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# Substitute or complement? Quantity–quality effects of agricultural production diversity and market access on diets

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ABSTRACT

In many developing countries, rural households meet their food needs through both self-production and market purchases, but evidence on the relative and joint roles of these channels in shaping dietary diversity and dietary quality remains limited. Using household panel data from rural China spanning 2004–2011, we provide micro-level evidence from a major developing-country context to examine the quantity–quality effects of agricultural production diversity, market access, and their interaction on dietary diversity and dietary quality. Fixed-effect models combined with an instrumental-variable strategy are used to address potential endogeneity. We find that both greater production diversity and improved market access enhance dietary diversity and dietary quality. A one-standard-deviation increase in agricultural production diversity raises the dietary diversity score and the Chinese Healthy Eating Index by 0.5 and 0.71 standard deviations, respectively. Similarly, reducing the distance to markets by one standard deviation increases both outcomes by 0.03 standard deviations. Further analysis reveals an overall substitution relationship between production diversity and market access in improving dietary outcomes. The marginal contribution of production diversity on dietary diversity and quality diminishes as market access improves, and vice versa. At the food-group level, however, functional complementarity exists between these two channels for soybeans and nuts, vegetables, and aquatic products. Diversified production supports higher intake of these foods when market access is limited, while better market access attenuates reliance on self-produced items by expanding access to a broader set of foods. Taken together, the findings highlight the continued importance of agricultural production diversification in improving diets where markets are thin, and underscore the critical role of improving market conditions, particularly in regions such as Africa and South Asia with persistently high market frictions.

## 1. Introduction

Food insecurity and malnutrition are long-standing global challenges. More than two billion people worldwide suffer from undernutrition and micronutrient deficiencies (Barrett, 2010; Passarelli et al., 2024). Rural populations in many developing countries are often among the most affected, largely due to limited access to diverse foods and healthy diets (Ameye et al., 2025). China, as a major developing country, exhibits similar challenges. Over the past few decades, China's unprecedented economic growth has lifted millions of people out of poverty and hunger, yet challenges remain in achieving adequate dietary diversity and quality, particularly in rural areas (Wang et al.,

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2022). Building a more resilient and nutrition-oriented food system is crucial for promoting high-quality diets and enhancing population well-being (Wang, Cai, et al., 2025; Wang & Lotze-Campen, 2025). This is particularly important given that external shocks, such as conflicts, extreme weather events, and the COVID-19 pandemic, exacerbate malnutrition to alarming levels (Pörtner et al., 2022; Zhou et al., 2024).

Increasing dietary diversity is widely recognized as a key strategy to meet human needs for multiple nutrients (Torheim et al., 2004; Zhao et al., 2017), a principle endorsed by the Chinese Dietary Guidelines which recommend an average intake of more than 12 types of foods per day and more than 25 types of foods per week (Chinese Society of Nutrition, 2022). However, despite the consensus on its necessity, the quality aspect of diversified diets is often overlooked (Chen et al., 2022; Purushotham, 2022). While a strand of literature finds positive effects of higher dietary diversity scores on nutritional and health outcomes (Korir et al., 2022; Wang, Xuan, et al., 2025), other studies caution that higher scores of dietary diversity do not necessarily reflect healthier diets and can be associated with a higher intake of energy-dense foods (de Oliveira Otto et al., 2018; Jayawardena et al., 2013). Hence, there is a need for more nuanced research to explore possible mechanisms to achieve more balanced diets that emphasize not only the diversity scores, but also the quality of diets.

There is a growing literature focusing on the channels of improving dietary diversity (Chegere & Stage, 2020; Ecker, 2018; Sibhatu et al., 2015). Non-separable household models outline the interlinkage between production and consumption in agricultural households (de Janvry et al., 1991; Dillon et al., 2015). Like elsewhere in the developing world, agricultural households in rural China primarily rely on their own agricultural production for both income and food consumption (Ping et al., 2023; Rigg et al., 2016). Diversifying agricultural production thus appears to be a viable and resilient option to increase food availability and dietary diversity scores. Empirical evidence on this relationship, however, is more mixed. While many cross-sectional studies find a positive and significant association between agricultural production diversity and dietary diversity scores (Jones, 2017; Koppmair et al., 2017; Kumar et al., 2015; Snapp & Fisher, 2015), more recent studies using panel data find a positive but weak relationship (Chegere & Stage, 2020; Nguyen & Qaim, 2025). As suggested by the non-separable household model (de Janvry et al., 1991), households involved in various agricultural activities may have a diversified diet through self-production, and households' production behaviors may also be influenced by their eating habits and preferences (Smith, 2006). The existing literature recognizes the two-way relationship between agricultural production diversity and dietary diversity, but has not seriously addressed this reverse causality issue except for a small number of studies (Dillon et al., 2015; Hirvonen & Hoddinott, 2017). The lack of ability to control for unobserved heterogeneity of the large majority of cross-sectional studies and the lack of attention to address the reverse causality of the few studies using panel data are part of the reasons for the inconclusive results of the existing literature. More research that addresses both the heterogeneity and reverse causality issues is needed to draw a more reliable relationship between production diversity and dietary diversity.

As China has rapidly transformed from a subsistence-oriented farming system to a more market-oriented system, market channels have become increasingly important for food accessibility and therefore dietary diversity (Wang, Liu, et al., 2017). Improved market access is found to contribute to increased dietary diversity scores in China in the past few decades (Liu et al., 2014; Wang, Huang, et al., 2017), and appears more effective than diversifying agricultural production (Huang & Tian, 2019; Sibhatu et al., 2015; Nguyen & Qaim, 2025). A follow-up question naturally arises as to what extent markets complement or substitute own production. This is of importance to guide future policy design toward nutrition-oriented agricultural transformation. However, the joint impacts of agricultural production diversity and market access on dietary diversity scores are poorly understood, as are their effects on closing the nutrition gaps with respect to the dietary guidelines. In addition, own production and market access might have different individual effects across food and demographic groups. For example, households' own production and access to markets may be more critical for children in early childhood, as diets of children at this phase are primarily shaped by the availability and accessibility of food within the household (Hirvonen & Hoddinott, 2017; Lovo & Veronesi, 2019). In another case, a closer distance to markets may crowd out the intake of vegetables and fruits with processed food (Timperio et al., 2008). Thus, the effect of market access on dietary quality is still unclear and warrants further exploration.

We use a large-scale national cohort data, the China Health and Nutrition Survey (CHNS), which is known for its high-quality dietary intake and health data (Huang & Tian, 2019; Lei & Shimokawa, 2020; Ren et al., 2022). It is one of the few datasets from China that has detailed information on individual nutrient intake, household agricultural production, and food markets over time (Lei & Shimokawa, 2020), making it especially well-suited for this study. By incorporating agricultural production, market access, dietary diversity, and dietary quality into a unified framework, we provide a nuanced investigation into the quantity–quality effects of agricultural production diversity and market access, as well as their rarely explored interaction, on dietary diversity and dietary quality in rural China.

Our study extends the existing literature mainly in three aspects. First, our analysis is not limited to dietary diversity scores but also fills the knowledge gap on the potential quality effects of agricultural production diversity and market access on diets. While most existing studies simply regard dietary diversity scores as comprehensive indicators of dietary quality (Arimond et al., 2010; Torheim et al., 2004), more evidence is needed on the relationship between dietary diversity and dietary quality before the scores are widely recommended. Dietary quality is not fully captured by dietary diversity scores that neglect intake amounts, and a higher score does not guarantee optimal intake of food groups. Second, this study delves into the interplay between agricultural production diversity and market access on dietary diversity and dietary quality, an issue that has been little explored in the existing research. Existing literature about the impacts of agricultural production diversity and markets on diets (Chegere & Stage, 2020; Huang & Tian, 2019; Kumar et al., 2015) often treats the two food-supply channels separately but rarely considers potential substitution or complementary effects. We also extend the literature on the heterogeneous effects across income, age, and food groups. As individuals with different characteristics have different abilities to cope with shocks that could affect their diets, our study is particularly relevant to policy in the wake of war and pandemics, with market fluctuation impacting diets and rising malnutrition, and is expected to shed light on less developed countries that are facing similar ongoing agricultural and dietary transitions. Third, we use panel data with fixed-effect (FE) and instrumental variable (IV) methods to address the unobserved individual heterogeneity and the endogeneity issue. Using cross-sectional data and failing to address these issues in the existing studies could lead to biased and inconsistent results (Huang & Tian, 2019; Jones, 2017; Sibhatu et al., 2015).

