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Research Paper

The economic irrationality of closing the yield gap in rainfed maize production – An extensification v intensification assessment in Dodoma, Tanzania

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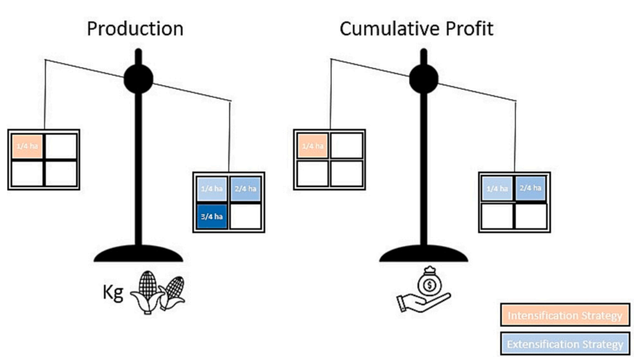
HIGHLIGHTS

- Extensification of rainfed agriculture predominates intensification in SSA.
- Extensification outperforms intensification 3:1 and 2:1 for production and economic profitability, respectively.
- Extensification is an economically sensible risk management strategy to pursue for smallholders.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Current trends in SSA show a rapid expansion of the area in rainfed cereal production with persistent low yields. This, despite the long-established efforts to close the yield gap in SSA and promote high(er) yielding agricultural intensification (re. Alliance for a Green Revolution in Africa).
Objective: In this paper, we show why the extensification of low yielding rainfed agriculture in SSA, as reported, persists and forms a sensible strategy to pursue for small holders – both from an agronomic and economic point of view.
Methods: We do this by presenting the comparative modelling analysis for the low yield extensification and high yield intensification strategy for rainfed maize cultivation in Dodoma, Tanzania. The contrasting strategies were modelled and assessed using crop growth modelling (AquaCrop), 9 years of climatic data and economic data for costs and revenues. Data were obtained from online sources and past studies.
Results & conclusions: Results show that low yield extensification under rainfed conditions is sensible, due to: (i) the staggering of planting dates that provide a better climate resilience for production; and (ii) a higher economic profitability, especially in the long term. Our results show that the economic risks (due to crop failure) of the high yielding intensification strategy become insurmountable for low-income households when both climate volatility and prices of chemical fertilisers increase.

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Significance: Expanding agricultural rainfed area under low input, low cost, and low yield (as reported by FAO) is, as supported by our modelling results, a sensible risk management strategy to pursue for low-income households, that helps to explain its continuing practice. Finally, we will argue that in an era of increasing climatic and financial volatility affecting agricultural production, we will need to reorient our agricultural production systems from yield maximisation to risk optimisation. To halt the continuing expansion of rainfed agriculture, at the expense of nature, the focus will have to shift towards increasing and stabilising income for poor household under volatile climatic conditions. Our methods can be applied to assess the climatic risks of rainfed agriculture regions by determining the cut-off ratio at which extensification outperforms intensification.

1. Introduction

The raising of rainfed agricultural yields has been targeted as a priority in multiple studies and policies of the past decades (Molden, 2007; Wani et al., 2009; Rockström et al., 2009). With rainfed agriculture accounting for more than 60% of global cereal production in 2000 (Molden, 2007), raising its yields to higher potential has been propagated as an essential step in meeting rising food demands of a growing population in a world of limited land and water resources. This, it is argued, on two related accounts: (i) there is a substantial theoretical potential to close the yield gaps of rainfed agriculture, which' yields tend to be low due to management practices (Lobell et al., 2009); and (ii) rising pressures on land, water, and biodiversity demand a minimisation of further agricultural expansion. Maximisation of the resources use efficiency of current land and water use is called for as a method of sustainable intensification (Ray et al., 2013; Godfray et al., 2010; Foley et al., 2011; Phalan et al., 2011; Van Ittersum et al., 2013).

Sub-Sahara Africa (SSA) has been widely characterised as a predominantly rainfed agricultural region with large yield gaps (Molden, 2007; Mueller et al., 2012). Average yields have been reported to be as low as 23–35% of the potential (Rockström et al., 2010). With the prospect of having to meet a tripling food demand of a 2.5-fold population by 2050 (Van Ittersum et al., 2016), calls to bring the originally failed Green Revolution to SSA were quick to follow (Toenniessen et al., 2008; Wise, 2020). The Alliance for a Green Revolution in Africa (AGRA), initiated in 2006, was set up with this purpose. It targeted the adoption of HYVs, fertiliser use and agricultural technologies in SSA with the explicit aim to reach agricultural intensification and closing of the yield gap. However, despite the initiative, only marginal yield improvements are evident to date (Wise, 2020; Ray et al., 2013), while fertiliser applications in SSA remain an order of magnitude lower than in other regions of the world (Bonilla Cedrez et al., 2020). As reported by Wise (2020) and Seijger et al. (2025) the reported increases in cereal production for SSA over the past two decades (as reported to FAOSTAT) have come from a massive expansion of agricultural land, at only marginal increases of yield that remain well below theoretical potential. This indicates that increases in agricultural production in SSA have predominantly been achieved by extensification of production (area expansion with low output yield per ha under low input) rather than the targeted intensification of existing land use (high output yield per ha under high input).

Agricultural extensification and intensification are well defined concepts that describe starkly different agricultural development strategies (Giller et al., 2021; Baudron et al., 2012; Godfray, 2015). Where extensification is generally referred to in terms of expansions of agricultural frontiers, intensification is associated with the intensification of the Green Revolution (Baudron et al., 2012). Intensification represents not only the opposite of extensification but also the modern western-style of farming (Godfray, 2015). In areas (and countries) where farm (plot) sizes are delimited by land scarcity, intensification is often the only option to increase production from delimited land-size (Baudron et al., 2012; Erenstein, 2006). In the context of rainfed agriculture in SSA the latter premises, however, often do not hold as rainfed agriculture is conducted on small plots on vast communal (village/tribe) land under customary tenure (Chimhowu, 2019; Krantz, 2015). Whereby the size of sown area, tends to be determined/restricted by household labour, input, and machinery availability. In large tracts of SSA rainfed agriculture thus constitutes an agricultural frontier characteristic, providing households with the alternative opportunity to expand their agricultural activities, rather than intensify. As evidenced by the officially reported production statistics to FAO (Wise, 2020; Seijger et al. (2025); FAOSTAT), expansion and extensification have been taken up 'en-masse' over the last two decades to raise SSA's rainfed production.

