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Identifying yield and growing season precipitation gaps for maize and millet in Cameroon

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ABSTRACT

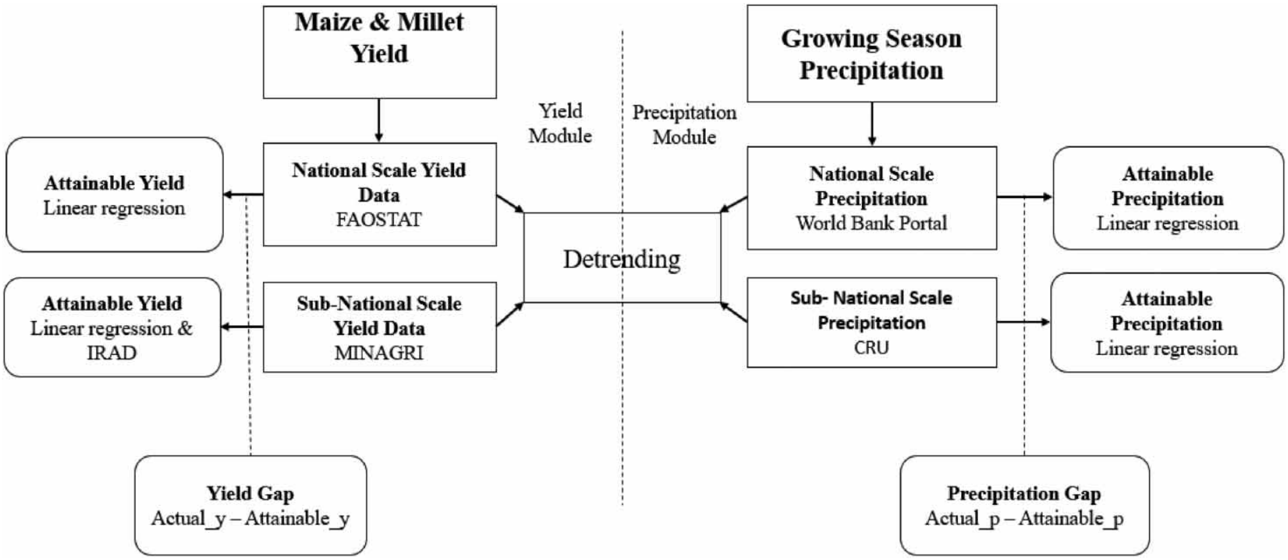
Climate change drives huge differences between the actual and projected yield and growing season precipitation. Therefore, this work identifies yield and precipitation gaps for maize and millet at the national and subnational scales as well as policy considerations for agricultural policy experts that can mitigate these gaps. Yield data for the national and subnational scale analyses were obtained for the period 1961–2021 from the FAOSTAT and the Ministry of Agriculture (MINAGRI)/IRAD of Cameroon, respectively. Growing season precipitation data for the national and subnational scales were collected from the World Bank climate change portal and the Climate Research Unit (CRU). Various machine learning algorithms were used to bias-adjust the data and to compute the potential yield and growing season precipitation from which the yield and precipitation gaps were computed. The results show a positive correlation between yield and precipitation gaps, with millet depicting the strongest correlation. The average yield gap for maize is 0.55 t/ha, higher than the average yield gap for millet that is 0.28 t/ha. Not all years with yield gaps are correlated with precipitation gaps. The average precipitation gap for maize is 108 mm/year, and it is higher than the 101 mm/year recorded for millet.

Key words: gaps, maize, millet, precipitation, yield, synergy

HIGHLIGHTS

- There is a positive correlation between yield and precipitation gaps.
- Millet depicts the strongest correlation.
- Not all years of yield gaps are correlated with precipitation gaps.
- Spatially, yield and precipitation gaps increase northwards.

GRAPHICAL ABSTRACT



INTRODUCTION

The veracity of climate change is unquestionable as global temperatures continue to rise while precipitation remains unreliable (Intergovernmental Panel on Climate Change (IPCC) 2022). Across Africa, the situation is daunting as the continent is more vulnerable to the effects of climate change despite its limited contribution to the global crisis (Epule *et al.* 2022). One such sector that is significantly affected due to its high level of vulnerability is agriculture (Mbuli *et al.* 2021). Therefore, to ensure food security by 2050 for a global population of over 9 billion, global food production needs to be increased by 70–100% (Dubois 2011). If concerted actions are not taken, global food production will decline by about 1% by 2050 (Bruinsma 2009). These global changes will continue to have more devastating effects in Africa as about 70% of all agricultural production is in the hands of small-scale farmers who are poorly adapted to climate change (Epule *et al.* 2021b). Moreover, the vulnerability of small-scale farmers to climate change has been attributed to factors such as their dependence on rain-fed agriculture, cultivating marginal areas, and their lack of access to technical or financial support that can enable them to invest in more climate-resilient agriculture (Donatti *et al.* 2018).

Another food security challenge across Africa is the absence of fit-for-purpose research that enhances our understanding of food security, yield, and precipitation gaps, among others (Benabdelouahab *et al.* 2021; Devkota 2022). It is essential to understand the relationship between actual and potential yield to be able to quantify what quantity of yield is required to close the yield gaps. Yield gap reflects the difference between actual and potential yield; it can be positive if the actual yield exceeds the potential yield and negative if the potential yield exceeds the actual yield (Epule *et al.* 2017a, 2017b). Also, it is crucial to understand the relationship between actual growing season precipitation and potential growing season precipitation to be able to identify the actions that can be put in place by farmers to adapt to these challenges (Razouk *et al.* 2018). Precipitation gap reflects the difference between actual and potential precipitation. It can be positive when actual precipitation exceeds potential precipitation (Epule *et al.* 2017a, 2017b).

Cameroon is no exception to the dynamics described above. Like most countries across Africa and sub-Saharan Africa (SSA), in particular, Cameroon continues to witness increasing temperatures and highly intensive and unreliable precipitation (IPCC 2022). In the last 35 years, SSA witnessed a 0.2–2.0° C increase in annual surface temperatures (Epule *et al.* 2017a). These changes have implications on the growing season precipitation of several crops as well as on the patterns of yield and precipitation gaps. In Cameroon, agricultural production is mainly driven by rain-fed systems. Huge precipitation gaps are likely to trigger yield gaps. Due to unreliable precipitation, the mean crop growing season precipitation is around 200 mm for maize and millet (Epule *et al.* 2021b). However, as we move from the south to the north, there is a precipitation gradient depicted by declining precipitation. Precipitation declines from about 3,000 mm annually in the southwestern part of Cameroon to about 2,000 mm in the western highlands to about 1,600 mm annually in the southeastern region. Northwards, it drops to about 500 mm annually (Epule *et al.* 2021c). Due to the stress imposed by droughts, the annual precipitation often exceeds the growing season precipitation as often the annual is not available for agriculture.

In Cameroon, unfortunately, the concepts of yield and precipitation gaps have not been sufficiently studied and explored at all by the scientific community. A few studies that come close to assessing yields focus on different dimensions, such as the vulnerability of maize, millet, and rice to growing season precipitation and socio-economic proxies of adaptation (Epule *et al.* 2021a). Yengoh & Ardö (2014) examined the potential for increasing crop yield and food production to grapple with food security challenges; yield response to climate change (Tingem *et al.* 2009); economic effects of climate change on yield (Molua 2007); the impacts of climate change on water use and productivity using the CROPWAT model (Molua & Lambi 2006); and the onset of the rainy season and crop yield (Laux *et al.* 2009). From the above review, previous research has focused on the effects of climate on yield, a dimension that includes the crop–water nexus; unfortunately, there are no studies that have focused exclusively on yield and precipitation gaps at both the national and subnational scales. Consequently, this study aims at responding to the question, what are the yield and precipitation gaps for maize and millet in Cameroon at the national and subnational scales? What agricultural policy options can be integrated into land use policy in Cameroon to close yield gaps? The hypothesis is that there is a strong correlation between yield and precipitation gaps in Cameroon. Findings from this study will likely have colossal agricultural policy implications because a better understanding of yield and precipitation gaps will enable stakeholders to be able to identify adaptation actions that are context specific in reducing the yield gaps. For example, if the difference between actual and projected maize and millet crop yield is determined, it becomes possible to find out how much water and/or nutrient management might be needed by farmers to close such gaps.

Finally, maize (*Zea mays*) was selected for this analysis because it is among the most widely cultivated crops in the world (maize, wheat, rice, soybeans, barley, and sorghum) and the most affordable and most widely grown in Africa and Cameroon (Epule *et al.* 2017a, 2017b, 2021c). In Cameroon, maize is a common staple food consumed as fermented dough, roasted, used as corn porridge, or converted into beer and is produced primarily (~90%) by small-scale farmers. Millet, on the other hand, was selected because it is gaining increasing importance as it is now replacing wheat and used for baking and other commercial consumption uses since the Ukrainian crisis. Also, it is among the crops that have historical data for the period covered by this analysis.

STUDY AREA

In 2019, the population of Cameroon was estimated at about 25 million (Yengoh 2012). It is situated between latitudes 1.7° N–13.8° N and longitudes 8.4° E–16.8° E (Yengoh 2012). It is bordered in the south by Equatorial Guinea, Gabon, and Congo; to the east by Central African Republic and Chad; to the north by Chad; and to the west by Nigeria. In Cameroon, agriculture is the main primary industry employing between 65 and 70% of the population. It accounts for about 52% of the GDP, about 45% to export earnings and 15% to public revenue (Yengoh 2012; Yengoh & Ardö 2014) (Figure 1). Agriculture in Cameroon is rainfall dependent and is essentially carried out by small-scale peasant farmers.

