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A decade of maize yield gap studies in sub-Saharan Africa: how are farm-level factors considered?

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ABSTRACT
The study of yield gaps has become more complex, prompting the use of varied approaches to measure yields and a wider range of factors to explain these gaps. In the Global North, the focus is on precision farming, whereas in sub-Saharan Africa (SSA), a broader perspective is necessary due to pronounced variability in farmland conditions. While biogeophysical and management factors have been traditional focal points in yield gap analyses, socio-economic and institutional factors are increasingly recognized as significant, especially in SSA. This review synthesizes research from the past decade in SSA that integrates biogeophysical, management, farm characteristics, and institutional factors in yield gap discussions. The findings indicate a slow shift in including socio-economic factors, with management, particularly nutrient supply and crop management, remaining predominant. However, there is a growing trend towards methodological diversity, such as the adoption of remote sensing and GIS in recent years. Case studies from Kenya and Ghana, utilizing field surveys, interviews, panel data, and spatial analysis, highlight how a multifaceted approach can enhance our understanding of the various elements influencing maize yield gaps in SSA.

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Productivity gaps; considered factors; farm level; maize; food security

Highlights

- Increasingly more diverse yield measurement methods used and factors considered
- Management and farm(er) characteristics are the main factors considered
- Nutrient supply is the most considered management factor
- Farm size and its arrangement in spatial is the most considered farm(er) characteristic

1. Introduction

Global crop production needs to increase considerably to keep pace with the growing food demand, driven mainly by population and income expansion and changing consumption patterns (FAO, 2017; Hunter et al., 2017; van Dijk et al., 2021). In many regions, stagnating yield growth, or plateauing yields, contributes globally to the seriousness of current food insecurity challenges (Cassman & Grassini, 2020). The challenges are particularly serious in sub-Saharan Africa (SSA), where population growth is rapid while food insecurity is high (Giller, 2020; Van Ittersum et al., 2016). These challenges coincide with an increasing recognition that efforts to meet current and future demands for food need to respect planetary boundaries (Springmann et al., 2018). The need to produce more food without depleting natural ecosystems and other finite resources requires agricultural production expansion on existing farmland rather than bring new lands under cultivation (Cassman & Grassini, 2020). This imperative is driving research interest in new technologies and tools, as well as crop varieties and is spurring a revitalization of agricultural research seeking to understand levels, trends, and variations in farm yields (Snyder et al., 2017).

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Sustainable intensification – an approach that leverages innovations to increase productivity on existing agricultural land with positive environmental and social impacts – is often viewed as the most efficient way to obtain the necessary increases in productivity (see for example Cassman & Grassini, 2020; FAO, 2018; Godfray et al., 2010; Pretty & Bharucha, 2014). However, regional and local variations are huge, and adverse relationships between a number of complex factors can slow down this development. Yield gap studies are a strand of research in this quest to sustainably improve yields.

Yield gaps can be understood as the difference between observed crop yields in a given location and locally attainable yields using more optimal and timely cultivars, inputs and other management practices. While yield levels in much of Global North have reached the upper limit and have plateaued, there are notable yield gaps in the Global South (Grassini et al., 2013; Van Ittersum et al., 2016). The existence of such large yield gaps between potential and actual yields also implies more prospects and opportunities for yield improvements. An improved understanding of yield gaps and the typical diverse factors that constrain farmers from increasing productivity and yields may contribute to the identification of opportunities for sustainable intensification of farming (Beza et al., 2017; Foley et al., 2011). Such knowledge and insights can also help promote relevant policy for agricultural development in SSA.

While most yield gap research has focused on agriculture in the non-tropical regions, this study seeks to add to the literature on crop productivity in smallholder farming systems in SSA. These are often very different from those typical of the temperate zones and are generally characterized by high diversity and limitations in water management and control, soil fertility, weed and pest management, as well as socio-economic, financial, technical and infrastructure resources (Giller et al., 2011; Giller et al., 2021). Beyond the factors limiting yield levels is the observation of significant spatial yield variations over short distances and even within the same villages. Munialo et al. (2019b), for instance, found heterogeneous patterns of high, average and low yield gaps in different radii of homesteads, with differential application of fertilizers and weed control, as well as allocation of labour resources depending on the location of the field in the landscape. Even within farms, Wahab (2020); Wahab et al. (2020), have shown significant within-plot variability and the impact of these in yield levels.

In SSA, crop yields are generally low from an international perspective, and yield growth in the region has, for several decades, been markedly slower than the global average and even compared to those of low-income countries in other regions (Tittonell & Giller, 2013). Yield gaps, particularly for maize (*Zea mays* L.), are among the largest globally (Mueller & Binder, 2015). Maize, the region's most important staple crop, is produced primarily by smallholders cultivating less than two hectares (ha) per household. Smallholder farming households are at the same time among the region's most vulnerable to poverty and food insecurity. Consequently, research adopting a farm-level perspective when investigating yield constraining factors may help to break the vicious circle of poverty, food and nutrition insecurity and low agricultural productivity that traps many African smallholders (Dzanku et al., 2015; Tittonell & Giller, 2013). By adopting a farm-level perspective and including biogeophysical conditions, crop management, farm(er) characteristics and socio-economic conditions in the analysis of yields and yield gaps, the conditions under which farmers' decision-making takes place may be better understood. Studies taking this approach still seem warranted and would add important perspectives to the yield gap research in particular and agriculture in general, which often has focused on the field or crop level (Reidsma & Jeuffroy, 2017).

In a review of the global literature, Snyder et al. (2017) report that although socio-economic constraints were acknowledged in many studies, fewer than 13% of the 62 papers reviewed included socio-economic factors in their analysis of constraining factors. Similarly, in a review of yield gap explaining factors by Beza et al. (2017), an important finding was that management and soil factors were more often considered compared to farmer characteristics and socio-economic factors; yet, when the latter two categories were considered, they often had high explanatory power. The findings of Beza et al. (2017) highlight the need for interdisciplinarity, especially the combination of management, biogeophysical and socioeconomic factors in yield gap studies so that rather than focusing on one category of factors and neglecting others, the whole gamut of factors impinging on yields at the farm level is analyzed to better understand the yield gap problem in SSA.