In this paper we set out to analyse why extensification prevails over intensification in SSA rainfed agriculture, by unravelling the agronomic and economic risks and rationales behind these strategies. Agronomically, extensification offers the opportunity to stagger sowing dates across farm plots and disperse plots over the micro-hydrological landscape (e.g. depressions, bottom or top of the hill, slopes or flats). This may constitute an effective climate risk hedging strategy against climatic shocks of extreme temperatures, droughts, and floods (cf. Shah et al., 2021; Paymard et al., 2018; Nouri et al., 2017). In particular for rainfed agriculture, that is susceptible to the volatility of climate, such hedging of climatic risks may stabilize overall agricultural output when low performing (stressed) plots are offset by better performing plots. Economically, the extensification strategy may outperform the intensification strategy on two fronts: (i) extensification may provide overall higher and more stable yield and income than intensification; (ii) intensification of rainfed agriculture may be prone to high economic risks when crops (partially) fail due to climate volatility and the high investments for inputs (e.g. fertilisers) are not recouped. Extensification, with its low input low output strategy, has an intrinsic lower financial risk. As stressed by Lobell et al. (2009) and Godfray et al. (2010), farmers tend to seek economic optimisation/profitability rather than yield maximisation, and as rising costs of fertilisers and other inputs frequently start to outperform potential economic gains, yield maximisation becomes more difficult to achieve.

To explain the current observed trend of agricultural extensification in SSA, and put the above to the test, we conducted a case study analysis of rainfed maize production in Dodoma, Tanzania. Tanzania was selected as an indicative SSA rainfed region with limited fertiliser application, despite official policies to subsidise and increase fertiliser application (Wilson and Lewis, 2015; Palmas and Chamberlin, 2020). We compared the two agricultural strategies in both agronomic and economic terms. For the agronomic analysis, we used the AquaCrop growth model with online climate data for the period 2011–2020. For the profitability analysis, we used past scientific studies and grey literature.

2. Materials and methods

2.1. Case study area

To conduct our modelling analysis, we selected Dodoma region in central Tanzania. Dodoma region has been selected for this study as an illustrative case study, as it fulfils two criteria: (i) it is a rainfed (cereal) agriculture dominated area with high incidence of poverty where agriculture is dominated by food security/subsistence, conducted typically on communal village ground and has scope to further expand; (ii) it is a well-documented region for which on-line data on climate and soils, and

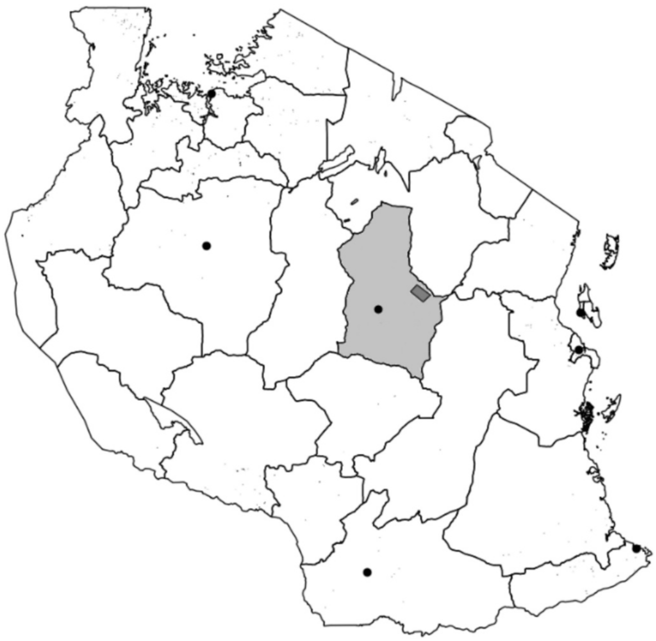

Fig. 1. Dodoma region in central Tanzania (bright grey), selected case study (dark grey), and available weather stations (black dots).

past studies on rainfed agriculture, are available (see S.M.1.). Elevation ranges from 900 to 1500 m amsl, with rainfall ranging between 200 and 800 mm per year (Perfect and Majule, 2010). Dodoma receives a mono-modal rainfall pattern, with the *Masimu* rains starting in November and ending in mid-May (Baijukya et al., 2020). Livelihoods are primarily dependent on annual crops, including maize production, and limited cattle raising, with nearly 50% of population living under the poverty line (Perfect and Majule, 2010). The case study area is shown in Fig. 1.

2.2. Agronomic analysis – AquaCrop modelling

To quantify and compare the productivity of agricultural extensification and intensification strategies under rainfed conditions, we modelled the cultivation of rainfed maize in Dodoma for two distinctive cropping strategies. AquaCrop, a crop growth model developed by FAO, was used to assess the productivity of the two strategies under varying climatic and agronomic conditions (see below). AquaCrop was chosen as it represents a dynamic crop growth model that simulates crop production in response to environmental and crop management factors. It is a well-established, and calibrated, model that uses a limited number of data inputs to simulate the effects of water, climate (temperature and energy), fertility management and weed competition on crop production[1] (Raes et al., 2022; FAO, 2017; Steduto et al., 2012; Raes et al., 2009; Steduto et al., 2009). It has also already been extensively used for agronomic analyses (Zhang et al., 2022; Er-Raki et al., 2021; Dhouib et al., 2022; Wellens et al., 2022; Umesh et al., 2022; Rashid et al., 2019). Data requirements for AquaCrop include the climate, the growing calendar, the crop, the field management practices and the soil profile.

Crop growth simulations were conducted over 9 consecutive growing seasons (9 years) to assess and compare the vulnerability of the crop growth strategies to the volatility of the climate. Climate data were obtained through NOAA for Dodoma weather station for the period 2011–2020 (see S.M.1). Soil characteristics, a critical component in determining the soil moisture holding capacity for the growth simulations, were derived for the region from the Harmonized World Soil Database (FAO, 2014) and defined as clay soils. The soil characteristics were uniformly set for both growth strategies (see S.M.1).

To assess the two crop growth strategies, maize was selected as a common representative staple crop of rainfed agriculture in Dodoma (and wider SSA). For this modelling purpose, use was made of the default crop file settings for maize as provided by FAO for AquaCrop (see S.M.2.). This means no crop varietal or genetical difference was applied across the two strategies; for both strategies the same crop, as defined by the crop file settings, has been applied, meaning that all differences in crop growth performance stem from variations in environmental (climate, water) and management (fertiliser application and weeding) conditions. The crop genetic responses to abiotic stresses (e.g. phenological development and harvest index (HI) responses to heat & cold stresses, water stress, water logging etc.) are set and defined as per the crop file settings. No attempt has been made to calibrate these settings to the most prevalent maize crop varieties used in Dodoma, as this was beyond the scope of this study. This is warranted as we focus on quantifying the effects of differing planting and management strategies on one and the same crop variety.