Cameroon has a humid forest agroecological zone, which is divided as follows: humid forest in the southern–central–eastern part of the country and a bi-modal precipitation; the western highland in the northwestern part of the country. In the north, the High Guinea Savana around the Adamawa Region and the Sudano-Sahelian region that stretches up to the Lake Chad region can be found (Figure 1). There is a decline in precipitation from the south to the north of the country. There are also occasional changes in the types of crops that are grown across the country (Yengoh 2012). The south generally supports the cultivation of tubers and some grains like maize, while in the north, the agroecological properties favour the cultivation of mostly grains/cereals. However, in Cameroon, maize is cultivated in both the south and north of the country, while millet is cultivated essentially in the north (Adamawa, north, and Far North regions). The most important zones of rice cultivation are the Western Highlands (northwest and western regions). In general, most of these crops are cultivated in the often dry and drought-stricken northern parts of the country.

METHODOLOGY

This study uses principally historical time series data for the period 1961–2021. These data comprise crop yield data for maize and millet (hg/ha) and growing season precipitation (mm) data for both crops for the same historical period. The crop yield data for maize and millet at a national scale were collected from FAOSTAT (FAO 2023) (https://www.fao.

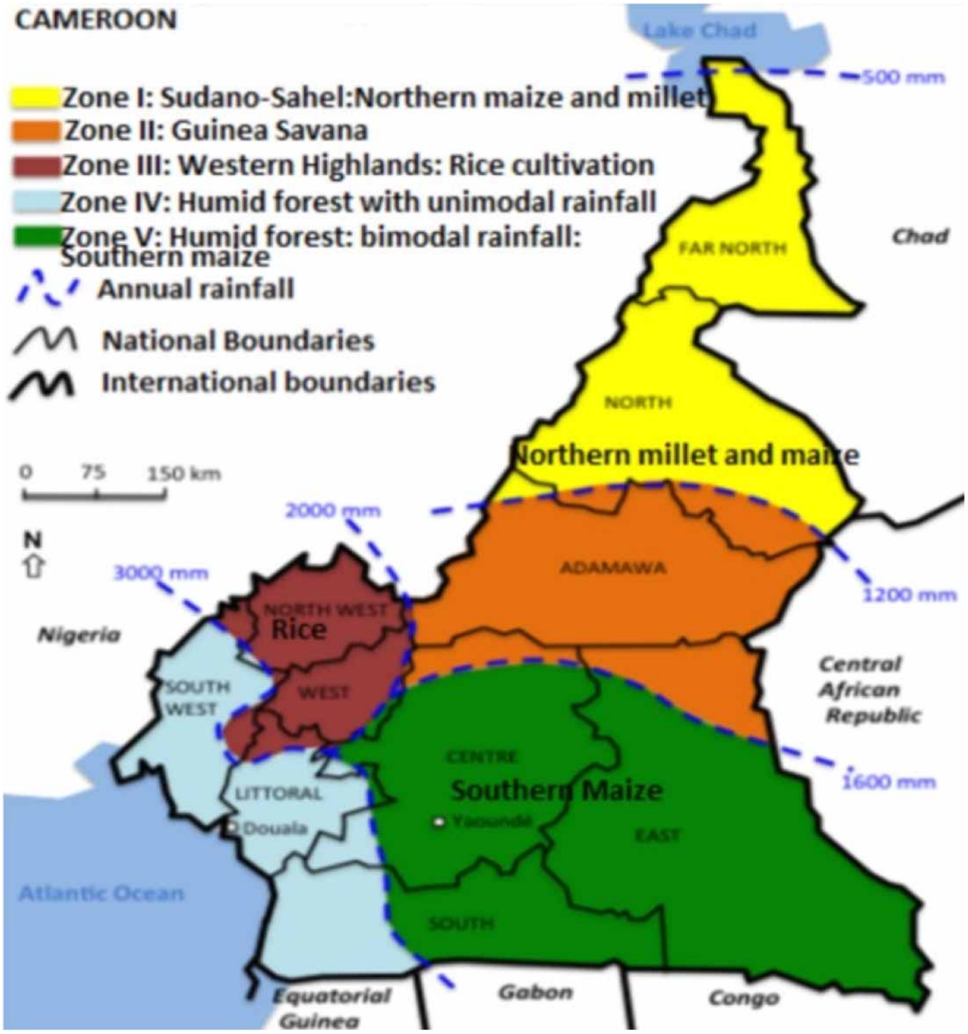


Figure 1 | Agroecological zones of Cameroon.

org/faostat/en/#home). The actual or observed yield data for the spatial variations in maize and millet production were obtained from the Ministry of Agriculture and Rural Development (MINAGRI 2022). The corresponding potential or attainable crop yield data were obtained from the Institute of Agricultural Research and Development (IRAD 2022) (https://irad.cm/index.php/en/). IRAD has five major centres across Cameroon as follows: Wakwa for the Adamaoua Region, Bambui for the northwest region, Ekona for the southwest region, Mbalmayo for the central region, and Maroua for the far north region. The time series of precipitation data at both national and subnational scales were generated from the World Bank Group Climate Change Portal (World Bank Group 2023) at a spatial resolution of $0.5 \times 0.5°$ (50 km $\times$ 50 km) (https://climateknowledgeportal.worldbank.org/download-data) and Climate Research Unit (CRU 2023) (https://crudata.uea.ac.uk) at a spatial resolution of $0.5 \times 0.5°$ (50 km $\times$ 50 km). From here, the growing season precipitation data were carved out based on the crop calendars for maize and millet (Figure 2). Table 1 shows the various data types used in this study and their sources.

The data were averaged over the maize and millet growing months for the $5' \times 5'$ grid for Cameroon from the global crop calendar dataset (Sacks *et al.* 2010). To adequately analyse the data, we focused on the growing season precipitation of each crop as proposed by crop calendars (Figure 2) (Sacks *et al.* 2010). The crop yield and growing season precipitation data were further subjected to bias correction by detrending. The latter process helped remove the effects of a linear model of the time series of observed yield and growing season precipitation by dividing the projected linear trend by the actual linear trend. Detrending removes the effects of technology, highlights the annual yield variations caused by precipitation, and reduces

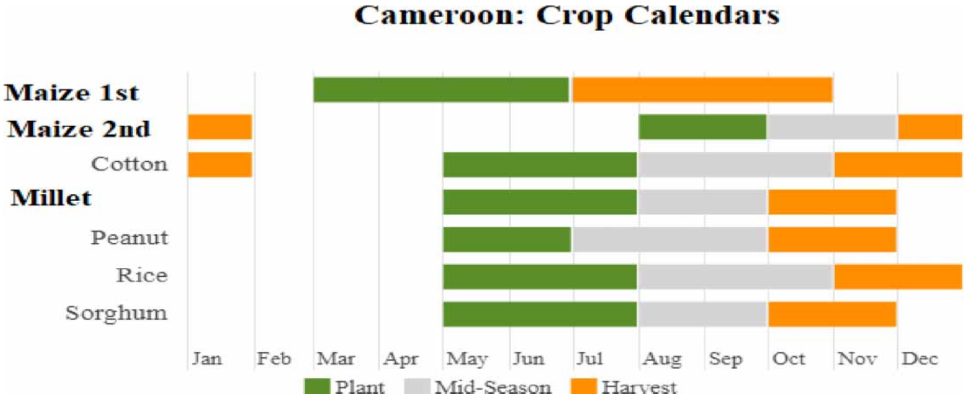


Figure 2 | Crop calendars in Cameroon.

Table 1 | Data and sources

Crop yield data	**Source**
National scale actual crop yield dataset for maize and millet	FAOSTAT: https://www.fao.org/faostat/en/#home
Subnational scale actual crop yield dataset for maize and millet	MINAGRI: Ministry of Agriculture and Rural Development
National and subnational potential crop yield dataset for maize and millet	IRAD: https://irad.cm/index.php/en/
Precipitation data	**Source**
National scale growing season precipitation data	World Bank Group: https://climateknowledgeportal.worldbank.org/download-data
Subnational scale growing season precipitation data	Climate Research Unit (CRU): https://crudata.uea.ac.uk

the bias introduced by consistent errors in reporting (Lu *et al.* 2017). Equations (1) and (2) were used in detrending the datasets (Figure 3).

$$\text{ProjDetrend}_Y = ax + b \tag{1}$$

where ProjDtrend_Y is the dependent variable or yield for maize and millet yields, x is the explanatory variable, a is the linear trend, and b is the intercept.

$$\text{ProjDetrend}_p = ax + b \tag{2}$$

where ProjDtrend_p is the dependent growing season precipitation variable for maize and millet, x is the explanatory variable, a is the linear trend, and b is the intercept.