## 2. Conceptual framework

In this section, we provide a conceptual framework taking into account the intrinsic interlinkages between agricultural production diversity, market access, and dietary diversity and quality (Fig. 1). First, agricultural production diversity affects dietary diversity mainly through two channels: 1) the direct impact of own production on dietary diversity through self-consumption, and 2) the indirect channel of agricultural production on household income. A large proportion of agricultural producers in China are primarily subsistence-oriented (Ping et al., 2023; Rigg et al., 2016), implying that the more types of agricultural goods produced, the more diversified diets that households can consume (Ecker, 2018). In addition to self-consumption, agricultural

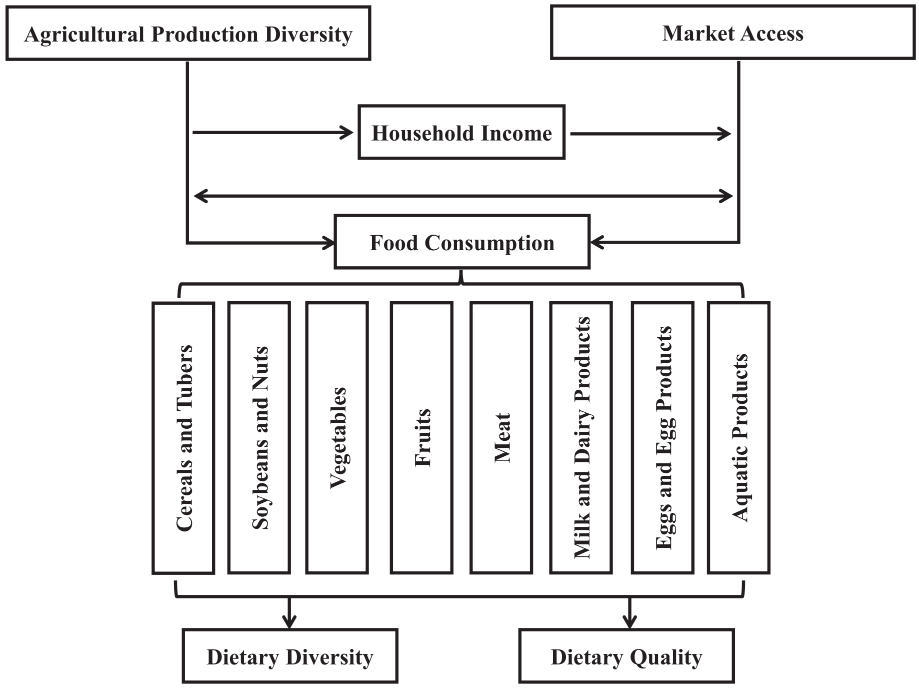


**Fig. 1.** A framework linking agricultural production diversity, market access, and dietary diversity and quality.

households can sell the remaining agricultural products, which affects household income and thus their affordability of diverse foods from the markets (Jones, 2017). The impact of agricultural production diversity on income is likely to be ambiguous. On the one hand, diversifying production is a common risk management strategy that spreads climate and market risks (Bowman & Zilberman, 2013). It allows market participation across seasons, potentially contributing to productivity and income growth (Di Falco et al., 2007). On the other hand, high levels of production diversity may also negatively affect income owing to the loss of economies of scale compared with specialization (Bowman & Zilberman, 2013). As Ecker (2018) finds that the production-consumption linkage rests mainly on the direct effect of self-consumption, we focus on the direct channel and propose our first hypothesis:

**Hypothesis 1.** *Agricultural production diversity has a positive and direct impact on dietary diversity when its impact on income is controlled.*

Second, with the increasing development of markets in rural areas, there is a growing literature emphasizing the role of market access in reducing malnutrition (Chege et al., 2015; Liu et al., 2014). Given the food affordability, the market appears to be a more convenient channel for food access and provides a richer variety of foods to meet diverse needs and preferences compared to diversifying self-production, which leads to the second hypothesis:

**Hypothesis 2.** *Market access has a positive impact on dietary diversity.*

As a widely adopted indicator to measure dietary quality, higher scores of dietary diversity generally accompany greater consumption of nutrient-dense foods and more balanced diets (Arimond et al., 2010; Torheim et al., 2004), which leads to the third hypothesis:

**Hypothesis 3.** *Agricultural production diversity and market access positively affect dietary quality.*

According to the non-separable household model (de Janvry et al., 1991), production and consumption decisions are jointly determined when markets are incomplete or costly to access. Market access influences the degree of non-separability by affecting transaction costs and, consequently, the household's shadow prices for home-produced versus market-purchased foods (Key et al., 2000). When households face poor access to markets, purchasing diverse foods entails higher transaction costs, such as long travel distances, limited price and quantity information, and greater quality uncertainty. These costs raise the shadow prices of market-purchased foods relative to home-produced foods, making self-production more attractive, and households may diversify agricultural production as a strategy to secure dietary variety.

As market access improves, transaction costs fall, and food becomes easier and cheaper to obtain from markets. This lowers the relative cost of market purchase and increases the opportunity cost of allocating labor and land to produce a wide range of foods at home. In response, households may shift resources away from labor- and land-intensive, subsistence-oriented production toward more specialized or market-oriented activities. This adjustment underlies a potential substitution effect, where greater market access may reduce the direct contribution of agricultural production diversity to dietary outcomes. Muthini et al. (2020) show that the positive effect of diversified production on children's dietary diversity may be offset by an increase in the food diversity purchased from the markets, which is consistent with this mechanism. Conversely, households with limited production diversity depend more heavily on markets to achieve dietary variety. Liu et al. (2014) find that improvements in market access have a stronger positive impact on dietary diversity in urban areas, where households rely almost entirely on markets for food, compared with rural areas. Therefore, we propose the fourth hypothesis:

**Hypothesis 4.** *Agricultural production diversity and market access have substitution effects in promoting dietary diversity and quality. Increasing market access dampens the positive impact of agricultural production diversity, while households with limited agricultural production diversity rely more on markets to achieve dietary diversity and quality.*

Despite the overall substitution effects, markets and self-production may provide agricultural households with different nutrients (Ogutu et al., 2020). Perishable and nutrient-dense items such as vegetables, fruits, and legumes may be more reliably produced at home, as households can control production timing, quantity, and quality while avoiding market transaction costs. In contrast, markets provide access to a wider variety of foods that households may not produce themselves, allowing households to complement home production without incurring additional labor or land costs. The better function of household production than markets in increasing the availability of nutrient-dense foods, such as vegetables and fruits, is highlighted by Blakstad et al. (2022), while markets that offer more diverse choices may help balance the varieties consumed, thereby improving the dietary quality (Ren et al., 2022). Thus, these two food channels improve dietary diversity and quality by adjusting the intake of different nutrients, and their impacts across food groups may be complementary, which leads to the following hypothesis:

**Hypothesis 5.** *Agricultural production diversity and market access have complementary effects for adjusting the consumption of specific food groups.*

Besides, the impact magnitudes of markets and household production may vary across different socioeconomic groups. Although markets are expected to have a positive effect, their impact may be substantial primarily for groups with higher food affordability (Abdul Mumin & Abdulai, 2022). For vulnerable groups, such as young children whose daily food intake is highly dependent on their household, household production diversity may be necessary to complement the limited role of markets (Saaka et al., 2017). Accordingly, the sixth hypothesis is:

**Hypothesis 6.** *Agricultural production diversity and market access have heterogeneous effects on providing diversified and higher-quality diets for different socioeconomic groups, with the latter being more important for groups with better food affordability.*

## 3. Empirical strategy

The main objective of this study is to quantify the impacts of agricultural production diversity and market access on individual dietary diversity and quality within agricultural households in rural China. Agricultural production diversity is the key explanatory variable of primary interest in this study. Most existing studies estimating the relationship between agricultural production diversity and dietary diversity primarily use cross-sectional data and rely on ordinary least squares (OLS) regressions (Jones, 2017; Koppmair et al., 2017; Kumar et al., 2015; Sibhatu et al., 2015). However, a major concern is the presence of potential omitted variable biases. Time-invariant individual characteristics (e.g., farming experience and dietary preferences) and time-varying common shocks (e.g., macroeconomic conditions and agricultural policies) may simultaneously affect both agricultural production diversity and dietary choices, leading to biased results. To control for unobserved heterogeneity at the individual and temporal levels, we exploit the panel structure of our data and employ a two-way FE model with individual-level FE and year FE. By including these fixed effects, we control for unobserved time-invariant individual heterogeneity and common temporal shocks that could otherwise confound the estimated effect of agricultural production diversity.

