522***	− 0.521***
	(0.088)	(0.076)
ln(non-college workers)	0.459***	0.633***
	(0.159)	(0.153)
ln(capital)	− 0.380***	− 0.256***
	(0.068)	(0.063)
ln(managers) × ln(college workers)	0.090***	0.050***
	(0.022)	(0.017)
ln(managers) × ln(non-college workers)	− 0.027	− 0.011
	(0.038)	(0.031)
ln(college workers) × ln(non-college workers)	0.020	0.029**
	(0.022)	(0.013)
ln(managers) × ln(capital)	− 0.073***	− 0.065***
	(0.018)	(0.015)
ln(college workers) × ln(capital)	− 0.024***	− 0.011
	(0.008)	(0.007)
ln(non-college workers) × ln(capital)	− 0.023*	− 0.045***
	(0.014)	(0.012)
ln(managers) squared	− 0.044*	− 0.042*
	(0.025)	(0.022)
ln(college workers) squared	0.014**	0.029***
	(0.007)	(0.006)
ln(non-college workers) squared	0.015	0.014
	(0.018)	(0.017)
ln(capital) squared	0.072***	0.064***
	(0.004)	(0.003)
Industry dummies	Yes	Yes
Provincial dummies	No	Yes
Observations	17,974	17,974
R-squared	0.62	0.68

Notes: the translog production functions are estimated with data from the 1995 Census of Industrial Firms of China. Standard errors, clustered over province-industry, are shown in parentheses.

* Significant at 10%.

** Significant at 5%.

*** Significant at 1%.

Appendix Table 3

First stage results of the effects of the supply of young skilled workers on college premiums in urban China.

Dependent variables	Full sample		Aged 20–24		Aged 25–29		Aged 30–39		Aged 40–60	
	Young Skilled (million)	College × Young Skilled	Young Skilled (million)	College × Young Skilled	Young Skilled (million)	College × Young Skilled	Young Skilled (million)	College × Young Skilled	Young Skilled (million)	College × Young Skilled
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
College	0.001**	0.194***	0.003	0.201***	0.002	0.199***	0.001	0.190***	0.001	0.196***
	(0.001)	(0.025)	(0.002)	(0.029)	(0.001)	(0.027)	(0.001)	(0.026)	(0.001)	(0.025)
Expansion (million)	1.721***	0.118	1.720***	0.201	1.753***	0.216	1.702***	0.083	1.723***	0.108
	(0.339)	(0.140)	(0.337)	(0.219)	(0.353)	(0.220)	(0.298)	(0.158)	(0.352)	(0.103)
College × Expansion	− 0.008	1.261***	− 0.018	1.250***	− 0.016	1.241***	− 0.008	1.289***	− 0.009	1.250***
	(0.006)	(0.113)	(0.013)	(0.122)	(0.009)	(0.115)	(0.007)	(0.105)	(0.005)	(0.120)
Male	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	− 0.000	0.000
	(0.000)	(0.001)	(0.000)	(0.002)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
Age	− 0.000*	− 0.000	0.000	− 0.009	− 0.005	− 0.011	− 0.000	− 0.003	0.001*	0.001
	(0.000)	(0.000)	(0.004)	(0.011)	(0.006)	(0.009)	(0.001)	(0.002)	(0.000)	(0.000)
Age squared	0.000*	0.000*	0.000	0.000	0.000	0.000	0.000	0.000	− 0.000*	− 0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Young Population	0.008	0.004	0.008	0.009	0.007	0.008	0.005	0.006	0.009	0.002
(million)	(0.017)	(0.005)	(0.017)	(0.008)	(0.018)	(0.007)	(0.016)	(0.005)	(0.018)	(0.004)
Observations	286,267	286,267	13,339	13,339	24,639	24,639	84,387	84,387	163,902	163,902
R-squared	0.984	0.967	0.982	0.955	0.982	0.969	0.985	0.97	0.983	0.966

Notes: standard errors, clustered over province, are shown in parentheses. Province dummies, year dummies, and province-specific time trends are controlled in all of the regressions. College is a dummy variable that equals 1 if the worker has a college degree, and 0 otherwise. Young Skilled is the number of college-educated workers aged 20–24 years.

* Significant at 10%.

** Significant at 5%.

*** Significant at 1%.

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