An expansion in the range of factors considered for explaining yield gaps will also necessarily entail a broadening of the tools and data sources. Current yield measurement approaches range from modelling through on-farm experiments, whole-field harvest, and crop cuts to farmer recalls and predictions. While self-reports of crop outputs are most widely applied, often through household and farm surveys, full-plot harvesting is viewed as the most accurate and reliable for yield determination even if least practical to implement (Fermont & Benson, 2011; Lobell et al., 2020). Experiments and modelling remain important, while remote sensing approaches are expected to play increasingly crucial, if only complementary, roles in yield measurement. The debate, however, continues on the applicability of new technologies and, specifically, crop cuts and remote sensing approaches, given the complexities and heterogeneity of farms in SSA (Gollin & Udry, 2021; Reynolds et al., 2015). The increasing spatial resolution of sensors and the application of drones as substitutes or complements in this area hold great promise for remote sensing of yields in SSA.

1.1. Aim

The broad aim of this paper is to capture the current profile of maize crop yield gap studies in SSA, as evidenced by articles published in peer-reviewed journals in the last decade. We build on the works of van Ittersum et al. (2013) and Beza et al. (2017) for a guide on the categorization of factors. Together, they provide an overview and summary of the crop yield gap literature up until about a decade ago, which provides the point of departure for this paper. Conceptually they differ, with van Ittersum et al. (2013) focusing on concepts, methods, and applications of yield gap analysis and Beza et al. (2017) studying the interplay between different factors affecting the yield gap in different regions of the world. Our starting point is, therefore, the Special Issue (Volume 143) of the *Field Crops Research* journal titled: 'Crop Yield Gap Analysis – Rationale, Methods and Applications' (2013) to investigate the onward development of the research field. To achieve our aim, we review which explanatory factors are considered in on-farm yield gap studies within the context of SSA agriculture. More specifically, the paper seeks to answer the following research questions:

1. What are the major categories of factors that have been considered in yield gap studies in the last decade?
2. Which factors or combination of factors are most frequently considered in those yield gap studies with farm-level focus?
3. Which methodological approaches and combinations of methods have been used in this area of research in the SSA context during the last decade?

In addition to addressing these questions using a review of the selected literature, we share some insights and lessons learned from a yield gap project built around two country-case studies in Ghana and Kenya. This is to illustrate how a combination of multiple data forms can help further shed light on the relative contribution of different factors groups to present maize yield gaps in SSA.

1.2. Structure of paper

The paper is organized as follows: In section 1, we introduce the relevance of yield gap research and motivate our regional (SSA) and crop (maize) focus as well as show the previous studies that we seek to build on and our point of departure. In section 2, we elucidate the methodology we adopted in the present study. Here, we adopt a pragmatic approach that starts with a systematic review of the literature in this domain of research but also exceed the protocols of a traditional systematic review by incorporating other sources to complement the results of our original search. In section 3, we present the results of analysis of the selected papers under three broad themes of the major factor categories that have been often considered in maize yield gaps studies in SSA in the preceding decade, the key factors under each broad category, and the emerging methodological diversification. We then complement the results of the review by presenting insights from our yield gap studies in Ghana and Kenya which employed these broadened categories of factors and methodologies. In section 4, we reflect on our approach to finding relevant studies, the importance of specific factors within the four broad categories and the relevance of the inclusion of these for understanding YGs in SSA. We further reflect on the broadening of methodological approaches and the implications of recent developments in big data for shedding more light on the yield gap conundrum in SSA. Finally, we reflect on the lessons learned from our studies in the two country-case studies for yield gap studies.

2. Methodology

We adopted a mixed methods review, a method of literature review which combines multiple methods for finding relevant literature, with the most significant component being a systematic search (Grant & Booth, 2009). Given our geographical – SSA, temporal – a decade, and specific crop – maize – focus, we envisaged that relying on a systematic review alone might yield a too limited number of relevant papers. Our choice of a mixed methods approach was thus motivated by the ambition to ensure that all relevant studies were included in the results. Apart from the systematic search for relevant literature, we also carried out a search of the bibliography of the papers identified through our original search to find the second category of papers which fit our search criteria. Finally, we brought in papers that we as individual authors were aware of but that had not turned up in the two preceding steps of the literature search.

2.1. Systematic literature search

The systematic literature search for this review commenced with a detailed search on the Scopus database (https://www.scopus.com/). The search picked any article that had any of the following phrases in the title, abstract or keywords: 'yield gap analysis,' 'yield gap,' 'potential yield,' 'yield variability,' 'water-limited yield,' 'yield gap variability,' 'yield factors,' 'yield level,' 'yield estimation,' 'crop yield explanations,' 'crop yield gaps' and 'maize' or '*Zea mays*' or 'corn.' In temporal terms, the search was limited to papers published between 2011 and 2021. Geographically, SSA was the region in focus. The exact search syntax in English and French is provided in Appendix 1. We also explicitly excluded materials reported in book chapters and non-peer-reviewed journals, as well as grey literature. This initial search yielded a sample of 558 peer-reviewed articles.

2.2. Review of studies and construction of mini-database

The relevance of each study for our research questions was assessed by examining the abstracts and, in some cases, the articles themselves to establish their appropriateness and rejecting those that did not fit. The four main inclusion criteria for the studies were:

1. yield gap-related studies based on maize production;
2. the study must have been carried out in SSA;
3. the analysis must be done at the farm level; and
4. published between the years 2011 and 2021.

The initial list, thus, was reduced to a *keep-list* of 128 peer-reviewed articles, where each full article was scrutinized by at least two of the co-authors. The main inclusion criterion at this stage was analysis being done at the farm level. Further appraisal of quality and relevance was then applied to cover the research design and methods used in the various articles. This additional scrutiny was important to exclude studies that were, for example, conducted only at agricultural research stations, implemented as reviews of methods for determining yields, were mainly modelling papers, or were designed to evaluate cropping systems or fertilizer regimes rather than actual yield gaps on farmers' fields. This additional screening process whittled the list of relevant papers down to 14, which formed the final list of the *original search* papers.

An additional list of 11 relevant peer-reviewed articles termed *references-in-references* was drawn from these. These were relevant works cited in the reference list of our original articles. We then compiled a list of *expert references* — peer-reviewed articles that we are aware of in our individual specializations that would ordinarily qualify for selection but had not, thus far, been picked up by our search. We were able to collate seven of these expert references. These together formed the mini-database of 32 articles (Appendix 2). The Figure 1 below shows, in graphical form, what papers we picked up in our original search, how many were dropped at each stage of the process and how many were retained as final set of papers for the analysis.