Remaining endogeneity concerns with the two-way FE model include the potential omitted time-varying unobserved variables, reverse causality, and measurement error issues. One aspect that can lead to the endogeneity issue is omitted time-varying variables. While individual FE controls for individual-specific characteristics, and year FE captures the common temporal trend, they do not account for time-varying differences within individuals or households. To partially address household-level time-varying variables, we control for a set of time-variant household characteristics including household size and composition. The number and composition of household members, which directly impact the labor available for agricultural production, can influence the household's capacity to diversify its agricultural production. We also account for individual time-varying characteristics related to demographics, education, and perceived importance of healthy diets, which can influence both agricultural production and dietary choices. We further include other time-varying variables such as individual dietary knowledge, household vehicle ownership, refrigerators ownership, as well as village-level transportation conditions, in robustness checks to strengthen the reliability of our analysis.

Although we include a series of household-level and individual-level control variables, time-varying unobserved factors may still exist, potentially biasing the FE estimates downward. For example, some households diversify their production activities to secure basic food or generate income, yet maintain relatively simple dietary patterns due to a preference for simple diets or habitual consumption of staple-based foods. In addition, households that are more vulnerable to environmental or market shocks may diversify production primarily as a risk management strategy (Di Falco et al., 2007), rather than to improve dietary diversity. In both cases, households may have higher agricultural production diversity without a corresponding increase in dietary diversity and quality, which can result in a downward bias in the FE estimates. It is also possible that the production diversification variables are measured with errors due to inaccurate reporting; classical measurement error in a key explanatory variable could also attenuate the FE estimates.

Another aspect of the endogeneity concern is the two-way relationship between agricultural production diversity and dietary outcomes. Individual preferences for diverse diets may influence their household production decisions. Individuals with preference for higher dietary diversity may be more likely to diversify their agricultural activities to ensure a supply of diverse food products. This would introduce a risk of reverse causality and cause upward bias in the estimates of the impact of agricultural production diversity on dietary diversity. The direction of the bias in the production diversification coefficient is, therefore, ambiguous.

To mitigate these remaining endogeneity concerns, we employ an instrumental variable approach to estimate the FE model (IV-FE). A valid IV must satisfy the relevance condition (its correlation with the endogenous regressor) and the exclusion restriction condition (no direct effect on the outcome variable except through the endogenous regressor). Following Dillon et al. (2015) and Hirvonen and Hoddinott (2017), we use a climate variable to instrument agricultural production diversity. More specifically, we use the minimum temperature as an IV for agricultural production diversity. The minimum temperature is created through matching the CHNS data with county-level temperature. We argue the county-level minimum temperature is a plausible IV as it satisfies both conditions.

First, concerning the relevant condition: agricultural households' production decisions are inherently shaped by local climate conditions, with temperature being a key factor determining both the feasibility and productivity of agricultural activities. Annual minimum temperatures reflect climate-induced constraints on household agricultural production choices, limiting the types of crops and livestock that can be raised and hindering crop growth, which can lead to potential yield losses (Xiao et al., 2022; Zheng et al., 2018). Agricultural households may adjust their production strategies to mitigate the risks when faced with such a challenge. One common risk management strategy is to diversify agricultural production (Bowman & Zilberman, 2013; Di Falco et al., 2007), which enables them to spread the risks across different production activities.

Second, concerning the exclusion restriction: temperature is not expected to directly affect individuals' dietary diversification behaviors except through its effects on production. While temperature may influence agricultural production, it does not have a direct or immediate impact on individual dietary preferences or the specific foods consumed. A potential concern with our IV is that low temperature may directly influence individuals' food choices. To get some insights into whether such a direct effect exists, we conduct a falsification test (Pizer, 2016). The test is grounded in the idea that if the IV affects dietary diversity and quality exclusively through agricultural production diversity, it should have no significant impact on the dietary outcomes of individuals who do not engage in agricultural activities or those who do not consume their produce. The results in Table A1 confirm that the selected instrument has no impact on the individual dietary diversity and quality of these two groups. Therefore, the county level minimum temperature is a valid IV for agricultural production diversity.

To empirically estimate the effects of agricultural production diversity and market access on dietary diversity and quality, we specify the following set of econometric equations: The standard two-way FE model is given by Equation (1), and the first- and second-stage estimation of the IV-FE procedure is given by Equations (2) and (3), respectively:

$$DD_{ihvt} = \alpha_0 + \alpha_1 APD_{hvt} + \alpha_2 DIS_{vt} + X'_{ihvt}\theta + Z'_{hvt}\vartheta + \lambda_t + \mu_i + \xi_{ihvt}, \tag{1}$$

$$APD_{hvt} = \beta_0 + \beta_1 IV_{ct} + \beta_2 DIS_{vt} + X'_{ihvt}\rho + Z'_{hvt}\varphi + \lambda_t + \mu_i + \epsilon_{ihvt}, \tag{2}$$

$$DD_{ihvt} = \alpha_0 + \alpha_1 \widehat{APD}_{hvt} + \alpha_2 DIS_{vt} + X'_{ihvt}\theta + Z'_{hvt}\vartheta + \lambda_t + \mu_i + \xi_{ihvt}, \tag{3}$$

where $i$ refers to an individual nested in a household $h$, a village $v$, and a county $c$; $t$ refers to the year. $\lambda_t$ is the time-fixed effect, $\mu_i$ is the individual-fixed effect, and $\xi_{ihvt}$ is the error term. $\alpha_1$ and $\alpha_2$ are the key coefficients of interests, capturing the effect of agricultural production diversity and market access on dietary outcomes, respectively.

$APD_{hvt}$ represents agricultural production diversity, measured as the number of production activities in which a household participates. One point is assigned for each of the four activities: farming, fishing, gardening, and livestock or poultry raising (Huang & Tian, 2019). In the main analysis, households not engaged in any agricultural activity are excluded, so APD ranges from 1 (engaged in only one activity) to 4 (engaged in all four activities). This measure captures variation in households' engagement in distinct agricultural production activities, distinguishing more diversified production patterns from more specialized ones.

$DIS_{vt}$ represents the distance to the nearest market, as a proxy for market accessibility. This measure captures households' geographic proximity to markets in rural China, where households located further from markets generally face more constraints in obtaining diverse foods and rely more on self-production. It is also widely used in the literature as a standard indicator of market access (Huang & Tian, 2019; Nguyen & Qaim, 2025). To avoid the effects of outliers, we winsorize the top 1% of market distances. To better compare the impact magnitudes of agricultural production diversity and market access, we standardize $APD_{hvt}$ and $DIS_{vt}$ in a comparable form.

$DD_{ihvt}$ represents the dietary diversity or dietary quality of individual $i$ from household $h$ located in village $v$ in year $t$. Dietary diversity is measured using the dietary diversity score (DDS), and the quality of diets is measured by the Chinese Healthy Eating Index (CHEI). Following Torheim et al. (2004), DDS counts the total number of food groups consumed over a 24-hour period over three consecutive days based on the eight pre-defined groups in accordance with the Chinese Food Pagoda Guidance (Chinese Society of Nutrition, 2022). Specifically, the eight food groups include: (1) cereals and tubers, (2) soybeans and nuts, (3) vegetables, (4) fruits, (5) meat, (6) milk and dairy products, (7) eggs and egg products, and (8) aquatic products. Considering that DDS is a simplified indicator that categorizes foods into eight groups and only counts the number of food groups consumed, it does not fully capture the diversity within each food group. From a nutritional perspective, diverse consumption within a single food group can also offer varied benefits. For an alternative measure of DDS, we use the food variety score (FVS) for robustness check, an indicator that calculates the number of food items consumed (Torheim et al., 2004).

