Precision agriculture research in sub-Saharan Africa countries: a systematic map

Article *in* Precision Agriculture · August 2021

DOI: 10.1007/s11119-020-09780-w

Precision Agriculture
https://doi.org/10.1007/s11119-020-09780-w

Precision agriculture research in sub-Saharan Africa countries: a systematic map

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Accepted: 30 December 2020

Abstract

Precision agriculture (PA) has a huge potential for growth in sub-Saharan Africa (SSA), but it faces a number of social-economic and technological challenges. This study sought to map existing PA research and application in SSA countries following the methodology for systematic mapping in environmental sciences. After screening for relevance, the initial about 7715 articles was reduced to 128. Results show that most of the studies were conducted in countries with socio-economic and technological advancement, mainly South Africa followed by Nigeria and Kenya. The studies were conducted at various scales ranging from field to country level with field scale studies being the most common. Most studies were conducted in relatively small farms typical of most farmlands in SSA. Studies done in relatively large farms are fewer, and such farms would likely belong to a few organisations and individuals with high economic capacity. Many of these studies have been conducted by researchers from outside SSA and a combination of researchers from within and outside SSA. However, based on authorship of the articles, it appears that most of the studies conducted in SSA on precision agriculture have either involved or depended on non-African researchers. It is concluded that there have been significant strides towards use of precision agriculture in SSA. However, with about 21 countries having no research done, there exists greater potential for precision agriculture in the region. Besides, there is need for more research to investigate the low usage of precision agriculture for livestock management.

Keywords Precision agriculture · Remote sensing · Sensors · GIS · Climate smart agriculture · Sub-Saharan Africa

Supplementary information The online version of this article (https://doi.org/10.1007/s11119-020-09780-w) contains supplementary material, which is available to authorized users.

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Published online: 15 January 2021

Introduction

Agriculture is the most important economic sector in many sub-Saharan Africa (SSA) countries, contributing more than one-third of the gross national product (GNP) and employing more than two-thirds of the labour force (FAO 2017). In spite of its central role in the region's economy, there has been a lack of strong agricultural growth (Fuglie 2013). Besides, low inherent soil fertility combined with increased population pressure has led to soil degradation and nutrient depletion in most of the SSA countries. For sustainable agricultural growth to be achieved a more efficient use of resources must be employed, and this calls for adoption of technologies such as precision agriculture.

Precision agriculture is defined by the International Society of Precision Agriculture (ISPA) as management strategy that takes account of temporal and spatial variability to improve sustainability of agricultural production (ISPA 2018). It combines information and technology-based farm management systems to identify, analyse and manage variability within fields for optimum profitability, sustainability and protection of the land resource (Mondal and Basu 2009). It aims to acquire, interpret and utilize as much spatial information as possible so as to optimize farm management based on existing needs within the field (Gebbers and Adamchuk 2010). Precision agriculture has three main goals: (1) Optimizing the use of available resources in order to increase profitability and improve the sustainability of agricultural operations; (2) Reducing the negative impacts associated with agricultural activities; and (3) Improving the quality of the work environment (Pierce and Nowak 1999).

The success of precision agriculture relies on application of the right inputs in the right place in the right time (Gebbers and Adamchuk 2010). Availability of accurate information and data on the state of the farm is therefore an important component of this agricultural system. Besides availability, such information and data need to be properly analysed for it to be useful in precision farming. Increased developments in precision agriculture have led to increasing demand in analyses that estimate more accurately the input requirements in a field in order to reduce costs incurred and improve the effectiveness of the applied input (Lowenberg-DeBoer 2003).

Precision Agriculture has evolved from an idea in the 1990s into a promising form of agriculture at present (Mulla and Khosla 2015). This has been made possible by satellite positioning and navigation which have made it possible to gather information required to apply decision-based precision agriculture. This ability to acquire on-farm information coupled with an increased awareness of variability of soil and crop conditions by the farmers have been the main drivers of the recent advancement of precision agriculture (Stafford 2000).In the early stages, it developed as a means of adapting fertilizer application to the variable soil conditions across fields. However, in the recent past, precision agriculture has advanced to use of automatic fertilizer application devices, autonomous farm machinery, use of on-field research and a range of computer software for management of various production systems (Gebbers and Adamchuk 2010). These advancements portend a number of benefits to farmers including increased productivity and therefore profitability, quality of farms, clean environment, food safety and sustainability. However, advancement in precision agriculture in SSA faces a number of social-economic and technological challenges. Social-economic challenges include lack of information, and in some cases inappropriate use of the same; lack of information on site-specific nutritional requirements; and lack of established agronomic service providers. Technological challenges include lack of machinery including sensors, limited access to global navigation satellite systems (GNSSs) devices, geographic information systems (GIS) and remote sensing (Robert 2002). All these challenges tend to restrict advancement of precision agriculture in the less developed parts of the world like the SSA. In SSA, precision agriculture has taken other forms which focus on specific aspects but which are less affected by these challenges. Climate smart agriculture (CSA) for example focuses on averting the social-economic effects of climate change while conservation agriculture (CA) focuses on promotion of conservation activities in farming.

In most parts of SSA, agriculture is practiced at small scales. The concept of precision agriculture in a SSA small holder farming setting has been described as site specific management; site specific farming (Cook et al. 2003) and climate smart agriculture (CSA) (Leslie et al. 2014). Precision farming as described by the Montpellier Panel Report (Imperial College London 2014) is in line with the model of sustainable intensification that is centred on producing more food with less environmental impact. The use of precision farming practices offers alternatives that address the problems faced by small scale farmers in SSA in terms of efficient use of resources, increased incomes and reduced negative impacts to the environment. Climate smart agriculture is a production system that increases yields, makes agriculture to conform to climatic changes and reduce GHG emissions from production through more efficient use of inputs (Lipper et al. 2014; FAO 2017). Site specific farming in the SSA context on the other hand is guided by the conditions of a given location. For example in semi-arid environments, the planting densities used by the farmers are low compared to the high rainfall areas. Such low density planting allows for the application of nutrients and/or water specifically to the planting spot (microdosing) that creates a favourable micro-climate in the surrounding area of the growing crop. Microdosing of inputs by the small scale farmers in SSA makes the best use of the scarce resources.