At the national scale, yield and precipitation gaps were determined by first computing the simulated/potential or attainable yield and growing season precipitation. Actual yield or growing season precipitation represents the observed yield and growing season precipitation. The simulated/potential or attainable yield or growing season precipitation is the hypothetical or theoretical yield and growing season precipitation recorded when optimal conditions are in place. Once the potential or attainable yield and growing season precipitation were determined (Equations (3)–(7)), computing yield and growing season precipitation gaps were now determined by subtracting the simulated/attainable/potential yield and growing season precipitation from the actual observed yield and growing season precipitation (Equations (8) and (9)). For the subnational scale, the potential yield data were predetermined from experimental farms operated by IRAD across Cameroon. The

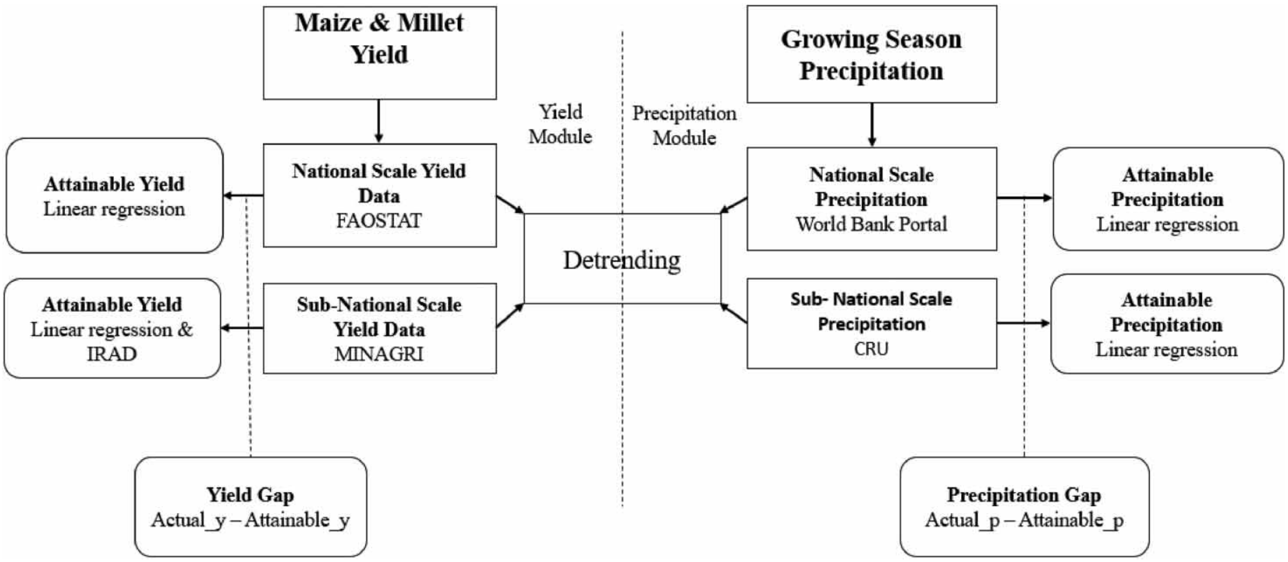


Figure 3 | Schematic of the methodology.

latter were subtracted from the actual yield data obtained from MINAGRI (Figure 3).

$$\text{Projected}_{\text{ymaize}} = 258.56x + 7,144.4 \tag{3}$$

where $\text{Projected}_{\text{ymaize}}$ is the projected/simulated maize yield, x is the year, 258.56 is the linear trend/slope, and 7,144.4 is the intercept.

$$\text{Projected}_{\text{ymillet}} = 122.8x + 6,146.8 \tag{4}$$

where $\text{Projected}_{\text{ymillet}}$ is the projected/simulated millet yield, x is the year, 122.8 is the linear trend/slope, and 6,146.8 is the intercept.

$$\text{Projected}_{\text{pmaize}} = -0.5274x + 875.76 \tag{5}$$

where $\text{Projected}_{\text{pmaize}}$ is the projected/simulated maize growing season precipitation, x is the year, -0.5274 is the linear trend/slope, and 875.76 is the intercept.

$$\text{Projected}_{\text{pmillet}} = -0.8614x + 943.92 \tag{6}$$

where $\text{Projected}_{\text{pmillet}}$ is the projected/simulated millet growing season precipitation, x is the year, -0.8614 is the linear trend/slope, and 943.92 is the intercept.

$$Y_{ik} = (\Sigma_{J=1}^{n} ykj)/n \times aik \tag{7}$$

where Y_{ik} denotes the potential yield of crop k in country i, ykj denotes the test yield of cultivar j of crop k in country i each year, aik represents the planting acreage of crop k in country i, and n is the number of cultivars currently grown in country i.

$$\text{Yield}_{\text{gaps\_ys}} = \text{Actual}_y - \text{Potential}_y \tag{8}$$

where $\text{Yield}_{\text{gaps\_ys}}$ represents yield gaps or surplus.

$$P_{\text{gaps\_s}} = \text{Actual}_p - \text{Potential}_p \quad (9)$$

where $P_{\text{gaps\_s}}$ represents precipitation gaps or surplus.

To be able to compare yield and precipitation gaps, the data were normalised since these indicators are in different scales. Normalisation is crucial when dealing with data that are in different scales. The outputs of normalisation are often within the range of 0–1, and this pertinent process makes it easy to compare data that do not have the same scale and are not comparable. To perform this, identifying the minimum and maximum values is critical. Equation (10) was used to normalise the time series data (Figure 3).

$$Y_{\text{pt}} = (x_{\text{pt}} - \text{min})/(\text{max} - \text{min}) \quad (10)$$

where Y_{pt} is the normalised output of precipitation, x_{pt} is the average regional precipitation data to be normalised, and max and min are the maxima and minimum average growing season precipitation data of the time series, respectively.

RESULTS

Actual versus simulated crop yields

These results have shown a generally positive relationship between actual/observed and simulated/potential maize and millet yields in Cameroon. However, slight variations in intensity do exist between the two crops. For example, between 1961 and 2021, simulated maize yields have increased consistently from below 10,000 to above 20,000 hg/ha. Parallel to this, actual or observed maize yields have increased in a cyclical and variable fashion (Figure 4(a)). An interesting observation is that simulated maize yield exceeds actual maize yield for most of the years with the exceptions of 1961, 1975, 1984–1991, and 1996–2011 (Figure 4(a)). In the case of millet, simulated yield has increased from slightly below 6,000 to above 12,000 hg/ha. In parallel, actual millet yields have also increased in a variable and cyclical fashion (Figure 4(b)). Even though the simulated millet yield exceeded the actual millet yield for most of the years, the reverse was the case as observed during the years 1961–1967, 1969, 1974–1975, 1985–1986, 1988, 1989, 1990, 1991, 1993, 2005–2008, and 2011–2019 (Figure 4(b)). Therefore, we can say that for both crops, the actual or observed yields are increasing in a variable and cyclical fashion but remain below the projected yield.

As shown in Figure 4(a) and 4(b), both crops have witnessed increasing observed yield over time, though cyclical and variable in principle. In addition, both maize and millet have recorded positive and high coefficients of determination (R^2), with the R^2 of millet being slightly higher than that for maize. The R^2 for maize is 0.61 or 61.0% (Figure 5(a)), while that for millet is 0.71 or 71.0% (Figure 5(b)). These R^2s depict the relationship between the observed and simulated yield for maize and millet. The R^2 of 0.61 for maize shows that in the linear relationship between observed and simulated or potential maize, 61.0% of the changes in simulated maize yield can be explained by changes in observed maize (Figure 5(a)). In the same way, the R^2 of 71.0% for millet shows that 71.0% of the changes in simulated millet can be explained by changes in observed millet yield (Figure 5(b)).

Maize and millet yield gaps

In terms of yield gaps for maize and millet, this work has found that specific periods are outstanding. In the case of maize yields, for example, three critical periods with yield gaps were observed, including a total of 35 years on a possible 60 years. More than 50% of the years during which maize was grown experienced yield gaps. The first period was from 1962 to 1983, the second from 1992 to 1995, and the third from 2012 to 2021 (Figure 6(a)). In the case of millet, two critical periods with yield gaps were observed with a total of 29 years on a possible 60 years. About 50% of the years during which millet was grown experienced yield gaps. The first period was from 1968 to 1984, and the second was from 1994 to 2003. Other independent years with yield gaps include 1987, 2009, and 2010 (Figure 6(b)). An interesting finding here is that most years with yield gaps for maize seem to overlap with the years of millet yield gaps. For example, the first period of maize yield gaps is 1962–1983; this coincides with the first period of millet yield gaps, which is 1968–1984. Also, some of the years during the second period of maize yield gaps (1992–1996) overlap with some of the years of millet yield gaps (1994–1984) (Figure 6(a) and 6(b)). The average yield gap for maize of 0.55 t/ha is higher than the average yield gaps for millet that is 0.28 t/ha.

