

Seed certification, certified seeds use and yield outcomes in Nigeria: Insights from nationally-representative farm panel data and seed company location data

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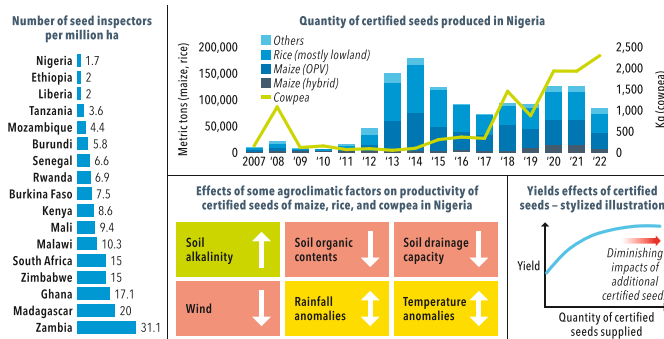
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HIGHLIGHTS

- Effects of seed certification on farm level outcomes in Nigeria are estimated.
- Location and production data of seed companies and farm panel data are used.
- Positive but declining marginal returns to certified seeds production in the state.
- Farmers' use of certified seeds is also affected by agroecological conditions.
- Farm level yield effects of certified seeds uses vary due to agroecological conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Despite the importance of enhanced seed quality to agricultural productivity growth, evidence remains scarce regarding the nature and possible drivers of returns to formal sector quality assurance systems, including certified seeds production in countries like Nigeria that focus significantly on the formal-sector seed systems.

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OBJECTIVE: This study narrows this knowledge gap by estimating the effect of the quantity of certified seeds produced and the spatial variations where they are produced on the use of certified seeds and yields. We also assess the yield effects of certified seeds use and their relationship with agroclimatic and socioeconomic conditions.

METHODS: We combine nationally-representative farm-household survey panel data with spatial data on the headquarters locations of seed companies, the quantity of certified seeds for maize, cowpea, and rice that they produce, and spatially explicit agroecological data. We apply panel fixed effects methods as well as instrumental-variable methods to address potential endogeneity associated with certified seeds use while also controlling for the use of improved varieties to separate their effects from the effects of certified seeds.

RESULTS AND CONCLUSIONS: Our findings indicate that the availability of certified seeds—captured by indicators of certified seeds produced by seed companies headquartered in the states of survey respondents—is associated with positive but declining marginal effects on certified seeds use and yields. These results are robust when we also consider the potential within-state heterogeneity in the proximity to seed company headquarters, as well as potential spillovers from the nearest adjacent states. The yield effects of certified seeds are heterogeneous and depend on agroclimatic conditions and farmers' socioeconomic characteristics. The use of certified seeds is somewhat higher in areas with higher yield effects after controlling for certified seeds production. These patterns partly lead to observed non-linearities in certified seeds use because certified seeds may be more likely to be used by farmers with higher expected returns than farmers with lower expected returns. These results underscore the importance of spatially targeted efforts in enhancing certified seeds production capacity, together with the exploration of intermediate quality standards in the short term where costs of seed certification are high relative to returns.

SIGNIFICANCE: The study provides unique quantitative evidence in a nationally representative framework in an African country that returns to seed certification systems in the current setting significantly vary depending on contexts, including agroclimatic conditions.

1. Background

Seed quality assurance has been integral to seed system development in many lower-income countries (Pray and Ramaswami, 1991; FAO, 2015). Seed quality assurance ensures that the physiological characteristics of the seed and the physical characteristics of the seed packet or lot meet desirable sets of standards and is thus able to ensure that farmers realize the genetic characteristics embodied in the seed (Cromwell et al., 1992). Production of “certified seeds” has typically been the most comprehensive process of seed quality assurance, including in some countries in Africa South of the Sahara (SSA) such as Nigeria.

Understanding the nature of the impacts of certified seeds production is critical for effective seed system development strategies, but the knowledge gap remains. Some of the critical questions are how the adoption and productivity responses to the supply of certified seeds change as the supply expands and what might be potential drivers of such changes. This question is relevant because while seed sector policies in many countries, including Nigeria, often focus on promoting significantly high (sometimes full) coverage of seeds by certified seeds (e.g., FMARD, 2022), it may face challenges in overcoming significant heterogeneity in the demand and benefits for certified seeds among farmers.

Our study narrows this knowledge gap by providing critical evidence from Nigeria. Precisely, we assess the effect of the quantity of certified seeds produced and the spatial variations where they are produced on the use of certified seeds and yields. We also assess the yield effects of certified seeds use and their relationship with agroclimatic and socioeconomic conditions. Our analysis combines nationally representative farm-household survey panel data from the Living Standard Measurement Study – Integrated Survey on Agriculture (LSMS-ISA) (NBS and World Bank, 2019) with spatial data on the headquarters locations of seed companies (the major certified seeds producers in Nigeria), the quantity of certified seeds that they produce, and spatially explicit agroecological data. We focus on three crops—maize, cowpea, and rice—which, according to the 2018 LSMS-ISA survey round, were the 2nd, 4th, and 8th most widely cultivated crops in Nigeria, respectively, and also account for a significant share of all certified seeds produced in Nigeria in the recent decades. We estimate the effects of seed certification per se rather than the effects of improved varieties that are

sometimes embedded in certified seeds. We apply panel fixed effects methods as well as instrumental-variable methods to address potential endogeneity associated with farmers' use of certified seeds and improved varieties. Results show that there are nonlinear returns to certified seeds production, which may be partly due to significant heterogeneity in the yield effects of certified seeds. We find diminishing returns to certified seeds use at the extensive margin: certified seeds use may be yield-enhancing among better-endowed, higher-return farms but tends to decrease when used on less-endowed, lower-return farms.

As is described more in detail in subsequent sections, we focus on the quantity of certified seeds produced by the seed companies headquartered in the state rather than attempting to track the quantity actually sold/supplied to distributors in each state. This is not only because the information for the former is more readily available than the latter but also because the former may be more directly responsive to the seed certification policy of the state than the latter, which the government may have less control over. Therefore, our findings should be interpreted within the specific context, i.e., the effects of certified seeds produced by seed companies within a particular state. Nonetheless, given that this context applies to Nigeria, the most populous country in the African continent, our study has broad implications for seed certifications in SSA.

For the remainder of the analyses, we refer to “certified seeds” reported at the farm household level as seeds that have been approved for sale and planting by the appropriate seed certification authority such as the Ministry of Agriculture (NBS and World Bank, 2019). In contrast, “improved varieties” are defined as varieties that have some better qualities/traits added to it by a farmer or a plant breeder. These new traits can include higher yield, drought resistance, or pest resistance, among others (NBS and World Bank, 2019).

Nigeria is an important case for examining our research questions. In recent years, the Government of Nigeria and many of its seed sector stakeholders have been keen to expand the supply of certified seeds. As is described in later sections, since the early 2010s, Nigeria significantly increased its production of certified seeds (particularly for maize and rice), which in some years reached quantities comparable to total seed use in the country. At the same time, Nigeria is characterized by significantly heterogeneous agroecological environments (e.g., Gyimah-Brempong et al., 2016) and the scarcity of public resources for the agricultural sector development (Takeshima et al., 2022), which can

both pose challenges in sustainable expansion of certified seeds production. Our findings are also relevant to other developing countries, including East Africa (e.g., [ISSD Africa, 2017](#); [Barriga and Fiala, 2020](#); [Mastenbroek et al., 2021](#)), West Africa (e.g., [Miklyaev et al., 2017](#); [Opoku, 2017](#)), and North Africa ([Kugbei et al., 2000](#), p.66) as well as Asia (e.g., [Lillie and Budhiyono, 1995](#)), where seed quality assurance system can be a resource-intensive undertaking with high marginal costs ([Spielman and Kennedy, 2016](#)).

This study contributes to the literature on the demand for certified seeds and the impacts of seed quality assurance policies. Most importantly, to the authors' knowledge, ours is the first study in developing country contexts to exploit the spatiotemporal variations in the production of certified seeds and assess their effects on key farm household-level outcomes, including the use of certified seeds use, and yield, using nationally representative panel data. Our study also shows that agro-ecological factors drive part of the heterogeneity in the use and effects of certified seeds, and supplements past studies highlighting other potential drivers of similar heterogeneity including socioeconomic factors and perceptions of net benefits relative to other classes of seeds, as well as knowledge of the benefits of certified seeds ([Opoku, 2017](#); [Maredia et al., 2019](#); [Mastenbroek et al., 2021](#); [Okello et al., 2023](#)). Our direct evidence on certified seeds also contributes to past studies that focus on more general seed sector policies and policy environments ([Waithaka et al., 2011](#)), theoretical analyses ([Auriol and Schilizzi, 2015](#)), or broader interventions within which the provision of certified seeds is one of the components ([Wossen et al., 2017](#); [Abate et al., 2018](#)). [Waithaka et al. \(2011\)](#), through the spatial equilibrium model, shows how improved policy environments for the seed sector, in general, can generate welfare effects that vary across countries in East Africa. [Auriol and Schilizzi \(2015\)](#) derives theoretical models showing that public seed certification is optimal only when net benefits from seed certification are sufficiently higher relative to the costs of certification and opportunity costs of public funds to expand the certification system are sufficiently low. [Wossen et al. \(2017\)](#) and [Abate et al. \(2018\)](#) show, based on farm survey data in Nigeria and Ethiopia, that input subsidy programs that provide certified seeds as part of the packages have had significantly heterogeneous effects on yield due to heterogeneity in land quality, or on the use of certified seeds due to heterogeneity in local seed market conditions. However, empirical farm-level evidence regarding the effects of certified seeds production per se remains scarce in most developing countries, which our study provides.

The remainder of the paper is structured as follows. Section 2 describes seed systems in Nigeria, with a particular focus on certified seeds production. Section 3 presents our empirical approach and data. Section 4 presents our results, and section 5 discusses their implications for policy and regulation. Finally, Section 6 concludes.

2. Seed systems and certified seeds production in Nigeria

In Nigeria, a majority of seeds used come from seeds recycled by farmers from previous years, which are sometimes sold to other farmers in the local market outside the seed quality assurance systems. Seeds that are provided through the formal seed systems are supplied by a mixture of both the public and the private sector agents. Breeder seeds are primarily provided by the National Agricultural Research Institutes (NARIs) and Consultative Group for International Agricultural Research (CGIAR) centers. Similar to certified seeds, breeder seed production quantity also fluctuated significantly over the years, ranging from near zero in 2012 to almost 300 tons in 2013 ([NASC, 2024](#)). Among the foundation seeds produced, maize and rice accounted for a significant share in the 2010s ([NASC, 2024](#)), typically at least two-thirds or more (except in 2013 when concerted efforts were made in the production of soybean foundation seeds). In 2011 and 2012, community-based seed organizations (CBOs) accounted for a significant share of production. Since 2012, production by seed companies has started growing substantially and has been the primary source of foundation seeds since

2014, although NARIs have continued to remain significant suppliers as well ([NASC, 2024](#)). Most certified seeds are produced by seed companies, as described below. Typically, small to medium-scale seed companies produce 500 tons per year, although some major seed companies produce on the order of 5000 tons in peak years like 2013 and 2014 ([NASC, 2024](#)). Government, often state governments, has remained among the primary buyers of certified seeds from seed companies, which would then distribute certified seeds to various farmers within the state while the remaining is sold directly to farmers by seed companies and distributors ([Waithaka et al., 2019](#)).