We then read and analyzed each study to construct the table in Appendix 3 with columns for the categorization of the factors considered in explaining yield gaps in SSA. Categories of possible explanatory factors were inspired by Beza et al. (2017) by adjusting where necessary to reflect the importance of smallholder farming of maize in SSA. The broad categorizations of the present paper are Management, Biogeophysical, Farm and Farmer characteristics, as well as Institutional setting factors. Under the management category, the main sub-categories are *nutrient supply* (fertilizer use, manure, mulching and return of preceding season's crop residue), *planting* (planting density, timeliness of planting and thinning), *crop characteristics* (variety, plant morphology, height and developmental stages), *weed control* (timeliness, frequency and methods), *crop protection* (insect pests, diseases and their control), *cropping system* (spatial and temporal arrangement of crops, sole stands or

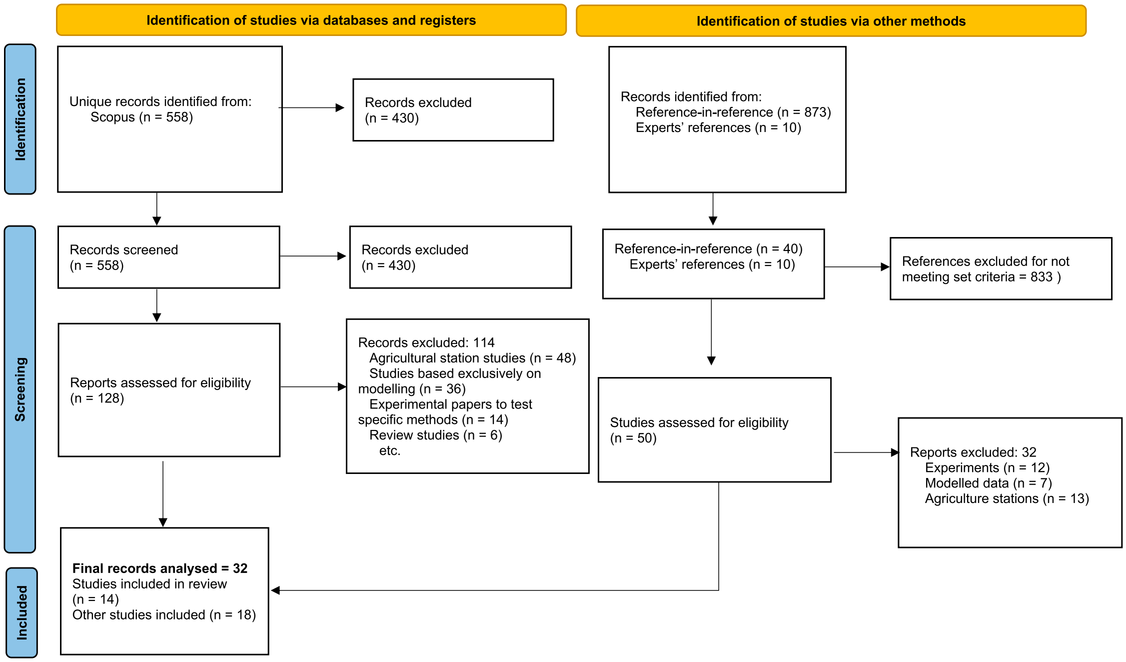

Figure 1. Literature search steps. Adapted from: http://www.prisma-statement.org/PRISMAStatement/FlowDiagram.

Note: While we use the preferred reporting items for systematic reviews and meta-analysis (PRISMA) Flow Diagram, our review does strictly adhere to the Prisma protocol.

intercrops), *land preparation* (method and frequency) and *soil and water conservation* (contour hedgerows, terracing, etc.). Under the biogeophysical category, the sub-categories include *soil properties* (soil texture, organic matter, pH, water-infiltration rate, alkalinity and salinity, as well as soil concentrations of the nutrients N-P-K, etc.), *climate* (length of growing season, heat and drought stress, etc.) and *landscape position* (slope, position in the landscape, flooding).

The farm and farmer characteristics had the following sub-categories: *farm size and spatial arrangement* (farm, field and harvested area, distance to fields, location in landscape, in-fields and out-fields, etc.), *mechanization* (use of draught power for tillage), *source of labor* (either family or hired), *labor input* (amount), *tenure status* (owned or rented fields) and *subsistence vs. commercialization* (orientation of production), *sources of income* (on-farm, off-farm), *assets and income level* (tools, cash inflow, etc.), *household size* (number of persons), *gender and ethnicity*, *agricultural knowledge* (educational level, number of years of experience, farmer-group participation, etc.). Under the institutional setting category, the sub-categories are *access to market and credit*, *access to extension/technical assistance*, *access to agricultural inputs* (seeds, fertilizers, pesticides, etc.), *labor dynamics* (availability and seasonality) and *land scarcity and tenure system* (in the area). As a departure from Beza et al. (2017), we aggregated sub-categories to classify them under the separate major categories of Edaphic factors and Climate into one category: Biogeophysical conditions. On the other hand, we included two categories describing socio-economic factors and the institutional setting at the village level and higher. The table in Appendix 2, with the categories and sub-categories enumerated above, was then used to arrive at a narrative synthesis using simple statistical summaries, such as percentages, to summarize both the quantitative and qualitative studies.

Finally, papers were harvested for specific information on data collection. Yield measurement methods were categorized as either farmers' self-reported yields, sub-plot crop cuts measured, or full-plot cuts measured. In addition, papers were categorized based on whether they also used modelling or experimental approaches and/or applied remote sensing and spatial analysis in addition to using data on farmers' actual yields.

3. Results

3.1. Selected papers and distribution

Altogether, 32 papers that fit our criteria were found and added to the database. Of these, 14 (44%) were from the original search from Scopus, 11 (34%) were references found in the 'original papers,' and seven (22%) were added as expert references. They reflect a publication pace of about three papers annually. Geographically, they cover 12 out of the 48 countries in SSA (Figure 2). Apart from the paper from Dzanku et al. (2015), which spans multiple countries, including Ethiopia, Ghana, Kenya, Malawi, Mozambique, Nigeria, Tanzania and Zambia, all other papers relied on data from individual countries. The number of papers per country varies between one and 11, with more than 60% of all studies conducted in three: Ghana, Ethiopia, and Tanzania.

The 32 papers were published in 22 different journals. Only the journals *Agricultural Systems*, *Agriculture*, *Agriculture & Food Security*, *Field Crops Research*, *Food Security* and *Nutrient Cycling in Agroecosystems* have more than one publication each (Appendix 2). The majority of journals belong to the subject area 'agriculture and biological sciences,' while six journals were classified as 'economy, econometrics and finance' or 'social sciences' in the Scopus database classification (Figure 3).