CHEI is a valid indicator to measure dietary quality in accordance with the Chinese Dietary Guidelines (Cai et al., 2025; Wang, Cai, et al., 2025; Yuan et al., 2017). Based on dietary recommendations, CHEI scores individuals' intake of 17 components. Twelve components are classified as encouraged food groups, including total grains, whole grains and non-soy legumes, tubers, total vegetables, dark vegetables, fruits, milk and dairy products, aquatic products, poultry, eggs and egg products, soybeans, seeds and nuts. The remaining five components are restricted food groups, including red meat, cooking oils, sodium, added sugar, and alcohol, for which intake should be limited or moderated. Because oils, sodium, added sugar, and alcohol are not included in the DDS measure, we exclude them from the CHEI scores used in this study. Each group is scored from 0 (least healthy) to 5 (most healthy), except for fruits, which are assigned the maximum score of 10 to emphasize their contribution to a healthy diet, placing them on par with vegetables. The maximum score of CHEI is 70 in this study. To calculate the CHEI scores, individual intake amounts are first converted into standard portions (SP) per 1000 kcal per capita per day based on daily energy intake and the SP–gram conversions provided in Table A2. For encouraged food groups, intakes at or above the recommended cutoff receive the maximum score, and zero intake receives a score of zero. For restricted food groups, intakes below the lower cutoff receive the maximum score, and intakes above the upper cutoff receive zero. Intakes between the cutoff points are scored proportionally using linear interpolation. The detailed calculation method is presented in Table A2.

$X_{ihvt}$ and $Z_{hvt}$ are column vectors of individual-level and household-level confounding factors. Following Chegere and Stage (2020) and Huang and Tian (2019), we control for household-level covariates, including household size, per capita annual household income, the proportions of adult females (aged 18–59), children (aged 3–17), and the elderly (aged 60 and above) in the household, and individual characteristics including age, education, and perceived importance of healthy diets. Household income is measured on a per capita basis to account for the large variation in household size. Income values are log-transformed to reduce skewness and are adjusted to 2015 Chinese Yuan (CNY) to enable comparability across survey waves. For the educational level of children under 18, we use their mothers' educational level instead. The perceived importance of healthy diets is measured by asking individuals the importance of "eating a healthy diet" on a scale of 1 to 5, ranging from most unimportant to most important. Given that there is no information on the perceived importance of healthy diets for children under 18, we use the head of the household's responses as a proxy. Standard errors are clustered at the household level to overcome the potential heteroscedasticity. Considering that unobservable village factors may be correlated with agricultural production diversity or dietary habits, we further perform robustness checks using village-level clustered standard errors and village-year clustered standard errors, and including additional village-level facility variables.

It is worth considering the inclusion of income as a control variable. To isolate the direct impact of agricultural production diversity on dietary diversity and quality, we control for per capita annual household income in our main analysis. However, we also examine the effect of agricultural production diversity on per capita annual household income, and estimate the total impact of agricultural production diversity on dietary diversity and quality by removing per capita annual household income from the set of control variables, offering some insight into the potential indirect income effect.

Another factor often mentioned in existing research but rarely addressed is seasonality (Zanello et al., 2019). Agricultural production, market conditions, and food availability are often marked by strong seasonal variation. The impact of agricultural production diversity on dietary choices may fluctuate across different seasons and may only affect the diets during the harvest period. Without accounting for seasonality, the impact of agricultural production diversity may be overestimated if the survey is only conducted during the harvest season, and underestimated if conducted during the non-harvest season. The dietary data we use is collected across various months, allowing us to further include the month of interview FE to control for the seasonality issue following Lovo and Veronesi (2019).

As another key explanatory variable in this study, market access is a crucial factor in understanding the relationship between agricultural production diversity and dietary behaviors. Access to markets affects the variety and availability of foods accessible to households. As market access improves, households may substitute their own agricultural production with foods purchased from the market. This substitution could reduce the reliance on diverse home-grown food sources, potentially weakening the positive effect of agricultural production diversity on dietary diversity and quality. Therefore, we further include the interaction term of $APD_{hvt}$ and $DIS_{vt}$ to investigate the substitution effect between agricultural production diversity and market access as follows:

$$DD_{ihvt} = \gamma_0 + \gamma_1 APD_{hvt} + \gamma_2 DIS_{vt} + \gamma_3 APD_{hvt} \times DIS_{vt} + X'_{ihvt}\delta + Z'_{hvt}\phi + \lambda_t + \mu_i + \varepsilon_{ihvt}, \quad (4)$$

where the direction of $\gamma_3$ is of particular interest to us. If the interaction term's coefficient is significantly positive, it would indicate a substitution relationship between agricultural production diversity and market access. With closer distance to markets, the effect of agricultural production diversity on dietary diversity or dietary quality diminishes.

## 4. Data

The CHNS is a large-scale national open cohort survey with detailed information on individual dietary intake. CHNS is an international cooperation project organized by the Carolina Population Center of the University of North Carolina at Chapel Hill and the National Institute for Nutrition and Health at the Chinese Centers for Disease Control and Prevention. Since 1989, ten follow-up surveys have been conducted, covering 12 provinces of China (Fig. A1). Since the dietary consumption data for 2015 have not yet been released, we use data from the waves of 2004, 2006, 2009, and 2011. These waves cover a critical phase in China's rural development, when households shift from primarily subsistence-oriented farming toward greater reliance on markets alongside self-production, providing an informative context for examining how agricultural production diversity and market access influence dietary outcomes. The dataset provides information on dietary intake, agricultural production, access to food markets, and socioeconomic and demographic variables, and has been widely used in applied economics for dietary and nutrition research (Huang & Tian, 2019; Lei & Shimokawa, 2020; Ren et al., 2022). Details of the data collection methods and questionnaires are available online.

Diet is assessed by a 24-hour dietary recall conducted over three consecutive days. Adults and children aged 12 years and older recall all foods they consumed. For children under 12 years, parents or guardians help report their food consumption at home, while children themselves report intake away from home. The days are randomly assigned from Monday to Sunday and are almost evenly distributed across the seven days of the week in each village, providing a better indication of regular dietary behaviors. For each individual, the number of food groups consumed and the intake of each group are statistically analyzed according to the Chinese Food Composition Tables (Yang, 2004).

Household and individual sociodemographic characteristics and village infrastructure information are also collected. Each household completes a household survey, which is answered by the household head or, if the household head is unavailable, by another adult familiar with the household's basic information. Adults aged 18 and above complete the adult questionnaire themselves. Children under 18 complete the child questionnaire, and those aged 10 or younger complete the questionnaire with the assistance of their parents. Village-level information is collected from local village leaders.

The temperature data are obtained from the China Meteorological Data Service Center, which is developed and currently managed by the Climatic Data Center, National Meteorological Information Center, China Meteorological Administration. It records daily maximum, minimum, and average temperatures for 824 weather stations in China. The meteorological station data are first interpolated to $0.1^\circ \times 0.1^\circ$ grid resolution and then aggregated to obtain annual, monthly, and daily data for each province, municipality, and county. We match the temperature data with the CHNS dataset for each county and use the annual minimum temperature as the IV.

