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Too much, too soon? Early-maturing maize varieties as drought escape strategy in Malawi

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ABSTRACT

Adopting early-maturing maize varieties can substantially increase yield and yield stability in suitable environments. Actionable recommendations that specify where early-maturing varieties can be suitably applied are lacking across low-income countries. We found for maize in Malawi that varieties with longer maturity duration provide on average the highest yield. However, if water stress occurs, we found that its timing determines which seed variety performs best. If water stress conditions are confined to the late season, early-maturing varieties escape drought and perform better than medium- and late-maturing varieties. Instead, if water stress conditions start already from mid-season, early-maturing varieties perform worst. Our results demonstrate that the typical seasonal timing of water stress can serve as a suitable criterion for recommending where to adopt early-maturing varieties. Finally, we propose an integrated research framework that complements our econometric analysis and allows to derive actionable variety suitability recommendations at the country level.

1. Introduction

Long-term productivity gains across agriculture in Sub-Saharan Africa (SSA) remain low in global comparison (Benin et al., 2011; Jayne & Sanchez, 2021), limiting progress in reducing poverty and food insecurity (de Janvry & Sadoulet, 2002; de Janvry & Sadoulet, 2010). With the global prevalence of undernourishment and extreme poverty increasingly concentrated in SSA, achieving decisive gains in agricultural productivity is of crucial importance (FAO et al., 2022; World Bank, 2022). While total agricultural output has increased in SSA since 2000, 75 percent of the increase in total production was due to area expansion and only 25 percent was due to productivity gains (Jayne & Sanchez, 2021). Low adoption rates of improved agricultural management practices, synthetic and organic fertilisers, mechanisation, and irrigation are major causes of slow productivity growth (Feder & Savastano, 2017). Across rainfed smallholder agriculture, weather-induced production risks are a primary barrier to adopting sustainable intensification strategies. Early-maturing crop cultivars have been widely promoted as a risk-reducing gateway technology that shall enable smallholders to commit limited resources more safely to on-farm intensification (FAO, 2014; Gebre et al., 2023). Since early-maturing cultivars require a shorter period of favourable weather conditions, they are the highest-yielding and lowest-risk cultivar choice when growing seasons are short. In short seasons, early-maturing cultivars use less water during vegetative stages than other cultivars and transfer water use towards the more drought-sensitive, yield-forming growth stages. If minor season conditions are strongly water-limited, early-maturing cultivars are often the only suitable option for transitioning from single to double cropping. Accordingly, they can be an important factor in increasing cropping intensities and providing more diverse options for farming systems design (Meynard et al., 2012; Waha et al., 2020).

This analysis provides empirical evidence of how early-maturing maize cultivars perform across different environments in Malawi. We investigate which cultivar maturation requirements provided Malawian farmers with the highest yield, both under average conditions and under different timing of water stress. We examine if there are general characteristics of production locations that underpin their suitability for

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specific cultivar maturation requirements. The analysis reviews whether recent adoption patterns of early-maturing cultivars occurred in suitable locations. In this way, we comprehensively evaluate the existing empirical evidence regarding the suitability and effectiveness of early-maturing cultivars to improve maize yield in a drought-resilient manner across Malawi. The analysis combines household surveys with high-resolution meteorological and coarse soil property data. We employ an instrumental variable approach to estimate the farmers' choice of the cultivar maturation requirement.

The potential of early-maturing cultivars to outperform mid- and late-maturing cultivars in suitable environments is well-documented across agronomic field trials, including for drought years (Rezende et al., 2020). However, smallholder production locations across SSA constitute a highly diverse *Target Population of Environments* (TPE) that strongly differ concerning the suitability of early-maturing maize cultivars. In environments that typically experience early-season drought, early-maturing cultivars may lead to substantial yield reductions due to the simultaneity of water stress and susceptible plant growth stages. Further, early-maturing cultivars are likely to provide strictly lower yields in environments with overall favourable weather conditions due to their shorter crop growth duration. Sutcliffe et al. (2016) found no empirical evidence that cropping seasons were getting shorter at two study locations in Malawi. They argued that the range of suitable locations for early-maturing varieties did not expand, and that recommendations for cultivar choices could be easily misguided when based on overly simplified climate information. Early-maturing cultivars do not constitute a "low-regret" technology that can be applied indiscriminately but require careful agroecological targeting. To date, little empirical work is available that identifies those smallholder production locations that are most suitable or particularly unsuitable for early-maturing maize cultivars.

While many policy guidance documents advocate for early-maturing cultivars as a suitable measure to improve drought resilience (Bhalla et al., 2024; FAO, 2014), such general recommendations lack the actionable specificity to be of value for policymaking at national and local levels across SSA. Instead, spatially more refined recommendations at the sub-national level are required. Data on the spatial suitability of early-maturing cultivars can inform public and commercial agricultural extension services to provide location-specific advice to farmers. For example, in Malawi, where the Ministry of Agriculture and the Seed Traders Association define which seed cultivars are available for subsidised purchase with seed coupons (Chirwa et al., 2013), the government controls a mechanism to spatially differentiate between the subsidised seed types and promote their adoption where most suitable. Knowing where early-maturing cultivars are appropriate would also narrow down the TPE, allowing breeding programmes of early-maturing cultivars to be more targeted.

Across the scientific literature, the performance of early-maturing cultivars has predominantly been evaluated using data from agronomic field trials across a limited number of locations (Rezende et al., 2020). Large-scale household survey data of smallholder systems usually do not contain explicit information on cultivars but only differentiate between certified versus recycled seed, or hybrid versus open-pollinating varieties (World Bank, 2021). Using a revised household survey dataset for maize in Malawi, we analyse the performance of early-maturing maize cultivars at the sub-national level.

In the following, section 2 identifies the utilised data and methodology, while sections 3 and 4 present and discuss the empirical results. Policy implications are derived in section 5, and section 6 provides an overall conclusion.

2. Data and methodology

2.1. Data sources

This analysis utilised geo-referenced household survey data in combination with spatially merged meteorological and soil data from gridded, high-resolution databases.

2.1.1. Meteorological data

We used daily precipitation data at a spatial resolution of 0.05 decimal degrees from the *Climate Hazards center InfraRed Precipitation with Stations* dataset (CHIRPS; Funk et al. (2015)). The dataset is based on an integrated methodological approach that combines remotely sensed infrared data, meteorological station data, and bias correction methods. Gebrechorkos et al. (2018) and Funk et al. (2015) found that CHIRPS compared favourably vis-à-vis other available precipitation databases when evaluated against weather station data in Eastern Africa.

Daily data on reference evapotranspiration, calculated using the Penman-Monteith equation (Allen et al., 1998), was obtained from FAO (2021) at a spatial resolution of 0.1 decimal degrees.

Daily data on mean, minimum, and maximum temperatures at a spatial resolution of 0.1 decimal degrees was used from the AgERA5 Daily Surface Meteorological Dataset for Agronomic Use (ECMWF, 2020).

2.1.2. Soil data

We used data on the plant-available water capacity (PAWC) of soils from a classification of 27 generic soil types at a spatial resolution of 5 arc-minutes from Koo and Dimes (2013). PAWC indicates the maximum amount of water that plants can extract from a fully filled soil profile (commonly referred to as the "*bucket size*" of a soil). In periods of drought, PAWC is a core characteristic that determines if plant water demand can be satisfied by water stored in the soil profile.

2.1.3. Household survey data

We used household survey data from the 2016/17 (NSO Malawi, 2017) and 2019/20 (NSO Malawi, 2020) waves of the Malawian *Integrated Household Surveys* (IHS) as distributed by the World Bank *Living Standards Measurement Study – Integrated Surveys on Agriculture* (LSMS-ISA; World Bank (2021)). While a total of four IHS waves are available, only the two most recent survey waves contain explicit information about the sown maize cultivars. Therefore, this analysis did not consider earlier waves. Descriptive statistics of the IHS variables used in this analysis are provided in Appendix A.