Seed certification has been the primary tool for assuring seed quality for farmers in Nigeria over the last few decades for a limited number of crops. Until 2019, the primary legal documents guiding the development of the seed sector in Nigeria were the National Seeds Decree of 1992 and the National Agricultural Seeds Act of 2004 ([NASC and SEEDAN, 2020](#)). Since 2007, the National Agricultural Seeds Council (NASC), an agency of the Federal Ministry of Agriculture and Rural Development, has been in charge of certification ([FMARD, 2015](#); [FMARD, 2022](#); [NASC, 2022a](#)). The NASC Act 2019 empowered NASC to provide legal backing for seed certification ([NASC and SEEDAN, 2020](#)). The Seed Certification, Quality Control, Crop Registration and Release Department within NASC is statutorily responsible for quality assurance and seed certification ([NASC, 2024](#)). Seed Certification Officers are located in each state of the federation, including the Federal Capital Territory (FCT) ([NASC, 2024](#)).

The Government of Nigeria is strategically focused on expanding certified seeds production in response to guidance provided by the National Seed Policy 2015 and the updated policy of 2022 ([FMARD, 2015](#); [FMARD, 2022](#)). In fact, significant efforts were made between 2013 and 2015 to produce certified seeds for maize, rice, and several other crops on an unprecedented scale relative to the quantity of seed used in previous years. Seed companies have played a significant role in these scaling efforts, accounting for 95 % or more of certified seeds produced in the country. A much smaller fraction of certified seeds is supplied by other entities like CBOs ([NASC, 2024](#)). CBOs also produce small quantities of quality declared seeds (QDS) for sale within their communities under NASC supervision ([Iorlaman et al., 2021](#)).

Seed certification capacity in Nigeria is, however, limited: the total number of seed inspectors and certification officers has been on the order of 50–75 ([Bentley et al., 2011](#); [Waithaka et al., 2019](#)), which is in the similar order of magnitude as in many other SSA countries ([Mabaya et al., 2021](#); [Waithaka et al., 2019, 2021](#)) despite that arable land in Nigeria is several times larger than in most other SSA countries.

Limited capacity in Nigeria can lead to significantly high seed certification costs. For example, in Ghana, the average cost per kg of producing certified cowpea seed is twice that of cowpea grain ([Opoku, 2017](#)), often rendering the use of quality seeds unprofitable ([Maredia et al., 2019](#)). In Indonesia and Tanzania, due to hidden transaction costs, de facto seed certification costs are much higher than official certification fee schedules ([Lillie and Budhiyono, 1995](#); [ISSD Africa, 2017](#)). Because direct estimates of seed certification costs in Nigeria are not readily available but are likely to be substantial, assessing the patterns of productivity effects of certified seeds can inform how efforts in seed certification should be prioritized.

3. Analytical approach

3.1. Data and key variables

Our farm household-level data are originally from four survey waves of the LSMS-ISA: 2010/11, 2012/13, 2015/16, and 2018/19 (see [NBS and World Bank \(2019\)](#) for additional details on these survey waves). We primarily focus on waves 3 and 4 that contain information on the use of certified seeds and improved varieties, although the first 2-waves are also used in some supplementary analyses. The waves 3 and 4 provide a nationally representative panel dataset of 1507 households in 2015/16

and 2018/19 (NBS and World Bank, 2019). These are random subsamples of the original 5000 panel households surveyed in waves 1 through wave 3, which remained in the sample in wave 4 when new sampling framework was used. The original 5000-panel households were selected through two-stage probability sampling methods. First, 500 Enumeration Areas (EAs) were selected based on the probability proportional to size (PPS) of the total EAs in each state and FCT among all EAs within the country defined by the National Bureau of Statistics (NBS) from the 2006 Population Census. Second, in each of the 500 EAs, 10 households were randomly selected. These 5000 households were reinterviewed in Waves 2 and 3. The 1507 households in Wave 4 were selected from a random sample of 159 EAs of the original 500 EAs (NBS and World Bank, 2019). Within these panels, our analysis focuses on agricultural households, which account for approximately 60 % of the samples in each wave.

LSMS-ISA data are supplemented with information on quantities of certified seeds produced by seed companies between 2007 and 2017 (NASC, 2024) and the locations of their headquarters (state) (NASC 2022b). For each of these years, the NASC annual reports describe the quantity of certified seeds for different crops (including maize, rice, and cowpea) by each seed company.

Historical and spatial data on rainfall and temperature are extracted from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al., 2015) and Climatic Research Unit (CRU) (2022), respectively, using the geographic coordinates of EA where respondents reside. The historical average of windspeed at 10 m above the ground is extracted from CRU (2022), while various soil parameters are extracted from FAO/IIASA/ISRIC/ISSCAS/JRC (2012). Nighttime light intensity data are from Elvidge et al. (2021). Each of CHIRPS, CRU and FAO/IIASA/ISRIC/ISSCAS/JRC (2012) is available at 1 km × 1 km resolution, thus suitable for capturing sufficient variations across our sample households. Conflict intensity data are from The Armed Conflict Location & Event Data Project (ACLED) data (Raleigh et al., 2010).

3.2. Empirical model

Our empirical approach relies on farm-level panel fixed effects model. Specifically, we estimate, separately for each crop $k =$ maize, rice, cowpea. Variable C_{kijt} is a binary variable indicating whether the household i in state j in year t used certified seeds for crop k . Variable Y_{kijt} is the yield (ton/ha) for crop k by farm household i in state j at year t .

$$C_{kijt} = \alpha_k + \alpha_{ks1} S_{kijt} + \alpha_{ks2} S_{kijt}^2 + \alpha_{kx} X_{ijt} + \sum_t^T \alpha_{gt} D_t G_i + u_{kij} + \varepsilon_{kijt}, \ln(Y_{kijt})$$

$$= \alpha_k + \alpha_{ks1} S_{kijt} + \alpha_{ks2} S_{kijt}^2 + \alpha_{kx} X_{ijt} + \sum_t^T \alpha_{gt} D_t G_i + u_{kij} + \varepsilon_{kijt}, \text{ for each crop } k$$

$$= \text{maize, rice, cowpea}$$

(1)

Each of these indicators are regressed on a proxy variable for certified seeds for each crop k supplied before the beginning of year t by seed companies whose headquarters are located in state j where farm household i is located (S_{kijt}), and on its squared term (S_{kijt}^2), year dummy (D_t with $t = 2010, 2012, 2015, 2018$, and $T = 2018$) interacted with geopolitical dummy variables (G_i), as well as other time-variant exogenous control variables (X_{ijt}) (explained more in detail below). The variable S_{kijt} is standardized to a per capita base, using the state's population in the most recent population census (National Population Commission of Nigeria, 2016). Notations α 's are estimated parameters in equation for each crop k . Notation u_{kij} is a parameter that controls for time-invariant fixed effects for the farm household i (in state j) in each regression for crop k . Notation ε_{kijt} is the idiosyncratic error term. Parameters α_{ks1} and α_{ks2} capture the marginal effects of proxy variables for certified seeds quantities, and by including S_{kijt}^2 , we also focus on whether the marginal effects significantly change at the intensive margin. We include S_{kijt}^2 as we suspect that the marginal effects may decline due to

significant heterogeneity in the patterns of certified seeds use and its yield effects, which we discuss in the subsequent sections. Similar models assessing the effects of district or state level variables on household-level outcomes have been used in previous studies (e.g., Ramaswami et al., 2002; Takeshima et al., 2022).

3.3. Proxy variable S_{kijt}

As was mentioned earlier, we proxy access to certified seeds through the quantity of certified seeds produced by companies headquartered in the state. Various studies also provide supporting anecdotal evidence for its general suitability. First, in Nigeria, most seed companies sell seeds through agrodealers or directly to farmers, as well as to governments (Mabaya et al., 2021). Because seed companies often need to monitor payments from agrodealers, and poor road infrastructure raises transactions costs from moving seeds across vast geographic space, it may make sense for companies to procure and sell more seeds locally rather than regionally (Bentley et al., 2011). Second, many seed companies, including major ones like Premier Seed Ltd., have at least one warehouse located at their headquarters where they store seeds (Bentley et al., 2011). This suggests that many headquarters' locations indeed signify where their companies' certified seeds are physically stored. Thirdly, seed companies have accounted for a significant share of certified seeds produced in Nigeria, especially since the 2010s, often accounting for 95 % or more, while former producers like the Agricultural Development Projects (ADP) have significantly reduced their shares (NASC, 2024).

In some cases, however, farmer i may be located sufficiently close to seed producers outside i 's home state. To control for the effects of possible cross-state spillover of certified seeds, we add to X_{ijt} certified seeds produced by seed companies located in the nearest adjacent state for i . The nearest adjacent state is based on the Euclidean distance to the state border, which depend on i 's location within its home state. We also add to X_{ijt} the factors that may affect the access to certified seeds; conflict intensity in the local government area (LGAs) where farm household i is located as well as all surrounding LGAs, proxied by the total number of violent incidents reported in the ACLED data between January and June (6 months leading up to the planting seasons in most parts of Nigeria), which can be negatively associated with spatial mobility of certified seeds between seed companies and i ; nighttime light intensity (as a proxy of quality of local infrastructures including roads) which can be positively associated with spatial mobility of certified seeds; and Euclidean distance between i and the nearest seed company for i (using the centroid of the LGAs where seed companies are located). In the robustness check section, we also check how results change if we allow α_{ks1} and α_{ks2} vary depending on these additional factors.

3.4. Other control variables

Variables X_{ijt} also include a similar set of factors as in previous studies conducted in Nigeria (e.g., Takeshima, 2019; Takeshima et al., 2022). Specifically, they consist of household demographics; household wealth and capital; input markets; infrastructure access; community-level shocks; and agroclimatic condition. Household demographics variables include the number of members differentiated by gender and age group (children aged 14 years or younger, working-age members aged between 15 and 60, and elderly aged 61 years or older), as well as gender and age of the household head.

Wealth and capital variables include human capital (years of education completed by the household head), household asset values, whether receiving remittances, whether having non-farm incomes, size of exogenous farmland endowment (owned by the household or distributed by the local chiefs) as well as the number of plots owned. Wealth variables include the value of livestock owned and the value of agricultural equipment owned, both of which are evaluated at their market prices.