The sample selection process is illustrated in Fig. A2. We start with observations from the 2004, 2006, 2009, and 2011 waves of the CHNS that include dietary intake and geographic information, enabling linkage to temperature data. Since this study focuses on agricultural households in rural areas, we exclude urban residents and observations with missing values in key covariates. We exclude households that do not engage in agricultural production from the main analysis, as our focus is on how variation in agricultural production diversity affects dietary outcomes among agricultural households. In robustness checks, we additionally include these non-agricultural households or restrict the sample to those with positive APD in at least two survey waves to examine the robustness of our results (Table A3). Children aged two years or younger are excluded, as a diet measured by the CHEI is designed for individuals aged above two years (Yuan et al., 2017). Singleton groups, defined as individual-wave combinations with only one observation, are also removed because maintaining such groups in linear regressions with fixed effects nested within clusters can overstate statistical significance and lead to incorrect inference (Breuer & Dehaan, 2024). To assess whether our findings are robust to this exclusion, we present robustness checks that include these singleton groups in Table A4. After all exclusions, a total of 8,984 observations with 3,237 individuals are included in our main analysis.

Table 1 presents the definition and summary statistics of the variables. On average, agricultural households in rural China are engaged in 2 types of agricultural production activities. The average distance to the nearest food market is 5.583 km with a large dispersion of one standard deviation of 12.724 km. Individuals in agricultural households consume an average of 4.462 groups and 27.341 types of food over three consecutive days. The average CHEI in the sample is 27.983.[2] The average household size is around 4 persons, including 1–2 elderly persons aged 60 years and above, 0–1 child under 18 years old, and 1–2 adult females below 60 years old on average. The average age is 44 years old. The average education level is 1.418, which means a large part of the participants have an education level lower than a high school degree. Individuals have a relatively good knowledge and perceive that healthy diets are important with an average score of 3.153.

Food consumption based on own production is expected to be a major channel affecting diets, especially in agricultural households (Ecker, 2018). Around 98.81% of agricultural households consume at least one type of product that they produce, with the shared value of self-consumption amounting to more than half (Table A5). Particularly, the ratio of fruits and vegetables produced in household gardens for self-consumption exceeds 90%, suggesting that self-production remains key to providing nutrient-dense foods and enhancing daily diets in rural China.

Fig. A3 shows the dietary structure in rural China. Notably, the diets are suboptimal. With respect to the recommended intake by dietary guidelines (Chinese Society of Nutrition, 2022), in our sample, cereals and meat consumption are higher than the upper level of the recommended intake among the majority of respondents, whereas vegetable consumption is less than the lower level of the recommended amount. Likewise, the intake of fruits, milk and dairy products, eggs and egg products, and aquatic products is far lower than the recommendations. Only about a quarter of the respondents fulfill the dietary guidelines of consuming at least 40 g of eggs and egg products per day. Compared to urban counterparts, respondents in rural areas have overall less optimal diets, especially those with lower income, who consume more cereals and tubers, and less meat, aquatic products, milk and dairy products, eggs and egg products, and fruits (Fig. A4 and Table A6), underscoring

[2] The maximum possible CHEI score in this study is 70. CHEI is a continuous index designed to assess adherence to dietary guidelines. While CHEI has been evaluated as a dietary quality index, there are no widely accepted thresholds for classifying a given score as adequate.

**Table 1**
Definition of the variables and summary statistics.

| Variables | Definition | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| ***Dependent variable*** | | | | | |
| DDS | Dietary diversity score | 4.462 | 1.242 | 1 | 8 |
| FVS | Food variety score | 27.341 | 6.733 | 1 | 71 |
| CHEI | The Chinese Healthy Eating Index | 27.983 | 8.795 | 5.762 | 65 |
| ***Key independent variables*** | | | | | |
| APD | Agricultural production diversity | 2.184 | 0.846 | 1 | 4 |
| DIS | Distance to the nearest food market (km) | 5.583 | 12.724 | 0 | 80 |
| ***Control Variables*** | | | | | |
| ***Village-level characteristics*** | | | | | |
| Bus stop | Whether the village has a bus stop? 1 = yes;0 = no | 0.577 | 0.494 | 0 | 1 |
| Train station | Whether the village has a train station? 1 = yes;0 = no | 0.100 | 0.300 | 0 | 1 |
| River | Whether the village is proximal to a navigable river? 1 = yes;0 = no | 0.132 | 0.338 | 0 | 1 |
| Location | Near a special economic zone (< 2h by bus)? 1 = yes; 0 = no | 0.382 | 0.486 | 0 | 1 |
| ***Household-level characteristics*** | | | | | |
| Hhincome_pc | Per capita annual household income (ln) | 8.869 | 0.899 | 4.786 | 12.939 |
| Hhsize | Family size | 4.337 | 1.632 | 1 | 11 |
| Female | Proportion of adult females (aged 18–59) in a family | 0.248 | 0.124 | 0 | 1 |
| Child | Proportion of children (aged 3–17) in a family | 0.143 | 0.160 | 0 | 0.714 |
| Old | Proportion of the elderly (aged 60 and above) in a family | 0.369 | 0.260 | 0 | 1 |
| Tricycle | Any household member own tricycle? 1 = yes; 0 = no | 0.227 | 0.419 | 0 | 1 |
| Bicycle | Any household member own bicycle? 1 = yes; 0 = no | 0.719 | 0.450 | 0 | 1 |
| Motorcycle | Any household member own motorcycle? 1 = yes; 0 = no | 0.521 | 0.500 | 0 | 1 |
| Car | Any household member own car? 1 = yes; 0 = no | 0.059 | 0.236 | 0 | 1 |
| Refrigerator | Any household member own refrigerator? 1 = yes; 0 = no | 0.424 | 0.494 | 0 | 1 |
| ***Individual-level characteristics*** | | | | | |
| Age | Years of age | 43.812 | 16.717 | 3 | 92 |
| Edu | Highest level of education attained: 0 = below primary school; 1 = graduated from primary school; 2 = lower middle school degree; 3 = upper middle school degree; 4 = technical or vocational degree; 5 = university or college degree; 6 = master's degree or higher | 1.418 | 1.023 | 0 | 6 |
| DietImportance | Importance of healthy diets: 1 = not important at all; 2 = not very important; 3 = important; 4 = very important; 5 = the most important | 3.153 | 0.646 | 1 | 5 |
| Knowledge | Dietary knowledge | 32.350 | 3.330 | 17 | 46 |
| ***IV*** | | | | | |
| Temp | Minimum temperature throughout the year (°C) | −9.255 | 8.447 | −32.135 | 3.562 |

the need to improve the dietary quality in rural China.

## 5. Results

### 5.1. Impacts of agricultural production diversity and market access on dietary diversity

Panel A, columns (1)-(3) of Table 2 report the FE estimates of the impacts of agricultural production diversity and market access on DDS. Column (1) presents the simplest specification with only agricultural production diversity and market distance as explanatory variables. In subsequent columns, we progressively add individual-level covariates (column (2)) and household-level covariates (column (3)). While the negative coefficient on DIS (the distance to market) gives the expected sign (better market access is positively correlated with DDS), it is statistically insignificant throughout the specifications. The positive and significant coefficients (albeit at 10% for the full model specification in column (3)) on agricultural production diversity across different model specifications suggests positive association between APD and DDS, consistent with *Hypothesis 1*. However, the magnitude of the coefficient estimates is relatively small.[3] This is consistent with cross-sectional or FE estimates reported in earlier research (Sibhatu, 2018). Given the endogeneity concerns inherent in the FE estimation, we now turn to the more reliable IV-FE estimation results presented below.

Panel B, columns (1)-(3) of Table 2 show results from IV-FE estimations where the minimum temperature is used as an IV for agricultural production diversity. According to our preferred estimate in column (3), a one-standard-deviation (SD) increase in agricultural production diversity leads to a 0.614 increase in DDS, with the average DDS in our sample being 4.462. The results confirm *Hypothesis 1*, that is,

[3] APD in this study is measured as the number of production activities in which a household participates, with one point assigned for each of the four activities: farming, fishing, gardening, and livestock or poultry raising. This differs from many studies that use the number of food groups or product types (Muthini et al., 2020; Usman & Haile, 2022).