3.2. What major categories have been considered in yield gap studies in the last decade?

A key finding from this study is that yield gap studies are increasingly adopting more integrated approaches with regards to study design and general data collection. The majority of papers included factors from all four categories (Appendix 2): Management, Biogeophysical, Farm and Farmer characteristics, and Institutional setting categories. Factors from the Management category were considered in all papers, with a minimum of two factors included, and three of the 32 papers (Assefa et al., 2020; Assefa et al., 2021; Bucagu et al., 2020) considered all eight reported factors under the Management category. All except two papers (Mourice et al., 2015; Owusu Danquah et al., 2020) included factors from Farm and Farmer characteristics. Less well represented were Biogeophysical factors (nine out of 32 did not consider any) and Institutional setting category factors (seven out of 32 did not include any).

Figure 4 shows that the Farm and Farmer characteristics category was the most-considered category, followed by Management, with the Biogeophysical category being the least frequently considered. Although the Management category was considered in more papers, the Farm and Farmer characteristics category had a higher frequency due, perhaps, to having more sub-categories.

3.3. Which factors or combination of factors are most frequently considered in yield gap studies?

Disaggregating the factor categories sheds more light on the most considered factors for each category. Figure 5 summarizes the three most often considered factors per category. The Management category is well represented in both the number and diversity of factors considered. All reviewed papers included data on nutrient supply, and most papers also considered planting (22 studies) and crop characteristics (21 studies) (Appendix 2). Additionally, the Farm and Farmer characteristics category is well represented; a majority of papers consider five or more factors from this category, with farm size and spatial arrangement (26 studies) being the most considered in the category, followed by an equally frequent consideration for agricultural knowledge (19 studies), labour input (19 studies), and gender and ethnicity (19 studies). In the Institutional setting category, access to market and credit (19 studies) and access to extension and technical assistance (15 studies) were the most-considered factors. IIn the Biogeophysical category, none of the factors were considered in more than half of the reviewed studies. The most-considered factors in this category was soil properties (16 studies), climate (14 studies) and position of farm in the landscape (12 studies).

Identifying any consistent pattern of how factors are combined between and within categories is difficult. However, a principal component analysis (Appendix 3) indicated a tendency for papers that consider fewer factors from the Farm and Farmer characteristics category to also consider fewer factors from the Institutional setting category.

3.4. What are the methodological approaches in recent yield gap studies in Sub-Saharan Africa?

Regarding methods for measuring yields, there is a general trend towards methodological diversification. The vast majority of the studies (28

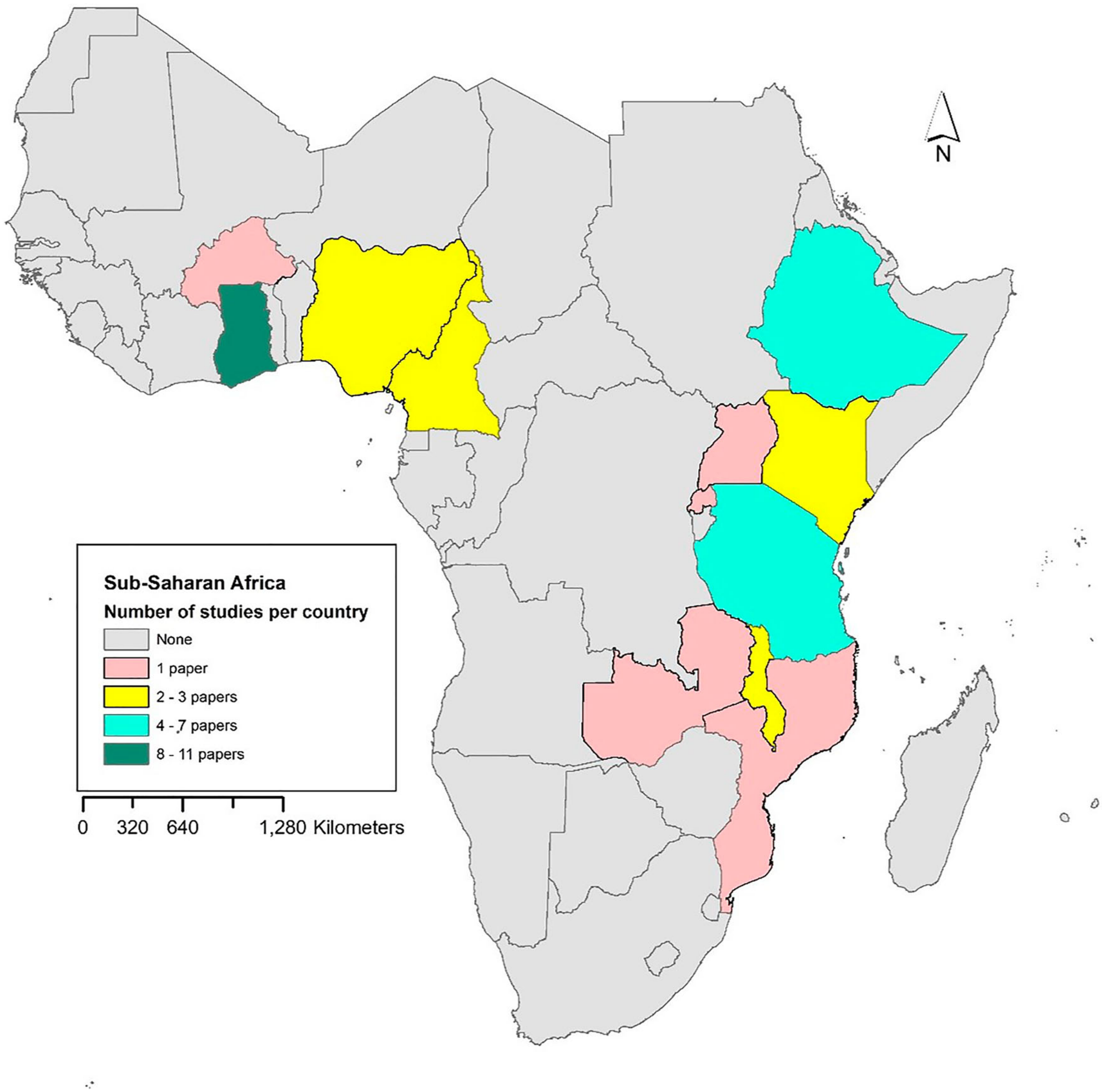

Figure 2. Spatial distribution of publications across Sub-Saharan Africa.

studies) used farmers' self-reported yields data collected through surveys. Three of the remaining four were not explicit as to the method used to collect crop-yield data. Only six papers used crop cuts of sub-plots to measure yields, with five of these published in the last three years of the review period. Even fewer studies (three) used full-plot harvests to determine crop yields in addition to self-reports through surveys, crop cuts of sub-plots and full-plot harvest. Sida et al. (2021) also tested other approaches, such as farmer predictions, plot-transect approaches, and various crop-cut approaches.