Proxies for input markets include the local prices of key inputs other than seed, including fertilizer and labor, as well as access to agricultural extension. Access to infrastructure is captured by physical distance to the nearest market and administrative center. Proxies for community-level shocks include community representatives' perceptions of the incidence of key agricultural shocks (drought, flood, crop diseases/pests, and livestock disease) in the community during the past 12 months, as well as several other positive and adverse events. Specifically, positive events include development project implemented in the community, new employment opportunity, new health facility, new road, new school, improved transportation services, on-grid electricity, off-grid electricity. Negative events include human epidemic disease, sharp change in prices, massive job lay-offs, loss of key social service(s), power outage(s), and any other negative incidents.

Agroclimatic variables include the z-score of current annual rainfall and average temperature, which we constructed by comparing their historical averages and standard deviations between 1980 and 2009 (one year before the first wave of LSMS-ISA).

As in (1), control variables also include year dummy (D_t) interacted with geopolitical dummy variables (G_i). Including these interaction terms controls for other remaining region-wide shocks that may affect access to certified seeds and their effects on yields. These shocks include, for example, the release of new varieties (which are sometimes provided with certified seeds) in certain years, developed by major breeding institutes/universities in each geopolitical zone, whose diffusions may be disproportionately concentrated within these geopolitical zones at least in the short term. This is because, in West African countries like Nigeria, the varietal release is still relatively infrequent and breeding institutes/universities are relatively few (Takeshima, 2019), and the diffusion speed of new varieties often remains slow (e.g., Diagne and Demont, 2007).

3.5. Instrumental variable regression when outcome in (1) is yield (Y_{kijt})

Importantly, when the outcome of regression in (1) is yield (Y_{kijt}), we also include a dummy variable indicating whether the respondent used improved varieties. Including this dummy variable allows us to more clearly identify the effects of seed certification separately from the effects of improved varieties. The use of improved variety can be endogenously affected by S_{kjt} (particularly because a significant share of certified seeds produced may be those of improved varieties). We therefore use the instrumental variable (IV) regression approach to address potential endogeneity of the dummy variable for improved varieties. Specifically, we use the sample share of peer respondents who use improved varieties within the EA of the respondent as an excluded IV. Similar approaches of using the average within EA or other local administrative areas have been used widely in recent studies (e.g., Dillon et al., 2019; Dolislager et al., 2021). The proposed IV here is suitable because once the improved variety variable is controlled, more neighbors using improved varieties (IV used in our model) are unlikely to affect the yield, thus satisfying exclusion restrictions assumptions. This is because of generally high crop market integration across broader geography in Nigeria (e.g., Hatzenbuehler et al., 2017), so most producers are sufficiently small and thus do not affect the production outcomes of other producers through market mechanisms. This is unlike the case with more segmented markets within each producer, which is much more influential in each market outcome. Identifying the effects of certified seeds separately from the effects of improved varieties is possible using LSMS-ISA because a significant share of respondents using certified seeds indicated those seeds were traditional varieties rather than improved varieties (while there are also respondents using improved varieties but are not certified seeds). For example, many certified seeds for rice and maize produced in the early 2010s were those of varieties that had been released in the 1990s or early 2000s and thus had been considered rather traditional from farmers' standpoint (e.g.,

SUWAN-1-SR released in 1996 and Samaz-14 released in 2005 for maize (Wossen et al., 2023), and FARO 15 released in 1974 and FARO 44 released in 1993 for rice (Gyimah-Brempong et al., 2016).

Importantly, it is worth clarifying that S_{kjt} is exogenous because S_{kjt} is measured at state level. Farm household level outcomes (which are our outcome variables in (1)) may be unlikely to affect state-level variable S_{kjt} , thus ruling out reverse-causality. Furthermore, there are unlikely to be other factors that affect both state-level variable S_{kjt} and farm household-level outcome variables, after we control for improved varieties and other household characteristics.

3.6. Heterogeneity in the use and yield effects of certified seeds

Eq. (1) assesses the relationship between S_{kjt} and yield or seed use patterns at the farm level. We also conduct supplementary analyses that provide insights into particular effects of S_{kjt} in (1) by further investigating the effects of key time-invariant variables (agroecological variables and household wealth in the initial wave) on certified seeds use and its effects on yield. Specifically, we first estimate

$$\hat{u}_{kij} = \beta + \beta_Z \cdot Z_{ij} + \beta_X \cdot X_{ij}^* + \varepsilon_{kij}. \quad (2)$$

where \hat{u}_{kij} is the predicted value of time-invariant fixed effects on the use of certified seeds estimated in (1) with dependent variable C_{kijt} . Prior studies use similar specifications as (2) to estimate the effects of time-invariant fixed effects and other time-invariant variables (e.g., Dercon, 2004; Jacoby and Minten, 2009; Takeshima, 2019). Z_{ij} is the set of time-invariant agroecological variables, namely soil parameters, the historical average of annual rainfall, annual average temperature and wind speed, which is considered an important variable affecting yield in Africa (Tittone and Giller, 2013). X_{ij}^* consists of the values in the initial survey period of a subset of the time-variant exogenous variables X_{ijt} that capture key farm household wealth as well as conflict intensity and nighttime light intensity. β 's are estimated parameters. Unlike (1) which estimates effects of time-variant factors on certified seeds use, eq. (2) estimates the effects of time-invariant factors on certified seeds use.

We then estimate

$$\ln(Y_{kijt}) = \gamma + \gamma_C \cdot C_{kijt} + \gamma_{CZ} \cdot (C_{kijt} \cdot Z_{ij}) + \gamma_{CX} \cdot (C_{kijt} \cdot X_{ijt}^*) + \gamma_X \cdot X_{ijt} + v_{kij} + \varepsilon_{kijt}. \quad (3)$$

The time-invariant agroecological variable Z_{ij} is defined as above, while X_{ijt}^* is a subset of the time-variant exogenous variable X_{ijt} that capture key farm household wealth as well as conflict intensity and nighttime light intensity. γ 's are estimated parameters. Eq. (3) estimates the heterogeneous effects of certified seeds uses on yield, with heterogeneity depending on Z_{ij} and X_{ijt}^* . Specifically, X_{ijt}^* includes farm size, agricultural capital, household asset, and gender of household head—the latter being time-variant because the household head may change due to death, emigration, or other factors.

In (3), C_{kijt} and all interacted variables are potentially endogenous, because C_{kijt} is also modeled as a dependent variable in (1). Similar to yield regression for (1), X_{ijt} here also includes a dummy variable indicating the use of improved variety. We therefore estimate (3) with both Ordinary Least Square (OLS) fixed effects (where C_{kijt} and interacted variables are treated as exogenous), and an IV fixed effects method, where C_{kijt} and interacted variables, as well as the improved variety dummy variable, are potentially endogenous and instrumented using $S_{kjt} \cdot X_{ijt}^*$ and $S_{kjt} \cdot Z_{ij}$, as well as the EA-sample share of peer respondents using improved variety as excluded IVs.

For both (2) and (3), we also estimate additional models which exclude wealth variables from X_{ijt}^* , in order to account for the possibility that wealth variables may be endogenously determined by more exogenous factors Z_{ij} .

We estimate (2) and (3) for maize-only sample, as well as for samples combining maize, rice and cowpea, instead of estimating them separately for cowpea-only and rice-only samples. This is because the sizes of cowpea-only and rice-only samples for (2) is fairly small (as (2) uses only one wave per respondent) and, while the sizes of cowpea-only and rice-only samples for (3) are larger, IV-regression results are somewhat imprecise. The results for (2) and (3) should therefore be interpreted with caution for rice and cowpea.

3.7. Descriptive summary

3.7.1. Certified seeds production

Fig. 1 illustrates the trend of certified seeds production in Nigeria for target crops in recent years. Fig. 1 shows that certified seeds production for maize and rice has increased significantly since 2012 compared to previous years. This surge in production in 2013 and 2014 was likely due to a shift in focus under the then-administration’s Agricultural Transformation Agenda, which promoted the significant increase in the supply of certified seeds of maize and rice. The production declined somewhat since 2016 under the new administration. A significant share of certified seeds in the peak period (2013–2015) was supplied due to seed companies’ trust in guaranteed purchase by the government, including state governments. However, the governments often failed to provide timely payment to seed companies for the certified seeds produced, and a significant share of seed companies either stopped the production of certified seeds or went out of business since 2016 (Waithaka et al., 2019), leading to a substantial decline in the production of certified seeds since 2016 relative to 2013–2015. Although the volume of certified seeds production has dropped from its peak in 2014, it has remained above pre-2013 levels since then. In recent years, certified seeds production has been largely concentrated in maize (particularly open-pollinated varieties (OPVs)) and rice (particularly lowland varieties). Certified cowpea seed production remained low relative to maize and rice but was significantly higher in 2020 and afterward compared to previous years (Fig. 1, line). The reason behind the greater production of certified cowpea seed in 2020 is unclear, although it might have been partly driven by the Nigerian government’s interest in promoting cowpeas as an export crop under The Agriculture Promotion Policy implemented between 2016 and 2020 (FMARD, 2016).

Fig. 2 illustrates the distribution of certified seeds production for target crops across geopolitical zones, based on seed companies’ headquarters locations. The northern states have accounted for a significant majority of certified seeds production and fluctuations over time for maize, rice and cowpea. The dominance of northern states in certified seeds production may be driven by the fact that Northern Nigeria (North West, North East, and North Central zones) historically accounted for the significant share of production of these crops. For example, the production of maize, rice, and cowpea in these three northern

geopolitical zones (out of all six geopolitical zones of Nigeria) accounted for about 65–75 %, 70–80 %, and 75–95 % of total rainy seasons production in Nigeria in years corresponding to the LSMS-ISA survey years (2010, 2012, 2015 and 2018) (NAERLS, 2024). In addition, Northern Nigeria is broadly more suitable for improved varieties often imported from more temperate regions in the world that share similar agroecological conditions (e.g., longer daylight during major production season than in lower latitude zones of Southern Nigeria for rice (Gyimah-Brempong et al., 2016) and maize (USAID, 2016) and is generally more conducive to the growth of certified seeds production businesses. Importantly, within the Northern Nigeria, we still observe spatial heterogeneity in certified seeds production due to factors like the tendency of some seed companies to locate near each other to facilitate information flows (Tripp, 2001; Bentley et al., 2011) and often restricted access to foundation seeds provided by the nearby breeding institutes (Bentley et al., 2011), which we can exploit in our analyses.