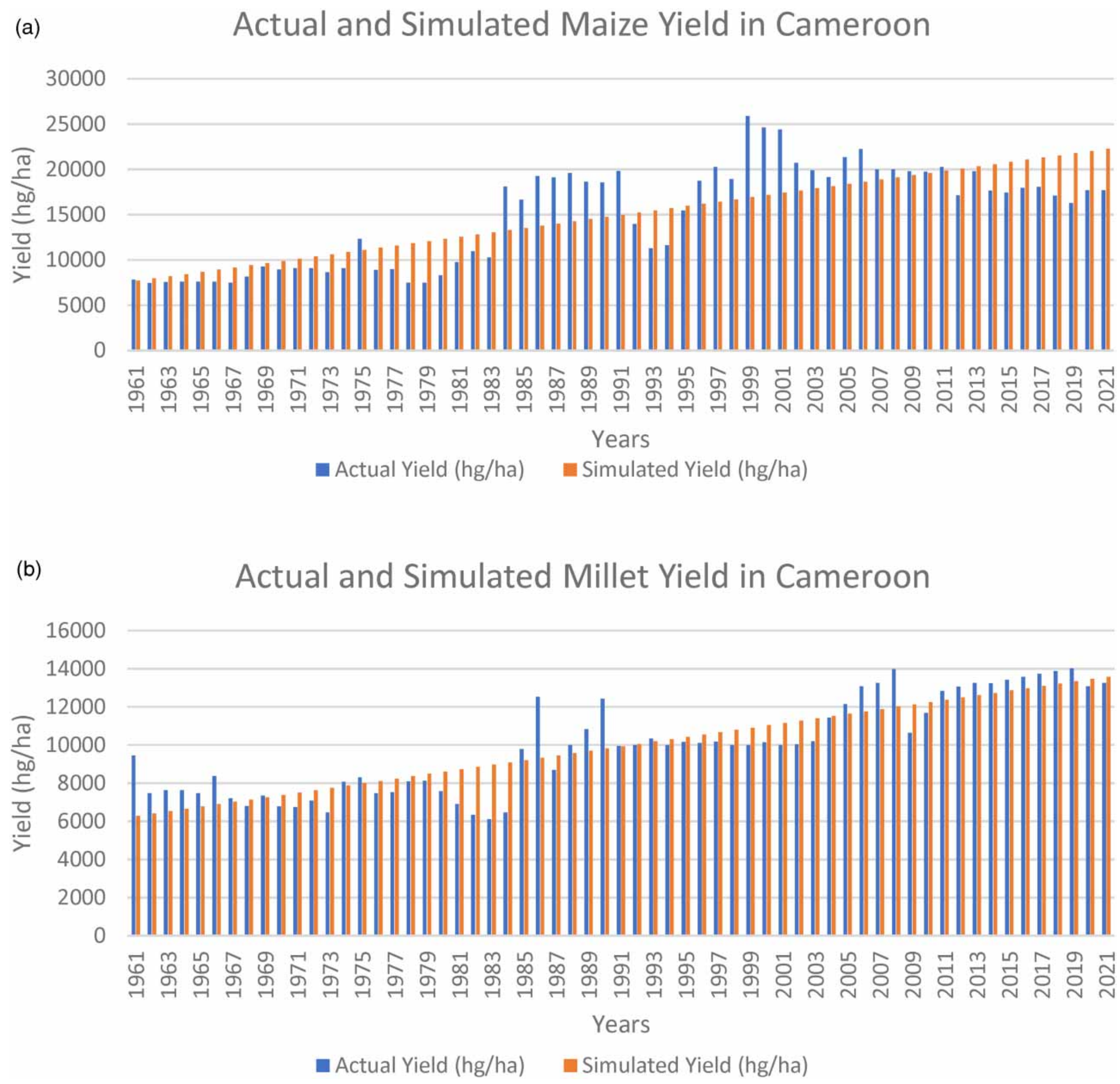


Figure 4 | Actual and simulated yield: (a) maize and (b) millet.

Actual versus simulated growing season precipitation

In terms of the growing season precipitation for maize and millet, this work has found that the evolution is similar for both maize and millet. It was observed that simulated maize growing season precipitation has declined slowly from 873 to 841 mm, as depicted by the time series data (Figure 7(a)). This declining trend is maintained in the case of millet, with growing season precipitation decreasing from 943 to 891 mm during the same time series (Figure 7(b)). When we consider actual observed growing season precipitation, we observe similar patterns for both crops as they are highly variable and cyclical; implying the changes in growing season precipitation for both maize and millet continue to rise and decline in continuous cycles, variations that herald the notion of stress and instability. Since these rising cycles have been observed for a long period of over 60 years (1961–2021), one can easily conclude that climate change has its mark in the study sites through rising and declining growing season precipitation. In a nutshell, a total of 29 years of the data series witnessed scenarios with actual maize growing season precipitation exceeding simulated maize growing season precipitation, while a total of 30 years during the series witnessed actual millet growing season precipitation exceeding simulated growing precipitation. This implies that about 50% of the years experienced scenarios in which actual growing season precipitation exceeded simulated growing season precipitation for both crops. It can be observed that precipitation in Cameroon is very variable, making it difficult to identify the break-even point. However, an analysis of the historical data shows that low levels of precipitation

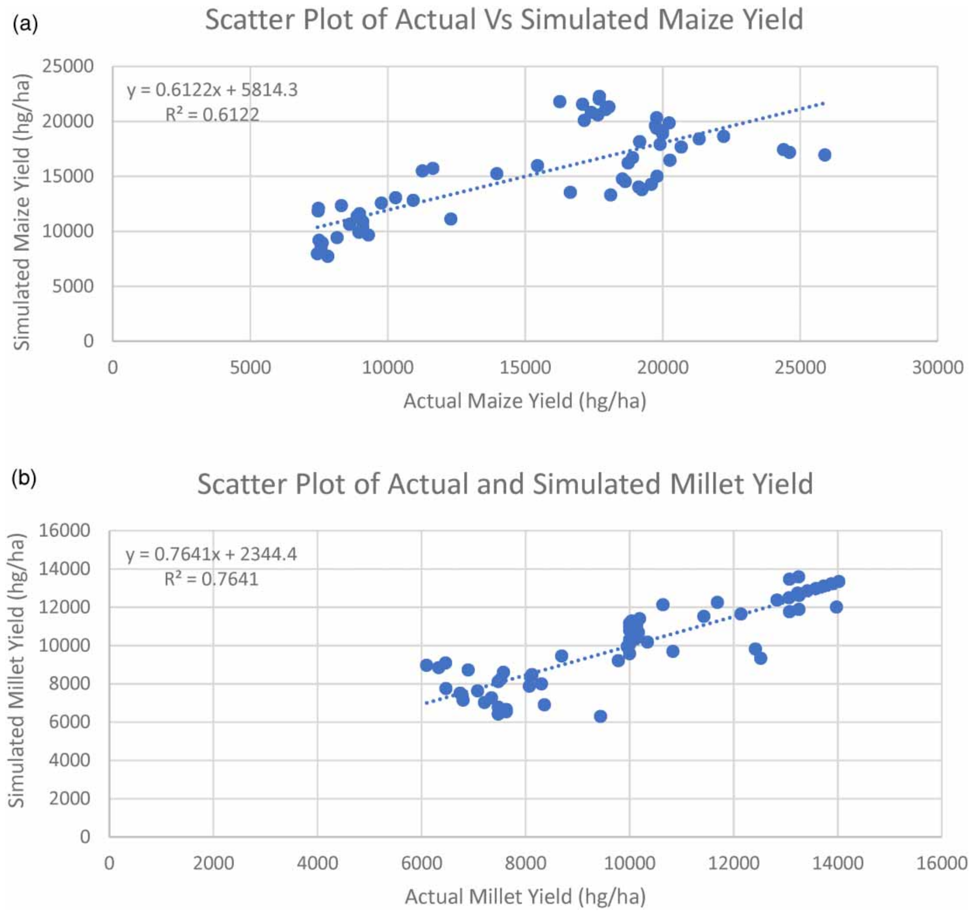


Figure 5 | Scatter plots of actual and simulated yield: (a) maize and (b) millet.

were recorded between 1975 and 1985 during which the region was impacted by droughts. After 1985, there was a recovery as the precipitation levels in the region have increased and the region has become greener.

Growing season precipitation gaps

Unlike yield gaps, growing season precipitation gaps are not clustered into groups of periods with gaps and others without gaps. Most of the years of growing season precipitation gaps are spread or scattered all through the data series. In general, maize records 23 years with growing season precipitation gaps, while millet records 24 years with growing season precipitation gaps (Figure 8(a) and 8(b)). Even though growing season precipitation is generally cyclical in its trend, growing season precipitation gaps do not follow the same pattern because years or periods of declining cycles in growing season precipitation do not necessarily trigger growing season precipitation gaps. The spread in the growing season precipitation gaps for both crops heralds the notions of moisture stress and the colossal uncertainty associated with precipitation in the study site. The average precipitation gap for maize is 108 mm/year, and it is higher than 101 mm/year for millet.

Yield and precipitation gaps

When yield gaps are interpolated with growing season precipitation gaps for maize, we find that precipitation gaps witness less change when compared to the yield gaps for maize. The most significant change in precipitation gaps that reduced the gaps were recorded during a recovery period between 1961 and 1962 and in 1969 (Figure 9(a)). Negative changes that reinforce the yield gaps were recorded in 1963, 1964, 2005, 2009, 2011, and 2013. In terms of yield gaps, five significant periods with maximum changes were recorded (Figure 9(a)). In terms of millet, the changes in yield and growing season precipitation gaps are remarkably consistent as the yield gaps match the precipitation gaps; this is unlike the case of maize where