The IHS does not disclose the exact geographic locations of cultivated plots or surveyed households for confidentiality reasons. Instead, it releases a single reference location for each enumeration area, which are predefined geographic zones from which a determined sub-sample of households has been drawn. The reference location within each enumeration area was calculated as the spatial average of all interviewed household locations which was further anonymised by applying a small random offset. For each reference location, we matched meteorological and soil data from the nearest locations in the referenced biophysical datasets. The level of imprecision introduced from using enumeration area locations instead of plot locations is comparably low since the spatial extent of enumeration areas is small. For example, according to the most recently available definition (NSO Malawi, 2013), each enumeration area covers an average of 10.4 square kilometres. A map of enumeration areas and further details are provided in Appendix H.

2.2. Quantification of cultivar maturation requirements

For each maize cultivar recorded in the household survey, we quantified the precise number of days required to reach physiological maturity, referred to as cultivar maturation requirement throughout this study. As the starting point, we harmonised the spelling of the recorded maize cultivar names (e.g., Kanyani, Knyani, Kwnyani refer to an identical cultivar) and converted corresponding local and commercial names to a unique identifier (e.g., SC403 instead of Kanyani). Then, we identified the breeding channel (local vs. certified), pollination type (open-pollinating variety (OPV) vs. hybrids), the cultivar maturation requirement, and a derived rough maturity group (early: <= 115 days, mid: 116–134 days, late: >= 135 days of maturation requirement). The thresholds for categorising maturity groups were chosen to ensure that a sufficient number of reported cultivars were represented across groups and to relate to thresholds used in the scientific literature (Bankole et al., 2022; Masuka et al., 2017).[2] As the maturation requirements could not be identified for all cultivars in terms of thermal time (Soltani & Sinclair, 2012, p. 56 ff.), they were instead quantified in terms of calendar days. Data on the breeding channel, pollination type, and maturation requirements were collected from the scientific literature on agronomic field trials and publicly available information from seed companies (see Appendix B). A comparison of the literature-derived maturation requirements with the farmer-reported crop growth duration is provided in Appendix C. In the household survey, many respondents only reported utilising "local" maize cultivars, which does not permit quantifying the maturation requirements and such observations were excluded from the analysis.

2.3. Extreme Degree Days

We interpolated hourly temperatures from daily minimum and maximum values, assuming a sinusoidal temperature oscillation throughout the day. We calculated the daily accumulated thermal time (Soltani & Sinclair, 2012, p. 56 ff.), measured in units of Growing Degree Days (GDD), following the phenological temperature sensitivity of maize defined by the cropping systems model APSIM-Maize (Brown et al., 2024) as described in Appendix D. Subsequently, the seasonal total of Extreme Degree Days (EDD) was calculated as the accumulated daily thermal time above the threshold temperature of 29 degrees Celsius during the crop growth period (Schlenker & Roberts, 2009). Temperature conditions are a crucial determinant of maize phenological development and growth. However, insufficient thermal time is not a major limitation across the production environments in Malawi. Instead, heat stress is a more relevant factor in reducing maize yields. Therefore, we exclusively consider EDD to characterise the impact of temperature conditions on maize production but not accumulated daily thermal time or average daily temperature during the growing season.

2.4. Water stress index

We calculated a climatological water stress index and water stress dummy that indicate the intensity and presence of water deficits, respectively. The water stress index is defined as the ratio of total seasonal reference evapotranspiration (Allen et al., 1998) over total seasonal precipitation. It approximates the intensity of water limitations for plant growth during the sub-seasonal reference period p at plot i during growing season t.

$$water\ stress\ index_{pit} = \frac{reference\ evapotranspiration_{pit}}{precipitation_{pit}}$$

The water stress dummy takes a value of one whenever total reference evapotranspiration exceeds total precipitation and zero otherwise.

$$water\ stress\ dummy_{pit} = \begin{cases} 1\ if\ water\ stress\ index_{pit} > 1 \\ 0\ otherwise \end{cases}$$

This water stress index and water stress dummy were calculated for two sub-seasonal reference periods p: the mid and late cropping seasons. The mid cropping season is defined as days 40–79 after the reported planting date. Early-maturing cultivars likely experience most of their critical plant growth stages in this period. The late cropping season is defined as days 80–119 after the reported planting date. Mid- and late-maturing cultivars likely experience a larger proportion of their critical plant growth stages during this period than early-maturing cultivars. The temporal intervals defining the mid and late cropping season were derived from the typical timing of major crop developmental stages of maize in tropical environments – specifically considering flowering, seed set and grain filling (GRDC, 2017, p. 25; Tollenaar & Dwyer, 1999).[3]

The water stress dummy was calculated for each farmer-reported production location and growing season. In addition: (i) we calculated the water stress dummy for long-term average conditions at each production location, considering a 15-year period. Thereby, we did not consider the 15 years directly before the reported cultivation season but systematically excluded three years of data prior to the reported season (i.e., considering years 18 to 4 prior to the cultivated season). In that way, we intend to characterise long-term water stress conditions while avoiding that our long-term indicator is correlated with recent climatic conditions that may still impact current production outcomes through lagged effects.

Further, (ii) we calculated the water stress index for the thirty years preceding the reported cultivation (1990–2019) across a regular spatial grid of 0.05 decimal degrees for all of Malawi. Such maps characterise long-term water stress patterns at high spatial resolution (i.e., beyond the geo-referenced locations in the household survey data). This data is purely used for descriptive purposes and is not included in our econometric estimations. We calculated separate water stress indices for early, medium, and late planting dates as a sensitivity test.[4] The timing of planting may alter if water stress coincides with critical planting stages: Farmers that plant, for example, early-maturing cultivars at early planting dates face a different likelihood of being exposed to water stress during critical growth stages than when employing mid or late planting dates.

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[2] Empirically relevant thresholds for distinguishing maize maturity groups will vary significantly depending on the production environment. More generally, in cross-environmental cultivar maturity classifications, early-maturing varieties are often defined as having a maturation requirement of less than 100 days until physiological maturity (Bankole et al., 2022) or less than 70 days until anthesis (Masuka et al., 2017). The here defined maturity group classification is of limited importance in this study, as the primary empirical analysis instead relies on the specific maturation duration of each cultivar (in days).

[3] Under most conditions, we expect the difference in the timing of growth stages between the maize cultivars reported in the IHS to be relatively short – ranging from just a few days to a maximum of about 20 days. Accordingly, carefully defining the temporal extent of the mid- and late-season periods is essential to ensure that a larger proportion of critical growth stages for early-maturing cultivars occur during the mid-season than for late-maturing cultivars. Crop physiological observations at agronomic field trials in Malawi would be required to review the appropriateness of these temporal intervals in a rigorous manner. Given the conceptual importance of setting agronomically sound threshold values and the relatively small differences in growth stage timings across cultivar maturation requirements, we expect that the results of this study are sensitive to the selected time intervals. Specifically, if the intervals are defined such that the critical growth stages of both early- and late-maturing cultivars occur in the same period, the seasonal timing of droughts may not have distinct effects across different cultivars (as discussed in subsequent sections of this article).

[4] For each grid point in Malawi, the *medium planting date* was calculated as the average farmer-reported planting date from the nearest recorded IHS location. We then calculated the median of the observed standard deviation in planting dates across all IHS locations (14 days). The *early/late planting dates* were calculated by subtracting/adding 14 days to the medium planting date at each location.