3.7.2. Farm household variables

Table 1 shows the household-level outcome variables. Outcome variables indicate that most respondents exhibit low yield and limited use of certified seeds. “Certified seeds” reported at the farm household level here are defined as seeds that have been approved for sale and planting by the appropriate seed certification authority such as the Ministry of Agriculture (NBS and World Bank, 2019). Table 1 shows that use of certified seeds is quite rare for all three crops. It is worth noting, however, that the use of certified seeds of hybrid varieties is considerably lower than the use of certified seeds, suggesting that, according to respondents’ perceptions, most certified seeds for maize are OPVs rather than hybrids.

Appendix Table A1 provides the descriptive statistics of exogenous variables. For our sample, the quantity of certified seeds produced by seed companies located in the same state as respondents, is typically 1 kg per capita per year for maize and rice and 0.02 kg for cowpea. Households surveyed are primarily asset- and resource-poor smallholders, mostly male-headed, somewhat remotely located from the markets. In survey years, respondents were typically in areas that experienced above-average rainfall and temperature compared to historical averages during the period between 1980 and 2009.

4. Results

4.1. Effects of certified seeds production by seed companies located in the state

Overall, our results indicate a positive relationship between certified seeds production in proximity to farm households and farm-level improved variety use, yields, and output, although this effect is diminishing at the margin. We report results on a crop-by-crop basis below

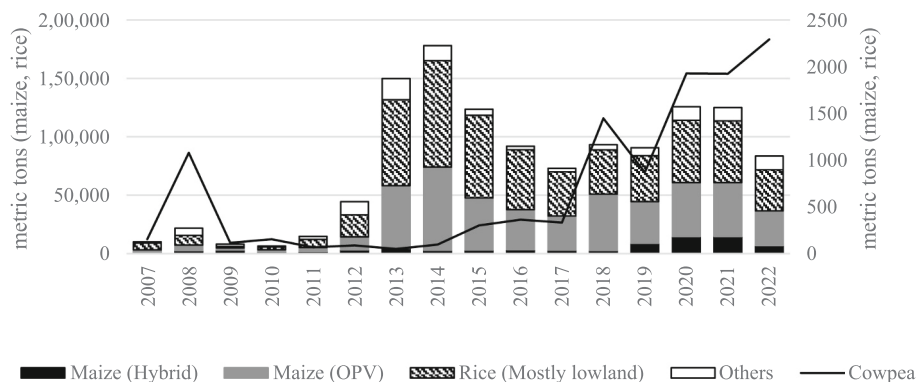


Fig. 1. Quantity of certified seeds produced in Nigeria. Source: Authors’ calculations based on NASC (2022b, 2024) in left-hand side panels.

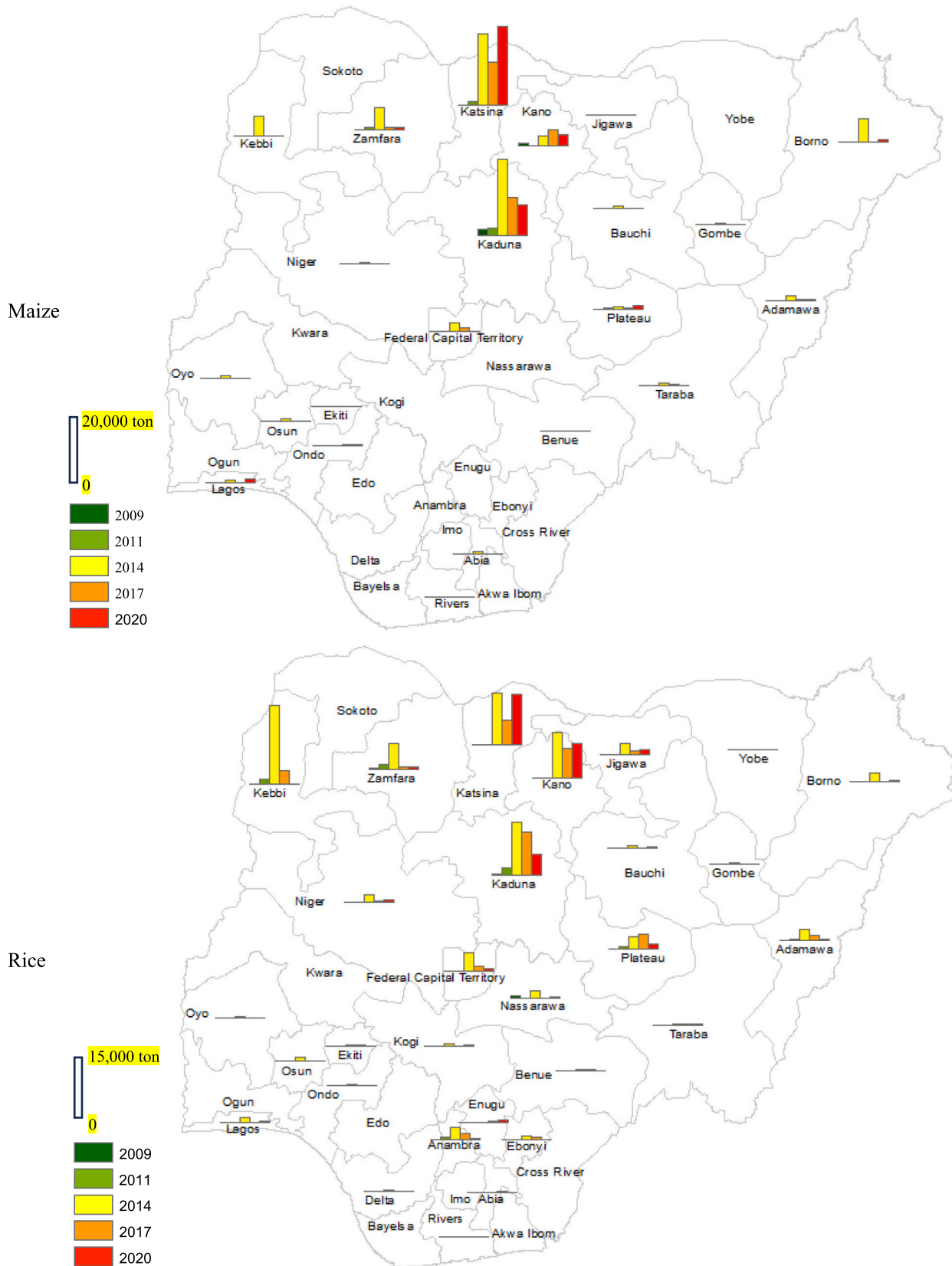


Fig. 2. Quantity of certified seeds produced by seed companies located in each state in selected years^a.

Source: Authors calculations based on NASC (2024).

^a Figures shown are for years corresponding to each of the 4 waves of LSMS-ISA (i.e., certified seeds produced in 2009 were used in 2010 which is wave 1, and so forth). Figures for 2020, another peak year with significant certified seeds production (Fig. 1), are also shown to illustrate potential relevance of our study findings in more recent years.

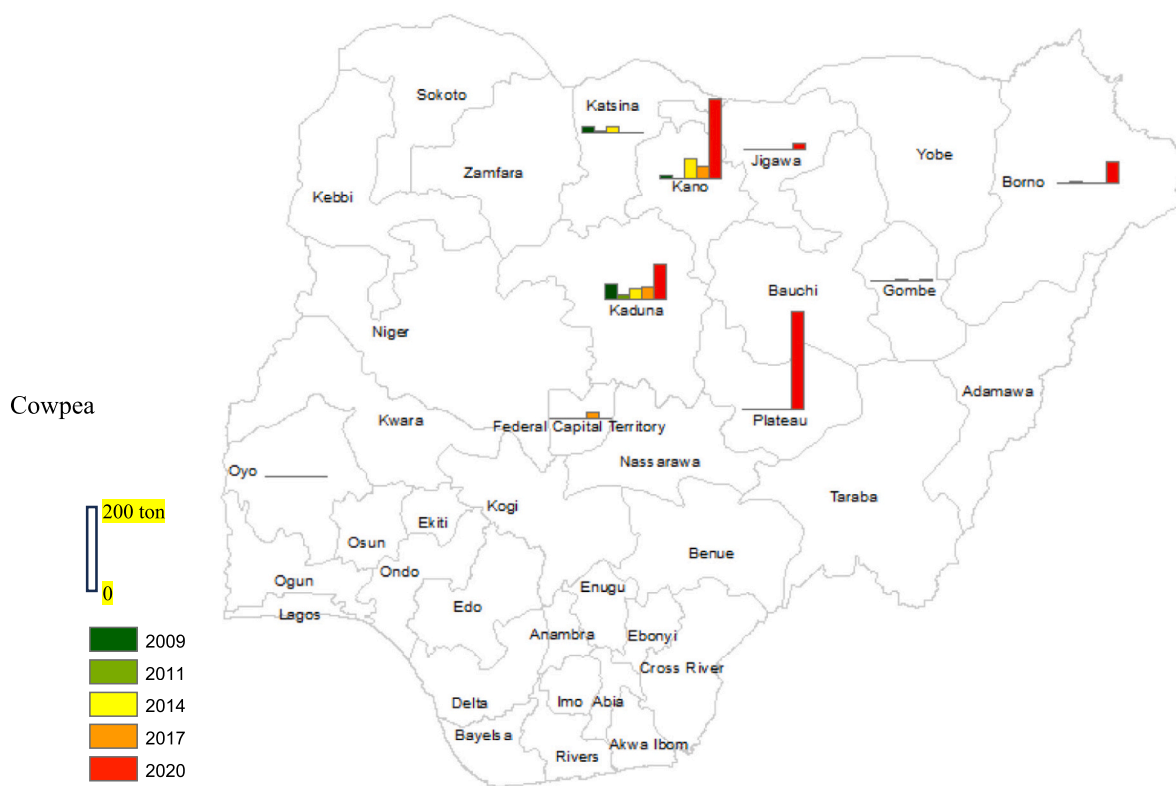


Fig. 2. (continued).

Table 1
Outcome variables.

Variables	Crops	Average (all 4 rounds)	Median (all 4 rounds)	Standard deviations (all 4 rounds)
Yield (tons / ha)	Maize (OPV and hybrid)	2.063	1.172	2.374
	Rice	2.723	1.976	2.357
	Cowpea ^b	1.304	0.700	1.685
Using certified seeds (yes = 1) ^a	Maize (OPV and hybrid)	0.079	0.000	0.259
	Maize (Hybrid)	0.033	0.000	0.107
	Rice	0.076	0.000	0.255
	Cowpea ^b	0.036	0.000	0.183

Source: Authors based on NBS and World Bank (2019).

^a Only reported in Wave 3 (2015) and Wave 4 (2018).

^b While LSMS-ISA data combine data for cowpea and beans, we interpret the information mostly applicable to cowpea given that the production of other beans has been generally small relative to cowpea production (often on the order of 1/10 of cowpea production based on FAO (2022)).

and highlight the significance and magnitudes of these relationships, with details provided in Table 2 through Table 4.