There are differences between precision agriculture practiced in Europe and North America and the ones employed in developing countries such as the SSA (Gebbers and Adamchuk 2010). In Europe and North America, precision agriculture involves the use of advanced information systems such as the use of satellites and/or drones to acquire data in determining the specific site input requirements (Tiwari and Jaga 2012). However, in countries such as those in SSA, precision agriculture is mainly guided by farmers' observations and experiences (Mondal and Basu 2009; Tittonell et al. 2016). The advanced technologies are not used because they are too costly, and often not available. The precision practices in SSA include planting the crops with the highest yields on the best land and applying mulch on degraded land (Osbahr and Allan 2003). The use of fertilizers and irrigation depends on the soil properties and the expected amounts of rainfall (Tiwari and Jaga 2012). The potential of precision agriculture in SSA exists given that quite a lot of information on agricultural production constraints is available and a number of technologies to address the constraints have been developed (Aune and Bationo 2008). However, it is important to note that the technologies should be geared towards the farmers' needs and existing constraints.

In the current study, the mapping of the scientific literature aimed to document existing precision agriculture research in the context of SSA countries. The main objective was to map research that investigates the application of precision agriculture concepts in SSA countries, specifically to: (1) Evaluate how the research on precision agriculture concepts vary among SSA countries, crop and scale of production; (2) Generate a map on the precision agriculture research in SSA; and (3) Determine the research gaps on precision agriculture research and application in SSA in order to inform future primary research and options for its application among SSA farmers. Information gathered from these objectives would provide answers to the research question "To what extent has precision agriculture been studied in SSA? It was hypothesised that primary research on precision agriculture in SSA is low due to the prevalent smallholder farming systems. This hypothesis was tested by evaluating the numbers of primary research done at various spatial scales in different SSA countries.

Materials and methods

The method used in the development of the systematic map was adapted from a methodology for systematic mapping in environmental sciences (James et al. 2016). While systematic maps are developed using similar approaches to those used in systematic reviews, the methods developed by James et al. (2016) points out that systematic maps aims to describe the state of knowledge for a question while systematic reviews aims at providing either a qualitative or a quantitative answer to such question. The systematic mapping process is outlined in Fig. 1.

Literature search

A broad search of numerous sources was conducted to ensure an un-biased sample of both published and grey literature. The search was limited to publications in English, but articles in other languages (e.g. French or Portuguese) but with an English summary or abstract were also included. The searches were conducted through specialist peer-reviewed publication databases in order to best capture a broad spectrum of agronomic, environmental or economic literature base as well as individual journals or repositories to offer a platform to capture regionally specific or further freely accessible literature. The peer-reviewed publication databases included: Web of Science (CABI: CAB abstracts®, core Collection, BIOSIS citation index, Current content connect, Data citation index, MEDLINE®); SCOPUS; PubMEd; Science4Life; Science direct; and Springerlink. Individual journals or repositories included; African Journals Online (AJOL), Directory of Open access Journals (DOAJ); CGSpace-CGIAR and International Society of Precision agriculture (ISPA; ispa.org).

Search terms

Based on the research question "To what extent has precision agriculture been studied in SSA?", the following search string was used to search the online databases:

> "sub-SaharanAfric*" OR Afric* OR "Afric* countries" AND "precision agriculture" OR "precision farming" OR "site specific farming" OR "climate smart agric*" OR "variable application" Or "crop sensors" or "soil sensors" OR "proximal soil sensors"

However, for African online journals and the repositories (cgspace.cgiar.org and ISPA), the search string was changed due to differences in database functionality to: "precision agriculture" AND "sub-Saharan Africa countries ".

The results of the searches were imported into the Zotero reference manager (Zotero 5.0.60) ("Zotero – Roy Rosenzweig Center for History and New Media" 2006). Separate folders were created in the main library for each of the databases/website searches made. The main library captured the total number of references stored in the various folders and this number was recorded. Using the duplicate function in the Zotero software, duplicates

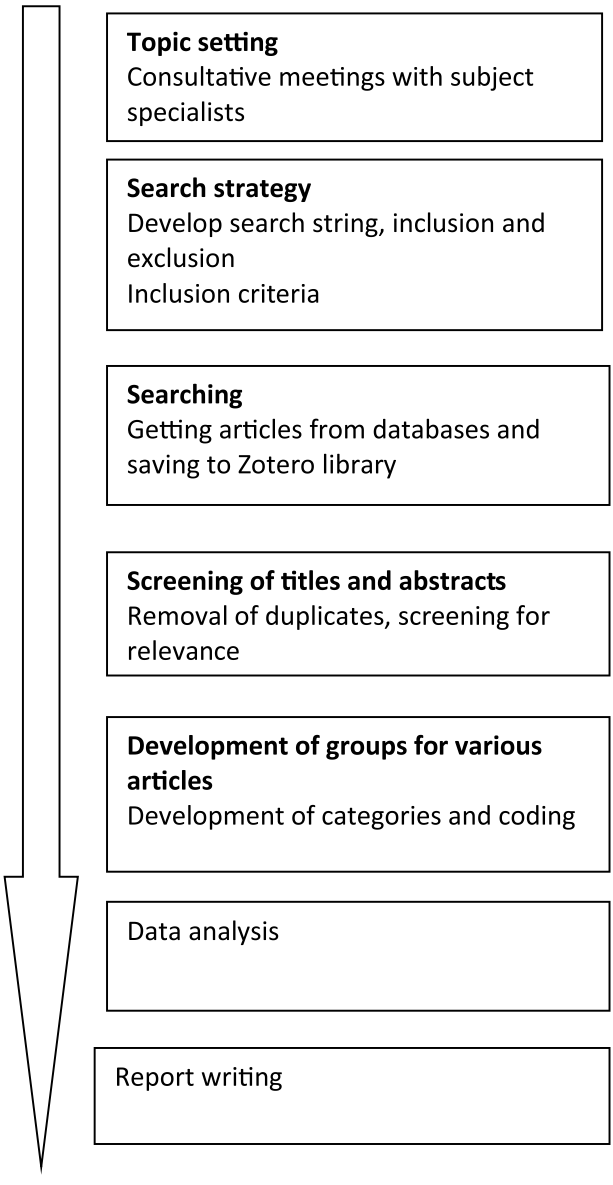


Fig. 1 Stages of mapping (adopted from Clapton, Rutter and Sharif (2009) in Randall and Katy (2012) with modifications)

of similar format were removed while duplicates of different file formats were retained (book, book chapter, book review and article).