2.3. Cropping strategies and scenarios

To assess the two cropping strategies of extensification (area expansion with low output yield per ha under low input) and intensification (high output yield per ha under high input), the cropping calendar (sowing dates) and crop management criteria were defined as listed in Table 1. Plot size was set at ¼ ha for the intensification strategy and 4 times ¼ ha (1 ha total) of staggered sowing plots for the extensification strategy. As becomes evident from the economic analysis (see below), this is warranted as the total investment costs of three ¼ ha extensive plots equals that of one ¼ ha intensive high input (see S.M. 3–6 and 5–2), thus encapsulating the extensification option of extending low cost and low input agriculture at the same investment level. Determining the sowing date for rainfed crops is both critical and insecure, as it needs to anticipate the volatility of the climate. The DEPTH criterion has been applied to specify the sowing date at which ≥40 mm of precipitation over 4 days has fallen (Raes et al., 2004; Mhizha et al., 2014). Three additional sowing dates were set at −15, +15, and + 30 days for the staggered sowing of the extensification strategy, allowing for the spreading of labour input. For the intensification strategy the DEPTH criterion was enhanced to ≥50 mm precipitation over 4 days to protect the high initial investment on fertiliser application. The extensification strategy was further defined as poor weed control, with 35% relative weed cover, and low fertiliser application, resulting in 58% fertility stress for the extensive maize crop. For the intensive maize crop full weed control and recommended fertiliser application (based on Baijukya et al. (2020), see Table S.M.2–1) were assumed, with consequently no weed cover and no fertility stress. Sowing density was adjusted to recommended levels based on Baijukya et al. (2020) for both strategies (see Table S.M.2–1).

2.3.1. Initial soil moisture conditions

In the modelling of rainfed crops, the setting of initial soil moisture content (ISMC) at the start of the simulation forms a critical value as it

Table 1
Crop management criteria.

	Extensification	Intensification
Plots	4 x ¼ ha	¼ ha
Sowing date	≥ 40 mm rain over 4 days; −15, +15, +30 days staggering	≥ 50 mm rain over 4 days
Weed control	Low, 35% weed relative cover	High, no weed cover
Fertility management	Low, 58% fertility stress	High (recommended), no stress

[1] https://www.fao.org/aquacrop/en/#:~:text=AquaCrop%20is%20a%20crop%20growth,and%20management%20on%20crop%20production.

may impact upon the total seasonal water availability for the crop, and thus overall crop performance. To ensure reasonable estimations for the ISMC the following method was applied. First, we assumed soil water content at the end of the rainy season in mid-May 2011 to have reached field capacity (FC), by considering no prior agricultural use of the land. During the subsequent dry season, natural vegetation reduces the soil moisture content. The growth, and water consumption of natural vegetation was simulated in AquaCrop by defining a generic crop (in GDD) starting mid-May 2011 with ISMC at FC. This simulation, or pre-run, was set to end at the start of the sowing season. This was then used as an input for the ISMC of the first rainfed season 2011–2012 (set the same for both extensification and intensification strategy runs[2]). Each subsequent simulation, for each season and plot, was run for a full year, using the soil moisture content at the end of the run as the ISMC input for the next run. A summary of all data and file settings used in the AquaCrop simulations is provided in S.M.2.

2.4. Economic (risk) analysis

Rainfed agriculture is particularly prone to the risks of crop stress/failure as incurred by the volatility of the climatic growing conditions. Intensification, with its high input high output focus, will have a higher risk susceptibility due to its high initial investments. To assess and compare these risks, the AquaCrop simulation results for the intensification and extensification strategies were also converted into their economic profitability for households. Profits for this study, were defined as the difference between earnings, obtained from selling of maize yields at farmgate prices, and costs incurred with production (profit = earnings – costs).

Earnings were derived from multiplying simulated yields with regional farm gate prices. A range of maize farm gate prices between 320 and 800 Tsh.kg^{-1} is reported in literature (Kadigi et al., 2020; WFP, 2015; Palmas and Chamberlin, 2020; see S.M.3–1). Accommodating for the economic market rationale that good years with high yields return low farm gate prices, and vice-versa, farmgate prices were inversely correlated to simulated yields (see Table S.M.3–2). Costs were determined by the management practices that define the two cropping strategies and were obtained from Utonga (2022). Seeds were costed at 48,957 Tsh.ha^{-1}, overhead (188,815 Tsh.ha^{-1}) and fixed (34,091 Tsh.ha^{-1}) costs cover plot size expenses. These costs increase for the extensification strategy as more plots are taken into cultivation. Fertiliser costs are the main differentiated costs between the two strategies. For the extensification strategy, fertiliser costs (146,505 Tsh.ha^{-1}) are adopted from Utonga (2022) and reported to relate to current level of fertiliser application which is one of the lowest in the world (around 9 kg.ha^{-1}.year^{-1}) (Wilson and Lewis, 2015). For the intensification strategy, fertiliser costs were calculated based on the recommended application rates by Baijukya et al. (2020) at government subsidised prices (2023) listed for Dodoma (Tanzania Fertiliser Regulatory Authority,[3] see S.M.3). Fertiliser costs for the intensification strategy ranged between 633,500 to 1,137,050 Tsh.ha^{-1},[4] depending on the fertiliser choice and the use of subsidies (see Tables S.M.3–3, 3–4 and 3–5). Labour costs were not accounted for.[5] Further details of the economic calculations are provided in S.M.3.

Economic risk of cultivation was simply and crudely analysed as the profitability of the two cultivation strategies over the 9 consecutive simulated growing seasons. This allowed us to assess: (i) the economic vulnerability/sensitivity of each strategy to the volatility of the climate; (ii) the cumulative economic performance over 9 years; and (iii) determine the cut-off point in number of additional plots cultivated (1–4) in the extensification strategy at which it will economically outperform the intensification strategy.

2.4.1. Farmgate prices, fertilisation and subsidy scenarios

For the intensive cropping strategy, two fertilisation strategies were considered: (i) applying NPK for the basal application, followed by CAN as a top-up application; (ii) DAP for the basal application and UREA as the top-up application. The NPK-CAN is more expensive than the DAP-UREA one. To assess the sensitivity of the profitability of the intensive strategy to input price ranges, both fertilisation strategies were assessed for government subsidised, and non-subsidised, prices (S.M. 3–3 and 3–4). This allowed us to assess the impact of Government fertiliser subsidies on profitability and rate of return.

Farmgate prices for maize were initially set to be variable according to a crude price-elasticity model, in which good years with relative high yields resulted in low farmgate prices, and vice-versa low yield years having high farmgate prices (Table S.M. 3–2). To assess the sensitivity of our profitability analyses, the assessments have been repeated for consistent high farmgate price (at 800 Tzs.kg^{-1}) and average price (at 560 Tzs.kg^{-1}).

In our simulation runs we were confronted with two consecutive drought years (2013–14 and 2014–15) in which the rains failed after germination. For these years assessments were run with and without drought adjustment of fertilisers applications. For the intensive strategy adjustment was defined as the discarding of the top-up application, and for the extensive strategy the halving of the fertiliser costs for 9 kg.ha^{-1} application (see S.M. 3 for details).