The trend toward methodological diversification is similar in the application of remote sensing and geographic information science tools; seven studies (Assefa et al., 2020; Bucagu et al., 2020; Burke & Lobell, 2017; Lobell et al., 2020; Munialo et al., 2019b; Tamene et al., 2016; Wahab et al., 2020) employing RS/GIS were published within the second half of the review period.

Given the highlighted importance of multi-disciplinarity in this area of research, we also sought to analyze the number of methods adopted for yield-data collection or estimation in the selected papers. Most (25) papers used only one or two

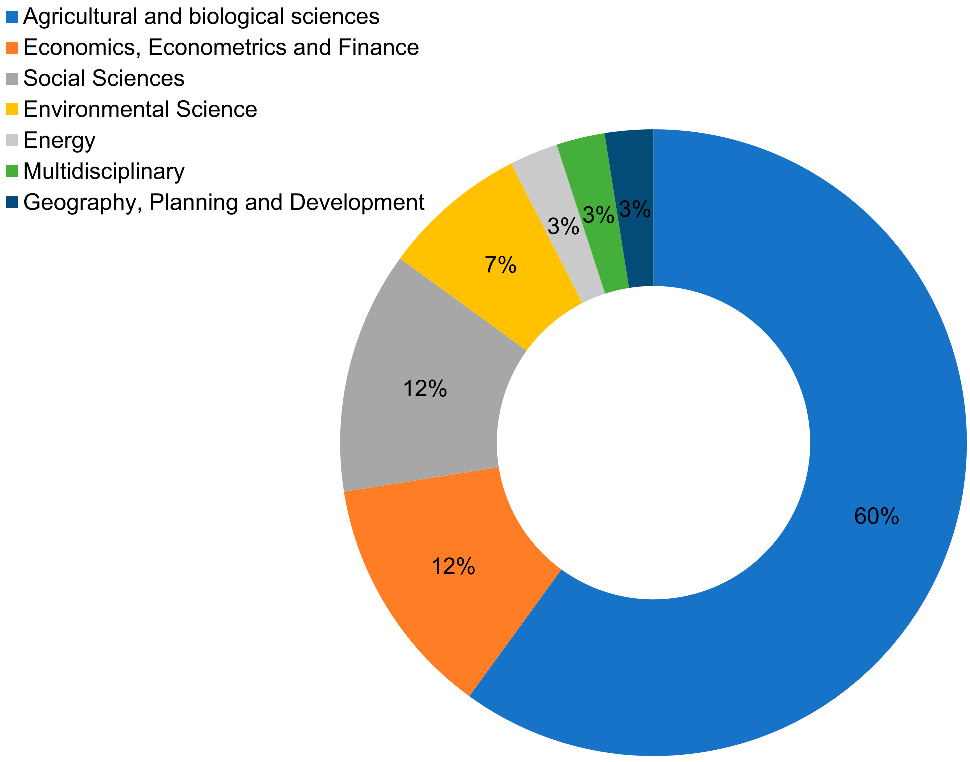

Figure 3. Classification of journals that published the selected papers, according to Scopus database classification.

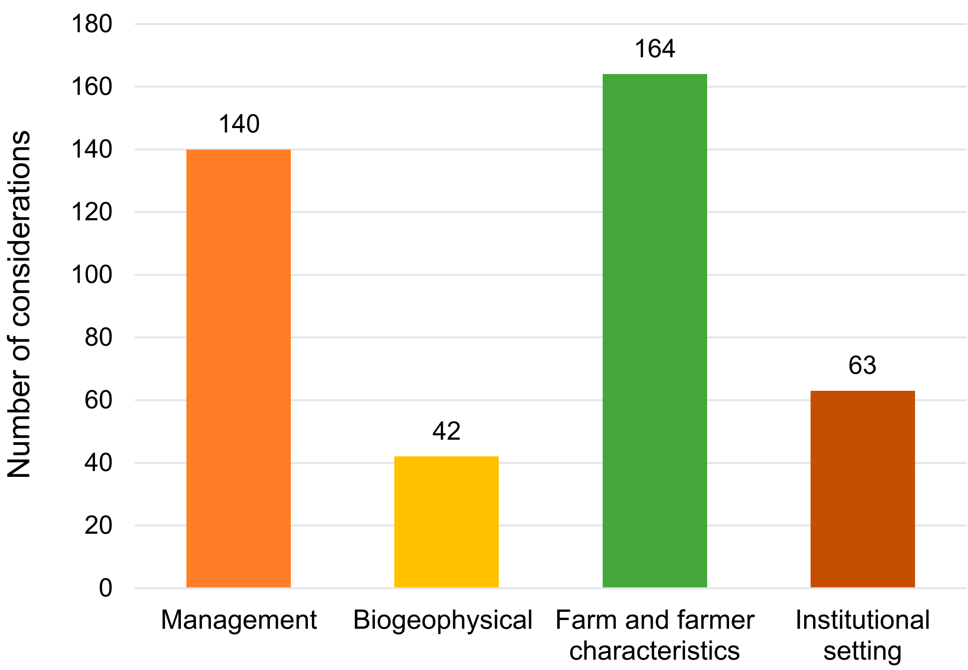

Figure 4. Distribution between the four broad categories of factors considered in all studies.