Inclusion/exclusion criteria

The library was then screened for references with relevant topics according to the following inclusion criteria:

(i) Studies that have used precision agriculture/climate smart/site specific farming/ smart farming concepts fully or partially in SSA
(ii) Studies that have used precision agriculture/climate smart/site specific farming/ smart farming concepts/conservation agriculture elsewhere, fully or partially, but with SSA links. These were considered relevant and included.

Screening

A first screening was done on title level excluding titles which were clearly on studies done outside the geographic scope of SSA (SSA), or outside the general topics of agriculture, environment and economics.

A second screening was done on abstract level. Studies without available abstract or summary or without an English abstract were excluded. Abstracts outside the geographical scope of SSA or with no geographical identity were also excluded. Abstracts outside the general topics of agriculture, environment and economics, or abstracts that only mention precision agriculture concepts without any supporting data on its application in SSA or without precision agriculture data or information were excluded as well.

The inclusion and exclusion criteria were applied by two reviewers to all studies at title and abstract level. At this stage, screening was done up to the abstract level only, and so full text was not retrieved. Whenever it was not clear whether a study met the criteria the two reviewers consulted a third reviewer. The reviewers discussed the procedures to ensure a consistent understanding of the criteria at both levels of screening and in the following classification and analysis of the final database.

Screening included classifying articles as precision agriculture studies based on the nature of the study and the reasons for which the study was done as follows:

(i) The types of intervention that a study sought to address: Interventions that aimed to improve land, crop and animal productivity, and they included soil mapping, crop mapping, growth monitoring, water, nutrient and pest management, yield predictions, and animal pest control and monitoring
(ii) Types of outcome: Evidence of precision agriculture concepts in use on agronomic, environmental or economic outcomes.
(iii) Types of study: Any type of study that investigated precision agriculture concepts was considered, including terms such as precision farming, site specific farming and climate smart agriculture that are closely related to precision agriculture concepts. Only primary research studies were incorporated into the final systematic map. After the screening, articles were then classified into the geographical locations in which the studies were done, scale of the study and on the key subject area that the study addressed.

Coding for the systematic map

Geographical location and scale

Studies were categorised based on the countries in which they were conducted in SSA. Further, they were categorized according to whether they were conducted in small or large scale farms. Besides the scale of the farm sizes, the articles were also categorised according to the scale of the study. These included farm, field, village, county, catchment and country scales.

Key subject area

Keywords were used to describe, categorize and code studies. The keywords were generated from the primary question, expert knowledge in the subject area and topics reported in the studies. Studies were placed in six (6) broad categories based on the PA technology used, but were further put in fourteen (14) specific categories. The six categories were: Microdosing; Variable rate application; Mobile phone and related technologies; Modelling; Sensors; and GIS, remote Sensing and Drones. The fourteen specific categories were:

- *Crop management-protection* Studies on control of weeds, insect pests and diseases
- *Crop management-water* Studies to determine the irrigation frequency;
- *Crop management-nutrients* Studies that have focused on the rates of nutrient use/requirements by crops
- *Crop mapping* Studies to estimate area under a specific crop in a given area;
- *Soil mapping* These consisted of studies involving determination of soil nutrient variations for fertilizer application and determination of soil properties for either fertilizer application or irrigation requirements;
- *Growth monitoring-plants* These included studies on determination of water requirements, nutrient status, or land cover change within a field crop;
- *Animal monitoring* Studies that have focused on use of technology to monitor growth, movement, and productivity of livestock
- *Animal protection* Studies that have focused on use of precision agriculture concepts in protection of animals from pests and diseases
- *Conservation agriculture* Studies to control infestation, deforestation and encroachment;
- *Plant yield prediction* Studies to quantify good and bad areas of the field or farm to determine the expected yields;
- *Plant yield enhancing* Studies that involved the precision agriculture practices carried out to improve crop yields;
- *Testing Geographical Information System and Remote Sensing tools* These included all studies carried out to test GIS and remote sensing (RS) tools that have been used in precision agriculture.
- *Testing of sensors* These included studies in which proximal sensors have been tested for use in precision agriculture.

Critical appraisal

Articles used in the final database were checked at full text for their relevance and reliability as an indication of their quality. The overall quality was determined by scoring standard research design categories for each article. Each article was given a value based on a system of evidence designed following systematic review guidelines for conservation as described by Pullin and Knight (2001) and a system adapted from their subsequent method (Pullin and Knight 2003). This scoring system provides a quality comparison for the studies. The scoring system was designed for biological and agronomic research, and is most useful in those domains. The Pullin and Knight scoring system may be less useful for engineering, economic and social science research. Quality scores were given to the articles based on the following research design categories: Study type, Study length, Randomization, Control and Replication (Table 1). The quality scores in the different categories were combined and used as indicators of the quality of studies used in the systematic map.