The simulation runs for the extensive plots in AquaCrop were run with maximum fertility stress (58% stress). In the profitability assessment of the extensive strategy two scenarios were run. One, assuming minimal fertiliser application (and associated costs) of 9 kg.ha^{-1}, and one with assuming no fertiliser application.

This has led to a total of nine scenarios that were run for the extensive plots and 4 intensive plots (NPK+ subsidies, NPK no subsidies, DAP + subsidies, DAP no subsidies) as presented in Table 2.

2.4.2. Investment burden and rate of return

To assess the investment burden for households, the investment costs of the cropping strategies were determined and expressed as a percentage of mean annual income of small-scale food producers in Tanzania for the period 2009–2019 (S.M. 5–2). For the NPK-CAN strategies (subsidised and non-subsidised) the investment burden of ¼ ha intensive equates to that of ¾ ha extensive at around 25% of mean annual income. For the DAP+UREA this ratio stood at ¼ ha intensive to ½ ha extensive. For all the scenarios the rate of return on investment was determined for the 9 consecutive seasons as: (Σ annual profits - Σ annual investments) /(Σ annual investments).

[2] Topographic and hydrological differences that may affect the effective rainfall capture and soil moisture content at micro scale, were not considered as this lay beyond the scope of this study. However, as allured to in the introduction, our hypothesis is that the effective staggering of plots across the micro hydro-topography will form an effective additional climate risk hedging strategy.

[3] Official figures from the Tanzania Fertiliser Regulatory Authority, derived from https://www.tfra.go.tz/documents/fertilizer-indicative-price?page=1

[4] The assumption was made that fertilisers are applied in two applications (at the start of the season, followed by a top-up). In case of extreme dry years (13/14 and 14/15 in our case) the top-up application was discarded, and fertiliser costings for the intensive strategy were adjusted (see S.M. 3–6).

[5] Labour can be regarded as in-kind household contributions compensated by economic profits made. In addition, labour input and costs per ha can be expected to be higher for the intensive cultivation strategy (regular weeding, applications of fertiliser) than for the extensive strategy, for which we had no means to account and differentiate for here. Also the application (labour and costs) of agro-chemicals for weed and pest control, expected to be higher for the intensive strategy, are not accounted for.

Table 2
Scenario runs for assessment of the profitability and rate of return.

	No Top-up +9 kg in extensive			No Top-up +0 kg in extensive			Full application +9 kg in extensive		
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
Farmgate price	variable	high	average	variable	high	average	variable	high	average
Ex ¼ ha									
Ex ½ ha									
Ex ¾ ha									
Ex 1 ha									
Int ¼ ha NPK + sub									
Int ¼ ha NPK no sub									
Int ¼ ha DAP + sub									
Int ¼ ha DAP no sub									

3. Results

3.1. Yield analysis

Using the climate, crop and soil data described above, five (5) crop growth simulations per growing season were set up and run in AquaCrop for 9 consecutive growing seasons (2011/12–2019/20). Four staggered plot simulations were run for the extensification strategy and one for the intensification. These simulations returned significant different yields, with yields of the intensive plot 46–65% higher than the average yield obtained from the extensive plots for 6 out of the 9 years (Fig. 2a). Intensification yields reached a peak of 9.2 $t.ha^{-1}$ in 2011/12. For the season 2013/14 and 2014/15 the simulated maize crop failed in both intensive and extensive plots. These crop failures are the result of unfavourable growing conditions in the region in terms of water availability – e.g. low precipitation and a depleted rootzone (by previous year crop) that result in highly stressed growing conditions (Fig. 2b) and long delays in crop germination (Fig. 2c). For the season 2019/20 the yields of the extensive plots are similar to that of the intensive plot. Even though seasonal rainfall seems favourable (> 1100 mm, see Figure S. M.1–3), both cropping systems suffer from aeration stress[6] throughout the season that results in pronounced stomatal closure and reduced biomass production (Fig. 2b).

The lower yields of the extensification strategy, compared to the intensification strategy, are mainly due to two factors: (i) low fertiliser application results in structural fertility stress of 58%; and (ii) poor to no weed management results in 35% relative cover of weed infestation that competes for water (see Table S.M.4–2). The former results in a lower biomass water productivity ratio that defines the rate of biomass production per unit of transpiration – e.g. a lower photosynthetic efficiency due to nutrient stress (Steduto et al., 2007; De Wit, 1958). The latter leads to weed competition for limited available water resulting in water stressed induced reduced transpiration (and biomass production) for the maize crop – around 25% competition for water is taking place due to weeds (see Table S.M.4–2). The yields of the staggered plots P1-P4 for the extensification strategy varied slightly intra-seasonal, but less than anticipated. Variations in planting and germination dates (Fig. 1c) resulted in slight variations in water availability and growing conditions (see Table S.M.4–1) that influenced plot yields.

Simulated plot biomass and maize yields were consistently higher for the intensive plot than for the extensive (staggered) plots, except for the season 2019/20 (Table S.M.4–1). In this last season, excessive rainfall leads to high aeration stress in the intensive plot, resulting in 75% stomatal closure (Fig. 2b) that reduces biomass (and yield) produced. For the extensive plots, the two plots with early planting are less affected by aeration stress (53%) resulting in higher biomass (and yield) production that brings up the average produced yield for the extensification strategy. Aeration stress induced stomatal closure during the yield formation phase has no effect on the Harvest Index (HI) in AquaCrop (Raes et al., 2022; Githui et al., 2022) – i.e. yield reductions are solely attributed to reduced biomass production, not to alterations in biomass partitioning by plant responses. However, caution is needed as further research on how aeration stress affects yield is needed, as crop growth models tend to over-simplify this aspect (Githui et al., 2022).

The simulated yield variations, across cropping strategies, plots and growing seasons, stem primarily from variations in biomass production related to water, aeration and nutrient stresses. Our simulations show very limited differences in Harvest Index (HI) between the two cropping systems and planting dates – much less than anticipated, except for the season 2015/16 (Table S.M.4–1). Following the crop failure of 2014/15, soil water availability at the start of the 2015/16 season is very limited, leading to water stress that restricts canopy expansion and stomatal closure. These stresses, depending on their timing and severity, affect the HI positively or negatively, as well as possibly affect pollination. Water stress that leads to canopy growth reduction during the vegetative growth stage, leads to increase in HI (as well as lower depletion of soil moisture). Whereas water stress, and stomatal closure, after flowering reduces HI (Raes et al., 2022). For the season 2015/16 different HI, due to differences in water stress, were obtained across the plots, due to differences in planting dates. For plots P1 and P2 of the extensive strategy, and the intensive plot, planting takes place in December. This results in a small reduction of HI (~ 3%) due to water stress and stomatal closure during the yield formation stage. The extensive plot P3 has the most favourable planting date for optimal HI, despite a limited effect of water stress on pollination. Lastly, plot P4 has the lowest HI due to pronounced water stress (resulting in reduced canopy expansion) during vegetative growth that affects pollination (Table S.M.4–1).