**Table 2**
Impacts of agricultural production diversity and market access on DDS and CHEI.

| | Dietary Diversity | | | | | |
|---|---|---|---|---|---|---|
| | DDS | | | CHEI | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| ***Panel A: FE*** | | | | | | |
| APD | 0.066** | 0.067** | 0.050* | 0.345 | 0.346 | 0.355 |
| | (0.030) | (0.030) | (0.030) | (0.214) | (0.214) | (0.217) |
| DIS | −0.032 | −0.032 | −0.034 | −0.184 | −0.182 | −0.201 |
| | (0.026) | (0.026) | (0.026) | (0.209) | (0.209) | (0.207) |
| ***Panel B: IV-FE*** | | | | | | |
| APD | 0.559** | 0.573** | 0.614** | 5.474*** | 5.406*** | 6.237*** |
| | (0.248) | (0.249) | (0.258) | (1.982) | (1.980) | (2.082) |
| DIS | −0.039*** | −0.039*** | −0.041*** | −0.259** | −0.256** | −0.275** |
| | (0.014) | (0.014) | (0.014) | (0.114) | (0.113) | (0.115) |
| Cragg-Donald Wald F statistic | 40.68 | 40.58 | 39.29 | 40.68 | 40.58 | 39.29 |
| Household covariates | No | No | Yes | No | No | Yes |
| Individual covariates | No | Yes | Yes | No | Yes | Yes |
| Individual FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 8,984 | 8,984 | 8,984 | 8,984 | 8,984 | 8,984 |

Notes: *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively. Standard errors in parentheses are clustered at the household level. APD and DIS are standardized.

engaging in a larger number of agricultural production activities contributes to diverse diets, which is consistent with previous studies (Chegere & Stage, 2020; Ecker, 2018; Kumar et al., 2015). Notably, the magnitude of APD effects on DDS is larger in the IV-FE model than that in the FE model and exceeds the effect sizes reported in existing literature based on cross-sectional data (Bellon et al., 2016; Jones, 2017). This discrepancy suggests that conventional estimates are likely to be underestimated if endogeneity issues are not addressed. The null hypothesis about the exogeneity of the agricultural production diversity is rejected in the endogeneity test, further supporting the use of IV-FE models. Table A7 reports the first-stage results, showing that lower minimum temperatures are associated with higher agricultural production diversity. The strength of the instrument variable is confirmed by Cragg-Donald Wald F statistics that are well above Stock and Yogo's 10% maximal bias threshold of 16.38.

As income is one channel through which agricultural production diversity affects dietary diversity presented in our conceptual framework (Fig. 1), we also investigate the effect of agricultural production diversity on per capita annual household income and estimate the total effect of agricultural production diversity on dietary diversity. Consistent with Snapp and Fisher (2015), increasing agricultural production diversity results in higher per capita annual household income (Panel A, columns (1) and (2) of Table A8). Panel B, column (2) of Table A8 indicates that the total effect of agricultural production diversity on DDS is larger than the direct effect, confirming the indirect effect through income. Although the coefficient of the effect increases from 0.614 to 0.620, the magnitudes of the change are relatively modest, indicating that the direct effect of agricultural production diversity on DDS is rather dominant, consistent with Ecker (2018).

Consistent with Liu et al. (2014), our IV-FE estimation results indicate that market access is also important in promoting individual DDS with the control of agricultural production diversity, confirming *Hypothesis 2*. With a one SD decrease in distance from the food markets, DDS is likely to increase by 0.041 (Panel B, column (3) of Table 2). The magnitude of our estimated effect is relatively larger than but broadly comparable to that reported in a study conducted on Ethiopia and Tanzania, where a 10% reduction in market distance, with a mean distance of approximately 68 km, increases household-level DDS by approximately 0.013 (Usman & Haile, 2022).

### *5.2. Impacts of agricultural production diversity and market access on dietary quality*

We then examine the impacts of agricultural production diversity and market access on dietary quality, measured by the Chinese Healthy Eating Index (CHEI). The IV-FE estimation results are presented in Panel B, columns (4)-(6) of Table 2.

The results confirm *Hypothesis 3*, demonstrating that both diversifying agricultural production and improving market access improve the quality of diets by bringing their dietary structure closer to dietary guidelines. According to Panel B, column (6) of Table 2, a one SD increase in agricultural production diversity contributes to a 6.237 increase in CHEI (equivalent to 22.289% increase relative to the sample mean), and CHEI is likely to increase by 0.275 (equivalent to 0.983% increase relative to the sample mean) with a one SD decrease in distance from the food markets.

### *5.3. Substitution effects on dietary diversity and dietary quality*

We further examine the interactions between agricultural production diversity and market access in influencing dietary diversity and dietary quality. The positive and significant coefficient of the interaction term reveals a substitution relationship between APD and market access in improving dietary diversity and quality, supporting *Hypothesis 4*. As shown in columns (3) and (6) of Table 3, the marginal effect of standardized APD[4] remains positive but varies with market distance. At the mean market distance of 5.583 km, the marginal effect of standardized APD is 0.836 on DDS and 7.327 on CHEI. The positive effect of APD declines as market access improves, consistent with Sibhatu et al. (2015). According to Barrett (2008), better market access and lower transaction costs facilitate household participation in the market, which may dampen the contribution of production diversity to diets. For households located one SD closer to market, the marginal effect decreases to 0.713 on DDS and 6.723 on CHEI, whereas for households one SD further away from markets, it increases to 0.959 on DDS and 7.931 on CHEI. This finding is similar to a study using data from rural sub-Saharan Africa, which shows that the positive effect of farm-level production diversity on children's height-for-age Z scores decreases as

[4] The marginal effects of standardized APD are calculated as $0.836+0.123 \times DIS_{vt}$ for DDS and $7.327+0.604 \times DIS_{vt}$ for CHEI.

**Table 3**
Substitution effects between agricultural production diversity and market access.

| | Dietary Diversity | | | | | |
|---|---|---|---|---|---|---|
| | DDS | | | CHEI | | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| APD | 0.776*** | 0.781*** | 0.836*** | 6.421*** | 6.403*** | 7.327*** |
| | (0.272) | (0.272) | (0.291) | (2.124) | (2.121) | (2.303) |
| DIS | −0.061*** | −0.061*** | −0.062*** | −0.355*** | −0.357*** | −0.378*** |
| | (0.016) | (0.016) | (0.017) | (0.127) | (0.127) | (0.131) |
| APD×DIS | 0.129*** | 0.124*** | 0.123*** | 0.562** | 0.594** | 0.604** |
| | (0.034) | (0.034) | (0.036) | (0.268) | (0.268) | (0.284) |
| Cragg-Donald Wald F statistic | 19.09 | 19.13 | 17.56 | 19.09 | 19.13 | 17.56 |
| Household covariates | No | No | Yes | No | No | Yes |
| Individual covariates | No | Yes | Yes | No | Yes | Yes |
| Individual FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 8,984 | 8,984 | 8,984 | 8,984 | 8,984 | 8,984 |

Notes: *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively. Standard errors in parentheses are clustered at the household level. APD and DIS are standardized.

proximity to city or town improves (Khonje et al., 2022).

Similarly, the marginal effects of standardized market distance are contingent on the level of APD[5] (columns (3) and (6) of Table 3). At the mean $APD_{hvt}$ of 2.184, the marginal effect of standardized market distance is −0.062 on DDS and −0.378 on CHEI. For households one SD below the mean APD, the marginal effects of market distance become more negative (−0.185 on DDS and −0.982 on CHEI), suggesting that improving market access yields greater benefits on diet for households with relatively low production diversity. This pattern is consistent with the findings of Huang and Tian (2019) and Nguyen and Qaim (2025), who find that production diversity has stronger positive associations with dietary diversity scores and dietary quality for households in remote rural areas than in areas better connected to markets or urban centers.