Results and discussion

Literature included and excluded at every stage of the screening process, including the resulting number of studies in each step is described in Fig. 2. A total of 7715 articles were collated from the 14 databases accessible through the Swedish University of Agricultural Sciences (SLU) library and these were reduced to 6 693 after removing duplicates. Of these articles, the highest hits were recorded in Scopus with 2 852 articles, representing 41% of the total number and the lowest was in Directory of Open Access Journals (DOAJ) at 0.03% (Fig. 3). However, all the articles were put in a common

Table 1 Study quality scoring system used to assess the relevance and reliability of articles in the systematic map

Research design category	Quality attribute	Quality score
Study type	Manipulative study	3
	Correlative study	2
	Monitoring study	1
	Sampling study	0
Study length	Study done over one or more years	1
	Study done in under one year	0
Randomization	Full or partial randomization	1
	No randomization	0
Control	Before and After Control (BACI) design	3
	Control	2
	Comparisons	1
	No control	0
Replication	Temporal and Spatial replication	2
	Temporal or Spatial replication	1
	No replication	0

Adapted from Pullin and Knight (2003)

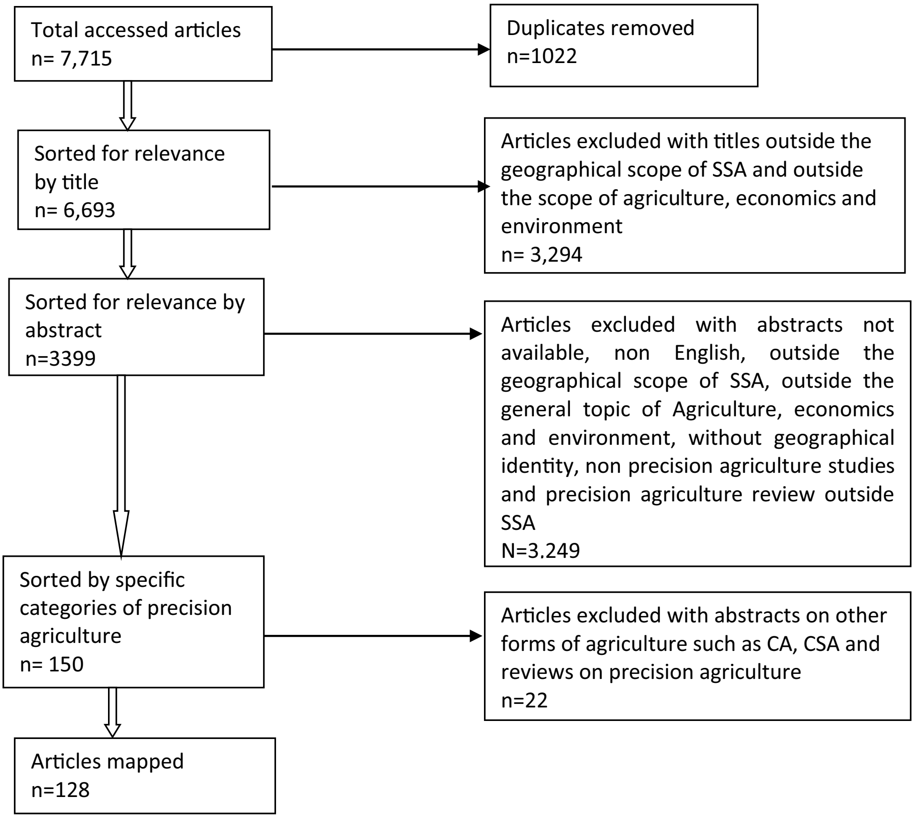


Fig. 2 Literature included and excluded at every stage of the systematic mapping process

database from where they were screened primarily at the title and abstract levels. The three areas of agriculture, environment and economics were considered to be most relevant to precision agriculture and in which research on the area is most likely. A total of 2 012 articles were removed at the title screening level, leaving 4 681 articles for screening at abstract level. Screening at the abstract level revealed 394 articles that had no abstracts, Twenty-one articles that had abstracts in other languages than English while abstracts of 1 282 articles were outside the geographical scope of SSA. It also identified 358 articles that were outside the general topics of agriculture, economics and environment, 1 058 articles that did not identify the geographical area where they were conducted, and 1 238 articles in the fields of agriculture, economics and environment but without data on precision agriculture. In addition, 68 review articles were on precision agriculture concepts but conducted outside the geographical scope of SSA. All these articles were excluded from the database of articles considered for the map. Screening out all these articles at the abstract level excluded a total 4,419 from the database, leaving 262 for the final screening process. Since this map only considered articles with primary data, all review articles were excluded, although considered relevant in the general analyses of precision agriculture. These included 112 review articles on precision agriculture concepts covering the scope of SSA.