The relatively small variations in HI we obtained across the staggered plots can be explained by the effect of delayed germination (Fig. 1c, for germination criteria see S.M.4). For most of the growing seasons crop germination of the intensive plot and P1 and P2 of the extensive plots took place on the same date (e.g. Plot 1 had a delayed germination) (Fig. 1c). This diminishes the effect of staggered sowing – advancing sowing before the DEPTH criterion is met has no effect[7] – resulting in similar growing and water conditions for the 3 plots in question. Also, the topography of the land and fields has not been taken into account, due to data limitations. In our simulations all plots have the same soil and hydrological conditions. In practice, especially in accentuated terrain, one might expect micro-hydrological conditions to vary and differ – e.g. high and sloping plots less prone to waterlogging and aeration stress, or "bottom" fields that catch and retain more water throughout the season. Staggering of plots in such conditions is expected to capture diverse micro-hydrological conditions that may affect the

[6] The clay soil of the region will be more susceptible to this stress than light soils.

[7] Despite the smaller than anticipated effect on climatic hedging, due to delayed germination, staggered sowing (and land preparation) still needs to be applied in the extensification strategy to assure a staggered application of limited household labour resources.

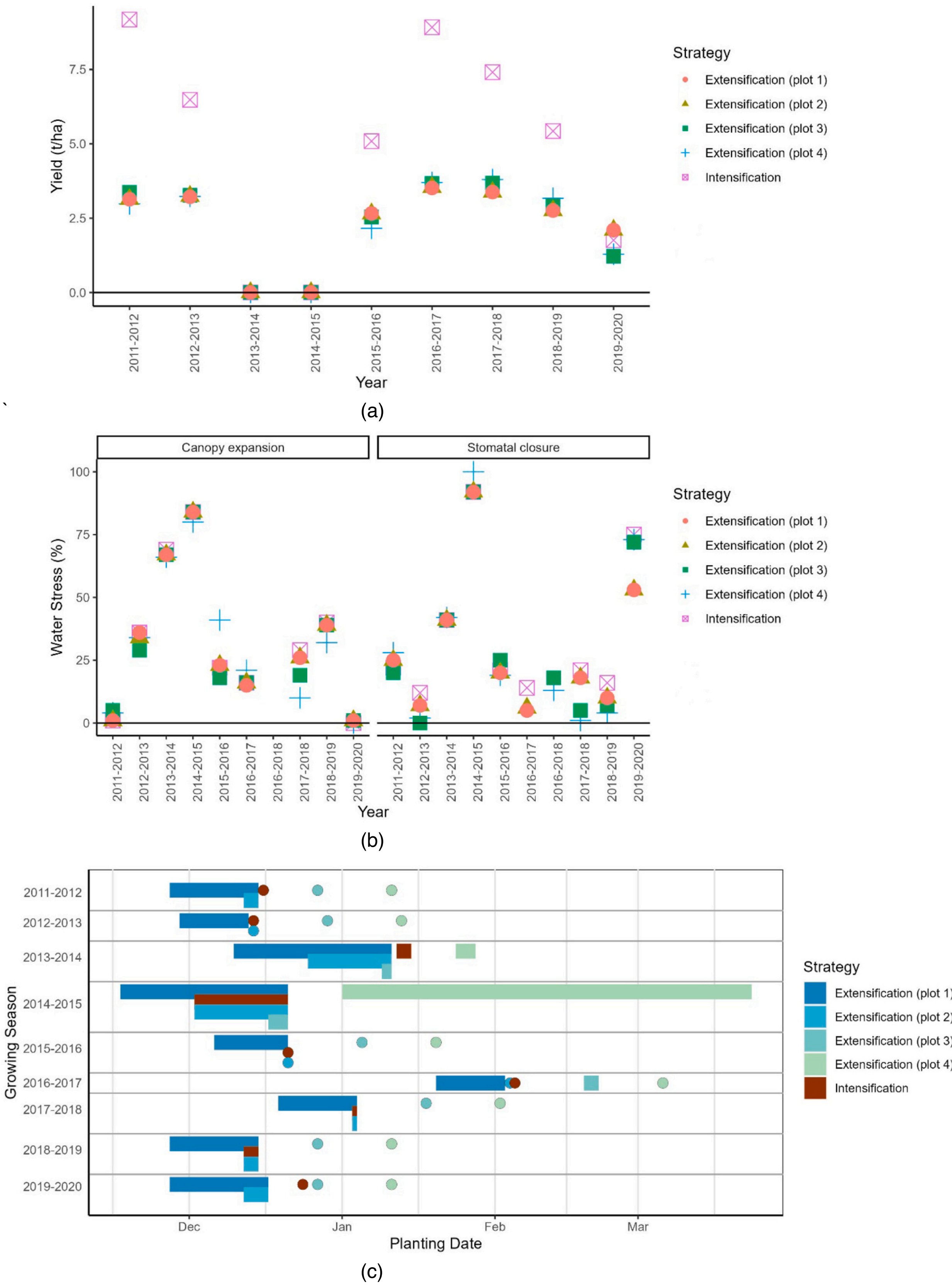

Fig. 2. AquaCrop results for a) yield, b) water stress for canopy expansion and stomatal closure, and c) planting dates (the continuous bar indicates delayed germination while a point indicates germination after sowing).

crop growth and water conditions and affect crop performance. This was, however, beyond the scope of this study.

The productivity (t.ha^{-1}) of the intensive plot is highest (good fertility and no water-weed competition) in all seasons, except 2019/20. Nonetheless, different sowing dates result in different levels of water stress incurred by the crop. For the extensive plots, staggering sowing dates spreads the risk of "lock-in" of production in unfavourable climatic conditions. This is the most apparent for the last season (2019/20), when the productivity of the extensive plots P3 and P4 outperform the intensive plot, which is subdued to high aeration stress. For all other seasons, the effects of staggered sowing are less pronounced. But, with the increase of climate volatility due to climate change, the frequency of years in which productivity and yields will be depressed – and small differences in growing conditions may have a larger relative impact – are likely to increase. And, as indicated above, in typography induced micro-hydrological diverse landscapes, staggering across micro-hydrological conditions may be expected to yield higher hedging effects.