### 5.4. Robustness check

We conduct several robustness checks to verify the validity of the main results. Firstly, an alternative measure of dietary diversity named FVS is used (Table A9). FVS is the sum of the number of food types consumed (Torheim et al., 2004), and the positive and substitution effects of agricultural production diversity and market access are robust to the different measures of dietary diversity. Secondly, instead of excluding non-agricultural rural households in our main estimates, we conduct an additional robustness check by including them in the estimation. The results show that the effect of agricultural production diversity remains significant (columns (1) and (2) of Table A3). Considering that an APD of zero in a single wave may not necessarily indicate persistent disengagement from agriculture, and that households with a positive APD in one wave may not consistently participate in agricultural production, we conduct an additional test restricting the sample to households with an APD greater than zero in at least two waves. The impacts remain robust for households with more sustained agricultural activity (columns (3) and (4) of Table A3). Thirdly, considering that there could be village-level omitted variables that both affect agricultural production diversity and dietary outcomes, we further use village-level clustered standard errors following Bellon et al. (2016) as well as village-year clustered standard errors to control within-year cross-village correlations (Sun et al., 2018). The results (columns (2)-(3) of Table 4) remain consistent with Table 2. Fourthly, we re-estimate the models by adding the village- and household-level facility variables (listed in Table 1). The impact magnitude of agricultural production diversity (column (4) of Table 4) becomes smaller but remains significant and positive. As individuals' perceived importance of healthy diets may not fully capture their dietary knowledge, we additionally control for dietary knowledge scores, with results remaining robust (Tables A10 and A11). In addition, as the effects of agricultural production diversity could vary across seasons (Zanello et al., 2019) and the dietary survey is undertaken at various months, we further include month of interview fixed effects to control for the seasonality following Lovo and Veronesi (2019). The impact of agricultural production diversity on DDS and CHEI remains significant and positive, with impact magnitudes (column (5) of Table 4) slightly smaller than in the baseline results (column (1) of Table 4). Finally, to address potential concerns regarding the exclusion of singleton groups, we re-estimate the main specifications including these 2,315 singleton observations. As shown in Table A4, the direction, statistical significance, and magnitude of the key coefficients remain largely unchanged from the baseline results.

### 5.5. Complementary effects on different food group consumption

We regress the intake amount of each food group on agricultural production diversity and market access (Table 5) to shed light on the effects on the consumption of specific food groups. Engaging in a specific agricultural production activity may lead to a higher intake of the corresponding food group, which could potentially influence the overall impacts of agricultural production diversity on dietary diversity. We divide agricultural production diversity into distinct activities, including farming, gardening, livestock or poultry raising, and fishing, and further test by excluding the corresponding production activity related to each food group to isolate the impact of agricultural production diversity on dietary diversity (Table A12).

Agricultural production diversity (both including and excluding the corresponding production activity of the food group) provides more diverse food availability and promotes the intake of soybeans and nuts, vegetables, fruits, eggs and egg products (columns (2)-(4) and (7) of Table 5 and Table A12). Given that agricultural households consume vegetables, fruits, eggs and egg products, and aquatic products far below the recommended range (Fig. A3), engaging in diversified production activities can help reduce nutrient deficiency, in accordance with Blakstad et al. (2022) and Ping et al. (2023). For cereals and tubers, when the market is relatively distant, increasing agricultural production diversity would reduce the consumption of cereals and tubers (column (1) of Table 5 and Table A12). The possible explanation is that households with limited market access rely more on their own production, and diversified agriculture may reduce reliance on cereals by offering more food variety. For milk and dairy product consumption, the effects of

[5] The marginal effects of standardized market distance are calculated as $-0.062+0.123\times APD_{hvt}$ for DDS and $-0.378+0.604\times APD_{hvt}$ for CHEI.

**Table 4**
Robustness check.

| | Baseline | Village-level cluster | Village-year cluster | Add variables | Month FE |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| ***Panel A: Impacts of APD and market access on DDS*** | | | | | |
| APD | 0.614** | 0.614** | 0.614** | 0.521** | 0.509* |
| | (0.258) | (0.258) | (0.258) | (0.255) | (0.286) |
| DIS | −0.041*** | −0.041*** | −0.041*** | −0.048*** | −0.046*** |
| | (0.014) | (0.014) | (0.014) | (0.015) | (0.014) |
| Cragg-Donald Wald F statistic | 39.29 | 39.29 | 39.30 | 39.11 | 30.87 |
| ***Panel B: Impacts of APD and market access on CHEI*** | | | | | |
| APD | 6.237*** | 6.237*** | 6.237*** | 5.881*** | 5.889** |
| | (2.082) | (2.082) | (2.082) | (2.070) | (2.341) |
| DIS | −0.275** | −0.275** | −0.275** | −0.315*** | −0.290** |
| | (0.115) | (0.115) | (0.115) | (0.120) | (0.117) |
| Cragg-Donald Wald F statistic | 39.29 | 39.29 | 39.30 | 39.11 | 30.87 |
| ***Panel C: Substitution effects on DDS*** | | | | | |
| APD×DIS | 0.123*** | 0.123*** | 0.123*** | 0.121*** | 0.142*** |
| | (0.036) | (0.036) | (0.036) | (0.035) | (0.037) |
| Cragg-Donald Wald F statistic | 17.56 | 17.56 | 17.56 | 17.49 | 14.99 |
| ***Panel D: Substitution effects on CHEI*** | | | | | |
| APD×DIS | 0.604** | 0.604** | 0.604** | 0.585** | 0.802*** |
| | (0.284) | (0.284) | (0.284) | (0.280) | (0.299) |
| Cragg-Donald Wald F statistic | 17.56 | 17.56 | 17.56 | 17.49 | 14.99 |
| Household covariates | Yes | Yes | Yes | Yes | Yes |
| Individual covariates | Yes | Yes | Yes | Yes | Yes |
| Village covariates | No | No | No | Yes | No |
| Individual FE | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes |
| Month FE | No | No | No | No | Yes |
| Clustering | Household | Village | Village-year | Household | Household |
| Observations | 8,984 | 8,984 | 8,984 | 8,836 | 8,758 |

Notes: *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively. Standard errors in parentheses are clustered at the household level for columns (1), (4), and (5); at the village level for column (2); and at the village–year level for column (3). APD and DIS are standardized.

**Table 5**
Effects of agricultural production diversity and market access on consumption amount of various food groups.

| | Food group consumption amount (g/capita/day) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Cereals and tubers | Soybeans and nuts | Vegetables | Fruits | Meat | Milk and dairy products | Eggs and egg products | Aquatic products |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| APD | 52.044 | 68.313*** | 92.387* | 71.270*** | −36.098** | 7.558 | 38.552*** | 5.074 |
| | (46.496) | (19.052) | (48.308) | (27.060) | (17.264) | (6.545) | (10.121) | (11.854) |
| DIS | −7.483*** | −4.304*** | 3.443 | −0.333 | 2.079** | −0.591 | −0.191 | 0.123 |
| | (2.651) | (1.086) | (2.754) | (1.543) | (0.984) | (0.373) | (0.577) | (0.676) |
| APD×DIS | −27.167*** | 9.552*** | 26.361*** | 2.169 | 2.680 | 0.431 | 1.396 | 6.745*** |
| | (5.741) | (2.352) | (5.964) | (3.341) | (2.131) | (0.808) | (1.250) | (1.464) |
| Cragg-Donald Wald F statistic | 17.56 | 17.56 | 17.56 | 17.56 | 17.56 | 17.56 | 17.56 | 17.56 |
| Household covariates | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Individual covariates | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Individual FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 8,984 | 8,984 | 8,984 | 8,984 | 8,984 | 8,984 | 8,984 | 8,984 |

Notes: *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively. Standard errors in parentheses are clustered at the household level. APD and DIS are standardized.

agricultural production diversity and market access appear to be insignificant (column (6) of Table 5), possibly resulting from the food culture in rural China where residents do not consume many dairy products.

Notably, our estimation results indicate a functional complementarity between market access and agricultural production diversity in adjusting the intake of soybeans and nuts, vegetables, and aquatic products, in accordance with the argument raised by Bellon et al. (2016). *Hypothesis 5* is thus confirmed. Agricultural production diversity increases the intake of soybeans and nuts, vegetables, and aquatic products. However, among households engaged in diverse agricultural production, closer markets are associated with a net reduction in the total consumption of these foods (columns (2), (3), and (8) of Table 5 and Table A12). One possible explanation is that these households already consume relatively high amounts of these food groups from self-production, and improved market access encourages them to diversify their diets and allocate resources toward other market-purchased foods. As a result, their intake of these particular food groups may decline. In contrast, among households with relatively low production diversity, closer markets increase their consumption of soybeans and nuts, vegetables, and aquatic products, by providing access to food groups that are not readily available from their own production. For fruits, engaging in varied production activities increases the intake amount, while market access has no significant impact (column (4) of Table 5 and Table A12).