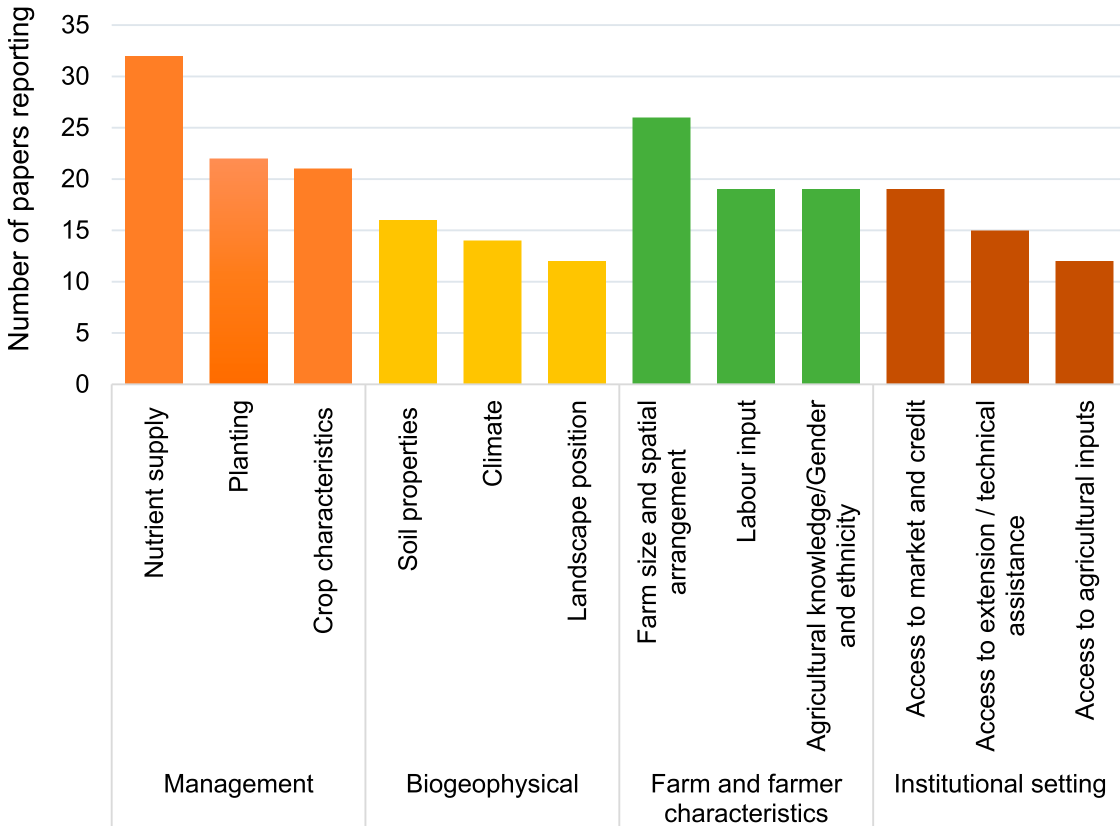

Figure 5. Frequency of the three most considered factors in each major category (N = 32).

Note: Gender and ethnicity were a separate factor but was equally considered as Agricultural knowledge. Access to extension and technical assistance were classed as one factor.

methods, whereas seven used three or more methods, all published in 2017 or later, suggesting an increase in diversification in the methods applied. Yield reports from household surveys was the most frequently used, with modelling and remote sensing approaches being the second and third most frequently used (Figure 6).

3.5. Using a combination of approaches, including spatial methods in yield gap studies – examples from Ghana and Kenya

Developing a clearer understanding of current yield limitations is vital to achieving targets of closing yield gaps. Each individual factor that drives current crop yield levels is well-researched. A major limitation of current approaches, however, has been the disciplinary focus of most such endeavours, as well as the approach to the study at spatial scales, which do not allow for the exploration of actual interactions at the farm level. The Yield Gap Africa project (https://portal.research.lu.se/sv/projects/unraveling-the-causes-and-implications-of-crop-productivity-gaps-) sought to fill this gap. We aimed to use a multi-disciplinary approach to unravel the drivers of low-crop yield levels and the heterogeneity of yield gaps at the various scales – from plot to farm and village scales. Thus, rather than approach the yield-gap conundrum in SSA with a single-discipline focus, we approached it from a multi-disciplinary perspective. The project used a combination of biophysical data (field surveying of soils and crops and climate data), socio-economic data (surveys and interviews) and an augmentation of these with remote sensing data (satellite and drones) to unravel yield-controlling factors at various scales. Developing a comprehensive understanding of limiting factors and their interactions is expected to help improve effectiveness of interventions in agriculture.

Data were collected from four villages, two in Ghana and two in Kenya, and cover remote sensing

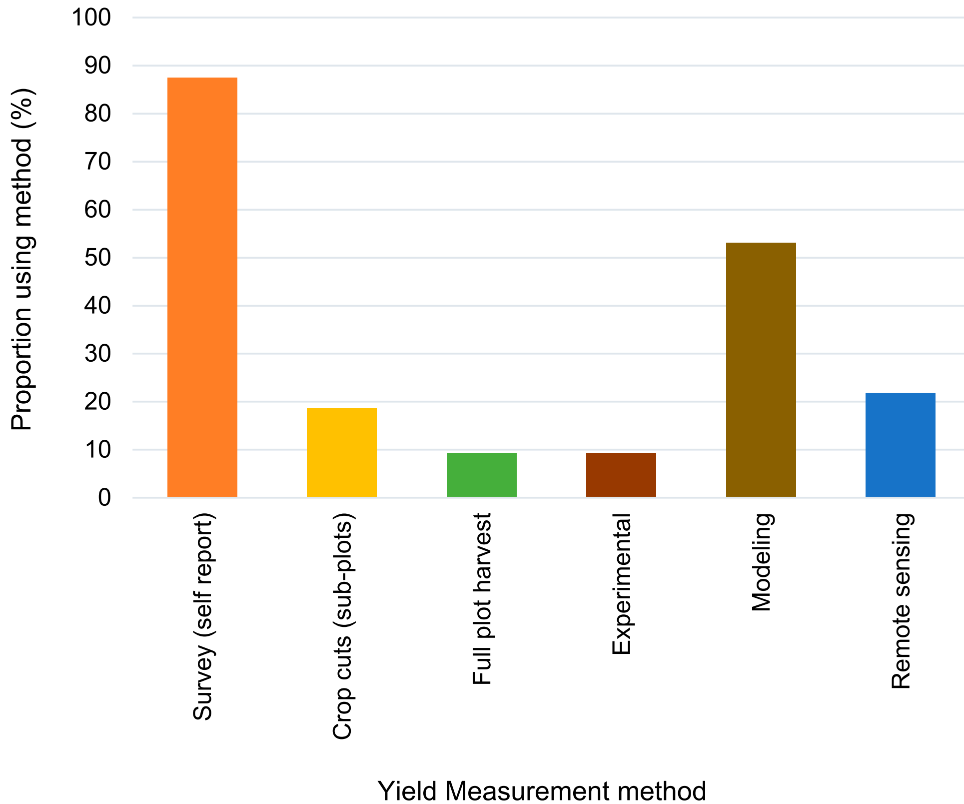

Figure 6. Methods used for yield measurement and estimation in the 32 papers.

of crops and yields (Hall et al., 2018; Munialo et al., 2019b; Wahab et al., 2018), methodologies in yield measurements and their limitations in rain-fed farming systems (Wahab et al., 2018), edaphic – and management-related factors' contribution to maize yield gaps (Munialo et al., 2019a; Munialo et al., 2019b), yield gap mapping to identify and understand field-specific utilization of production factors (Wahab, 2020), a more integrated approach to using the different factor categories to explain yield levels (Wahab et al., 2020) and smallholder perceptions and attitudes to yield levels and the variability on their plots (Wahab et al., 2022).