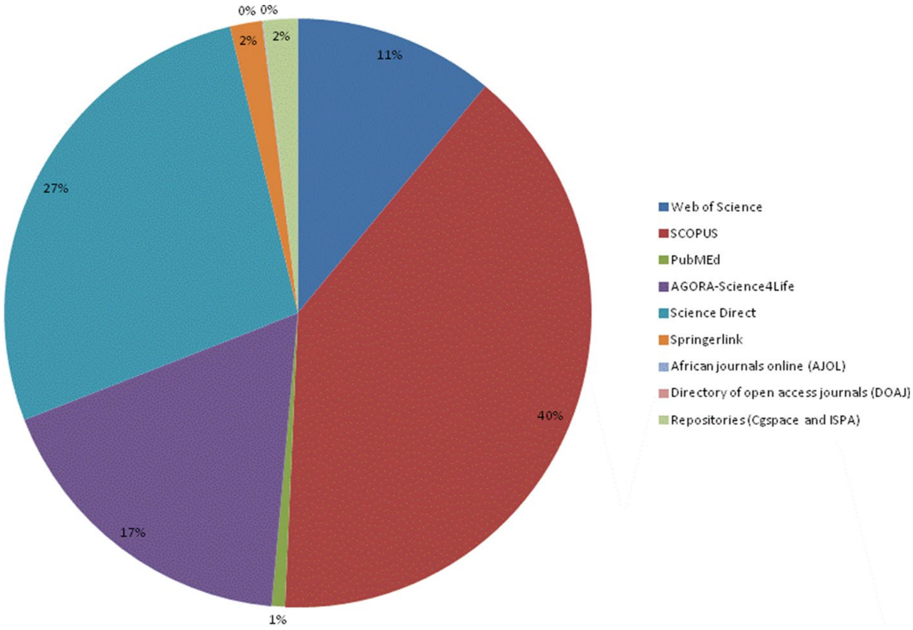


Fig. 3 Percentages of articles accessed from various databases

Sorting by specific categories of precision agriculture

The final screening process was also at the abstract level but involved sorting out the 150 articles into the different forms and concepts that have variously been used to describe precision agriculture and precision farming in SSA. In some of the articles where the form or the concept of precision agriculture used was not clear in the abstract, screening was extended to the full text. From these articles, three different categories of the various forms and concepts of precision agriculture were identified. These were CA, CSA and PA itself. Some of the work that has been done on precision farming in SSA has taken the form of either CA or CSA (Tittonell et al. 2016). Out of the 150 articles, 22 were found to be in either of these two categories, and only 128 were categorised as Precision Agriculture following the definition by ISPA (2018). These (128) are the articles that were included in the systematic map (Fig. 2).

Final database

Geographical distribution and scale

The results showed that the precision agriculture research as mapped and categorized in this study was mainly conducted in 25 SSA countries (Figs. 4, 5). South Africa had the highest number of studies at 35 followed by Nigeria (19), Kenya (16) and Niger (11). Togo, Mauritania, Burundi, South Sudan and Madagascar had only one study each conducted on precision agriculture. This trend appears to be synonymous to the social-economic and

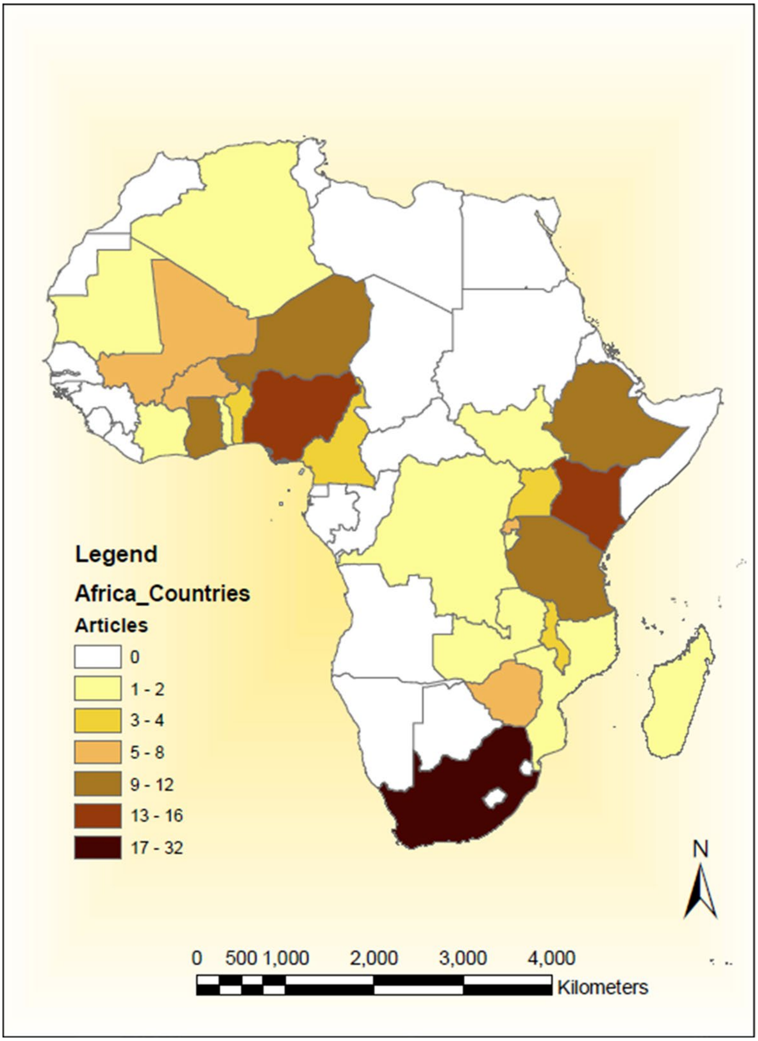


Fig. 4 Geographical distribution of number of precision agriculture studies per country in SSA

technological advancements of these countries. Precision agriculture is said to be technology dependent (Robert 2002), due to its heavy reliance on advanced machinery and computer software. These are closely related to social economic development. South Africa being the most economically advanced country in sub-Saharan Africa is expected to offer a more conducive environment for precision farming relative to other African countries. Countries such as Togo, Mauritania, Burundi, South Sudan and Madagascar have more social-economic and technological challenges and thus their capacity for precision farming is greatly limited.

The studies were conducted at various scales, from smallholder plots, fields, farms, village, county, catchment and country. Most of the studies (54) were conducted at field scale (Fig. 6). In Africa, most farmers are small holders where precision agriculture is rarely practiced. Field scale studies appear to have been done mainly in farming units owned by