3.2. Economic analysis

As detailed above, the productivity (t.ha^{-1}) of maize was governed by the intensity of the cultivation strategy (fertiliser application and the presence of weed-water competition) and the volatility of the climate between 2011 and 2020. The two farming strategies were simulated to assess whether, and when, the extensification strategy – expansion of low input, low output cultivation, staggered over sowing dates to hedge against climate risks – outperforms the intensification strategy that concentrates resources and inputs on a limited area. This requires the consideration of maize production (tons) and economic profits (revenue minus costs) (see S.M.3 for details) over the farming strategy (rather than plots), as well as the 9 years growing period. This allows the determination of the cut-off point or ratio at which the extensification strategy outperforms the intensification one.

Table 3a lists the tons of maize produced by each cropping system, for the 9 growing seasons simulated and the cumulative production over 9 seasons. For the intensification strategy the production of ¼ ha plot of maize grown under optimal management conditions under prevailing climate conditions, is listed as the benchmark target for each season. For the extensification strategy, the cumulative values of one (p1), two (p1 + p2), three (p1 to p3) and four (p1 to p4) ¼ ha plots are listed to determine the cut-off ratio at which it will outperform the benchmark. Values listed in bold black exceed the seasonal benchmark of intensification and values in red are below. The production is variable over the years, susceptible to the volatility of the climate (including two seasons of crop failure in 2013/14 and 2014/15). The intensification strategy showed two relative productive seasons (2011/12 and 2016/17), one poor (2019/20) and three moderate. The extensification strategy also shows a variability of production across the seasons, but less pronounced than the intensive. The cut-off ratio at which the extensification strategy outperforms the intensive thus varies, from 3 extensive plots : 1 intensive plot in favourable climatic years, to 1:1 in poor years (aerations stress due to excessive rainfall). Taken over the 9 growing seasons, the extensification strategy will outperform the intensification strategy at a 3:1 ratio for production.

For households, however, production is not the only consideration. Table 3 (b) lists the economic profitability (in 1000 Tzs) of the maize farming strategies simulated. The profits were calculated as [production*farmgate price] minus [costs]. Due to the high relative cost of fertiliser, the cut-off ratio at which the extensification strategy outperforms the intensification strategy is reduced to 2:1 over the 9 growing seasons considered.

Only 2 out of 9 years, in which climatic conditions are relatively favourable, is the economic cut-off ratio increased to 3:1. For the 3 poor years (two crop failures and one year in which the intensification strategy yields lower than the extensification one) the relative high investment costs for fertiliser application (even if adjusted for extremely dry years) bear heavily on the economic return and risk of the intensification strategy. Over the 9 years, the climatic volatility thus yields a poor economic return for the intensification strategy. In table S.M.5–2 the economic rate of returns for different fertilisation strategies for the intensive plot are listed – expensive (NPK and CAN) v cheaper (urea and DAP), with and without government subsidies, and for different farmgate prices.

In S.M 5 the full economic analysis of profitability for all fertiliser strategies and farmgate price scenarios, as listed in Table 2, is provided in figure (Figure S.M.5–1) and table (table S.M.5–2) form. These were conducted to assess the sensitivity of the outcomes to (i) farmgate price settings, and (ii) assumptions in fertiliser application strategies.

Table 3
Comparison and cut-off ratios between the cropping strategies for a) production under two different strategies and 9-year cumulative, and b) economic profitability (using expensive NPK and CAN fertilisers and governmental subsidies.

	(a)									
	Maize Production (tons)									
Strategy	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	Cumulative Production
Intensive, 1/4 ha	2.30	1.62	0.00	0.00	1.27	2.23	1.85	1.36	0.44	11.07
Extensive, 4/4 ha	**3.16**	**3.24**	0.00	0.00	**2.50**	**3.61**	**3.56**	**2.90**	**1.68**	**20.65**
Extensive, 3/4 ha	**2.41**	**2.43**	0.00	0.00	**1.96**	**2.68**	**2.61**	**2.11**	**1.36**	**15.57**
Extensive, 2/4 ha	1.57	1.62	0.00	0.00	**1.33**	1.77	1.69	**1.38**	**1.05**	10.40
Extensive, 1/4 ha	0.79	0.81	0.00	0.00	0.67	0.88	0.85	0.69	**0.53**	5.20
Cut-off Ratio	*3:1*	*3:1*	–	–	*2:1*	*3:1*	*3:1*	*2:1*	*1:1*	*3:1*

	(b)									
Profit Analysis: Expensive Fertiliser (NPK + CAN) @ subsidised prices (in 1000 Tsh)										
Strategy	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	Cumulative Profit
Farmgate Price	*Low*	*Low*	–	–	*Average*	*Low*	*Low*	*Low*	*High*	
Intensive, 1/4 ha	430	214	−186	−186	409	410	289	130	48	1558
Extensive, 4/4 ha	**593**	**619**	−344	−344	**984**	**737**	**722**	**511**	**924**	**4401**
Extensive, 3/4 ha	**459**	**465**	−258	−258	**786**	**545**	**522**	**362**	**771**	**3394**
Extensive, 2/4 ha	294	**308**	−172	−172	**535**	356	**332**	**233**	**631**	**2344**
Extensive, 1/4 ha	147	153	−86	−86	268	177	166	116	**316**	1171
Cut-off Ratio	*3:1*	*2:1*	-	-	*2:1*	*3:1*	*2:1*	*2:1*	*1:1*	*2:1*

For the scenarios with adjustment of the fertiliser application in the drought seasons of 2013/14 and 2014/15 (no top up application) and the assumption that 9 $kg.ha^{-1}$ of fertilisers are applied in the extensive plots, the effects of applying variable, high and average farmgate prices are listen in figures S.M. 5–1 (a), (b) and (c), and the corresponding tables in table S.M. 5–2. Higher or lower farmgate prices affect all cropping strategies in the same manner, in that the profits and rate of returns increase with higher prices. Where under variable prices the rate of return for extensive plots is positive (20–30%), they are negative for the intensive strategies, except for the subsidised 'cheap' (DAP + Urea) that achieves a rate of return of 16%. With high and average farmgate prices all rates of return increase (see also table S.M. 5–1), in which the rate of return of the extensive cultivation strategies tend to be substantial higher than those of the intensive strategies – except for the 'cheap' subsidised (DAP + Urea) option that returns a slightly higher rate of return under high and average farmgate prices. The cut-off ratios at which the extensive cultivation outperforms the intensive cultivation in terms of profit show, on average, a low sensitivity to farmgate prices. For the cumulative 9-year profits the 'expensive' (NPK + CAN) fertilising strategy the cut-off ratio of 2:1 is not affected by the farmgate prices. For the 'cheap' (DAP + Urea) option, subsidised and not subsidised, the cut-off ratio improves to 3:1 for high and average farmgate prices. For individual cropping seasons, farmgate prices may slightly affect the cut-off ratio. The government subsidies provided to farmers, however, do not affect the cut-off ratios. The subsidies do, however, improve the rate of return on investments.