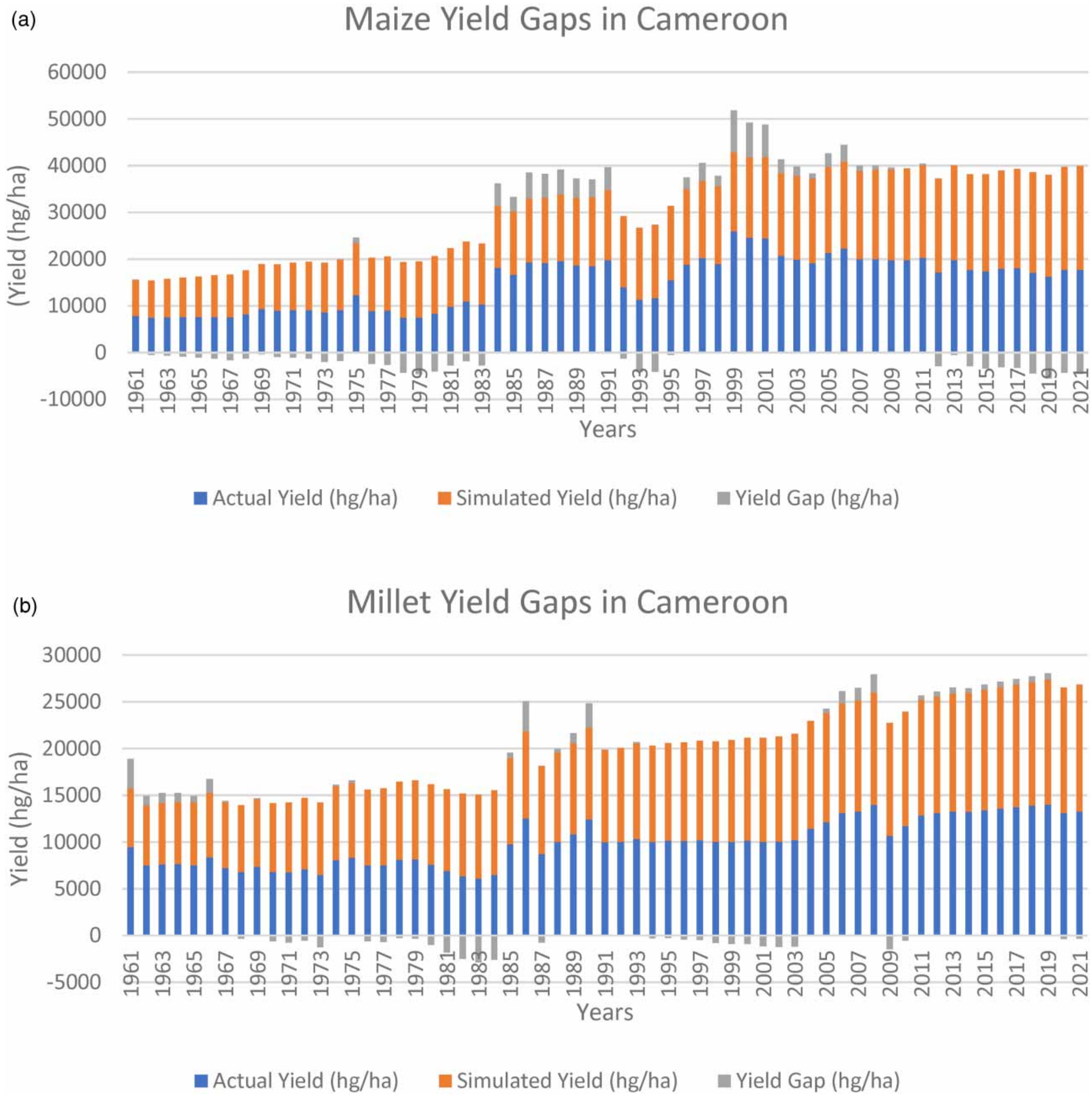


Figure 6 | Yield gaps in Cameroon: (a) maize and (b) millet.

maize yield gaps were not consistent with maize growing season precipitation gaps (Figure 9(b)). Therefore, we can say that millet is more tied to growing season precipitation than maize.

Yield and growing season precipitation gaps are seen to vary across Cameroon. In terms of maize yield, a north–south gradient seems to exist in this variation. This is evident as maize yields recorded very low gaps in the south and increased progressively northwards. This gradient can be accounted for by the changes in precipitation, which also reduced northwards in Cameroon. In terms of millet yield gaps, three key major gap zones are observed. We have the southern Cameroon plateau extending to the western highlands, together with parts of the north and far north regions. Typically, the southern Cameroon plateau and the western highlands are not the best lands traditionally cultivating millet (Figure 9). Due to biophysical conditions, millet is more favoured by the conditions in the northern parts of the country. However, the north and far north of the country are facing increasing climate stress due to unreliable growing season precipitation. In terms of precipitation gaps, a similar gradient is observed. For most of the growing season months for maize and millet, the gaps are lower in the south and higher towards the country's north. Invariably, as we transition from the south to the north, temperatures become incredibly high, precipitation is more erratic and unreliable, and when it comes, it is highly intense and does not come during the growing season of the crops (Figure 10). From these results, we have observed that there are several

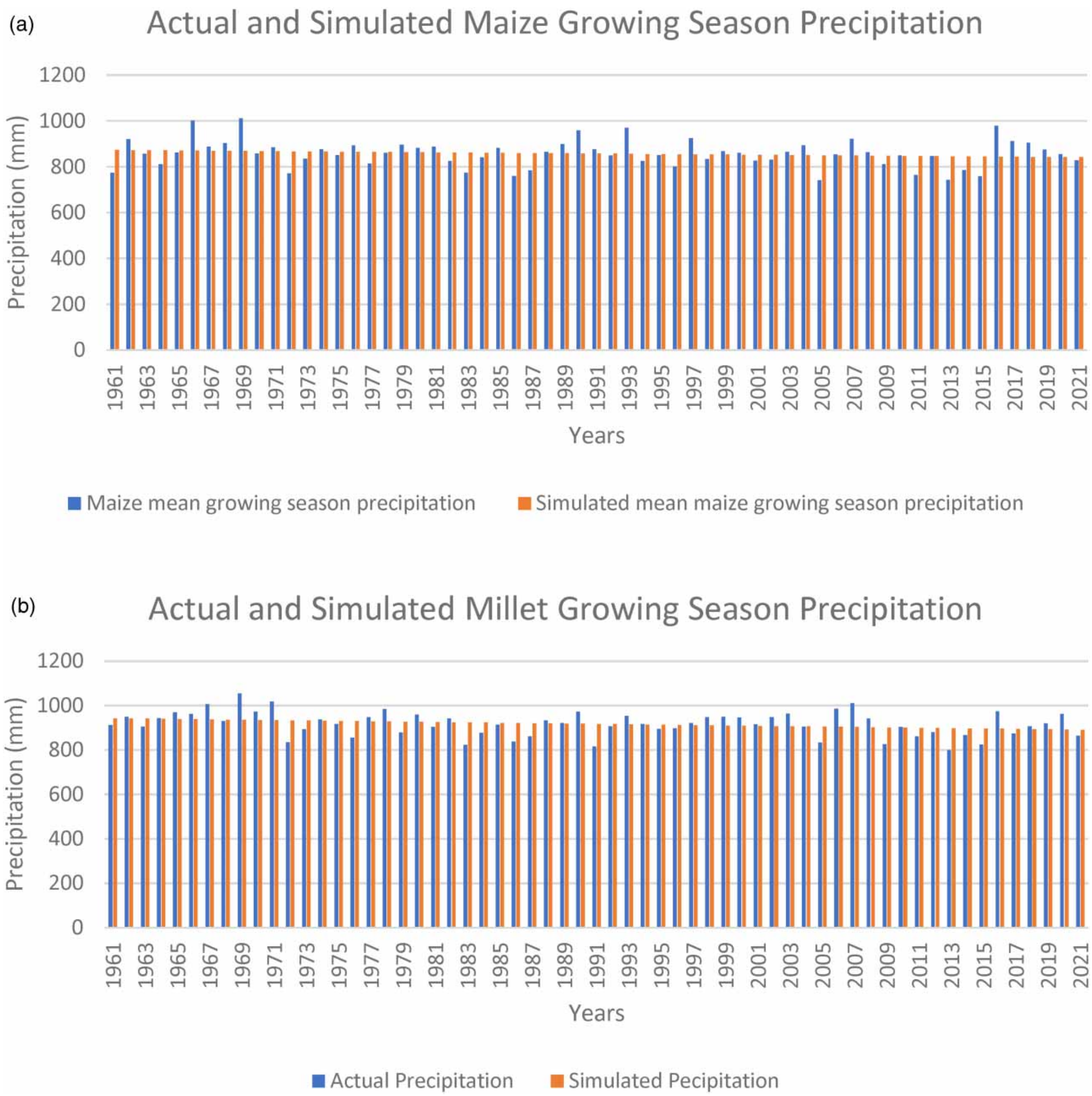


Figure 7 | Actual and simulated growing season precipitation: (a) maize and (b) millet.

years of yield gaps that equally recorded precipitation gaps. However, not all years that recorded yield gaps recorded precipitation gaps. This implies that yield gaps are not only explained by precipitations gap. We can therefore state that the hypothesis that yield and precipitation gaps have a strong correlation is partly true but not entirely as such a conclusion requires further verification by assessing the contribution of other potential drivers of yield gaps such as soil, fertilisers, irrigation, pest, and diseases, inter alia (Figure 11).

Scatter plots of the correlation and coefficient of determination between growing season precipitation and crop yield for maize and millet show contrasting results that are however consistent with the yield gaps. Maize that recorded the highest yield gaps has a correlation of −0.32, which depicts a weak inverse relationship between maize yield and maize growing season precipitation. This is evidently tied to the fact that maize is a crop that requires much water through precipitation for its growth (Figure 11 and Figure 12). The corresponding coefficient of determination for that relationship is about 10% implying that only about 10% of the changes in maize yield can be explained by changes in growing season precipitation. On the other hand, millet records a correlation of 0.61, which is average and positive and thus implying that millet yield increase with increase in growing season precipitation. The corresponding coefficient of determination is about 37%,