2.5. Empirical strategy

As the basis for the empirical analysis, we consider a classical agricultural production model that identifies the transformation of inputs via energy and mass conversion into output while using specified technologies under exogenously determined environmental conditions (Chambers, 1988). Specifically, we consider a Cobb-Douglas production function of the form:

$$y_{it} = \alpha + \sum_{k=1}^{K} \beta_k x_{kit} + \mu v_{it} + \sum_{p=1}^{P} \gamma_p z_{pit} + \sum_{m=1}^{M} \theta_m w_{mit} + \sum_{j=1}^{J} \tau_j s_{ji} + \omega r_{it} + u_{it} \quad (1)$$

where:

y_{it} the natural logarithm of the maize output from plot i in growing season t.
α the intercept term.
x_{kit} the natural logarithm of the k^{th} production factor.
v_{it} a dummy variable indicating pesticide use.
z_{pit} the water-stress dummy variable during the sub-seasonal period p.
w_{mit} the m^{th} interaction effect between the cultivar maturation requirement and the water stress dummies.
s_{ji} the natural logarithm of the PAWC of the j^{th} time-invariant soil-type.
r_{it} the natural logarithm of a proxy variable for a relevant unobserved factor (access to agricultural extension services).
u_{it} a composite residual error term.

The dependent variable quantifies the total maize output (kg) on the cultivated plot i in growing season t. The vector of production factors x comprises the cultivar maturation requirement (days), the seed quantity (kg), the seed age (years since last purchase), the cultivated area (m^2), the total labour days (person-days), the quantity of synthetic fertiliser (kg of nitrogen), and the seasonal total of Extreme Degree Days (GDD above threshold). The dummy variable v indicates pesticide use. The two water-stress dummy variables z indicate water stress during the sub-seasonal periods p (i.e., mid or late cropping season) for the farmer-cultivated growing season t at plot i. The input-climatological interaction terms w combine the cultivar maturation requirement with the aforementioned water stress dummy variables z. We included the time-invariant plant-available water capacity (mm) s of each soil-type. As proxy variable r for the unobserved availability of information about the best agricultural management practices (e.g., through access to extension services), we included the distance (km) to the closest agricultural extension officer. Access to information on good agricultural management practices centrally determines how much output farmers are able to produce with the chosen input quantities, i.e., their level of output-oriented technical efficiency (O'Donnell, 2018).

Assuming that farmers choose input quantities of x_{kit} to maximise a predetermined (profit) objective, the error term is likely to contain unobserved variables correlated with x_{kit}. Specifically, farmers may have different access to information about maize cultivar characteristics and performance, which will impact whether they adopt early-maturing cultivars. Differential information access may stem from different exposure to seed dealers, extension agents, or neighbouring adopters (Dar et al., 2024; Rogers, 2003). Accordingly, the farmers' choice of the cultivar maturation requirement is likely endogenous. We employ an instrumental variable approach using two-stage least squares estimation (2SLS) to control for time-variant sources of endogeneity regarding the choice of the cultivar maturation requirement. Time-variant causes of endogeneity may play a relevant role in input choice decisions by smallholder farmers (Manda et al., 2018; Ricker-Gilbert et al., 2011). For instance, farmers' access to cultivar-related information likely changes over time due to the increasing promotion and adoption of early-maturing cultivars in the overall population, changes in the accessible seed product palette (Dar et al., 2024), or succession of the farm enterprise.

A valid instrument must be correlated with the farmer's adoption decision of the cultivar maturation requirement while being uncorrelated with potential unobserved factors. As instrumental variables, we propose: (i) the number of agricultural input salesmen in the community (approximated by the number of hybrid seed and fertiliser salesmen in the community); (ii) the distance to the closest population centre (defined as the major towns Blantyre, Lilongwe, Mzuzu, and Zomba); and (iii) the long-term water stress dummies that indicate the average presence or absence of water stress during the mid and late cropping season across recent fifteen years, but excluding the three years directly preceding the recorded cultivation.

We argue that the instruments are relevant for the following reasons: (i) A large share of farmers predominantly recycle maize seed over multiple years, frequently utilising cultivars from non-certified breeding sources. With a larger number of agricultural input salesmen present in their community, purchasing specific cultivars of a targeted maturation requirement becomes more accessible. Input salesmen can also be anticipated to impact farmers' decisions regarding the maturation requirement of their maize seed by providing agronomic advice about the characteristics and suitability of specific cultivars (Dar et al., 2024). As we are not exclusively interested in the accessibility of hybrid seed and further noting that agricultural input dealers commonly provision a wide range of agricultural inputs (seed, pesticide, fertiliser), we considered all types of agricultural input salesmen for which data was available, i.e., hybrid seed and fertiliser salesmen. (ii) The proximity to urban centres translates into lower transaction costs for purchasing maize seed, access to a wider range of cultivars of different maturation requirements, and better access to information about specific cultivar characteristics such as their agro-climatic suitability. (iii) When farmers consistently experience water stress in a specific sub-segment of the cropping season – as measured by the long-term water stress dummy variables during the mid and late cropping season – farmers are likely to select cultivars that avoid the occurrence of critical growth stages (particularly anthesis and grain filling) in those periods. E.g., Guido et al. (2020) found for smallholder farmers in Kenya, that farmers' expectations of the forthcoming seasonal rainfall strongly determined which maize maturity group they cultivated. Katengeza et al. (2019) found that farmers with recent drought exposure had higher adoption rates of drought-tolerant cultivars in Malawi.

Further, we argue that the instruments are exogenous for the following reasons: While the number of agricultural input salesmen in the community as well as the distance to urban centres are not controlled by the farmer, both variables are likely to be correlated with better access to extension agents, that provide information about good agricultural production practices regarding all major production factors (fertiliser, pesticides, etc.). Further, the presence of input salesmen will increase the accessibility of all production factors, not only of seed. Consequentially, we explicitly control for the distance to agricultural extension agents and the quantity of all production factors in model (1) to address the mentioned potential limitations to instrument validity. We are not aware of any other reasonable pathway by which these community characteristics could simultaneously affect both technology adoption and maize output. We suggest that the long-term water stress dummies do not have any impact on current crop yield since we deliberately excluded the three years that directly preceded the reported cultivation season. Our long-term water stress dummy variables are accordingly not correlated to any recent drought events that may still impact farmer-reported crop yields. In addition, we directly control for the water stress conditions during the farmer-reported cultivation season in model (1).

The further input choice variables, labour days, seed quantity, as well as the quantity of synthetic fertiliser, may also be subject to further endogeneity. Particularly, farmers may choose input levels based on their plots' soil characteristics that co-determine the marginal product of inputs. A major soil characteristic in rainfed smallholder agriculture that co-determines the productivity of other inputs is the capacity of soils to store water. To control for this possible source of endogeneity, we included the PAWC of soils in model (1). PAWC is further the main soil property that directly influences the frequency, intensity, and timing of plant water stress.

Kubitza and Krishna (2020) reviewed instrumental variable strategies across 31 studies on the adoption and impact of agricultural practices in smallholder maize production systems. A large number of studies used the geographic distance to information and service providers as well as climatological variables as instruments – equivalent to the here suggested approach. They report that another common instrument was the average adoption rate of agricultural technologies among neighbouring farmers (Arslan et al., 2017). However, we argue that instruments based on neighbouring adopters likely suffer from limited exogeneity, as unobserved factors influencing technology adoption on neighbouring farms are also likely to affect the reference farming household. For this reason, we did not include such instruments in our analysis.

3. Results

3.1. Descriptive statistics: Adoption pattern and yield of cultivar maturity groups

The household surveys contain records on 2203 early-, 1495 mid-, and 1432 late-maturing maize cultivations between 2014 and 2019. The adoption of specific cultivar maturity groups varied strongly among locations (Fig. 1). Many directly adjacent localities exhibit large differences in the average maturation requirement of the grown maize cultivars. Only few spatially continuous adoption clusters seem apparent from descriptive, visual inspection. Further, adoption patterns were not consistent over time. In the growing seasons 2017 and 2018, for example, one can observe a shift towards a larger usage of late-maturing cultivars compared to the 2014 and 2015 growing seasons.