Key insights from our study in Ghana and Kenya include demonstrating the feasibility of leveraging drone imagery-derived vegetation indices for assessing crop health and yields in complex farming systems in SSA (Hall et al., 2018; Wahab et al., 2018) where access to cloud-free satellite data is often scarce. We also found significant disparity between two popular yield measurements approaches relying on farmers' self-reported yields and crops cuts. Much of the uncertainty was attributable to substantial intra-farm variability and area loss during the season (Wahab, 2020). In seeking to shed light on the role of the location of the farm in the landscape, we found that farmers tended to give preferential treatment – in terms of inorganic fertilizer application, weed control, and plot preparation – to plots which are, in spatial arrangement, further from homesteads compared to those in closer proximity to homesteads (Munialo et al., 2019). Still, there are significant yield gaps – ranging between 35% and 54%, with key limiting factors of soil quality, timing of planting, fertilizer use, and weed control being influenced by socioeconomic factors of land tenure and labour availability (Munialo et al., 2019; Wahab et al., 2020). Given farmers' aim for yield optimization rather than maximization, the importance of farmers' agency and rationality became prominent, thereby helping to understand why on-farm investments are still lacking despite clear evidence of possible yield increases in such contexts (Wahab et al., 2022).

4. Discussion

4.1. Reflections on the methods applied

A concern for all literature reviews is whether all studies of relevance were included in the analysis. Considering the range and diversity of disciplines studying agricultural productivity, we developed a paper-selection process that is best characterized as mixed method review (Grant & Booth, 2009). We applied a three-stage selection process starting with a formal database search in Scopus, followed by a reference-in-reference search and, finally, additional expert-identified references to ensure that a major part of the relevant papers was identified. This process reduced the impact of potential misidentification based on single keywords in the initial search. This more than doubled the number of publications, highlighting the challenge of identifying all relevant publications using only keyword searches. For reasons detailed above, our main concern encompassed factors relevant to yield gaps observed in smallholder farming in SSA, particularly on-farm and related to maize. Papers that relied on field and farm-level data, even if employing empirical modelling, were included in the study.

4.2. Major categories of factors considered and their frequency

In comparison to the results obtained in the reviews by Beza et al. (2017) and Snyder et al. (2017), which showed that socio-economic and institutional factors were 'neglected,' our results show a relatively broad inclusion of categories and many other factors. This can perhaps be explained by the differences in focus; while the papers by Beza et al. (2017) and Snyder et al. (2017) both had a global focus, our review focuses on SSA. For example, within the SSA context, socio-economic factors may simply be more important than they would be, say, in the USA, where management decisions may be of greater importance. Our understanding is that among agricultural researchers working in SSA, there is a gradually growing awareness of the importance of non-agronomic factors on the yields that farmers derive from their farms.

As our results show, the farm(er) characteristics and management categories are the two most-considered groups of factors, accounting for 164 and 140 times reported, respectively, across all the studies analysed. For the farm(er) category, the most considered factor is the farm size and spatial arrangement of the farm in the landscape. This is hardly surprising given the long-standing debate on the inverse relationship between farm size and productivity (Carter, 1984; Pol, 1984). The state-of-the-art on this debate is that where a relationship between farm size and productive exists, it is U-shaped (Muyanga & Jayne, 2019), though much of it is related to measurement errors which are chiefly driven by uncertainties in farmer-reported production and crop area data (Carletto et al., 2013; Desiere & Jolliffe, 2018; Gollin & Udry, 2021; Gourlay et al., 2017; Gourlay et al., 2019). Despite the popularity of farmers' self-reported yield data, the tendency to round off quantities, average outputs over several seasons and over- and under-report through conversion errors (Carletto et al., 2015) render this unreliable, if not misleading. The reliability of crop outputs data could be improved if due consideration is given to cropping systems (mixed versus mono-cropping) as well as detailed probing on post-harvest losses, in-kind payments to landowners and labour and green maize harvests (Wahab, 2020).

Apart from farm size, other frequently considered factors in the farm(er) characteristics category include agricultural knowledge, labour input, and gender and ethnicity (each considered in 19 studies), source of labour, and household size (each considered in 17 studies), assets and income levels and sources of household income (14 studies). Interestingly, the level of mechanization (5 studies), production orientation – subsistence versus commercial (6 studies), and tenure system were the least frequently considered factors. This is somewhat surprising given the linkage between agricultural commercialization and mechanization (Daum & Birner, 2017, 2020), disappointing given the increasing recognition land markets and tenure dynamics (Christiaensen, 2017; Wahab et al., 2020). Interestingly, two of the selected studies (Mourice et al., 2015; Owusu Danquah et al., 2020) did not consider any of the factors in farm(er) characteristics category at all, with a further two (Burke & Lobell, 2017; Kihara et al., 2015) considering just one of 11 farm(er)_characteristics – in both instances, farm size and spatial arrangement. On the other hand, Dzanku et al. (2015) and Tamene et al. (2016) both considered 9 of 11 factors in this category.

The management category of factors (considered a total of 140 times across 8 factors) is the second most frequently considered category. Its relative weight derives from the overwhelming consideration of nutrient supply – both organic and inorganic sources by all 32 selected papers. The high frequency of nutrient supply was also found by Beza et al. (2017) in their review of yield gap explaining factors and they further found that in addition to being the most considered factor, it contributed to explain the yield gaps in most (94%) cases when it was considered. Just like Beza et al. (2017), we found that the quantity was the most frequently considered aspect of fertilization, although recent studies (such as Wahab et al., 2020) demonstrate that the timing of application is even more important, or at least, as important as fertilizer quantity. Similarly frequent in the management category are factors related to planting (considered in 22 studies), crop characteristics (21 studies), and weed control (17 studies). The least frequently considered factors in this category – soil and water conservation, and land preparation (9 studies each) are not too surprising given the limited use of irrigation systems for maize crops in much of SSA (Binswanger-Mkhize & Savastano, 2017). Overall, the management category is the most important at the level of individual studies, with the least number of factors (2 out of 8 factors) being considered by one study (Essilfie et al., 2011) and most studies considering 4 or more of the eight factors.