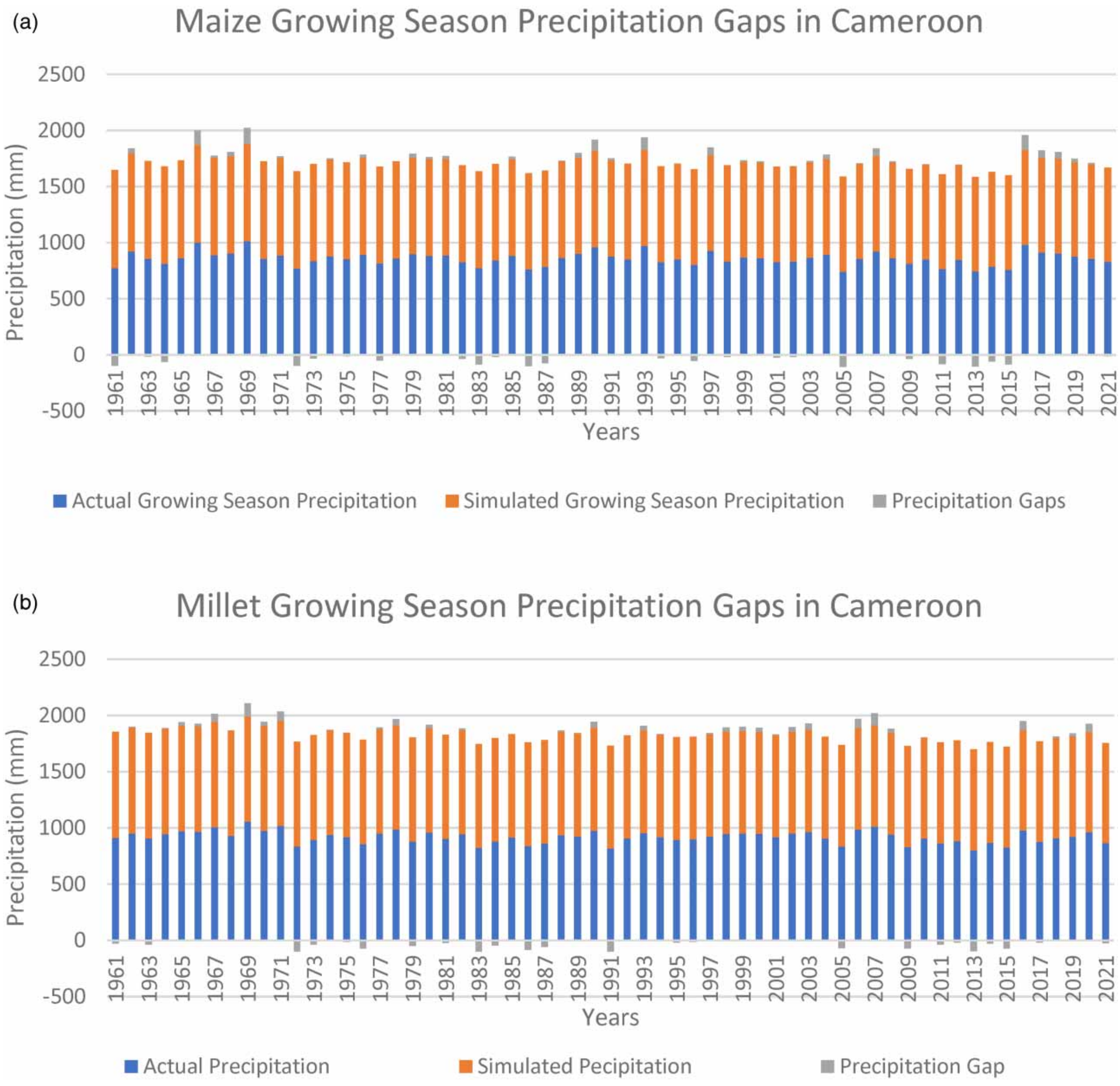


Figure 8 | Growing season precipitation gaps in Cameroon: (a) maize growing season and (b) millet growing season.

much higher than that of maize, implying that about 37% of the changes in millet yields can be explained by changes in growing season precipitation.

DISCUSSION

This study has shown that Cameroon, like most other SSA countries, is currently witnessing the impacts of climate change on its agricultural sector. To support this view, our findings have shown that most years with yield gaps for maize and millet equally have precipitation gaps. The intensity of the latter observation varies between the two crops as millet showed a stronger correlation between yield and precipitation gaps as both gaps replicated themselves. This strong association between yield and precipitation is a common phenomenon across Africa, where agriculture is essentially precipitation-based (Parry *et al.* 2004; Challinor *et al.* 2008). Spatially, there is a considerable decline in moisture availability for agriculture as we move from the south to the north of the country mainly due to reduced precipitation and increased incidence of climate shocks such as droughts (Figure 11). In fact, the severity of the yield gaps identified at both scales in this study shows that in terms of precipitation, production is mainly carried out under sub-optimal conditions of water stress (Yengoh 2012; Harahagazwe *et al.* 2018).

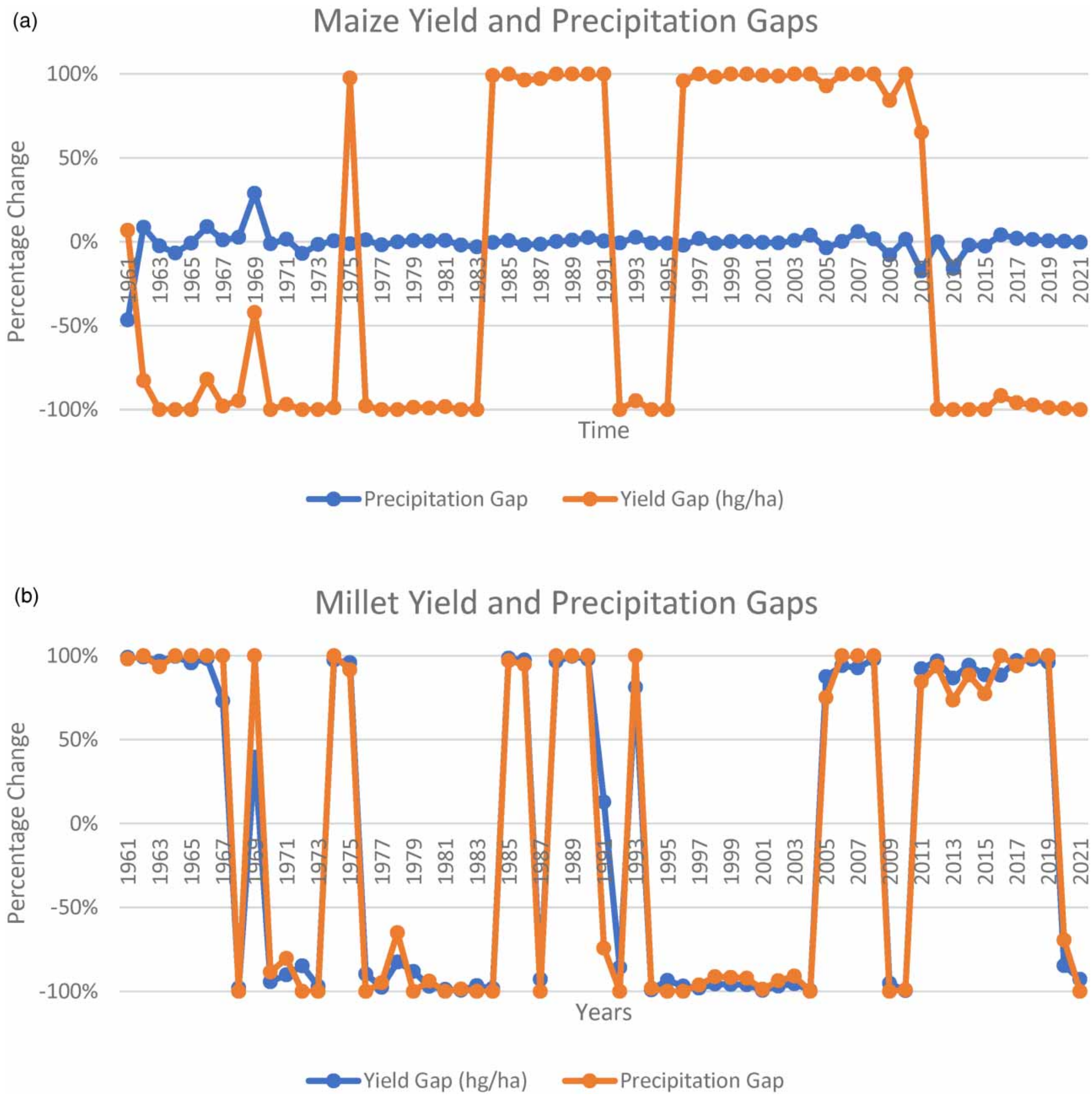


Figure 9 | Yield and growing season precipitation gaps in Cameroon: (a) maize and (b) millet.

Maize yield records an inverse correlation with growing season precipitation, while millet records a positive correlation with growing season precipitation. The coefficients of determination for both crops are consistent. Traditionally, maize has a heavy water use requirement when compared to millet, and it is likely to get into stress during water-scarce conditions (Singh & Singh 1995). Singh & Singh (1995) showed that in an experiment involving sorghum, maize, and millet, maize consumed water more than the other crops and was more likely to be stressed under conditions of water scarcity. In addition, Muchow (1989) showed that the productivity of maize reduced relative to millet and sorghum in a semi-arid and tropical condition of water stress.