When considering the entire dataset, late-maturing cultivars (1610 kg/ha) provided the highest average yield, followed by medium-maturing cultivars (1420 kg/ha), while early-maturing cultivars (1383 kg/ha) provided the lowest average yield (Fig. 2). When differentiating between pollination types, hybrid cultivars (1516 kg/ha) provided a higher average yield than OPVs (1114 kg/ha). The yield difference between OPVs and hybrids was larger than between maize cultivars of different maturity groups.

When examining crop yield under different water stress conditions, yield was highest without water stress and lowest if water stress prevailed during the entire seasons – indifferently of the cultivated maturity group (Fig. 3). Early-maturing cultivars yielded on average less than other maturity groups across nearly all water stress conditions. Even when water stress occurred exclusively in the late season, early-maturing cultivars did not observe a higher average yield than other maturity groups. Further, the 25th yield percentile of late-season cultivars did not consistently fall below that of other cultivars, indicating that late-season cultivars did not exhibit a higher level of downside risk.

3.2. Intensity and variability of water stress

The thirty-year average and standard deviation of the water stress index characterise the typical intensity, timing, and regularity of water stress in Malawi. During the thirty years (1990–2019) that directly preceded the timeframe observed by the IHS, intense water stress was generally more common and widely spread during the mid- than late-season (Fig. 4). This finding generally holds across all planting dates. Mid-season water deficits were slightly larger for early planting dates, while late-season water deficits became more intense and spatially spread for late planting dates.

Water stress during mid-season occurred all across Malawi, while its intensity varied strongly within most districts, even between directly adjacent localities. High water stress intensity during the mid-season most commonly occurred in parts of the districts Chitipa, Karonga, Rumphi, Mzimba, Nkhata Bay, northern Kasungu, Nkhotakota, Salima, Dedza, Chikwawa, and Nsanje.[5] High water stress intensity during the late-season was geographically more confined (particularly if avoiding late planting dates) and predominantly affected parts of the districts Chitipa, Karonga, Rumphi, Mzimba, Mangochi, Chikwawa, and Nsanje. Based on these findings, the water stress hotspots of Malawi that regularly experience high levels of water stress during the entire maize growing season are predominantly Chikwawa and Nsanje in southern Malawi as well as to a slightly lesser extent Karonga, Rumphi and Mzimba in northern Malawi.

Across large parts of Malawi, water stress conditions were highly variable between years (Figure E. 1). Locations that frequently observed a high intensity of water stress, intermittently observed growing seasons without any water stress. Generally, locations with high long-term average water stress also observed high inter-annual variability of water stress. A brief discussion of the specific water stress conditions at IHS locations during the reported survey years is included in Appendix E.

3.3. Regression diagnostics

We estimated the agricultural production model specified in equation (1) via OLS and 2SLS as shown in Table 1. The coefficient estimates of the instrumented choice variables, i.e. the cultivar maturation requirement and its interaction terms, strongly differ between the two estimation strategies. The OLS results suggest that the cultivar maturation requirements have only a minor impact on maize output. As discussed in section 2.5, we suggest that the accessibility of diverse cultivars and access to information about cultivar suitability are the most crucial unobserved variables. We further argue that better access to a larger cultivar palette and suitability information is (i) positively correlated with maize output, and (ii) correlated with a more location-suitable choice of cultivar maturation requirements. Based on the production location, the omitted variable may thus be positively or negatively correlated with the choice of cultivar maturation requirements. However, given that the availability of early-maturing cultivars is highly limited in remote areas without access to numerous agricultural input salesmen, we argue that higher access to input salesmen will on average be negatively correlated with cultivar maturation requirements (i.e., lead to more frequent adoption of early-maturing cultivars). In case the suggested endogeneity prevails, the OLS coefficient underestimates the impact of the cultivar maturity requirement. In agreement with these hypotheses, the 2SLS results suggest that the cultivar maturation requirement has a much stronger impact on maize output than in the OLS results. This may support our hypothesis of prevailing endogeneity as well as a negative bias of the OLS coefficient estimate.

We conducted various diagnostic tests of our estimation strategy using instrumental variables. The Durban-Wu-Hausman test of endogeneity rejects the null hypothesis that the cultivar-type choice is exogenous. The null hypothesis of weak instruments is rejected for all three employed instruments when comparing the first-stage F-statistics to Stock-Yogo critical values. The Sargan test of overidentifying restrictions does not reject the null hypothesis that the instruments are uncorrelated with the error term in the structural equation. The available evidence suggests that the OLS results may suffer from endogeneity and we accordingly base our following interpretation on the model estimated via 2SLS.

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[5] As reference, a map of the districts of Malawi is provided in Appendix G.