The scenarios with adjustment of fertiliser application in drought years (no top up application) and assuming no fertilisers are applied in the extensive plots (figures S.M. 5–1 (d), (e) and (f) and corresponding tables S.M. 5–2), slightly favour the extensive strategy over the intensive strategy, by lowering the investment costs of the former. Overall, this results in little differences in cut-off ratios, except for the 'cheap' (DAP + Urea) option that falls back to the cut-off ratio of 2:1 under all farmgate prices scenarios, for both the subsidised and non-subsidised scenarios.

The scenarios with no drought adjustment of the fertiliser applications and assuming 9 $kg.ha^{-1}$ application in the extensive plots slightly favour the extensive strategy, as the incurred losses during the two drought years are higher for the intensive scenarios. Yet, in overall cut-off ratios this only led to marginal differences: only the subsidised 'cheap' (DAP + Urea) option retains a 3:1 ratio under the average farmgate price scenario, and non-subsidised 'expensive' (NPK + CAN) option falls back to a 1:1 ratio under the variable farmgate prices scenarios. (figures S.M. 5–1 (g), (h) and (i) and corresponding tables S.M. 5–2).

Overall, the extensive strategy economically outperforms the intensive strategy with a cut-off ratio of 2:1. Only at favourable farmgate prices (high and average) does the subsidised 'cheap' (DAP + Urea) perform better with a cut-off ratio of 3:1. With and investment burden of 17% and 25% of annual mean income (table S.M. 5–1), the extensive strategies of ½ ha and ¾ ha, against ¼ ha of intensive cultivation at similar investment burdens, is the economically most secure strategy to pursue under all farmgate price ranges.

4. Discussion

Our simulation results for extensification (up to four staggered plots) and intensification strategy for rainfed maize over nine growing seasons in Dodoma, Tanzania, confirm the agronomic and economic rationale that underpins the widespread prevalence and expansion of extensive low yielding (cereal) rainfed agriculture in SSA (Wise, 2020; Seijger et al., 2025). Both, in terms of production and in terms of profits/income, the extensification strategy outperforms the intensification one with an area to area cut-off ratio of 3:1 and 2:1, respectively, when considered over nine growing seasons. Interannually the cut-off ratio varies in response to the volatility of the climate, with maxima of 3:1for relative favourable climatic years in which the intensive strategy performs well, to the more sobering 2:1 and 1:1 when growing conditions are less favourable. Economically, the 3:1 (and 4:1) ratio is only reached in "good" years in which the plot reaches yields >8 $t.ha^{-1}$ – which in our simulation runs occurs only 2 out of 9 seasons. The economic risks of trying to close the yield gap in rainfed maize cultivation through intensification are high for households to bear in an increasingly volatile climate. Even with subsidised fertiliser prices, the investment costs for ¼ ha of intensive maize production amount to 17–30% of average annual household income,[8] against 8% for ¼ ha of extensive production. Over the nine growing seasons simulated, the economic return on investment then ranges from −13 to −59% for the intensification scenarios, and 16% for the subsidised 'cheap' (DAP + Urea) option, against around 22 to 30% for the extensification strategies, under variable farmgate prices (table S.M. 5–1) For high and average farmgate prices all rates of return are positive, with the extensification strategy outperforming the intensive scenarios, except for the subsidised 'cheap' (DAP + Urea) option. The subsidies on fertiliser prices introduced by the Government of Tanzania in general do not affect the cut-off ratios on profitability, except for the 'cheap' (DAP + Urea) option, where the subsidies applied improve the cut-off ratio from 2:1 to 3:1 under high and average farmgate prices. Future potential volatility in fertiliser and farmgate prices might impact both smallholders' and governmental budgets for relative low returns on investment. Potential income from extensive maize, at a steady rate of returns, may be two to three-fold that of intensive at cultivation ratios of 2:1 to 3:1 with an investment burden equally to that of ¼ ha intensive cultivation (S.M.5).

Our results strongly support the analysis of Lobell et al. (2009), Burke et al., (2017), Koussoubé and Nauges (2017) and Godfray et al. (2010) that the high costs of fertilisers and intensification may frequently undermine the potential economic gains of this strategy. In our case, the economic optimisation and highest profitability is clearly achieved with extensification, and not intensification. This provides a strong economic rationale for the prevalence, and recent exponential growth, of extensive low yield agriculture in SSA (Wise, 2020; Seijger et al., 2025; FAO, 2024). It also raises questions on the widespread prevalence of analysis on, and calls for, closing the yield gap in SSA rainfed agriculture through intensification and widespread application of subsidised fertilisers (re. new Green Revolution for Africa) (Toenniessen et al., 2008; Vercillo et al., 2020). The volatility of the climate is such, that good yields are only sparsely obtained (2 out of 9 seasons in our case) and frequently superseded by crop failure and poor yields (3 out of 9 seasons in our case) due to both too little or too much rainfall.[9] For poor households this constitutes a high economic risk; at high rates of investment (18–24% of annual income for ¼ ha) against poor rates of return compared to the extensification. As long as land is available for expansion, the economic risks and rationale will favour extensification over intensification. With the onset of climate change and increased climatic volatility (Franzke, 2022; Swain et al., 2018), the economic risks of production are only set to increase (Gatti et al., 2023) and further favour extensification. As long as this economic risk and rationale of volatile rainfed agriculture in SSA is not acknowledged and addressed in the discussions on yield gap analysis (Van Ittersum et al., 2016; Van Ittersum et al., 2013) and potential productivity gains in rainfed agriculture (Rockström et al., 2009; Molden, 2007), the realities on the ground (as evidenced by FAOSTAT) will show that increase in production stem from expansion of stagnating low yielding extensification, rather than increases in yield from intensification; and will continue to do so, as they have done for the past decades. To address the

[8] Average annual income of small-scale food producers is around 1 million Tzs. Eldridge et al. (2022) indicate 0.91 million Tsh while FAOSTAT data indicate an average of 534 USD (or 1.25 million Tsh) between 2009 and 2019, using exchange rate of September 2023 of 2338.51 Tsh/USD.

[9] Whereby the impact of too much rainfall (aeration stress) seems to be curiously overlooked and understudied in the assessments on rainfed yields.

plight of rainfed farming and farmers in SSA there is a need to focus on risk management, rather than yield gaps and productivity. The more so as these risks are set to increase with the onset of climate change.