For maize, results indicate that an increase in certified seeds production by seed companies located within the state is associated with a statistically significant increase in yields for the farm households in that particular state. An increase in certified seeds production by 0.1 standard deviations from zero predicts the increases in the likelihood of certified seeds use by a 5.307 percentage point ($= \left[\int_0^{0.1} (0.538 - 2 * 0.073 * \theta) d\theta \right] * 100(\text{percent}) = (0.538 * 0.1 - 0.146 / 2 * 0.1^2) * 100$), although the rate of increase declines as certified seeds production expands (Table 2, columns a).

Similarly, an increase in certified seeds production by seed com-

panies located in the state by 0.1 standard deviations from zero predicts a 2.7 ($= (0.274 * 0.1 - 0.040 * 0.1^2) \sim 5.4$ ($= (0.548 * 0.1 - 0.078 * 0.1^2)$) percent increases in yield (Table 2, columns (b) through (e)). Results from columns (b) through (e) are largely robust, and this is important because each model refers to different samples and/or models. Column (b) is based on samples that grew maize in at least 2 out of all 4 waves (and thus panel). Columns (c) through (e) are based on samples that grew maize in 2 out of 2 waves, waves 3 and 4, for which we also have dummy variable indicating whether the farm household used improved varieties (which is reported in only in waves 3 and 4). Columns (c) through (e) differ in terms of whether the dummy variable for improved variety is included (column (c) against (d) or (e)), and whether this dummy variable is endogenous or not (column (d) against (e)). The results in column (e) suggest that the dummy variable for improved variety is only weakly exogenous (with p -value = 0.158). The p -value of 0.000 against the null hypothesis of under-identification in column (e) indicates that IV provides sufficient identification power (Table B1 in Appendix B summarizes the first-stage regression results for the IV regressions in Tables 2). In column (e), the coefficient for improved variety is statistically significantly positive, indicating that controlling for whether the seeds certified are of improved variety or not leads to unbiased and consistent estimates of the effects certified seeds. Generally, the coefficient for the squared term of certified seeds is statistically significant and negative, indicating diminishing yield returns to the expansion in certified seeds production.

Importantly, as is shown in the last row of Table 2, estimated marginal effects are positive for at least up to the 99th percentile of the certified seeds production variable in our sample. Therefore, the expansion of certified seeds production for maize during the study period broadly contributed to increased adoption of certified seeds by farmers, as well as yield growth. The bottom rows of Table 2 show that marginal effects at the 5th percentiles of certified seeds production level in the sample are about 1.05 times higher than those at the average levels of certified seeds production, but they are only about 0.7 times at

Table 2
Maize: Effects of one-standard deviation change.

Categories	Use of certified seeds (yes = 1)	Yield (proportional increase)	Yield (proportional increase)	Yield (proportional increase)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)
Model	OLS panel fixed effects	OLS panel fixed effects	OLS panel fixed effects	OLS panel fixed effects	IV panel fixed effects
	(a)	(b)	(c)	(d)	(e)
Certified seeds production by seed companies in the same state as farm household <i>i</i>	0.538** (0.221)	0.274** (0.111)	0.508** (0.255)	0.519** (0.256)	0.548** (0.270)
Certified seeds production squared	-0.073*** (0.027)	-0.040** (0.022)	-0.072* (0.037)	-0.074** (0.037)	-0.078** (0.038)
Improved varieties (yes = 1)				0.213 (0.176)	0.734* (0.433)
Other controls	Yes	Yes	Yes	Yes	Yes
Wave dummy * Geopolitical dummy	Yes	Yes	Yes	Yes	Yes
Intercept	Yes	Yes	Yes	Yes	Yes
Samples responding at least two rounds ^a	650	2239	650	650	650
p-value (H ₀ : model is insignificant)	0.000	0.000	0.000	0.000	0.000
p-value (H ₀ : instrumental variables underidentified)					0.000
p-value (H ₀ : improved variety is exogenous)					0.158
Marginal effects at different percentiles of CS production (average = 1)					
5th percentile	1.050	1.051	1.053	1.053	1.050
Average	1.000	1.000	1.000	1.000	1.000
95th percentile	0.677	0.680	0.662	0.660	0.688
Percentile at which marginal effects turn negative	> 99	> 99	> 99	> 99	> 99

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

^a Sample sizes are much smaller for models other than column (b) because “certified seeds” variable (dependent variable in column (a)) and “improved variety” variable (used in column (d) and (e)) are only reported in waves 3 and 4, and households that grew maize in only 1 of the waves 3 and 4 are further excluded from the analysis.

95th percentiles of certified seeds production levels. While we cannot translate these to net returns in certified seeds production due to insufficient data on the cost of such production, the extent of declines in marginal effects can have potentially meaningful effects on the viable expansion of certification for maize seeds. The extent of declining marginal returns that correspond to the negative coefficients on squared

terms may still be meaningful because our results correspond to gross returns rather than net returns that would account for the potentially rising marginal cost curve of certified seeds production. The marginal cost curve may be rising due to various reasons. For example, in seed inspection, inspectors’ travel costs to the field account for a significant share of overall inspection costs (ISSD Africa, 2017), and expanding the

Table 3
Rice: Effects of one-standard deviation change^a.

Categories	Use of certified seeds (yes = 1)	Yield (proportional increase)	Yield (proportional increase)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)
Model	OLS panel fixed effects	OLS panel fixed effects	OLS panel fixed effects	OLS panel fixed effects
	(a)	(b)	(c)	(d)
Certified seeds production by seed companies in the same state as farm household <i>i</i>	0.972*** (0.258)	0.269** (0.117)	0.793** (0.108)	0.843*** (0.122)
Certified seeds production squared	-0.154*** (0.048)	-0.040* (0.022)	-0.159*** (0.049)	-0.159*** (0.045)
Improved varieties (yes = 1)				0.686*** (0.214)
Other controls	Yes	Yes	Yes	Yes
Wave dummy * Geopolitical dummy	Yes	Yes	Yes	Yes
Intercept	Yes	Yes	Yes	Yes
Samples responding at least two rounds ^b	142	637	142	142
p-value (H ₀ : model is insignificant)	0.000	0.000	0.000	0.000
p-value (H ₀ : instrumental variables underidentified)				
p-value (H ₀ : improved variety is exogenous)				
Marginal effects at different percentiles of CS production				
5th percentile	1.074	1.059	1.079	1.075
Average	1.000	1.000	1.000	1.000
95th percentile	0.543	0.577	0.435	0.468
Percentile at which marginal effects turn negative	> 99	> 99	> 99	> 99

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

^a Unlike in Table 2, we omit IV-fixed effects model in Table 3 due to very small size for panel samples when only waves 3 and 4 are include (waves in which variable “improved varieties” is available), and limited reliability of IV models in such cases.

^b Sample sizes are much smaller for models other than column (b) because “certified seeds” variable (dependent variable in column (a)) and “improved variety” variable (used in column (d) and (e)) are only reported in waves 3 and 4, and households that grew rice in only 1 of the waves 3 and 4 are further excluded from the analysis.

inspection site may require increasingly high travel costs. Furthermore, expanding certification requires additional resources to train and capacitate new certification officers and expand seed testing labs and other infrastructures, which may need to be financed through significant increases in certification fees given that the NASC, as well as other agricultural agencies in Nigeria, are constrained by limited budgets (Takeshima et al., 2022).

Table 3 shows similar patterns for rice: the effect on the likelihood of using certified seeds is positive and non-linear. Specifically, an increase in certified seeds production by 0.1 standard deviations from zero predicts a 9.57 percentage point increase ($= 0.972 \times 0.1 - 0.154 \times 0.1^2$) in the likelihood of certified rice seed use, and 8.27 % increase ($= 0.843 \times 0.1 - 0.159 \times 0.1^2$) in yield, although the rates of increase decline as certified seeds production expands as indicated by the statistically significant negative squared terms (Table 3, columns a, d). Results using all 4 waves and dropping the improved variety dummy variable exhibit similar patterns (Table 3, column b). The comparison between columns (c) and (d) shows that using improved varieties has statistically significantly positive effects on yield. The bottom rows of Table 3 show that, for the use of certified seeds and yield, marginal effects at the 5th percentiles of certified seeds production level in the sample are about 1.06–1.07 times higher than those at the average levels of certified seeds production, but they are only about 0.5 times at 95th percentiles of certified seeds production levels. Unlike in Table 2, we omit IV-fixed effects model in Table 3 due to very small size for panel samples when only waves 3 and 4 are include (waves in which variable “improved varieties” is available), and limited reliability of IV models in such cases.

Cowpea exhibits similar patterns, which can be seen in Table 4. An increase in certified seeds production by 0.1 standard deviations from zero predicts a 0.6 percentage points increase in the likelihood of using certified seeds, and 14–15 % increase in yield, although the rates of increase decline as certified seeds production expands as indicated by the statistically significant negative squared terms. Results using all 4 waves and dropping the improved variety dummy variable exhibit similar patterns (Table 4, column b). The result in column (e) indicates that the dummy variable for improved variety is fairly likely to be

exogenous (with *p*-value of 0.788) and thus the OLS result in column (d) is likely to be unbiased and consistent. The comparison between column (c) and (d) suggests that using improved variety has statistically significantly positive effect on yield. The bottom rows of Table 4 show that marginal effects at the 5th percentiles of certified seeds production level in the sample are about 1.3 times higher than those at the average levels of certified seeds production, but they are only about 0.39–0.46 times at 95th percentiles of certified seeds production levels. The column (e) in Table 4 summarizes the IV-panel fixed effects model (Table B1, under column heading “cowpea” in Appendix B summarizes the first-stage regression results for the IV regressions in Tables 4). Similar to Table 2, the *p*-value of 0.000 against the null hypothesis of under-identification in column (b) indicates that IV provides sufficient identification power. While the endogeneity test suggests that “improved variety” variable is mostly exogenous, the results of IV panel fixed-model is generally consistent with OLS panel fixed effects model.

Importantly, as we described earlier, the variables consisting of state-level certified seeds production are less likely to be endogenous in Tables 2 through 4, given that these variables are aggregated and less responsive to individual farmers’ yield potentials. Nonetheless, the patterns in OLS regression in columns (d) and IV regressions in (e) in Tables 2 (maize) and 4 (cowpea) for the coefficients of improved varieties are worth noting. Although these coefficients are not statistically significantly different between (d) and (e) in both Tables, coefficients in column (e) are qualitatively larger. One possibility is negative self-selection, i.e., in our studied samples, those with lower overall yield potentials are actually the ones who would experience greater yield increases from improved varieties. Such patterns can arise due to various factors, such as specific types of improved varieties mainly used during the studied period and their peculiar interactions with agroclimatic and socioeconomic conditions. These findings further caution readers that our results should not be blindly generalized but rather be interpreted within the specific contexts from which our samples are extracted.