### 5.6. Heterogeneous effects

We further investigate the heterogeneous effects of these two food channels across different demographic groups. We do so by adding dummy variables for young children (8 years old and below) and higher income group (per capita annual household income above the mean), and interacting them with our measures of agricultural production diversity and market access respectively (Table 6).

Early childhood is a crucial stage of cognitive and physical development (Sánchez et al., 2024). For the pre-school age group, their diets are primarily shaped by the food supply within the household. In contrast, once they enter school, particularly with policies like school consolidations that lead to more boarding students (Li & Gao, 2024), their diets become more influenced by school-provided meals and other external environments (Liu et al., 2017). To explore whether agricultural production and market access have different effects for this age group, we introduce a dummy variable for young children aged 8 and below. Columns (1)-(2) of Table 6 present the estimates. The significant coefficients of the interaction terms suggest that the effects differ between young children and adults. Agricultural production diversity appears to be more influential for young children than older individuals. Market access also plays an important role in children's diets, confirming the findings of Hirvonen and Hoddinott (2017).

As dietary structure differs across income levels (Fig. A4 and Table A6), we split the sample according to the mean per capita annual household income for each province each year, and further explore the heterogeneous effect across different income levels. Columns (3)-(4) of Table 6 show that the positive impact of agricultural production diversity is greater for low-income groups, whereas better access to markets plays a more important role for households with income above the mean in providing diverse foods. This supports *Hypothesis 6* and is consistent with Saaka et al. (2017), since the lower income groups are often associated with lower food affordability.

**Table 6**
Heterogeneous effects by age and income levels.

| | Age | | Hhincome_pc_high | |
|---|---|---|---|---|
| | DDS | CHEI | DDS | CHEI |
| | (1) | (2) | (3) | (4) |
| APD | 0.545** | 5.965*** | 0.696*** | 6.323*** |
| | (0.254) | (2.055) | (0.232) | (1.846) |
| DIS | −0.036** | −0.225* | −0.042** | −0.032 |
| | (0.014) | (0.117) | (0.018) | (0.139) |
| APD×Age (≤8) | 0.611** | 4.075* | | |
| | (0.304) | (2.462) | | |
| DIS×Age (≤8) | −0.125* | −1.302** | | |
| | (0.067) | (0.543) | | |
| APD×Hhincome_pc_high | | | −0.311** | −1.669* |
| | | | (0.123) | (0.978) |
| DIS×Hhincome_pc_high | | | 0.011 | −0.502** |
| | | | (0.026) | (0.203) |
| Cragg-Donald Wald F statistic | 20.00 | 20.00 | 21.43 | 21.43 |
| Household covariates | Yes | Yes | Yes | Yes |
| Individual covariates | Yes | Yes | Yes | Yes |
| Individual FE | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes |
| Observations | 8,984 | 8,984 | 8,984 | 8,984 |

Notes: *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively. Values in brackets are clustered standard errors. APD and DIS are standardized. We add dummy variables for young children (8 years old and below) and higher per capita annual household income group (above the mean) and interact them with our measures of agricultural production diversity and market access. The coefficients of the individual dummy variables are not shown in the table.

## 6. Conclusion and policy implications

This study conducts a nuanced investigation into both dietary diversity and dietary quality of individuals from agricultural households in rural China attributed to agricultural production and market access using a large-scale national cohort survey data. We provide the first evidence, to our best knowledge, that market access and diversification of self-production have substitution effects on promoting both dietary diversity and dietary quality. In addition to the overall substitution effects, agricultural production diversity and market access complement each other in adjusting the intake of specific food groups and play different roles in improving the diets of different socio-economic populations in China. Agricultural production diversity increases the intake of soybeans and nuts, vegetables, fruits, eggs and egg products, particularly improving diets for children in early childhood and lower-income groups. Markets provide access to more diverse foods, complementing self-production by attenuating the intake of foods promoted by high production diversity, while supporting households with low production diversity in increasing their intake of soybeans and nuts, vegetables, and aquatic products. Improving dietary diversity and quality requires a combination of diverse production layouts and market access improvement.

Several policy implications can be drawn from this study. First, at the national or regional scale, comprehensive layouts of diversified production should be designed (Nguyen & Qaim, 2025), accelerating the transformation toward nutrition-oriented agriculture. Then, market access should be ensured across all regions to provide people with convenient access to a wide variety of foods. Under the ongoing trend of agricultural specialization and marketization, improving market access can be an effective and prioritized policy investment, as improved food market access can generally substitute for the contribution of agricultural production diversity to dietary diversification, particularly in well-accessed areas where the marginal returns of production diversity diminish. Despite the growing importance of markets, our findings highlight that agricultural production diversity continues to play a unique role in providing nutrient-dense foods and supporting subsistence resilience among vulnerable groups. For remote villages, agricultural production diversity may be of great importance to help buffer the risk cascading through the market and strengthen food resilience (Ecker & Hatzenbuehler, 2022; Rasmussen et al., 2024). Areas and groups that are less resistant to external risks can maintain a certain level of self-production, especially encouraging the production of nutrient-dense crops such as vegetables and fruits (Blakstad et al., 2022).

A few caveats should be considered when interpreting our results. First, our measure of agricultural production diversity captures variation in the number of production activities a household engages in, specifically farming, fishing, gardening, and livestock or poultry raising. However, the diversity within each activity is also important, as producing a wider range of crops may contribute more to dietary diversity than producing a single staple crop. Due to the lack of information on product types in the dataset, within-activity diversity cannot be measured. Nonetheless, our measure still provides useful information on the degree to which households participate across major production activities. Future research incorporating more detailed product-level production data could enable a more nuanced assessment of how different dimensions of agricultural production diversity shape dietary outcomes. Second, our measure of market access, distance to the nearest market, may not capture all aspects of accessibility. For example, it does not reflect differences in market size, product variety, food prices, or transportation costs that can also influence households' ability to obtain diverse foods. Distance to the nearest market is, however, widely used in the literature as a standard proxy for market access, as it largely determines households' access to food and participation in local markets.

In rural China, where many villages are relatively remote, households located further from markets face more limited access to fresh vegetables, fruits, legumes, and animal-source foods, and tend to rely more on self-production. In addition, the data waves used in this study are somewhat dated and may not fully reflect current conditions in China. Nevertheless, this period represents a critical phase in China's rural development from primarily subsistence-oriented farming toward greater reliance on markets alongside self-production, providing an informative context for understanding how agricultural production diversity and market access shape dietary outcomes. By providing micro-level evidence from a major developing-country context, this study offers insights that are highly relevant for other developing countries undergoing similar transitions, particularly in regions such as Africa and South Asia where poor market access remains widespread and self-production continues to play a central role (Reardon et al., 2019). Future research could investigate how the relationships between agricultural production diversity and market access evolve over time using more recent or long-term data. The mechanisms underlying dietary quality improvements, the role of food processing and storage, and whether similar patterns hold in other developing countries also warrant further exploration.

## CRediT authorship contribution statement

**Jiaqi Xuan:** Data Curation, Methodology, Formal analysis, Visualization, Investigation, Writing – original draft, Writing – review & editing. **Xiaoxi Wang:** Conceptualization, Methodology, Formal analysis, Supervision, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Changzheng Yuan:** Methodology, Formal analysis, Supervision, Writing – review & editing. **Songqing Jin:** Methodology, Investigation, Writing – review & editing, Funding acquisition. **Xu Tian:** Data curation, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.worlddev.2026.107400.

## Data availability

The CHNS data described in the manuscript and the codebook is available at https://www.cpc.unc.edu/projects/china/data/datasets/data-downloads-registration after registration, and the village-level data will be made available upon request pending application and approval. The temperature data can be applied at http://data.cma.cn/. The complete datasets used in this analysis are available from the corresponding author upon reasonable request.

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