Our simulations and agronomic and economic analysis have been limited to the cultivation of rainfed maize in Dodoma, Tanzania, for nine consecutive rain seasons from 2011/12 to 2019/20 which turned out to have a very volatile climate (both in terms of drought and excessive rainfall). This is limited in scope. Yet, our analysis underwrites and illustrates our hypothesis of climate and economic risk hedging the extensification strategy in rainfed agriculture in SSA provides for households. It provides a compelling rationale for the widespread prevalence and expansion of low yielding rainfed agriculture in SSA, as evidenced in FAOSTAT. However, it remains to be further tested and refined across other regions and rainfed crops. Cut-off ratios and rates of return may be expected to vary – with volatility of the climate, and with crop specific sensitivities to abiotic stresses. When such further assessments of "rainfed production risks" are conducted at scale (e.g. regional, (sub)continental), one may expect to be able to identify climate hotspots (where cut-off ratios are particularly low 1–2:1, indicating high risk and favouring extensification) and rainfed green spots (with cut-off ratios >5:1) that may prove more favourable for intensification. Allowing thus for a better targeting of rainfed risks and cultivation strategies. Combining this analysis with climate change scenarios for the future, may then provide insights in how the "rainfed production risks" may shift with climate change.

In agronomic terms, the climate hedging results of our simulated extensification strategy proved less than anticipated in terms of differences in water stress, harvest index and yield across the staggered extensive plots. Delayed germination, due to climatic conditions, "undid" the effect of staggered sowing to quite an extent. Our inability to capture and differentiate for micro-hydrological conditions across undulating terrains has led to fairly uniform soil moisture conditions across the staggered plots. With more detailed mapping and modelling of micro-hydrological variations in undulated terrain, the agronomic (stress, HI, yield) and economic effects (profits) of hedging will be expected to increase (wider spread across plots). But this remains to be tested and refined.

Our simulated yields are likely overestimations. Reported yields for rainfed maize in the region range from 1.2 to 1.5 t.ha^{-1} (Utonga, 2022), 1.7 t.ha^{-1} (Falconnier et al., 2023) to 2.6 t.ha^{-1} (Palmas and Chamberlin, 2020), whereas our simulations for extensive plots reach yields in the order of 3 t.ha^{-1}. This may have various reasons, ranging from choice of variety, sowing density, disease occurrence to variations of (micro) climatic conditions. In our simulations the extensive plots were simulated with the same variety as the intensive, at the same sowing density, free of any diseases, and only subjected to fertility stress and weed competition. We also acknowledge that maize has a wide crop genetic base (often expressed in national and regional specific developed varieties) that diverge in their varietal specific responses to environmental conditions and stresses. This may also explain how our modelling results may deviate from average or specific obtained yields in Dodoma (either over or under) for specific years. In practice, other factors may vary considerably. The intercropping of rainfed maize with nitrogen fixing legumes, for instance, is a widespread, and promoted, practice in eastern Africa (Namatsheve et al., 2020; Kiwia et al., 2019), that results in lower maize sowing densities and water competition between maize and legumes. In our simulations, the relative weed cover of 35% in extensive plots resulted in a 25% reduction in seasonal maize transpiration – eliminating weeds (and water competition) effectively increases maize yields by 25% (see table S.M.4–2 for details of non-weed infected simulations). The latter implies that it may be more favourable to promote the cultivation of legumes, as soil improvement crops, in rotation across staggered plots, rather than as an intercrop for rainfed maize that will compete for available water.

In the propagation of the closing of the Yield Gap and Green Revolution for Africa, emphasis has been placed on facilitating the widespread uptake of chemical fertilisers through subsidy schemes (Jayne and Rashid, 2013; Wise, 2020). In our economic analysis of the profitability of extensification v intensification in rainfed maize cultivation in Dodoma, Tanzania, we therefore differentiated the analysis for subsidised and unsubsidised, and 'cheap' and 'expensive', fertilisers. The subsidies primarily target the intensification strategy with its full application of recommended fertilisers. Whereas increasing the benefits and rates of return for intensive cultivation, the subsidies have hardly any impact on altering the 2:1 cut-off ratio at which extensive cultivation is more profitable than intensive – except for the 'cheap' (DAP + Urea) option under high and average farmgate prices that improves the cut-off ratio to 3:1 (see S.M.5). This raises questions on the economic effectiveness of such subsidy schemes in diminishing the economic risks and improving the economic position of rainfed farmers. Directing these subsidies towards the widespread uptake of weeding in extensive rainfed cultivation might be productively and economically more effective.

As we showed with our simulations and analysis, the economic rationale (in terms of risks, rates of return and production) favours the extensification of rainfed agriculture over intensification. This underscores its rapid expansion and prevalence in statistics on SSA agriculture (cf FAOSTAT), and the continuing failing to close the Yield Gap. The climatic volatility that governs rainfed agricultural production, and which is only set to increase with climate change, drives the risk aversion and management advantages of extensification. Continued failure to put (economic and production) risk management central to agricultural development and improvement programmes in SSA will continue to foster extensification over intensification. This, at the price of converting natural landscapes into agricultural fields. To stem this trend, economic risk management and production stabilisation may have to take precedence over yield maximisation for the future of rainfed agriculture in times of climate change.

5. Conclusions

Our indicative simulation of extensive v intensive rainfed maize cultivation strategies in Dodoma, Tanzania, over nine consecutive growing seasons was able to identify the agronomic and economic risks to which households in Tanzania are increasingly subdued with the onset of climate change and fertiliser price volatilities. By defining these risks in terms of cut-off ratios at which the extensive rainfed cultivation strategy outperforms the intensive cultivation strategy – both in terms of production as economic return – we were able to develop a risk focused assessment method that is replicable across different (rainfed cereal) crops, and across different agroclimatic regions. Our risk assessment for rainfed maize cultivation in Dodoma showed:

- The extensification strategy of low input, low yield, outperforms the intensification strategy of high input, "high" yield, by a cut-off ratio of 3:1 for yield and 2:1 for economic returns. This underscores the economic and risk management rationale for the prevalence and expansion of low input, low yield rainfed agriculture in SSA. Our assessment shows, there is no economic or agronomic rationale for poor household to invest in intensive rainfed agriculture to close the yield gap as long as they can expand their cultivation.
- Fertiliser subsidies, as applied in Tanzania, mitigate the economic losses for households, but hardly affect the cut-off ratio at which extensification outperforms the intensification strategy – both in terms of yield and economic returns.
- Subsidies may be more effectively directed towards supporting weeding in the extensification strategy, with a potential to increase yields by 25%.
- The climate risk hedging of staggered sowing of extensive plots is expected to be more effective when accounting for micro-hydrological conditions of undulating terrains. This requires follow-up research.

- Our method of agronomic and economic risk modelling in rainfed agriculture is potentially up-scalable at regional level and across crops. This may lead to: (i) identifying climate-risk hotspots – defined in cut-off ratios – across landscapes and across rainfed crops; and (ii) when combined with climate change scenarios, assess the potential shifts in agronomic and economic risks in rainfed agriculture (captured in changing cut-off ratios) due to climate change.

CRediT authorship contribution statement

Gerardo E. van Halsema: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Maria Christoforidou:** Writing – review & editing, Visualization, Software, Investigation, Data curation.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.104656.

Data availability

Data will be made available on request.

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