Nonetheless, in sum, our findings are still generally consistent with the hypothesis that while increasing certified seeds production has positive effects on both yield and the use of improved or certified seeds

Table 4
Cowpea: Effects of one-standard deviation change.

Categories	Use of certified seeds (yes = 1)	Yield (proportional increase)	Yield (proportional increase)	Yield (proportional increase)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)
Model	OLS panel fixed effects	OLS panel fixed effects	OLS panel fixed effects	OLS panel fixed effects	IV panel fixed effects
	(a)	(b)	(c)	(d)	(e)
Certified seeds production by seed companies in the same state as farm household <i>i</i>	0.060* (0.035)	0.257*** (0.096)	1.561* (0.923)	1.512* (0.917)	1.358 (1.387)
Certified seeds production squared	−0.022** (0.010)	−0.260*** (0.056)	−0.478** (0.208)	−0.485*** (0.208)	−0.508* (0.300)
Improved varieties (yes = 1)				0.607* (0.356)	2.527 (7.320)
Other controls	Yes	Yes	Yes	Yes	Yes
Wave dummy * Geopolitical dummy	Yes	Yes	Yes	Yes	Yes
Intercept	Yes	Yes	Yes	Yes	Yes
Samples responding at least two waves ^a	248	2076	248	248	248
<i>p</i> -value (H0: model is insignificant)	0.000	0.000	0.000	0.000	0.000
<i>p</i> -value (H0: instrumental variables underidentified)					0.090
<i>p</i> -value (H0: improved variety is exogenous)					0.788
Marginal effects at different percentiles of CS production (average = 1)					
5th percentile	1.320	1.883	1.267	1.280	1.327
Mean	1.000	1.000	1.000	1.000	1.000
95th percentile	0.387	−0.693	0.488	0.463	0.374
Percentile at which marginal effects turn negative	> 99	75	> 99	> 99	> 99

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

^a Sample sizes are much smaller for models other than column (b) because “certified seeds” variable (dependent variable in column (a)) and “improved variety” variable (used in column (d) and (e)) are only reported in waves 3 and 4, and households that grew cowpea in only 1 of the waves 3 and 4 are further excluded from the analysis.

for maize, rice, and cowpea, these effects may diminish at higher rates of certified seeds production.

4.2. Robustness checks

4.2.1. Incorporating heterogeneous effects

As was described earlier, all results in Table 2 through Table 4 control for local conflicts, infrastructure proxied by nighttime light intensity, and distance to the nearest LGAs where seed companies are located. We also check the robustness of results in Table 2 through Table 4 by further allowing the effects of certified seeds production S_{kjt} (α_{ks1} and α_{ks2}) to vary depending on these factors. Results are shown in A2 and A3 for maize and cowpea. Results for rice are not shown because multicollinearity from added interaction terms is rather severe for the relatively smaller sample we have for rice equations. The top two rows continue to show the estimated coefficients α_{ks1} and α_{ks2} at the average levels of additional interacted variables. These results generally suggest that our main results are largely robust, i.e., positive but declining marginal returns of certified seeds production by seed companies located in the state, at the prevailing (average) levels of conflicts, nighttime light, and the distance to seed companies. Nonetheless, these additional interaction terms are statistically significant for certain (though not all) outcomes, suggesting that effects of certified seeds production may change depending on how conflicts, infrastructure and seed markets evolve in the future. For example, more intense conflicts could make the likelihood of using certified maize seeds to be less responsive to certified seeds production at the lower level of certified seeds production (as indicated by a significantly negative sign for “Certified seeds production \times heterogeneous factors” under Table A2 column (a)), although the concavity in this response curve may get somewhat attenuated at a higher level of certified seeds production (as indicated by a significantly positive sign for “Certified seeds production squared \times heterogeneous factors” under Table A2 column (a)) simply because the effects at that point are already lower than those at lower quantity of certified seeds. For cowpea in Table A3, more intensive conflict or being further away from seed company LGAs can make the response function more concave with potentially higher initial marginal effect at a lower level of certified seeds production, though this will decline faster at a higher level of certified seeds production. These results may reflect the possibility that, during the study period, the Nigerian government and the public-sector might have made conscious efforts to provide more certified cowpea seeds to conflict-hit areas or remote areas further away from certified seeds-producing companies (e.g., Iorlamen et al., 2021), as the public sector sometimes target seed distributions in responsive social/natural shocks like conflict in remote areas (e.g., Sperling and McGuire, 2010). Such targeted distribution might have more dominant effects for cowpea than for maize, given the smaller overall certified seeds production for the former. Therefore, our results should be interpreted as specific to existing contexts, and may not be generalized to changing contexts as they may evolve in the future.

4.2.2. Including certified seeds production in the nearest adjacent state

We also re-estimate (1) by adding to S_{kjt} the certified seeds production in the nearest adjacent state (Tables A4 through A6). Results are either generally consistent for some outcomes (yield and improved varieties for maize, and certified seeds for cowpea) or generally insignificant for other outcomes, suggesting that certified seeds production generally may not have significant effects on yield or certified seeds in neighboring states, and if it does have effects, they are similar to their effects within the own state.

4.2.3. Using certified seeds production per agricultural households instead of population

We also re-estimate (1) by replacing S_{kjt} by certified seeds production per agricultural households in each state, instead of per population as in our primary models. Due to the lack of reliable data during the years

covered by the LSMS-ISA data, we use state-level estimates of the number of agricultural households from the latest agricultural census in 2022 (Government of Nigeria, 2024), with the assumption that the figures in 2022 are good approximation for earlier years (given that population growth and general declining trends in the share of agricultural households during these periods may largely cancel each other out). Tables A7 – A9 in Appendix present the results that correspond to Tables 2–4. Results are generally consistent with our primary results from Tables 2–4.

Table 5
Determinants of certified seeds use (effects of one-standard deviation changes).

Variables	Dependent variable = 1 if the respondent used certified seeds			
	All crops combined (with crop dummies) ^a		Maize only	
	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)
Soil alkalinity (pH)	- 0.033 (0.025)	-0.031 (0.025)	0.123*** (0.037)	0.130*** (0.036)
Soil organic contents	-0.006 (0.025)	0.013 (0.024)	-0.036 (0.037)	-0.018 (0.036)
Soil texture (medium)	0.102*** (0.025)	0.096*** (0.025)	0.056** (0.028)	0.050* (0.027)
Soil texture (fine)	-0.141*** (0.018)	-0.145*** (0.017)	-0.107*** (0.023)	-0.113*** (0.022)
Soil salinity	0.030* (0.017)	0.038** (0.017)	-0.107 (0.097)	-0.104 (0.098)
Soil sodicity	-0.023 (0.020)	-0.031 (0.020)	-0.092*** (0.025)	-0.099*** (0.024)
Soil drainage (poor drainage)	-0.007 (0.016)	-0.010 (0.016)	0.004 (0.019)	0.004 (0.019)
Soil drainage (excess drainage)	0.014 (0.020)	0.016 (0.019)	0.017 (0.028)	0.030 (0.027)
Rainfall (historical average)	0.016 (0.036)	0.010 (0.035)	-0.214*** (0.036)	-0.208*** (0.035)
Temperature (historical average)	0.063*** (0.018)	0.058*** (0.018)	0.031 (0.022)	0.026 (0.022)
Wind (historical average)	-0.148*** (0.031)	-0.171*** (0.030)	-0.212*** (0.031)	-0.229*** (0.030)
ln (farm size)	-0.007 (0.013)		-0.002 (0.016)	
ln (agricultural capital)	0.007 (0.012)		-0.008 (0.013)	
ln (asset)	0.034*** (0.012)		0.022* (0.012)	
Female household head	0.012 (0.013)		0.013 (0.012)	
Geopolitical zone dummy	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Crop dummies	Yes	Yes		
Certified seeds production by seed companies in the state	Yes	Yes	Yes	Yes
Intercept	Yes	Yes		
Number of observations (panel samples growing the same crops in both waves)	1040	1040	650	650
p-value (H ₀ : model insignificant)	0.000	0.000	0.000	0.000

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

^a Due to small samples for cowpea and rice, we combine all three crops in the regression, while adding crop dummy variables.

4.3. Potential drivers of non-linearity

Next, we explore the potential drivers of the non-linearities, and heterogeneity observed in our results. Table 5 shows the estimated effects on the use of certified seeds of time-variant factors (Z_{it}^*) in (1), and time-invariant agroecological factors (Z_i) in (2). Similarly, Table 6 shows the effects on yields of Z_{it}^* and Z_i as the source of heterogeneous

Table 6
Heterogeneous effects of certified seeds on yields (effects of one-standard deviation changes in interacted variables on the yield effects of certified seeds use).

Determinants of yield	All crops combined		Maize	
	OLS-fixed effects model	IV-fixed effects model	OLS-fixed effects model	IV-fixed effects model
	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)
Used certified seeds	0.270	1.002*	0.809***	-1.360
× Soil alkalinity	(0.217)	(0.596)	(0.258)	(1.016)
× Organic contents	-0.336*	-1.326***	0.239	0.198
	(0.192)	(0.457)	(0.321)	(1.016)
× Soil texture (medium)	-0.071	0.138	-0.443**	0.344
	(0.205)	(0.403)	(0.210)	(0.501)
× Soil texture (fine)	0.071	0.163	-0.818***	-0.485
	(0.148)	(0.318)	(0.206)	(0.626)
× Soil salinity	0.107	-0.044	0.153***	0.181
	(0.115)	(0.305)	(0.042)	(0.143)
× Soil sodicity	-0.083	0.056	-0.339	0.145
	(0.188)	(0.435)	(0.365)	(1.657)
× Soil drainage (poor drainage)	0.255**	0.111	0.840***	-0.092
	(0.124)	(0.317)	(0.216)	(0.517)
× Soil drainage (excess drainage)	-0.075	-0.187	0.282	-0.182
	(0.179)	(0.429)	(0.186)	(0.712)
× Rainfall (historical average)	0.515	-1.744*	0.311	-2.953**
	(0.333)	(1.059)	(0.270)	(1.341)
× Temperature (historical average)	0.232*	-0.527*	0.366**	-0.950*
	(0.126)	(0.316)	(0.160)	(0.537)
× Wind (historical average)	0.143	-1.970***	-0.190	-2.763***
	(0.196)	(0.692)	(0.203)	(0.915)
× ln (farm size)	0.264**	0.012	0.260**	0.328
	(0.125)	(0.394)	(0.106)	(0.404)
× ln (agricultural capital)	0.217*	0.251	0.323***	0.717
	(0.111)	(0.317)	(0.114)	(0.581)
× ln (asset)	-0.205*	-0.280	-0.135	0.595
	(0.115)	(0.287)	(0.114)	(0.449)
× Female household head	-0.181	-0.637**	-0.056	-0.614
	(0.118)	(0.310)	(0.235)	(0.949)
Used certified seeds	Yes	Yes	Yes	Yes
Used certified seeds × crop dummy	Yes	Yes		
Used improved varieties	Yes	Yes	Yes	Yes
Certified seeds production by seed companies in the state	Yes	Yes	Yes	Yes
Certified seeds production × crop dummy	Yes	Yes		
Other controls	Yes	Yes	Yes	Yes
Number of observations ^a	1040	1040	650	650
p-value (H_0 : model insignificant)	0.000	0.000	0.000	0.000
p-value (H_0 : not underidentified)		0.042		0.096
p-value (H_0 : not overidentified)		0.489		0.145
p-value (H_0 : exogenous)		0.012		0.082

Source: Authors. ***1 %, **5 %, *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

^a Sample sizes are the same as those in Table 5.

effects of certified seeds use C_{it} . Due to small sample sizes for cowpea and rice, we combine all crops in the regressions for Table 5 and Table 6 and add crop dummy variables, while we also estimate another model using maize sample only. In Table 5, we also show the results in which wealth related variables (farm size, agricultural capital, household assets, and household head gender) are dropped as these can be possibly endogenously affected by agroecological conditions.