Within the institutional category, the most frequently considered factors being access to markets and credit (19 of 32 studies) is not surprising given the importance of this for accessing not only inputs such as fertilizers and improved seeds, but also outlets for farm produce. Market access has long been noted to promote agriculture commercialization and transformation (Amanor, 2019; Djurfeldt et al., 2011) and has been limited by generally poor infrastructure provision. The emergence of the other two most frequently considered factors – access to extension and other technical support (15 of 32 studies) and access to agricultural inputs (12 of 32 studies) – is not surprising either, given their relative importance in the context of SSA. It is also interesting to note that 7 of the 32 studies (including Owusu Danquah et al., 2020; van Dijk et al., 2020) did not include any institutional setting factors, with a further 5 considering only one of the five factors in this category. There is along way to go for this category of factors' inclusion in yield gap studies in SSA given historical and contemporary bottlenecks that have and continue to limit infrastructure, connectivity, and communication especially in rural areas. Continuing to neglect factors in this category would mean that national and international structures and policies do not consider the macro and meso factors that constrain agricultural development in SSA.

In the biogeophysical category, the most surprising finding was that climate factor was not more frequently considered (was considered in 14 of 32 studies), given the predominantly rainfed nature of maize cropping in SSA (Carter et al., 2018). This is the category with the most studies (9 of 32) not considering any factor at all, with a further 11 of 32 considering only one factor. Our findings of less frequent consideration of clearly important factors in the biogeophysical category – climate and soil properties – as well as other instrumental factors such as timing of fertilizers application may be attributable to the unavailability and inaccessibility to granular data at the farm level in SSA.

It is emerging, for example, that the timing of major management activities such as planting, fertilizer application, and weed control are more influential yield determinants though most studies do not consider data on these. While it cannot be expected that all yield gap studies include all factors at the farm level, a recognition of the context of the study and its unique milieu can contribute to ensuring that most germane factors that impinge on yields are considered. Studies should also take into cognizance the interlinkages between and amongst different factors to avoid redundancy in factors considered while other equally relevant factors remain unconsidered. While the implications of the non-inclusion of certain relevant factors to explain yields are not quite clear cut, we can surmise that such studies do not capture the full gamut of yield constraints, a fundamental requirement for overcoming the yield gap problem in under-performing regions.

4.3. Methodological approaches and combinations of methods used in recent studies in Sub-Saharan Africa

Using a combination of methods may increase the chances of capturing factors not often included in studies but which can add to our understanding of farmer behaviour and management decisions in relation to yield gaps. While the last decade witnessed an upsurge in new data, methods, and technology available for research – for example, GPS-receivers, GIS, camera-equipped UAVs and high-resolution satellite imagery – are now only beginning to gain some usage. Satellite and UAV imagery can be used to detect soil properties and measure biomass and yield. There seems to be a clear uptake in their usage, with seven papers applying remote sensing and GIS tools – all published in the last six years, while none of the papers in the preceding years used such data or methods. The increasing use of remote sensing tools and data in research, even in the complex and heterogeneous farming systems in SSA, can, to some extent, be attributed to the increasingly easier access to very high-resolution satellite imagery (Burke & Lobell, 2017), as well as to the increasing application of drones as remote sensing platforms (Munialo et al., 2019b; Wahab et al., 2020). One could make the case that data robustness is on the ascendency given the weakness of different methods and data sources (Fermont & Benson, 2011). Our finding of increasing methods and dataset sources per paper would therefore suggest that there would be increasing robustness of such studies.

4.4. Lessons from our yield gap project

From our yield gap project implemented in Ghana and Kenya, we note the potential value of complementarity of different approaches and data for maize yield prediction even in such complex farming systems (Wahab et al., 2018). Not only is this valuable for yield analysis but also in precision agriculture applications. It is also critical the pay closer attention to the effective area of fields to reduce the uncertainty inherent in yield measurements in SSA, particularly in contexts where area loss happens earlier on in the season and farmers do not expend – man-power and fertilizer – in such sections of the farm. Differentiating planted and productive area is key for not only improving the accuracy of yield measurements but also understanding of the factors driving current low yield levels (Wahab, 2020). Above these, delineating management zones based on different yield gaps patterns observed at the different scales could help improve site-specific management, and thus yields (Munialo et al., 2019). Adopting an integrated approach allowed for consistent and agroecological region-specific factors to be identified (Munialo et al., 2019), while helping to show the linkages between and among management, biogeophysical, farm(er) characteristics, and institutional factors to become clearer (Wahab et al., 2020). Overall, yield gap studies at the farm level are most revealing when the farm is not separated from the farmer as the latter's agency is key to understanding what happens on the former.

Like many other domains of research, yield gap studies continue to be hampered by a paucity in data availability in large parts of SSA. While there has been an explosion in the quantity and quality as well as availability in data and methods for analysing them, particularly in remote sensing of yields (Burke & Lobell, 2017), limitations relating to the reliability of ground truth data for validation and land cloud cover in satellite imagery persist. Based on our study in Ghana and Kenya, recent platforms such as drones are proving themselves as viable alternations. In that project, we used drone data quantitatively to measure crop vigour and related that to yields as well as used it in a qualitative manner as a complement in photo-elicitation interviews. The latter added a new dimension to how drone data can be used in yield gap studies in data-scarce regions of the world where mixed method approaches have added value because a sole data source might prove too unreliable to suffice.

5. Concluding remarks

Yield-gap research directly links to global calls for increased and sustained productivity growth on existing farmland. For SSA, a transition from area expansion to productivity growth is becoming urgent as land frontiers are closing and the sizes of smallholders' farms continue to decline in most countries. At the same time, pinning too much hope on the benefits of closing yield gaps to eradicate poverty and food insecurity among smallholders may be an unrealistic strategy. As argued by Giller et al. (2021), even in farming systems in agro-ecologically high potential areas, poverty and food insecurity can develop due to factors such as land fragmentation and lack of investments in land management and agricultural input use.

Frelat et al. (2016) point out that strategies other than those promoting agricultural production and closing yield gaps – for example, improving market access and promoting off-farm opportunities – may offer effective alternatives in targeting poverty.

While recognizing the importance of more targeted rural development approaches, including those not focusing directly on agriculture, there nevertheless remains an urgent need for research focusing on sustainable agricultural intensification in SSA. This clearly includes research aimed at understanding location-specific productivity constraints in the often highly diverse biogeophysical, market and socio-economic environments under which smallholders in the region operate. While our review indicates that on-farm yield-gap studies increasingly consider a broader diversity of factors, we also note that the current publication pace – approximately three papers annually – remains relatively limited given the seriousness of production challenges facing Sub-Saharan smallholder agriculture.

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