There are several other examples of findings across Africa that are consistent with this study. For example, this work found that yield gaps correlate strongly with precipitation gaps in Cameroon and that when we move from the south to the north of Cameroon, yield and precipitation gaps become more alarming. Similar findings have been obtained in Uganda, where it was found that crop yield vulnerability for maize increased towards the north of the country mainly due to unreliable precipitation (Epule *et al.* 2017a). Similarly, projections of future maize yield vulnerability in Uganda further depict the increasing vulnerability of maize with every extra degree of warming (1.5°, 2°, and 2.5°) towards the north (Epule *et al.* 2017b). Furthermore, like in Cameroon, a previous study found that maize yields did not only record persistent yield gaps but were also highly correlated to precipitation gaps. However, not all years of maize yield gaps were correlated to precipitation gaps. This implies

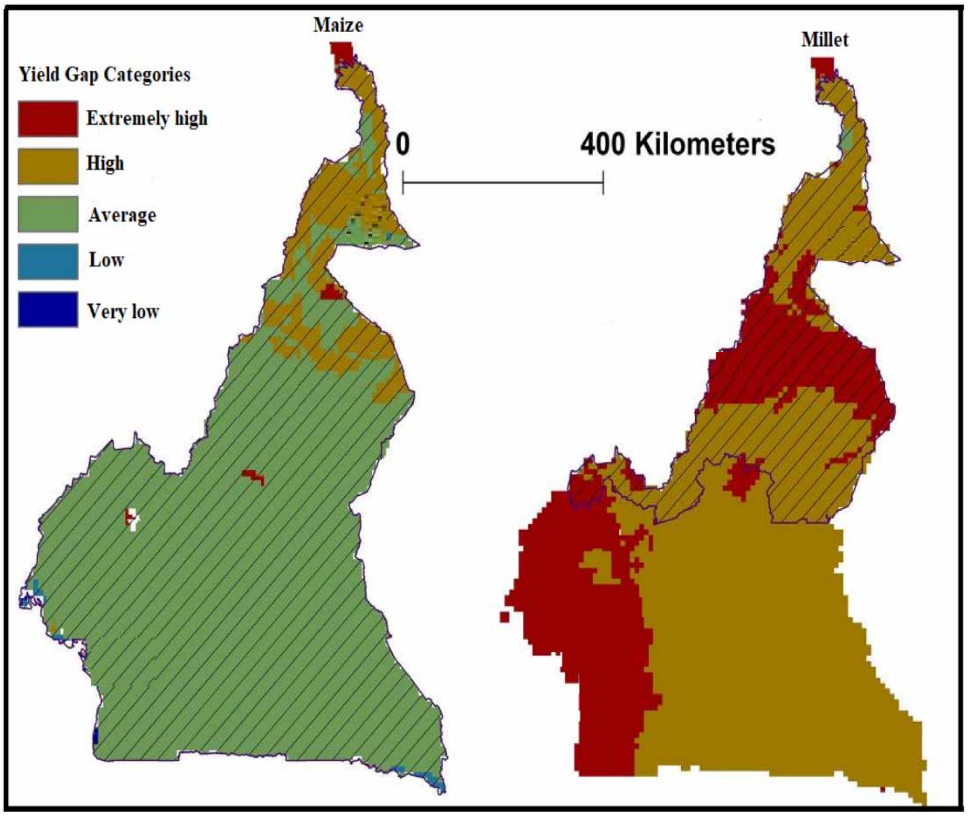


Figure 10 | Spatial variations in yield gaps for maize and millet in Cameroon.

that in the case of Cameroon and Uganda, maize production is complex and driven by several drivers (Epule *et al.* 2021c). A similar study in Morocco found that maize, barley, and wheat had strong correlations with precipitation gaps. However, spatially, and unlike in SSA (Cameroon and Uganda), the yield and precipitation gaps for these crops increased towards the south and reduced towards the north of the country, a phenomenon accounted for by the Sahelian effect in the south that triggers droughts and irregular precipitation and the Mediterranean and Atlantic effects in the north that trigger wetter conditions (Epule *et al.* 2022).

With these findings, land use policymakers might have vital information to consider when leveraging development policies. Four key land use policy stakeholders stand to benefit from these results. They are farmers, researchers, extension workers, and land use policymakers at different levels ranging from local to national. One of the ways through which this work can leverage the benefits of land use is through the integration of co-construction in the latter. In addition to benefiting from the finding that crop yield gaps are mostly correlated to precipitation gaps, policymakers who are responsible for planning land use may want to discuss these findings with other stakeholders and digest their personal preferences in terms of options required to create greater resilience of maize and millet cropping systems (Figure 13). This co-construction approach calls for including all stakeholders in the design, implementation, and evaluation of agricultural land use policies. As such, it will invariably enhance the level of acceptability of agricultural land use policies because all the stakeholders, especially small-scale farmers, are included in the policy-making process (Gourmelon *et al.* 2013). Therefore, any actions to build resilience and reduce yield gaps should focus on a participatory approach geared towards enhancing acceptability through the cross-fertilisation of knowledge and technologies. Studies have shown that this lack of acceptability and other socio-economic variables play a more critical role in driving environmental outcomes even more than climatic drivers. In most SSA countries, for example, the problem of persistent food security has just been made worse by the impacts of climate change. Moreover, non-climatic drivers now play a crucial role in food insecurity and are being amplified by systems of land tenure such as shifting cultivation and slash-and-burn cultivation (Kamga *et al.* 2022). To address this problem, therefore, a major recourse is to integrate populations' perceptions through co-construction and participative approaches (Figure 13).

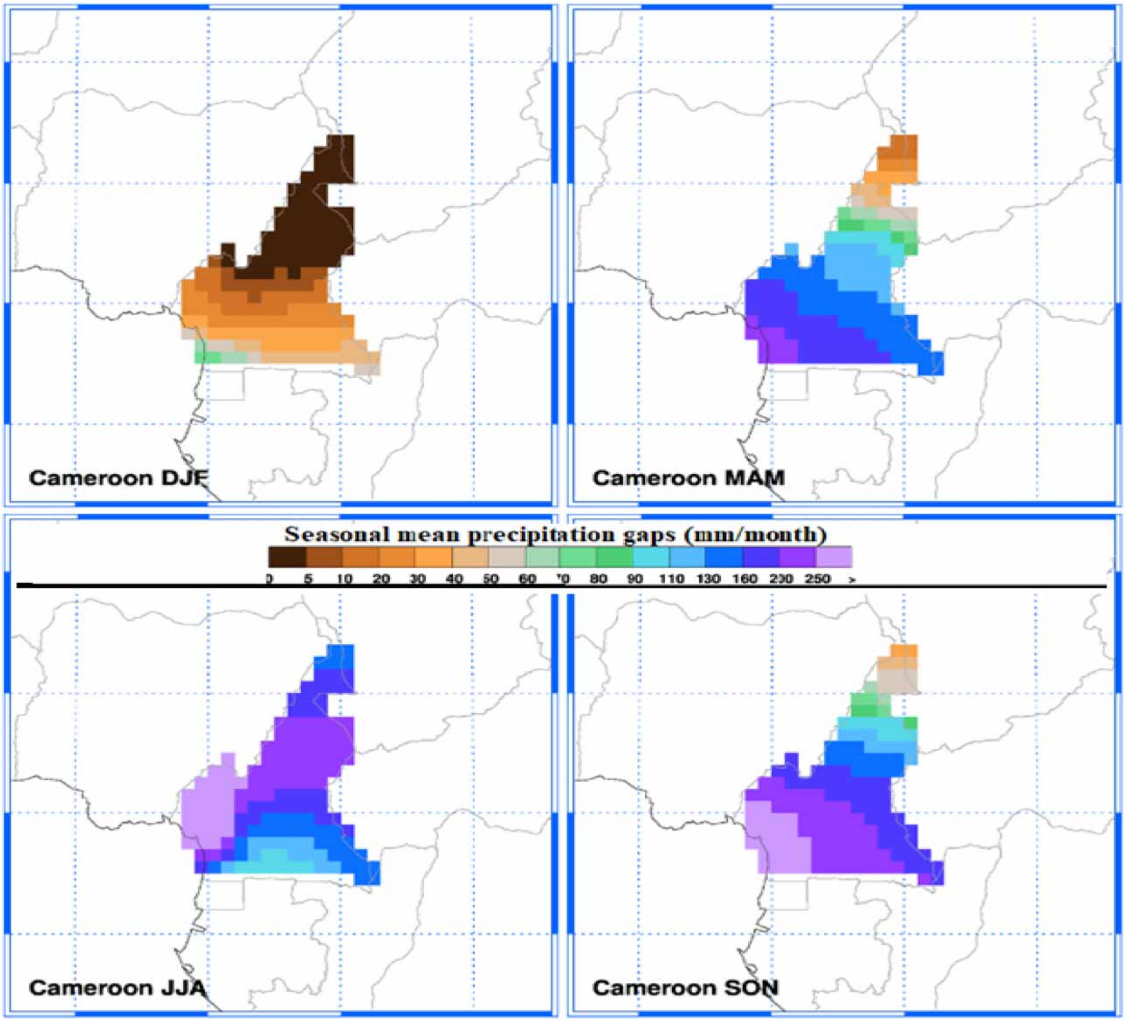


Figure 11 | Spatial variations in monthly precipitation gaps for maize and millet growing seasons in Cameroon.

In addition, apart from the socio-economic dimensions above through co-construction, it is essential to also focus further research and land use policies on how permutations of soil inputs can help close yield gaps. As mentioned already, across Africa in general and Cameroon in particular, some of the standard practices that damage the soil are shifting cultivation and slash-and-burn farming. These methods of farming may create more land for cultivation in the short term but, in most cases, lead to deforestation as well as destroy soil microbes as is with slash-and-burn cultivation (Tabi *et al.* 2013). To address this old ethic, a key area of land use policy action will be to use nutrient and water management practices through irrigation and fertilisation to restore the lost soil inputs. Unfortunately, land use policymakers cannot make this decision on their own as often it is unclear what quantities of nutrients and water should be added to the soils (Figure 13). Here, a synergy between land use policy experts, researchers, extension workers, and farmers will be helpful as the researchers can determine what combinations of nutrients and water are needed for a given group based on a given yield gap. Therefore, an essential aspect of potential future research will be to investigate how yield gaps can be closed through nutrient and water management (Figure 13). The synergy between researchers, agricultural policy experts, extension workers, and farmers is essential because it provides room for robust agricultural policy decision-making as well as information transfer as the researchers can be available to transfer the knowledge to all stakeholders (Lambin *et al.* 2014).