Table 5 shows that the use of certified seeds is significantly affected by not only the quantity of certified seeds produced by companies based in the state, but also various agroecological factors and socioeconomic characteristics. Generally, certified seeds use is generally higher in areas with higher soil alkalinity, more medium- and less fine-textured soils, lower soil sodicity, lower soil drainage property, less rainfall, less wind, and higher average temperatures within each geopolitical zone (controlled for by geopolitical zone dummies). While the effects of farm size and assets vary depending on how certified seeds is defined, they also contribute to heterogeneity in the likelihood of using certified seeds. Importantly, the signs and statistical significance of these agroecological variables are largely consistent when we exclude wealth-related variables.

Table 6 shows that the effects of certified seeds use on yield can vary depending on various agroecological and socioeconomic factors. We introduce an IV-fixed effects estimation given that the exogeneity of certified seeds criterion is rejected, suggesting that OLS-fixed effects may be inconsistent. Importantly, as was mentioned earlier, we also include an endogenous dummy variable indicating the use of improved variety so that the estimated effects of certified seeds variables indeed capture the impact of seed certification rather than the effects of improved varieties. The identification tests of IV-fixed effects indicate that excluded IVs satisfy necessary conditions, i.e., models are neither over-identified nor under-identified (Tables B2 and B3 in Appendix B summarize the results for first stage regressions of IV-fixed effects models in Table 6).

Results from the IV-fixed effects estimation suggest that the effects are more positive in areas with higher soil alkalinity, lower soil organic contents, lower rainfall, lower average temperature, and less wind, as well as for male-headed households. These patterns are generally consistent for larger samples with all crops combined, and maize-only samples. These results suggest that the yield effects of certified seeds use are more heterogeneous depending on agroecological conditions. Furthermore, the effects of certain agroecological factors (e.g., soil alkalinity, rainfall, and wind) are somewhat consistent with patterns of certified seeds use in Table 5, suggesting that farmers are more likely to use certified seeds in areas where the yield effects are greater as a result of these agroecological factors.

5. Discussion

Empirical results in the previous section highlight the overall importance of enhancing the capacity of seed certification and also pursuing intermediate seed quality assurance systems that are less stringent than seed certification, for cereals and pulses in Nigeria. Results suggest that the availability of certified seeds—captured by indicators of certified seeds produced by seed companies headquartered in the states of survey respondents—is associated with positive but declining marginal effects on use and crop yields, for the case of maize, rice, cowpea. For example, estimated quantities of certified seeds used for maize and rice, two major crops for which certified seeds have been supplied in Nigeria in recent years, based on LSMS-ISA data with sample weights for maize and rice in 2015 and 2018 (for which figures are available) are 28,051 and 33,413 tons, respectively, as opposed to the average of 49,394 and 54,236 tons of certified seeds supplied for these crops as shown in Fig. 1. The declining marginal effects on the use of certified seeds imply that there is a much higher production rate of certified seeds than the rate of adoption/use of certified seeds. Such a discrepancy is likely because some of the certified seeds that are not

purchased as seeds often end up being sold as grains (Bentley et al., 2011). If the discrepancy is due to the supply-side constraint, it can be mitigated by policies that promote the adoption of certified seeds. These include increased support for extension programs that can help farmers gain knowledge of the use of improved varieties (Lanteri and Quagliotti, 1997) and other media like radio programs to enhance the awareness of certified seeds (Okwu et al., 2007). The declining marginal effects on yield may be also partly mitigated by addressing such an information gap in the access and proper usage of certified seeds.

Furthermore, supplementary analyses suggest that the declining marginal effects may also be partly because the yield effects of certified seeds are heterogeneous and depend on agroecological conditions and farmers' socioeconomic characteristics. The use of certified seeds is generally higher in areas with higher yield effects after controlling for certified seeds production. These heterogeneous responses may arise due to the sensitivity of seed performance, such as germination rates, vigor, moisture retention, among others (which are separate from performance due to genetic traits). Intuitively, this may suggest that certified seeds is used primarily by farmers who are able to realize relatively higher returns from certified seeds use and are used less by farmers who are not. In sum, the substantial patterns of agroecological and socioeconomic heterogeneity across locations in both yield effects and certified seeds use effects may help to explain the observed non-linear patterns in Table 2 through Table 4.

These results suggest the importance of more spatially targeted efforts in enhancing certified seeds production capacity. Such approaches involve identifying locations where the uptake and returns to currently available certified seeds are lower and targeting more public support toward developing varieties suitable for agroecology in those areas. This can be, in one way, explored by extending the understanding of the spillover potentials based on "agroclimatic similarity" as highlighted by earlier studies on geographic targeting for plant breeding (e.g., Takeshima (2019)). Using the information of spatial heterogeneity in agroclimatic conditions, Takeshima (2019) shows that, in Nigeria, agricultural productivity is higher in areas that share similar agroclimatic conditions as in areas where most plant breeding is conducted, possibly because these varieties have higher spillover potentials in areas with higher agroclimatic similarity with plant breeding locations. Similar spillover potential can apply to certified seeds produced in certain locations. Using the information of agroclimatic distributions in the country, when outsourcing certified seeds production of certain varieties to private seed companies, the public sector should promote varieties with high spillover potential given where these companies produce certified seeds. Similarly, the public sector should identify production areas that share similar agroclimatic conditions (and thus have significant spillover potential across each other) but are low in terms of the use of certified seeds. Encourage the production of certified seeds of popular varieties in these areas by sharing such information with private seed companies and other seed stakeholders. Regulating agencies like the NASC can contribute by increasing certification officers in and around these localities while also collecting and sharing certified seeds use data with seed companies. Governments and development agents can support the provision of finances and training for current and potential future seed companies to invest in certified seeds production targeted to these areas while also supporting extension programs and other measures to enhance farmers' awareness and knowledge of appropriate certified seeds use in their locality.

At the same time, it also remains important to consider developing more pluralistic quality assurance systems, including the expansion of intermediate classes of seeds like QDS and Truthful Labeling, among others, in areas where certified seeds currently do not work well. Such approaches can be particularly beneficial if expanding the seed certification system is costly, as was briefly discussed in section 2, and any successful models in Nigeria (e.g., community-based seed schemes) or other countries (including Truthful Labeling widely used in other developing countries like India and Thailand, and QDS used in other SSA

countries like Uganda and Tanzania (ISSD Africa, 2017)) can be effectively transferred to the Nigerian contexts.

Our findings in Nigeria can also apply to other SSA countries, particularly where OPV maize, rice and cowpeas are produced. Our results indicate declining marginal returns to certified seeds production even within the states in Nigeria, which suggest significant heterogeneity in returns even within relatively small geographic areas. Such results imply that similar patterns may be observed in many other SSA countries which are smaller than Nigeria but similarly characterized by significant heterogeneity in agroecological conditions. Developing more decentralized, location-specific production of certified seeds may therefore be important when designing seed certification systems.

6. Conclusions

Using multiple waves of nationally representative household panel data from Nigeria, we assessed the relationship between certified seeds production and farm-level use and yields of certified maize, rice, and cowpea seed, as well as their heterogeneity due to agroecological and socioeconomic factors. We applied panel fixed effects methods as well as instrumental-variable methods to address potential endogeneity associated with farmers' use of certified seeds and improved varieties. We found robust evidence that the availability of certified seeds—captured by indicators of certified seeds produced by seed companies headquartered in the states of survey respondents—is associated with positive but declining marginal effects on use and crop yields. The yield effects of certified seeds are heterogeneous and depend on agroclimatic conditions and farmers' socioeconomic characteristics. More certified seeds are used in areas with higher yield effects, given the level of certified seeds production. These patterns partly lead to observed nonlinearities in certified seeds use because certified seeds may be more likely to be used by farmers with higher expected returns than farmers with lower expected returns. Results underscore the importance of spatially targeted efforts in enhancing certified seeds production capacity as laid out in the discussion section, together with the exploration of intermediate quality standards in the short term where costs of seed certification are high relative to returns.

Lastly, our findings have important contributions to the discussion around seed systems in general. Effective seed quality assurance can potentially play key roles in integrated seed sector development, such as increased seed and varietal replacement by farmers induced by the availability of quality seeds, seed market development induced by increased overall demand, enhanced information, and knowledge flows on seeds to farmers, among others. In countries like Nigeria, where a significant share of foundation seeds are produced by seed companies, seed quality assurance through improved certification systems can also potentially induce commercial growth of seed value chains. In terms of institutional development within seed systems, recent experiences in Nigeria indicate that seed companies can potentially be significant suppliers of certified seeds, an important instrument for seed quality assurance, compared to other actors like community seed growers or cooperatives. At the same time, our evidence also points toward the importance of maintaining the plurality in seed quality assurance systems where the returns to certified seeds are low and expanding seed certification capacity is costly, at least in the short-term, through simultaneous encouragements of other intermediate quality assurance systems other than seed certification.

CRedit authorship contribution statement

Hiroyuki Takeshima: Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Catherine Ragasa:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Temilolu Bamiwuye:** Writing – review & editing, Validation,

Methodology, Data curation. **Kwaw S. Andam:** Writing – review & editing, Supervision, Project administration. **David J. Spielman:** Writing – review & editing, Supervision, Funding acquisition. **Hyacinth O. Edeh:** Resources, Project administration, Data curation. **Adetunji Fasoranti:** Writing – review & editing, Formal analysis, Data curation. **Beliyou Haile:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Chibuzo Nwagboso:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Lucky Omoigui:** Writing – review & editing, Conceptualization. **Tahirou Abdoulaye:** Supervision, Funding acquisition, Conceptualization. **P. Lava Kumar:** Writing – review & editing, Supervision, Project administration. **Tesfamichael Wossen:** Writing – review & editing, Validation, Methodology, Investigation.