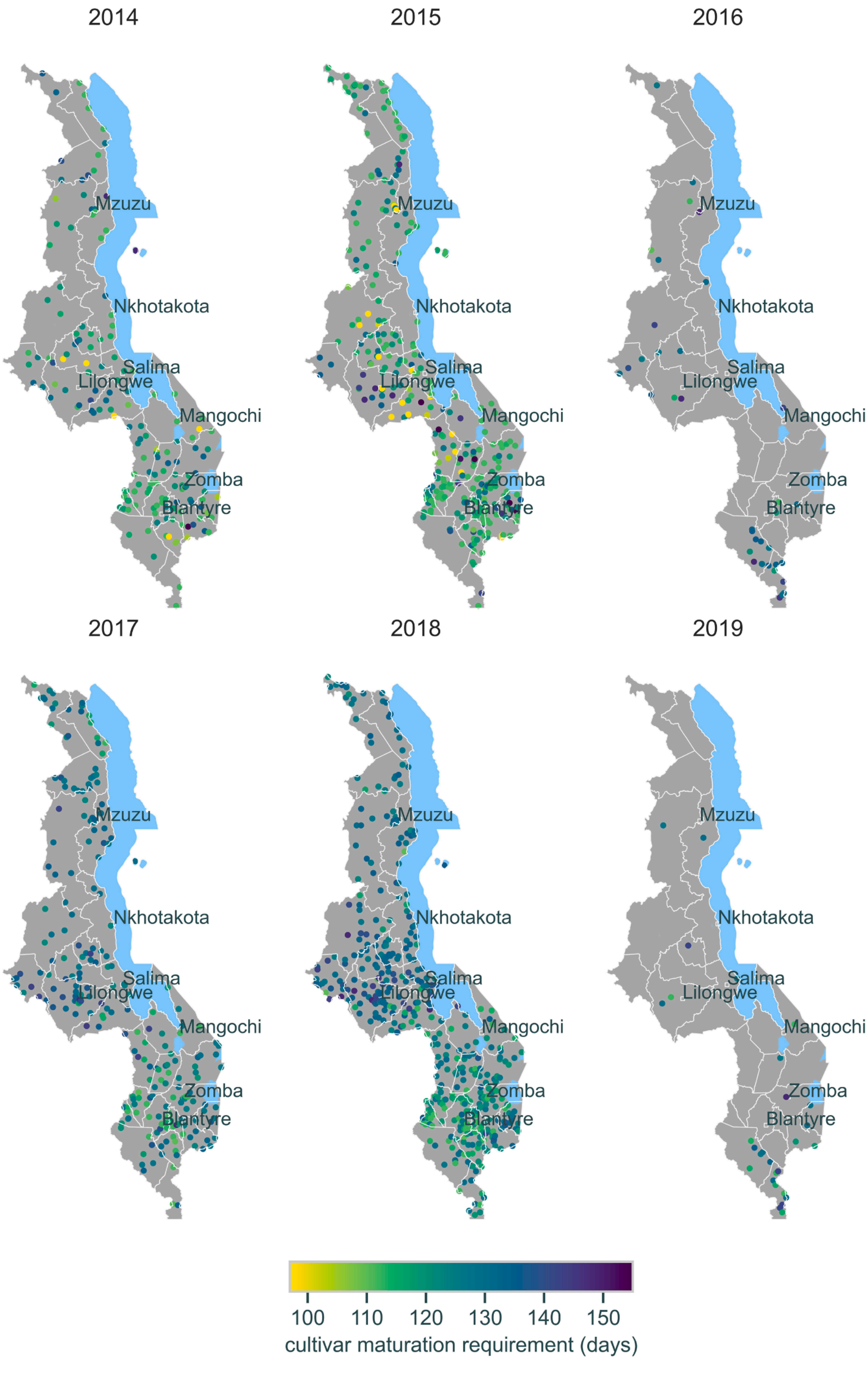

Fig. 1. Maturation requirements of farmer-grown maize cultivars in Malawi. Note: Maturation requirements of farmer-grown maize cultivars averaged by location for each growing season from 2014 to 2019. Boundaries denote districts and labels identify major cities. For the years 2016 and 2019 only few observations are available, as farmers were requested to report production for their most recent year of cultivation and the major growing seasons had not typically concluded by the time of enumeration of the 2016 and 2019 IHS survey waves.

3.4. Estimation results: Performance of different maize cultivars under water stress

Cultivars with longer maturation requirements provided a higher maize output, after controlling for water-stress conditions. The constant elasticity model estimates that a 1 percent increase in the cultivar maturation requirement increased maize output by 4.9 percent in the absence of water stress. However, the performance of maize cultivars of different maturation requirements strongly changed when exposed to water stress. We found strong interactions between water stress, both during the mid- and late-season, and the cultivar maturation requirement. Under mid-season water stress, a 1 percent increase in the cultivar maturation requirement is estimated to have increased maize output by 16.7 percent. Thus, early-maturing cultivars observed substantial output reductions when exposed to mid-season water stress, while late-maturing cultivars were much less susceptible. Under late-season

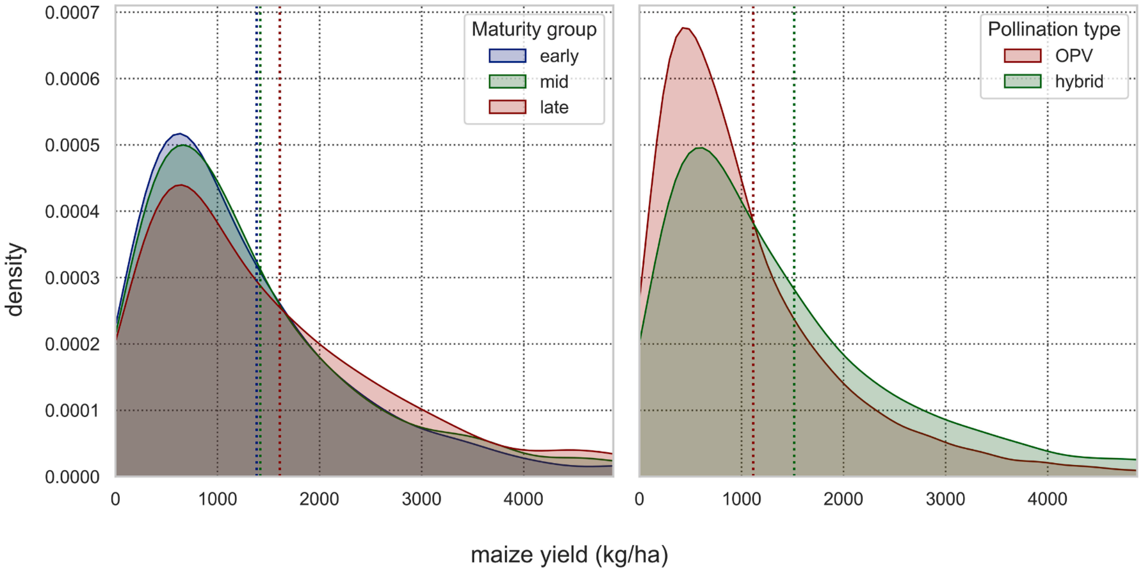

Fig. 2. Maize yield by maturity group (left) and by pollination type (right). Note: Probability distribution functions of maize yield in Malawi from 2014 to 2019 as reported in the IHS. Dotted lines indicate mean yields. The visualised x-axes range was capped at the 97.5 percentile for higher readability.

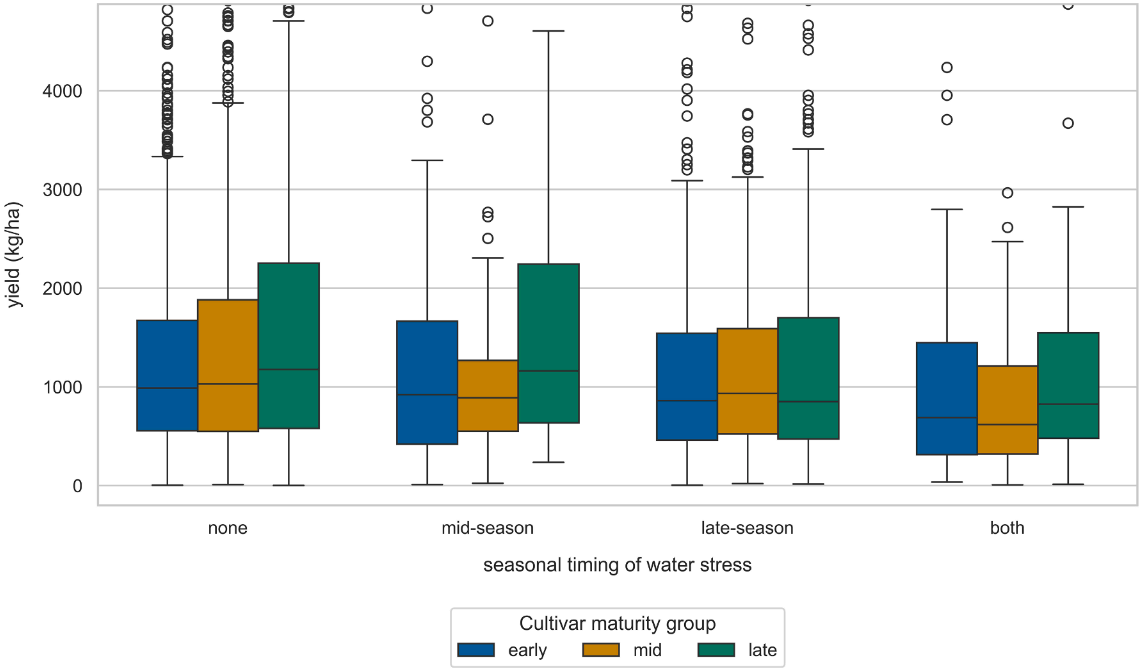

Fig. 3. Maize yield by timing of water stress for different cultivar maturity groups. Note: The visualised yield data range was capped at the 97.5 percentile for higher readability. Throughout the article, boxplots are defined as Tukey-boxplots, with whiskers extending to the most extreme datapoints within 1.5 times the interquartile range (Tukey, 1977).

water stress instead, a 1 percent increase in the cultivar maturation requirement is estimated to have decreased maize output by 8.6 percent. Accordingly, late-maturing cultivars experienced large decreases in output when exposed to late-season water stress, while early-maturing cultivars were comparably resilient. To assess the joint statistical significance of the main and interaction effects, we performed two joint F-tests of the main effect (i.e., the cultivar maturity requirement) and its interaction with the water stress dummies during either the mid- or late-season. The F-tests indicate that the joint effects were statistically significant with a p-value of 0.032 and 0.084 for the mid- and late-season, respectively.