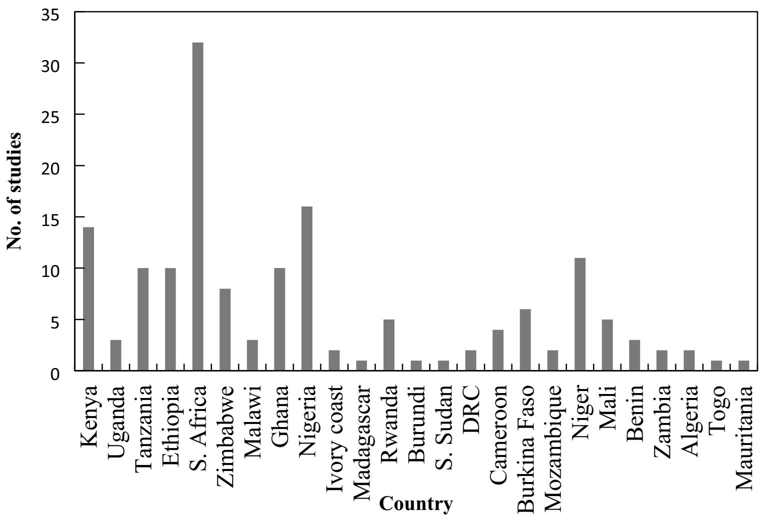
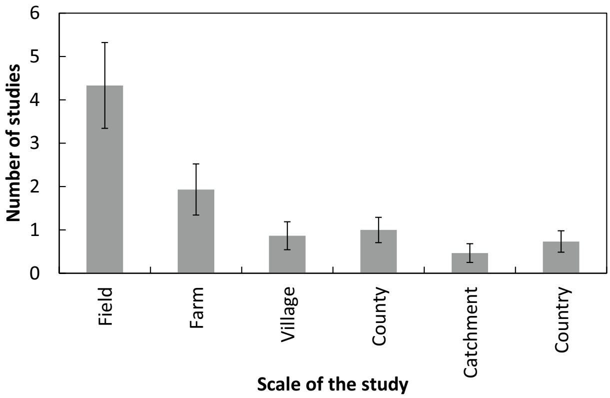


Fig. 5 Number of studies conducted in the various countries in SSA

Fig. 6 Means of the number of precision agriculture studies conducted in SSA at various scales



companies and multinational organisations. Such organisations often have a greater access to financial and monetary capital with greater possibilities of investing in precision farming. There were 29 studies conducted at the farm scale and 17 at the county scale suggesting that the farm was a more common study unit compared to a county. This may be linked to the fact that farming in units that transcend counties is rare. There were 13 studies conducted at village scale, 16 at country scale and only 6 at catchment scale. Most farming systems in SSA are organised as either small holder plots or village and home fields which are relatively large farm units within a village or a home (Tittonell et al. 2016). Farming systems at the village and catchment scales are rare, and this could partly explain the low numbers of studies conducted at these two levels. Studies at the country scale would have to be driven by governments and this is a rare occurrence in SSA.

The authors of most of the studies were either from outside SSA or working with those from the region (Fig. 7). Authors from outside SSA and a combination of these with those

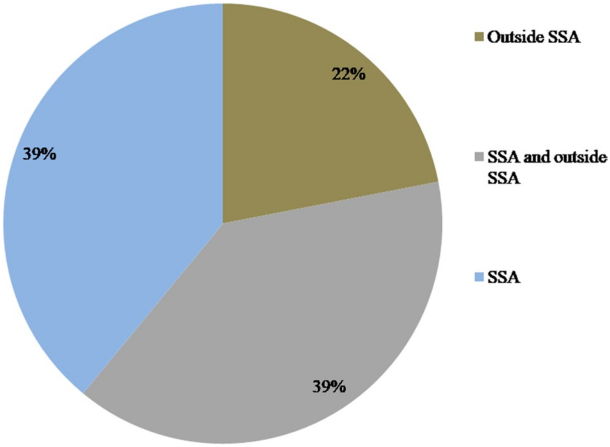


Fig. 7 Percentage contribution of authorship on studies done in SSA on precision Agriculture

from the region contributed 61% of the studies, individually contributing 22% and 39% respectively. Articles by authors from within the region represented 39% of all the studies. This implies that most of the studies conducted in SSA on precision agriculture have either involved or depended on non-African researchers. This may be attributed to the social economic and technological challenges in SSA. Most of researchers that are external to SSA were from the more developed countries, e.g. United States, United Kingdom, Germany, France, Sweden, Denmark, Spain and Italy. Their contribution to research in Africa is very significant in many fields, and is leading in exporting research on precision farming to the continent.

Type of PA studies

The 128 studies on PA in SSA were grouped in 14 specific categories based on the reason for which PA was practised in the farms on which the studies were done (Fig. 8). These reasons ranged from resource management for improved productivity to testing of PA tools like sensors and information management computer software. Majority of the studies were conducted on soil mapping (31), crop mapping (18) and growth monitoring of plants (18). The least number of studies were conducted on animal protection (1) and animal monitoring (3). The few studies on animals relative to those on crops may be attributed to faster evolution in precision agriculture in crops relative to extensive livestock of the type practiced in most of Africa. Worldwide, precision livestock technologies are widely used for intensive livestock (e.g. confined dairy, swine and poultry), but only rarely for extensively grazing livestock. A majority of the PA studies did not specify the relative farm sizes on which they were conducted (53), but most of those that did were conducted in relatively smaller farms (Fig. 9). This may be attributed to the fact that most arable land in SSA is divided into small parcels and farming is carried out at small holder levels mainly by family units. Large farm sizes are few and are mainly owned by government institutions, multinational organisations, companies and a few individuals.

While most of the studies done on the various PA categories were on small farm sizes, there were incidences where the opposite was true. Studies done on conservation, growth monitoring of plants; enhancing of crop yields, crop management in terms of