Declaration of competing interest

None.

Appendix A. Additional results

Table A1
Descriptive statistics of exogenous variables.

Variables	Average (all 4 waves)
Certified seeds produced (kg per capita in the state)	
Maize	0.920
Rice	1.196
Cowpea	0.018
Household demographics	52.329
Age of head (years)	
Gender of head (female = 1)	0.139
male (0–14)	1.426
female (0–14)	1.282
male (15–60)	1.357
female (15–60)	1.582
male (61–)	0.234
female (61–)	0.161
Education of head (years)	4.787
Household asset (value per capita, 100)	1.943
Household received remittance (yes = 1)	0.045
Household has nonfarm income (yes = 1)	0.601
Farm size (purchased or distributed) (ha)	0.596
Number of farm plots (number)	2.094
Livestock asset value (value, 1000)	1.951
Agricultural capital value (value, 100)	0.941
Fertilizer price (value)	1.018
Wage (male per day, value)	7.225
Access to extension (yes = 1)	0.136
Distance to administrative center (km)	74.521
Distance to market (km)	70.729
Community level shocks: drought (yes = 1)	0.056
flood (yes = 1)	0.197
crop disease / pests (yes = 1)	0.105
livestock disease (yes = 1)	0.067
number of positive shocks	0.547
number of other negative shocks	0.403
Annual rainfall (z-score)	1.026
Annual average temperature (z-score)	1.073
Annual rainfall, historical average 1980–2009 (mm)	1177.772
Annual average temperature 1980–2009 (°C)	26.935
Annual average windspeed at 10 m above ground (meter / second)	2.518
Soil alkalinity (pH)	6.006
Soil organic content (g / kg of soil)	0.880
Soil texture – medium (proportion, 1 = 100 %)	0.593
Soil texture – fine (proportion, 1 = 100 %)	0.051
Soil salinity (deciSiemens per metre)	0.244
Soil sodicity (% of soil)	3.106
Soil with poor drainage (proportion, 1 = 100 %)	0.229
Soil with excess drainage (proportion, 1 = 100 %)	0.121
Number of violent incidents within the LGA during January – June	2.024
Luminosity index (nanoWatt per cm ² per square radian, average in LGA)	3.750

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Table A1 (continued)

Variables	Average (all 4 waves)
Euclidean distance to the nearest seed companies (km)	
Maize seed companies	67.189
Rice seed companies	63.963
Cowpea seed companies	66.326
Use improved varieties (yes = 1) Maize	0.158
Rice	0.141
Cowpea	0.064
Certified seeds produced in the nearest adjacent state (kg per capita)	
Maize	0.613
Rice	0.808
Cowpea	0.010

Source: Authors based on NBS and World Bank (2019).

Note: "Value" is equivalent to the value of kilogram of staple food evaluated at local market prices.

Table A2
Robustness of marginal response considering heterogeneity (maize).

Categories	Use of certified seeds (yes = 1)			Yield (proportional increase)		
	Coef. (s.e.)			Coef. (s.e.)		
	(a)	(b)	(c)	(a)	(b)	(c)
Certified seeds production	0.421* (0.263)	0.520* (0.272)	0.634** (0.289)	0.289** (0.124)	0.393*** (0.119)	0.289** (0.129)
Certified seeds production squared	-0.072** (0.035)	-0.064* (0.038)	-0.110** (0.050)	-0.045* (0.024)	-0.044* (0.024)	-0.044* (0.026)
Certified seeds production × heterogeneous factors ^a	-0.143* (0.073)	0.044 (0.079)	0.531 (0.408)	-0.008 (0.053)	-0.051 (0.041)	-0.027 (0.057)
Certified seeds production squared × heterogeneous factors ^a	0.027** (0.011)	-0.059 (0.107)	-0.322 (0.236)	0.013 (0.012)	-0.072 (0.053)	0.016 (0.027)
Improved variety				Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes	Yes	Yes
Wave dummy	Yes	Yes	Yes	Yes	Yes	Yes
Intercept	Yes	Yes	Yes	Yes	Yes	Yes
Samples responding at least two rounds	650	650	650	650	650	650

Source: Authors. ***1 %. **5 %. *10 %.

^a Heterogeneous factors correspond to each column as the following; (a) = conflict; (b) = nighttime light; (c) = average distance to seed company LGAs.

Table A3
Robustness of marginal response considering heterogeneity (cowpea).

Categories	Use of certified seeds (yes = 1)			Yield (proportional increase)		
	Coef. (s.e.)			Coef. (s.e.)		
	(a)	(b)	(c)	(a)	(b)	(c)
Certified seeds production	0.058 (0.042)	0.061* (0.035)	0.075* (0.042)	0.267*** (0.096)	0.386*** (0.099)	0.258** (0.116)
Certified seeds production squared	-0.023*** (0.011)	-0.024** (0.010)	-0.029** (0.014)	-0.279*** (0.057)	-0.332*** (0.065)	-0.257*** (0.067)
Certified seeds production × heterogeneous factors ^a	0.028* (0.014)	-0.026 (0.050)	0.101** (0.048)	0.076 (0.075)	-0.505** (0.206)	-0.027 (0.062)
Certified seeds production squared × heterogeneous factors ^a	-0.013* (0.008)	0.015 (0.028)	-0.066** (0.033)	-0.017 (0.054)	0.255 (0.163)	-0.040 (0.055)
Improved variety				Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes	Yes	Yes
Wave dummy	Yes	Yes	Yes	Yes	Yes	Yes
Intercept	Yes	Yes	Yes	Yes	Yes	Yes
Samples responding at least two rounds	248	248	248	248	248	248

Source: Authors. ***1 %. **5 %. *10 %.

^a Heterogeneous factors correspond to each column as the following; (a) = conflict; (b) = nighttime light; (c) = average distance to seed company LGAs.

Table A4
Maize: Effects of one-standard deviation change, with adjacent state's certified-seed production added.

Categories	Use of certified seeds (yes = 1)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)
	(c)	(g)
Certified seeds production (State of seed companies)	0.344 (0.260)	0.273*** (0.093)
Squared	0.024 (0.036)	-0.035** (0.016)
Improved variety		Yes
Other controls	Yes	Yes
Wave dummy	Yes	Yes

(continued on next page)

Table A4 (continued)

Categories	Use of certified seeds (yes = 1)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)
	(c)	(g)
Intercept	Yes	Yes
Samples responding at least two rounds	650	650

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

Table A5

Rice: Effects of one-standard deviation change, with adjacent state's certified-seed production added.

ICategories	Use of certified seeds (yes = 1)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)
	(c)	(g)
Certified seeds production (State of seed companies)	-1.172 (0.745)	-0.156 (0.166)
Squared	0.049 (0.213)	0.030 (0.030)
Improved variety		Yes
Other controls	Yes	Yes
Wave dummy	Yes	Yes
Intercept	Yes	Yes
Samples responding at least two rounds	142	142

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

Table A6

Cowpea: Effects of one-standard deviation change, with adjacent state's certified-seed production added.

Categories	Use of certified seeds (improved) (yes = 1)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)
	(e)	(g)
Certified seeds production (State of seed companies)	0.250** (0.122)	0.043 (0.046)
Squared	-0.048*** (0.015)	0.009 (0.029)
Improved variety		Yes
Other controls	Yes	Yes
Wave dummy	Yes	Yes
Intercept	Yes	Yes
Samples responding at least two rounds	248	248

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

Table A7

Results for Table 2 using certified seeds production per agricultural households in the state.

Categories	Use of certified seeds (yes = 1)	Yield (proportional increase)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)
	(a)	(b)	(c)
Certified seeds production by seed companies in the same state as farm household <i>i</i>	0.416*** (0.084)	0.405* (0.232)	0.267** (0.113)
Certified seeds production squared	-0.081*** (0.007)	-0.064* (0.036)	-0.040** (0.022)
Improved varieties (yes = 1)		Yes	
Other controls	Yes	Yes	Yes
Wave dummy	Yes	Yes	Yes
Intercept	Yes	Yes	Yes
Samples responding at least two rounds	650	650	2239
p-value (H ₀ : model is insignificant)	0.000	0.000	0.000
p-value (H ₀ : instrumental variables underidentified)		0.000	
p-value (H ₀ : improved variety is exogenous)		0.126	

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

Table A8
Results for Table 3 using certified seeds production per agricultural households in the state.

Categories	Use of certified seeds (yes = 1)	Yield (proportional increase)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)
Model	OLS panel fixed effects	IV panel fixed effects	OLS panel fixed effects
	(a)	(b)	(c)
Certified seeds production by seed companies in the same state as farm household <i>i</i>	0.972*** (0.258)	0.843*** (0.122)	0.269** (0.117)
Certified seeds production squared	-0.154*** (0.048)	-0.159*** (0.045)	-0.040* (0.022)
Improved varieties (yes = 1)		Yes	
Other controls	Yes	Yes	Yes
Wave dummy	Yes	Yes	Yes
Intercept	Yes	Yes	Yes
Samples responding at least two rounds	142	142	637
p-value (H ₀ : model is insignificant)	0.000	0.000	0.000
p-value (H ₀ : instrumental variables underidentified)		0.100	
p-value (H ₀ : improved variety is exogenous)		0.114	

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

Table A9
Results for Table 4 using certified seeds production per agricultural households in the state.

Categories	Use of certified seeds (yes = 1)	Yield (proportional increase)	Yield (proportional increase)
	Coef. (s.e.)	Coef. (s.e.)	Coef. (s.e.)
Model	OLS panel fixed effects	IV panel fixed effects	OLS panel fixed effects
	(a)	(b)	(c)
Certified seeds production by seed companies in the same state as farm household <i>i</i>	0.066* (0.036)	1.410 (0.931)	0.217*** (0.097)
Certified seeds production squared	-0.020** (0.010)	-0.448** (0.200)	-0.213*** (0.053)
Improved varieties (yes = 1)		Yes	
Other controls	Yes	Yes	Yes
Wave dummy	Yes	Yes	Yes
Intercept	Yes	Yes	Yes
Samples responding at least two waves	248	248	2076
p-value (H ₀ : model is insignificant)	0.000	0.000	0.000
p-value (H ₀ : instrumental variables underidentified)		0.000	
p-value (H ₀ : improved variety is exogenous)		0.891	

Source: Authors. ***1 %. **5 %. *10 %.

Note: Standard errors (s.e.) are clustered at the level of EA, to account for potential serial correlation of idiosyncratic shocks at the EA level.

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agry.2025.104268>.

Data availability

Data will be made available on request.

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