Due to the novelty of the here utilised maize cultivar data, no similar estimates are available in the econometric literature that would quantify the impact of cultivar maturation requirements on maize output under water stress in SSA. Studies that instead analysed the performance of drought-tolerant maize cultivars found that they provided consistently higher yields than conventional maize cultivars in Malawi (Katengeza & Holden, 2021) and further countries in south-eastern Africa (Paul, 2021; Simtowe et al., 2019).

The estimated coefficients of the water stress dummies are negative for the mid-season and positive for the late-season. However, the sign and size of these coefficients should not be interpreted in isolation, as the water stress dummies are included in the previously discussed interaction terms. As the other main environmental factor, heat stress

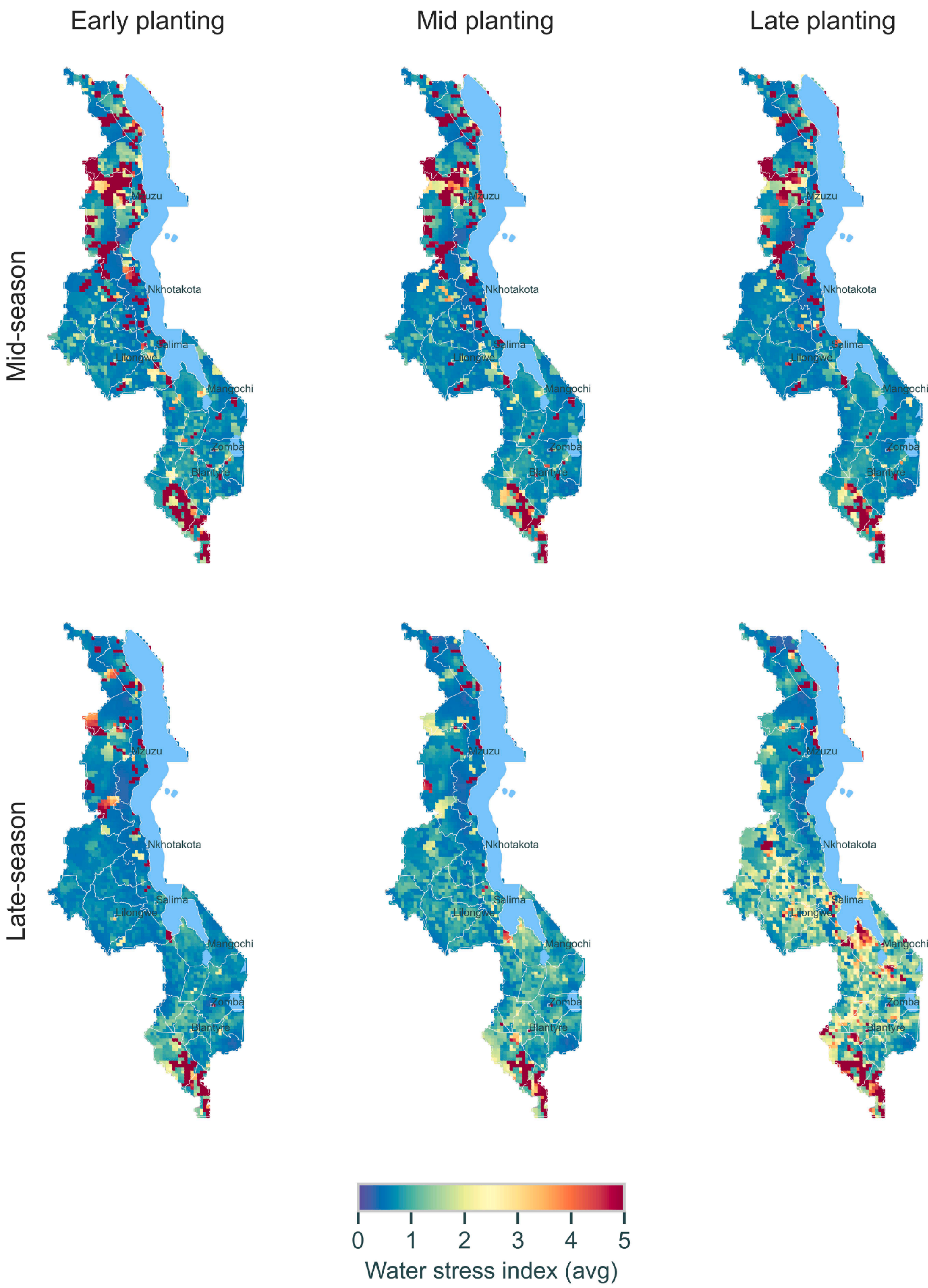

Fig. 4. Thirty-year average of the water stress index. Note: Water stress index for (i) different planting dates (columns) and (ii) different stages of the cropping season (rows) averaged over thirty years (1990–2019) of weather data across a spatial grid of 0.05 decimal degrees in Malawi.

was found to reduce crop output by 0.09 percent for each percent increase in Extreme Degree Days accumulated over the cropping season.

3.5. Estimation results: Coefficients of further production factors

The results also provide coefficient estimates for additional variables beyond the primary focus of this analysis. Since the estimation strategy did not prioritise assessing their impact on maize output, these coefficient estimates should primarily be given a descriptive and exploratory interpretation. The coefficients of production inputs are all according to theoretical expectations (Table 1). The elasticity of maize output with respect to seed is estimated as 0.4 percent and the elasticity with respect

Table 1
Determinants of maize output.

	ln(output)	
	OLS	**2SLS**
ln(cultivar maturation requirement)	**0.632****	**4.872**●
	(0.222)	(2.580)
mid-season water stress dummy *	0.306	**11.811**●
ln(cultivar maturation requirement)	(0.521)	(6.934)
late-season water stress dummy *	−0.396	**−13.507***
ln(cultivar maturation requirement)	(0.406)	(6.794)
mid-season water stress dummy	−1.488	**−56.456**●
	(2.505)	(33.194)
late-season water stress dummy	1.841	**64.679***
	(1.949)	(32.543)
ln(area)	**0.398*****	**0.364*****
	(0.032)	(0.049)
ln(synthetic fertiliser)	**0.295*****	**0.295*****
	(0.015)	(0.019)
pesticide dummy	**0.333*****	**0.289****
	(0.081)	(0.099)
ln(seed)	**0.371*****	**0.354*****
	(0.034)	(0.043)
ln(seed age)	−0.005	0.102
	(0.049)	(0.092)
ln(labour)	**−0.051**●	−0.005
	(0.027)	(0.049)
ln(Extreme Degree Days)	**−0.084*****	**−0.086****
	(0.024)	(0.033)
ln(plant-available water capacity of soil)	−0.018	−0.036
	(0.099)	(0.118)
ln(distance to extension officer)	−0.023	**−0.035**●
	(0.016)	(0.021)
intercept	−1.539	**−21.768**●
	(1.161)	(12.268)
Model statistics and regression diagnostics:		
observations	2998	2998
adjusted R^2	0.43	
F-statistic	**51.67*****	
(p-value)	(0.00)	
Durbin-Wu-Hausman test		**4.63*****
(p-value)		(0.00)
Sargan test		6.82
(p-value)		(0.15)
F-test for joint significance of the cultivar maturation requirement and the water stress dummies:		
ln(cultivar maturation requirement) * water stress dummy during mid-season		**6.87***
(p-value)		(0.032)
ln(cultivar maturation requirement) * water stress dummy during late-season		**4.95**●
(p-value)		(0.084)
First-stage F-statistics:		
ln(cultivar maturation requirement)		**14.76*****
(p-value)		(0.00)
ln(cultivar maturation requirement) * water stress dummy during mid-season		**25.30*****
(p-value)		(0.00)
ln(cultivar maturation requirement) * water stress dummy during late-season		**14.54*****
(p-value)		(0.00)