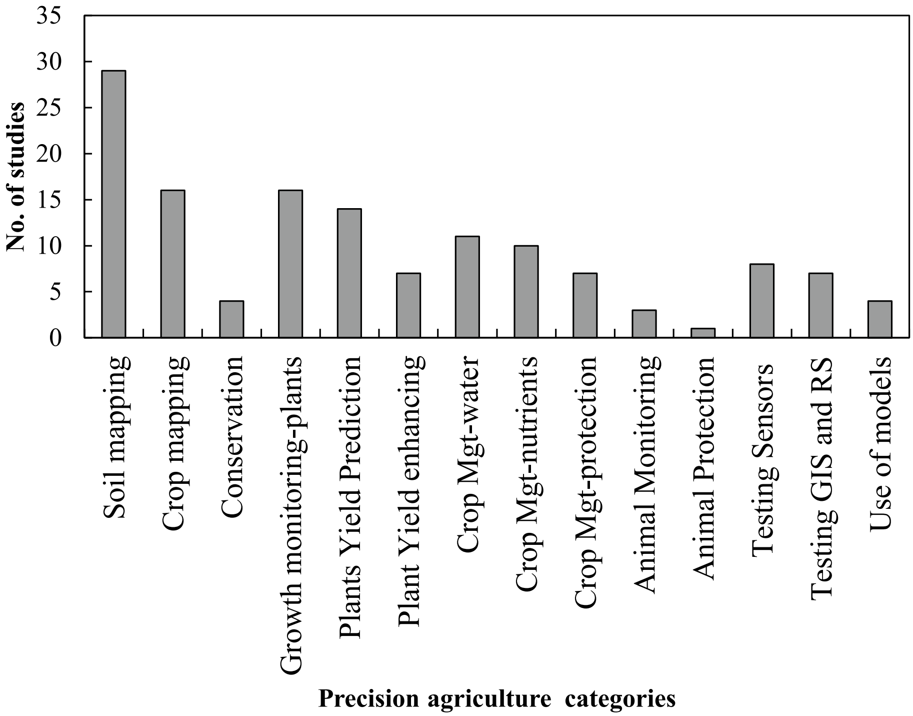
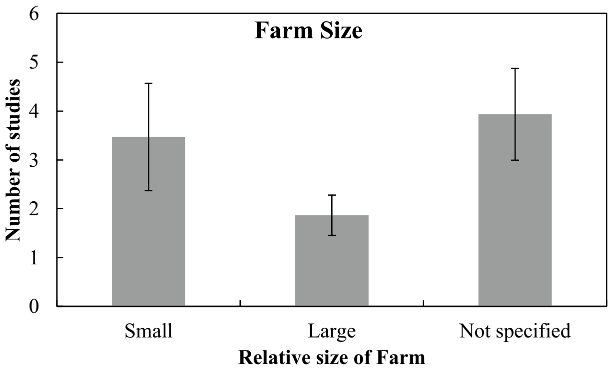


Fig. 8 Number of studies conducted under different precision agriculture categories in SSA

Fig. 9 Number of studies conducted on various relative farm sizes



nutrients and testing GIS and RS were more on large scale farms than small scale farms. Studies investigated different topics in both farm sizes. For example, Forkuor et al. (2017) used GIS and RS for yield mapping and quantity intensification on a large farm in Burkina Faso, while a study by Difallah et al (2017) used GIS and RS for growth monitoring to determine water stress and pest monitoring in a small sized farm.

Related review articles

The screening also identified 112 review articles on PA and related PA concepts within SSA. While most were dealing with the latter, only five articles (Aune et al. 2017; Tittonell et al. 2016; Rilwani and Ikhuoria 2006; Blackmore 2003; Cook et al.2003) could be said to fall under strict PA. Following the 14 broad categories of PA identified for primary research articles above, three of the reviews can be categorised under enhancement of plant yield, one would fall in the category of growth monitoring of crops and one on soil mapping. One of the reviews focused on PA in one country (Nigeria), whereas the others reviewed PA research in several, though different, African countries. Except for one article whose authorship is from SSA, the other four had authors from outside SSA.

Quality of relevant papers

To assess the quality of the articles included in the systematic map, five design criteria were used for each study: Study type; Study length; Randomization; Control; and Replication (Table 1). The maximum and minimum possible total quality scores for every article were 10 and 0 respectively, and an overall average of 2 scores. Randomization at either partial or full scale was the commonest quality attribute amongst the studies (94.6%) while lack of randomization was least common (5.8%) (Table 2). This research design category also had the highest difference between its quality attributes (Fig. 10). Such differences are expected in any database of scientific research articles since randomization is a key aspect of many research designs.

The study type and control design categories had the highest number of quality attributes (manipulative, correlative, monitoring and sampling studies for study type and Before and After Control (BACI), control, comparisons and no control for Control category) (Table 1). However, although most of the studies were under sampling (52) for study type category and no control (54) for the Control category, and the least under correlative (18) for the study type category and BACI for the Control category, the two had a more even distribution across all attributes compared to the other three (Table 2; Fig. 10). Since the systematic map targeted original research articles, this is an expected trend as original articles in agriculture and conservation are often sample based and with reasonable levels of control where applicable. Most of the studies (85) were concluded under one year and a similar number were replicated either spatially or temporally (Table 2).

Table 2 Percentages (and numbers) of studies under the five different research design categories per the quality scores of the different attributes

Research design category	Quality score			
	0	1	2	3
Study type	40.3% (52)	31.0% (40)	14.0% (18)	14.7% (19)
Study length	65.9% (85)	34.1% (44)	n/a	n/a
Randomization	5.4% (7)	94.6% (122)	n/a	n/a
Control	41.9 (54)	25.6% (33)	24.8% (32)	7.8% (10)
Replication	18.6% (24)	65.9% (85)	15.5% (20)	n/a

The scores 0, 1, 2 and 3 represent different quality attributes for each of the design categories

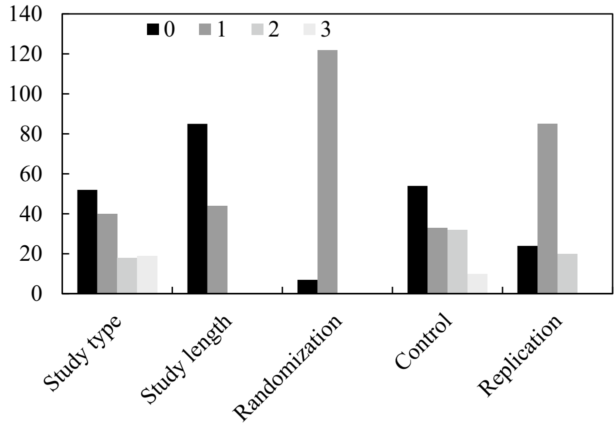


Fig. 10 Number of articles grouped according to quality attributes of different research design categories used in assessing the quality of articles in the systematic map