Finally, to grapple with yield and precipitation gaps and create resilience in agricultural systems, the systems thinking approach must be incorporated into developing agricultural policies. This implies that for a complete solution to be determined and implemented from an agricultural policy perspective, stakeholders (farmers, researchers, agricultural policy

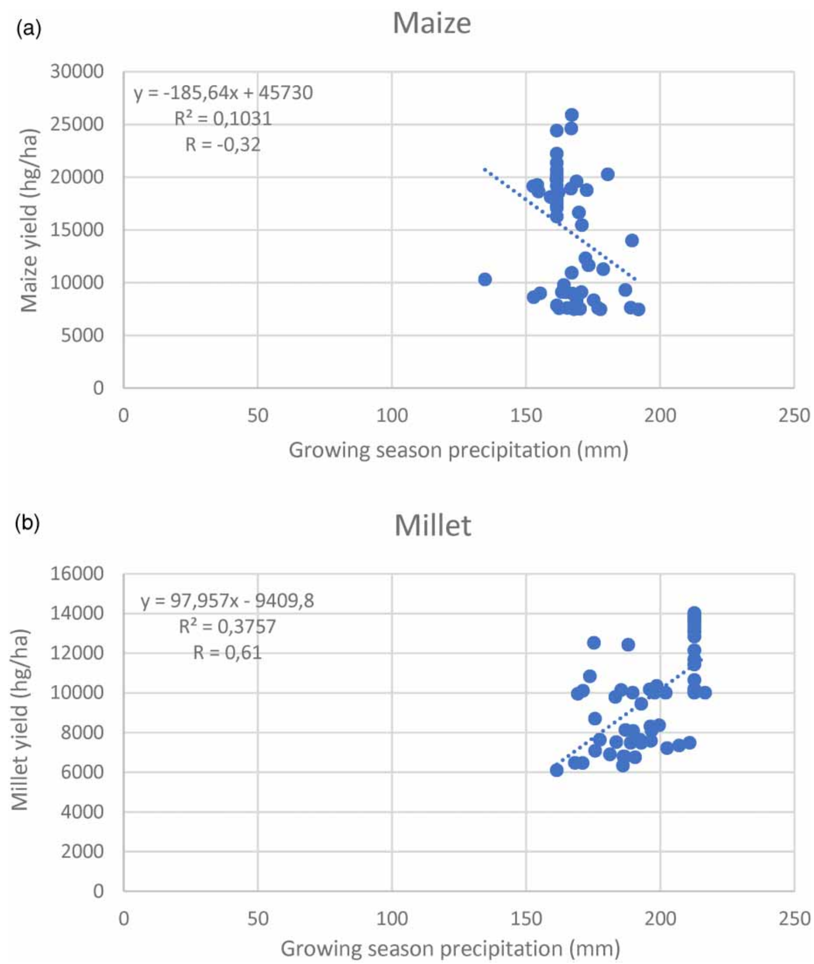


Figure 12 | Scatter plots of growing season precipitation versus yield for (a) maize and (b) millet.

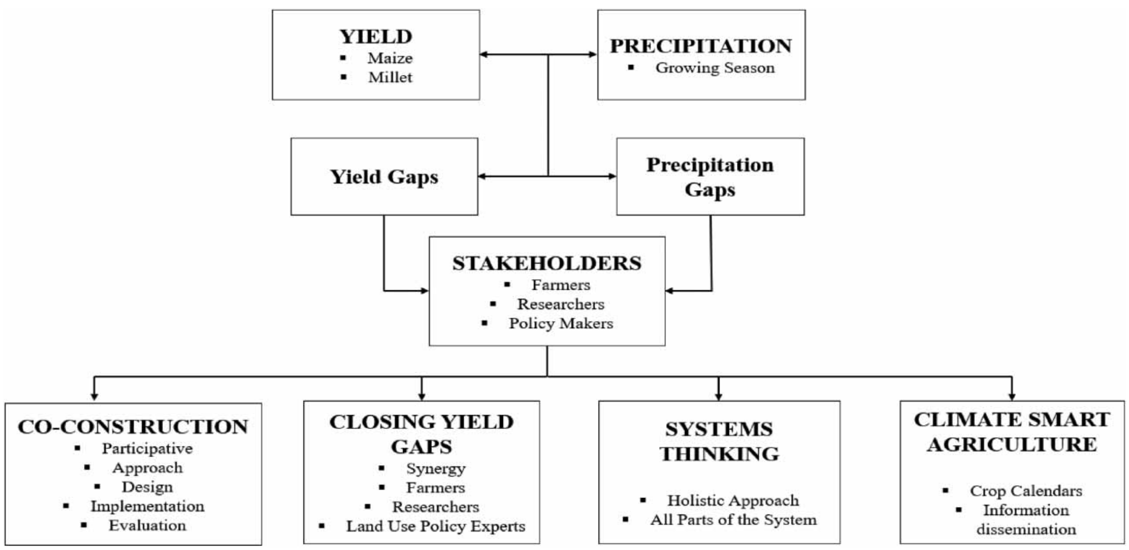


Figure 13 | Agricultural policy framework for yield and precipitation gaps mitigation.

experts) should transition from the tradition of looking only at a part of the concerned system to focusing on the different components of the system (Metta *et al.* 2021). In most cases, the complete picture of any problem, such as yield gaps, can only be obtained by clearly identifying the sub-systems within the entire framework and finally identifying the strengths and weaknesses as well as the contribution of each component in the outcome of the problem. Such a systematic approach will enable the stakeholders to identify the most critical drivers of the problem, and thus leading to a policy scale of preference based on the most important drivers of the problem (Metta *et al.* 2021). In the context of this current work, a system dynamic approach will entail not just the yield and climate sub-systems that invariably are important but will also analyse the role of other drivers such as land use, livestock, soil, fertiliser, irrigation, size of the farmland, land ownership, or rental, inter alia. The multiple linear regression (MLR) approach can then be employed to determine the most essential sub-system (Figure 13). Some studies have described this as a systematic approach to agricultural policy planning, which starts from identifying all the possible drivers and then narrowing down in a two-step regression to the most important drivers that will form the basis for the most urgent policy actions (Epule *et al.* 2014; Epule & Bryant 2015). Epule *et al.* (2014) examined policy options for deforestation reduction in Cameroon based on a systematic approach in which they used MLR to identify the key drivers of deforestation and then classified the most important drivers of deforestation as population growth and trade in forest products and cattle stocks. In a related study, Epule & Bryant (2015) investigated the drivers of arable production and policies to combat the latter in Cameroon. They identified the critical drivers of arable production through MLR made of independent variables such as forest area expansion, arable production, and cropland and population growth. They have now made policy recommendations using the systematic approach that identifies the key drivers, agents, location, products, production methods, and markets of these drivers. With such robust machine learning model-driven approaches, it becomes possible to identify specific policies (Figure 13).

The methodology deployed in this work is weakened by the narrow focus on the linear relationship between crop yield and precipitation. In real life, crop yield is a complex system that is often influenced by several variables beyond climate to soil, water balance, fertilisation, and pests and diseases (Epule *et al.* 2022). In addition, this work considered only two crops, which are maize and millet. The likely steps next will be to consider other crops even though the crops studied here have been described as crops that have gained economic relevance across Cameroon. In addition, the potential crop yield data were culled from IRAD; however, there is a need to validate these data through process-based experiments at various sites across the country. Despite these weaknesses, the methods used in this work provide an opportunity to assess yield and precipitation gaps based on the available data and resources. Most importantly, existing yield gaps estimation studies across Africa are essentially based on the catchment area. This study has gone beyond this to be able to use crop yield and precipitation data at large scales to be able to predict yield and precipitation gaps at such scales (Epule *et al.* 2021c).

CONCLUSION

This study has found that there is a close correlation with growing season precipitation for maize and millet in Cameroon. However, millet yield gaps are seen to be more correlated to precipitation gaps. In addition, the yield and precipitation gaps are higher when we move towards the country's north. The latter phenomenon could be explained by higher temperatures and unreliable precipitation recorded towards the north of the country. Also, the fact that all years of yield gaps are not accompanied by precipitation gaps heralds the argument that yields are complex and not always explained by a single driver. For this reason, this work has suggested using co-construction in agricultural policy formulation; synergy between farmers, researchers, and policymakers; climate-smart agriculture (CSA); and the systems thinking approach. CSA involves the use of technology in farm-level information dissemination such as changes in crop calendars to enable farmers to improve the farm-level decision-making. It aims at increasing productivity, building resilience, and reducing environmental footprints of concerned production systems. A limitation of the current study is that it only focused on the relationship between yield and precipitation gaps without looking at other potential drivers of yield gaps. In addition, this work focuses only on maize and millet; the results at the national scale are based on historical data and machine learning algorithms to predict yield and precipitation gaps. However, yield experiments for the two crops were used at the spatial scale. In terms of the next steps, there is a need for research on other potential drivers of maize and millet, the implications of co-construction, synergies, and system dynamics in further de-constructing the problem of yield gaps. Also, it is essential to consider aspects of information dissemination. This also remains key to agriculture in most developing countries, including Cameroon, because farmers are often small-scale growers who do not often have sufficient access to planting information. Therefore, a system in which information related to changes in their traditional growing season calendars is made available to farmers through extension workers might be incorporated into agricultural policy. Information that is fit-for-purpose is always a vital tool for reducing yield gaps because when farmers are aware of changes in their growing season calendars, they are more capable of adjusting the planting dates or acquiring the necessary inputs required to maintain actual production close to potential production. This approach can narrow the yield gaps.

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DATA AVAILABILITY STATEMENT

Data available on request.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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