Note: ● $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Values in parentheses below coefficient estimates indicate robust standard errors, clustered at the enumeration area level. Values in parentheses below test statistics indicate p-values.

to synthetic nitrogen fertiliser as 0.3 percent. The estimated output elasticity of synthetic nitrogen fertiliser lies within the wide range of values reported in the literature on smallholder farming in SSA (Deininger & Olinto, 2000; Ekbom & Sterner, 2008). The use of pesticides was estimated to strongly increase maize output. In the absence of more precise survey data on the applied pesticide types and underlying *Modes of Action* (MoA), this value should only be given a cautious interpretation. The effectiveness of pesticide selection and application practices has been shown to vary significantly across smallholder systems in SSA (de Bon et al., 2014). For the analysed sample of smallholder farmers that predominantly cultivated small maize plots (25th percentile: 0.15 ha, 75th percentile: 0.43 ha) we found an inverse relationship between plot size and maize yield, with maize output increasing by 0.4 percent for every 1 percent increase in plot size. While this finding is in agreement with a large number of empirical studies (Carletto et al., 2013; Muyanga & Jayne, 2019), it is controversial if an inverse relationship between plot size and productivity is a feature widely shared among diverse smallholder farming systems and contexts. Several recent studies found no evidence of an inverse relationship between plot size and crop yield once they disregarded self-reported data which were shown to systematically over-estimate yield on small plots and under-estimate yield on large plots (Ayalew et al., 2024; Desiere & Jolliffe, 2018; Mishra et al., 2023). An increase in the distance to extension officers by 1 percent was estimated to decrease maize output by 0.04 percent. We did not find labour to have a statistically significant impact on maize output. Self-reported household labour by smallholder farmers is typically impacted by measurement error due to recall bias since household labour is usually not renumerated and, accordingly, not subject to formal record keeping (Arthi et al., 2018). We did not find statistically significant impacts of the plant available water capacity of soils or the age of seed.

4. Discussion

The econometric estimation results suggest that cultivars with longer maturation requirements provide the highest yield in the absence of water stress. This supports the crop physiological principle that a longer maturation period allows the crop to accumulate more resources and achieve higher grain yield when exposed to average or above-average growing conditions. In the absence of water stress, the use of early-maturing cultivars comes with a penalty.

However, if water stress occurs, we found that its timing determines which cultivar performs best. If water stress conditions already start from mid-season, early-maturing cultivars perform worst. This finding supports the central hypothesis that early-maturing cultivars have the highest level of sensitivity to water stress that starts already from mid-season because it is likely to coincide with their critical plant growth stages (anthesis, seed set, grain filling).[6] If water stress is instead confined to the late season, early-maturing cultivars escape drought conditions and perform best. When arid conditions occur late in the season, early-maturing cultivars have finalised all critical growth stages and are largely drought-resistant. Under late season water stress, early-maturing cultivars thus play out their major advantage and design principle.

The estimation results highlight that the timing of water stress during the cropping season centrally determines which cultivar maturation requirement provides the highest yield and drought resilience. Therefore, the most likely timing of water stress occurrence is a suitable decision criterion for maturity type selection. Locations with small water stress during the mid cropping season, large water stress during the late cropping season, and low inter-annual variability in water stress timing are highly suitable for early-maturing cultivars. This decision rule is visually summarised in the decision tree presented in Fig. 5. Locations that fulfil these criteria are found in the southern districts of the Central region (Mchinji, Dowa, Salima, Lilongwe, Dedza, Ntcheu) and the northern districts of the Southern region (Mangochi, Machinga, Balaka, Neno, Zomba, Blantyre, Mwanza, Chiradzulu, Phalombe, Mulanje, Thyolo). Particularly, if farmers are not able to realise early planting dates, causing the effectively remaining cropping season to be short,

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[6] Mid- and late-maturing cultivars may be less affected by mid-season water stress for another reason: when moderate water scarcity occurs already during the initial vegetative growth stages, it results in reduced biomass production. Although this prevents plants from achieving their full yield potential, the smaller biomass also leads to lower water demand, making the plants more resilient to water stress during the later growth stages.

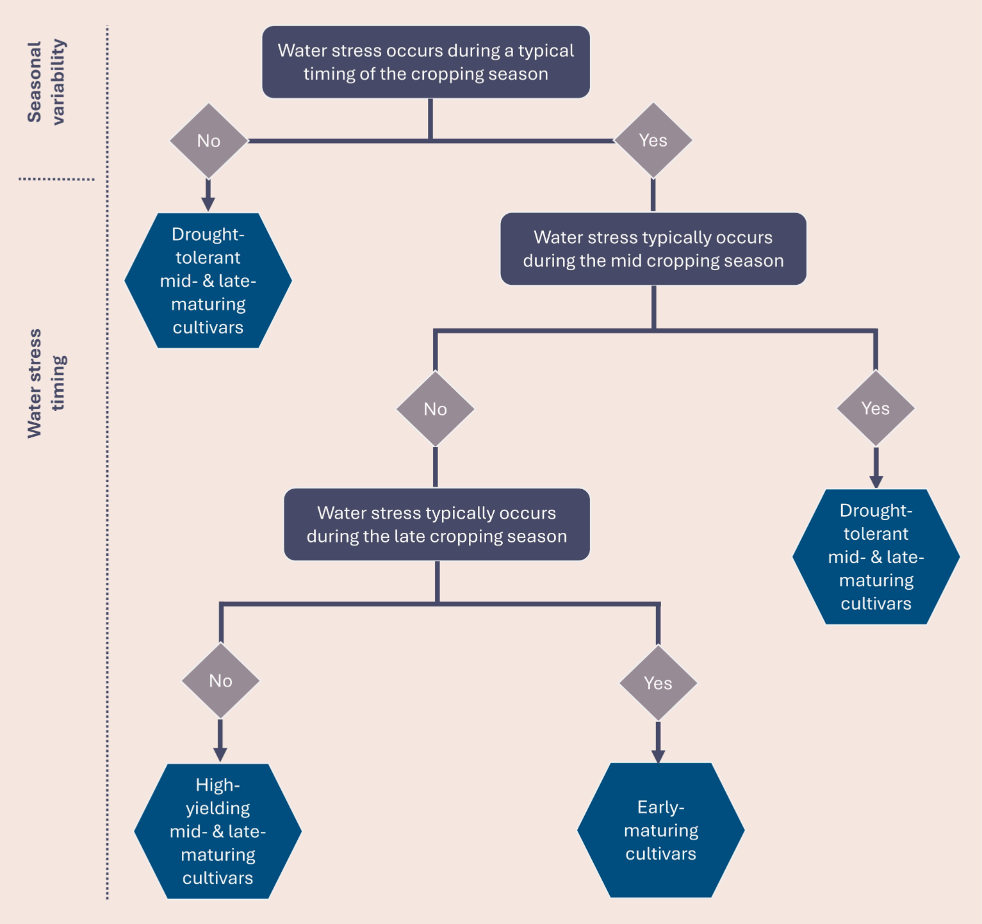

Fig. 5. Decision-tree for the selection of maize cultivar types based on the timing of water stress.

early-maturing cultivars are likely to provide sizeable benefits in these locations. If farmers and extension agents at a given location consider different decision tree outcomes equally likely (Fig. 5), combining cultivars with varying maturation requirements can be a suitable risk reduction strategy.