Research gaps

This systematic map documents primary research on precision agriculture in sub Saharan Africa. This is an important first step in exploring a largely unexplored field, and much more still remains unknown. In this regard, the map also highlights a number of areas that have been either less researched or completely unexplored, and which could form strong premises for further research. They include the following:

1. The very low volumes of primary research in sub Saharan Africa (128 articles out of the 7715 articles captured by the search string from 14 databases accessed through the (SLU) library indicates quite a low volume of research in precision agriculture. Yet still, most of these studies are concentrated in only four countries (South Africa, Nigeria, Kenya and Niger) with just a few others having one study each and the rest with none. These points to a significant potential for research in the area.
2. While most farming in SSA is smallholder, and therefore complicating possibilities for precision farming technologies that are designed for large tracks of land, there exists substantial number of large scale farmers in a number of countries in SSA where such technologies can be applied. This provides an important opportunity for precision farming in the region.
3. Microdosing is a precision farming technique that is largely specific to Africa mainly because most of the farmers are smallholder. However, there is still very little primary research work done on it in SSA (14 out of 128 studies) (Supplementary Table 1). Research in this area can greatly improve research output on precision farming for SSA.
4. GIS, satellite remote sensing and drones, together with use of sensors form the bulk of the precision agriculture technologies used in SSA with 48 and 25 studies respectively (Supplementary Table 1). While adoption rates for these technologies are still relatively low, their use is higher than other relatively cheaper technologies like mobile phone-based technologies, microdosing and variable rate application. With the high penetration of mobile phone use amongst small holder farmers in SSA, there exists significant potential for use of mobile phone-based technologies for research on precision farming.

Possible systematic review topics

The information on precision agriculture in SSA generated by this map offers an opportunity to interrogate in much greater detail various aspects of precision farming in SSA by way of a systematic review. While this map highlights important aspects of precision farming in SSA, a systematic review would aim at providing more qualitative or quantitative answers to research questions modelled around subtopics such as:

- The concentration of research in only 4 countries, with only one (South Africa) taking the bulk of them;
- Low research volumes in small holder farms despite them forming the bulk of farming systems in SSA;
- Dominance of researchers from outside SSA in PA research within SSA; and
- Low levels of PA research targeting livestock.

Based on these and other subtopics highlighted by the results of this map, a substantial amount of data could be compiled for meta-analysis that may provide answers to a number of specific research questions that include the following:

- What is the extent of the use of specific precision agriculture technologies in SSA?
- How does use of microdosing by smallholder farming communities in SSA influence productivity?
- To what extent has research in precision agriculture been embraced by governments and research institutions in SSA?
- To what extent is livestock managed using precision agriculture technologies in SSA?

Limitations of the map

Since the search string was applied only at the title and abstract levels, it is possible that some articles that lacked either of the search string words in both the title and the abstract but discuss important aspects of PA in SSA may have been left out of the search. A logical way to address this problem would be to widen the search string to include other relevant words to describe various PA technologies. The consequence however would be having a substantially high number of studies to be screened for relevance. Besides, since the field of PA is still growing especially in SSA, a wide range of words and techniques may be used to describe it.

The focus of this systematic map on studies reporting "primary data" may have inadvertently excluded some engineering research that sought to solve a technical problem, but did not collect data, and some modelling studies that focused on understanding the physical, economic and social relationships within farming systems based mostly on existing parameters. The quality scoring systems was designed for biological and agronomic research, and is most useful in those domains. The quality assessment of engineering, economics and social science research may need to be re-examined.

Prospects of precision agriculture and precision agriculture research in SSA

This map shows that out of the 46 countries in sub-Saharan Africa, there has been no scientifically published research (in the English language or with English abstract) on precision agriculture in 21 countries (Figs. 4, 5), thus presenting a significant potential for PA research in this region. Research information on PA in these countries would also be useful in evaluating the countries' potential for precision farming. There exist major variations between and within fields or farms in most of the farming systems in SSA. In these systems, there are no existing standards and precision are often lacking in resource use. In addition, advanced ways of improving them are not affordable. The situation is made worse by government recommendations on resource use that do not recognize the variability that exists between different farms or regions. Given this situation, studies that have been conducted on precision agriculture have shown great potential in improving productivity amongst small-scale farmers in SSA without extra use of inputs.

There are also very few studies focusing on extensive livestock production in SSA. While the field of precision agriculture on extensive livestock production practised in SSA is generally not as widespread as that on crops, there exists great potential for precision farming on extensive livestock production in the region. Many farmers across SSA depend on their livestock as a primary source of household food or income. The livestock sector also contributes to the economic growth of most of these countries. This reality, together with the fact that demand for animal protein continues to increase in SSA due to population growth and a rising middle class defies the trend of a sector that is often neglected when it comes to targeted investments. This represents a missed opportunity for precision agriculture studies and application in nutrition and animal health that would increase production potential and resource use efficiency.

Conclusions

Besides being a relatively new farming concept, and the many social-economic and technological challenges of precision agriculture, there have been significant strides towards its relevance and use in SSA. As expected, the testing and use of PA in SSA has followed a trend of advancement in technology with more technologically advanced countries having a higher number of studies compared to those that are least advanced. The fact that most of the within-field studies were conducted in areas where large farming is practised supports the hypothesis that primary research on PA in SSA is low due to the prevalent smallholder systems. Research on PA in SSA has mainly been conducted on soil and crop mapping, although it has also included other aspects such as crop protection and plant nutrition. However, very little research has been done on PA in animal husbandry, possibly because of the extensive livestock farming systems in SSA and that PA application in farming in Africa still is at its infancy. It is concluded that there exists great potential for growth of precision agriculture in SSA and more research that would lead to its adoption is recommended.

Acknowledgements This work was financially supported by the AgriFoSe2030 programme and Sida. Dr. Jeremiah Okeyo from the University of Embu helped in generating the geographical distribution map of precision agriculture studies per country in SSA. Furthermore, the authors are grateful to the Precision Agriculture Journal editor and two anonymous reviewers for their contributions which greatly improved the quality of the paper.

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