When focussing on locations with the highest intensity of water stress across Malawi, water stress typically starts already from mid-season – thus making early-maturing cultivars unsuitable. Specifically, across the earlier identified drought hotspots of Malawi – Chikwawa and Nsanje in southern Malawi, as well as Karonga, Rumphi and Mzimba in northern Malawi – the adoption of early-maturing cultivars would likely constitute a maladaptation. Advising farmers in these locations of Malawi to adopt early-maturing cultivars as a risk reduction strategy is evaluated as unsuitable and can be expected to drastically reduce yields.

The actual adoption pattern of cultivar maturity types shows that in the districts of northern Malawi that frequently face mid-season water stress and were identified as likely unsuitable for early-maturing cultivars, the adoption of early-maturing cultivars was indeed low. However, partial adoption of early-maturing cultivars in locations with unsuitable climate conditions was found in both northern and southern Malawi. In central and southern Malawi, adoption patterns were generally more variable and often did not match the identified suitability zones. In the districts Mchinji and Lilongwe in central Malawi, for example, predominantly late-maturing cultivars have been grown, although early-maturing cultivars are likely the most suitable cultivar choice to avoid water stress. Overall, the available data on the current use of cultivar maturity groups suggests that the maturity-type selection in Malawi can be improved.

The use of early-maturing cultivars and other drought escape strategies are only one possible drought management option. However, when production locations are consistently exposed to drought throughout the entire growing season, cultivar choices that prioritise drought tolerance over drought escape are more suitable (Fig. 5). Further, drought events often coincide with heat stress. Comprehensive drought management strategies should thus not exclusively rely on drought escape but also consider drought tolerance and heat stress tolerance as potential strategies.

A major remaining gap in the literature concerns the trait characterisation of non-certified maize cultivars. Locally-bred, non-certified maize seed is often considered to be predominantly medium- or late-maturing. However, high quality datasets that would characterise the wide diversity of maturation requirements and other characteristics of local maize cultivars are not commonly available. Consequently, it is unclear how the mix of maturation requirements among the population of maize cultivars in Malawi will evolve if certified maize cultivars with well-known maturation requirements increasingly replace non-certified seed. Further, the exclusion of plots cultivated with unidentified local cultivars, due to their unknown maturation requirements, represents a limitation of this study. Specifically, it is possible that farmers that were able to identify their maize cultivar(s) have better access to agricultural inputs and possess higher levels of agricultural knowledge as well as managerial skills. Although we controlled for all available covariates in our empirical model, further research is needed to determine whether our findings are generalisable to the broader population of smallholder maize farmers in Malawi.

5. Policy implications

Early-maturing cultivars should not be recommended blindly to all drought-prone locations. Instead, data is needed to ensure that early-maturing cultivars are used in locations with sufficient water availability during short growing periods. Across Malawi, the most drought-prone production locations are seldom free of mid-season water stress and are thus a poor fit for early-maturing maize cultivars. Here, drought-tolerant mid- and late-maturing cultivars are better equipped to cope with early-occurring water stress. Seed recommendations need to provide more explicit guidance on the site-specific suitability of early-maturing cultivars – particularly if they were not simultaneously bred for drought tolerance. Drought-tolerant mid- and late-maturing cultivars are likely more suitable across a larger diversity of drought timings and can thus be used more versatilely. In case of uncertainty about typical climate conditions at a specific location, drought-tolerant mid- and late-maturing cultivars are more suitable allrounders and are more likely to constitute a low-regret option across various weather conditions. E.g., Katengeza and Holden (2021) have found drought-tolerant cultivars to provide yield increases across diverse locations in Malawi.

An important strategy to reduce the risk associated with selecting the most suitable cultivar maturation requirement is the combination of different cultivars on individual farms (Lunduka et al., 2012). Abate et al. (2017) found that 35 percent of Malawian farmers utilised two different maize cultivars, with an additional six percent employing even three different cultivars. While the simultaneous application of several maize cultivars is thus already common, agricultural extension providers could offer more explicit information on the type of cultivar combinations that are suitable to spread the risk of crop failure under the most likely seasonal water stress scenarios (Fig. 5). E.g., Katengeza and Holden (2021) suggest that farmers in drought-prone areas of Malawi should cultivate at least one-third of their maize growing area with drought-tolerant cultivars.

Our analysis highlights ample opportunities for research to better inform the precise spatial targeting of cultivars in smallholder agriculture at refined spatial scales. The specific production locations identified in this analysis as suitable or unsuitable for early-maturing cultivars should not be used as the sole basis for cultivar recommendations in Malawi. Instead, the future availability of additional household survey waves will increase the overall size and temporal variability contained in the IHS dataset, which will enable testing the reliability of the econometric findings of this study. A multi-disciplinary approach should be used to provide directly actionable and prescriptive guidance at sub-national level. Econometric analysis is only one of the available tools to inform the spatial targeting of early-maturing cultivars and should be complemented and stress-tested by other methods. Specifically, agricultural experimental trials and crop modelling provide further independent methodological approaches for cultivar suitability studies. While it is challenging for agricultural experimental trials to identify locations that represent the full diversity of relevant environments, the findings from this econometric analysis can guide trial site selection across Malawi. Crop modelling studies allow the simulation of different cultivar maturation requirements at fine spatial scales across long periods. They are accordingly well placed to provide assessments that can be directly compared to the findings of this analysis. E.g., Tesfaye et al. (2016) utilised crop modelling to evaluate the suitability of drought-tolerant maize cultivars across multiple countries in Southern Africa. Crop modelling also allows to explicitly investigate if avoiding water stress during critical plant growth stages is indeed the main driving factor of the yield differences between maturity types. Integrating such multi-disciplinary research can provide a high confidence level for informing cultivar recommendations across Malawi and other countries in SSA.

Given the large share of certified maize seed in Malawi purchased via subsidised vouchers, the government already directly intervenes in cultivar choice decisions. Actively considering the spatial suitability of cultivar types in different locations could ensure that such seed subsidisation schemes provide the highest benefit to smallholder producers. Subsidised vouchers are predominantly used to purchase hybrid seeds. The purchase of certified seed remains rare when no subsidy is provided (Audet-Bélanger et al., 2016) and the replacement rate of improved maize cultivars in Malawi is the lowest in Eastern and Southern Africa (Chivasa et al., 2022). Therefore, when promoting early-maturing cultivars in Malawi, it should be considered that the gradual replacement of older seed material will be slow. This also implies that any successfully disseminated early-maturing cultivars are likely to remain in circulation for a prolonged period. Further, cultivar characteristics beyond the maturation requirement and drought tolerance, such as storability, pest resistance, nutritional quality and correspondence to dietary preferences, must be actively considered when developing cultivar recommendations (Audet-Bélanger et al., 2016; Nyirenda et al., 2021).

6. Conclusion

This analysis provides evidence that the current adoption pattern of early-maturing cultivars is suboptimal across Malawi. Instead, some adopters of early-maturing cultivars can achieve higher yields when adopting other cultivar maturity groups – and vice-versa. However, to date, little actionable information is available on the best target locations for different cultivar maturity groups at a fine spatial resolution.

This analysis provides evidence about likely locations that are particularly suitable or unsuitable for early-maturing maize cultivars in Malawi. We outlined how future econometric studies, crop modelling, and agronomic field trials can build on the current findings and provide cultivar suitability recommendations at high spatial resolution with a high confidence level. Such scientific findings on the spatial suitability of cultivar types can be used directly to revise agricultural extension advice. It could also be considered by the subsidised seed voucher system to ensure that the most suitable cultivar maturity groups are included in the subsidisation scheme for each location.

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CRediT authorship contribution statement

Uwe Grewer: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Dong-Hyuk Kim:** Writing – review & editing, Methodology, Conceptualization. **Katharina Waha:** Writing – review & editing, Methodology, Conceptualization.

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 material

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.foodpol.2024.102766.

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