Maize (Zea mays L.) plays a critical role in meeting the high food demand and is globally one of the most widely cultivated crops (FAO, 2017). Both the land area used for maize grain production and the amount of maize produced per unit area have been increasing in recent years (FAO, 2017). For example, from 2000 to 2014, maize crop area harvested in the United States, China, and Brazil increased by 13, 38, and 25%, respectively (FAO, 2017). During the same period, the total maize production in these three countries increased by 31, 49, and 60%, respectively, indicating that productivity (yield per hectare) increased dramatically since the start of the 2000s in these countries. In 2014, the projected total global production of maize grain was 1037.8 Tg (FAO, 2017).

Recent increases in maize grain yield can be attributed to genetic advances and to improved agronomic practices, including optimizing plant population (Ciampitti and Vyn, 2012). Plant population has a strong influence on maize grain yield (Van Roekel and Coulter, 2011), but this relationship is highly variable (Assefa et al., 2016) and can be affected by factors such as rainfall, tillage system, fertilization, and soil type. The optimum plant population depends on several crucial factors, including soil fertility, soil water-holding capacity, and hybrid maturity group (Sangoi et al., 2002). Interactions between plant genotype and plant population can also affect maize grain yield, with a recent study conducted by DeBruin et al. (2017) finding a positive

**ABSTRACT**

Maize (Zea mays L.) productivity has increased globally as a result of improved genetics and agronomic practices. Plant population and row spacing are two key agronomic factors known to have a strong influence on maize grain yield. A systematic review was conducted to investigate the effects of plant population on maize grain yield, differentiating between rainfall regions, N input, and soil tillage system (conventional tillage [CT] and no-tillage [NT]). Data were extracted from 64 peer-reviewed articles reporting on rainfed field trials, representing 13 countries and 127 trial locations. In arid environments, maize grain yield was low (mean maize grain yield = 2448 kg ha\(^{-1}\)) across all plant populations with no clear response to plant population. Variation in maize grain yield was high in semiarid environments where the polynomial regression model had a maximum point at \(140,000 \text{plants ha}^{-1}\), which reflected a maize grain yield of 9000 kg ha\(^{-1}\). In subhumid environments, maize grain yield had a positive response to plant population. In high-N-input \((r^2 = 0.19, \ p < 0.001, \ n = 951)\) production systems, the response of plant population to applied N was weaker than in medium-N-input \((r^2 = 0.49, \ p < 0.001, \ n = 680)\) systems. There exists a need for more metadata to be analyzed to provide improved recommendations for optimizing plant populations across different climatic conditions and rainfed maize production systems. Overall, the importance of optimizing plant population to local environmental conditions and farming systems is illustrated.
relationship between maize grain yields and plant population in modern hybrids, but a contrasting response in older hybrids. Modern hybrids possess the ability to withstand greater stress attributable to high population densities than older hybrids, which in turn enables producers to establish higher plant populations, leading to higher yields per unit area (Russell, 1984; Duvick, 1997). The agronomic practices implemented in a production system should allow the selected germplasm to react positively to the increased plant populations when favorable environmental conditions occur (Haegeli et al., 2014) while also being tolerant to increased plant-to-plant competition under suboptimal growing conditions (Tokatlidis and Koutroubas, 2004). Changes in agronomic practices such as fertilization, effective weed control, and tillage practices can further alter the relationship between population density and maize grain yield. Thus, it is important to adjust plant population accordingly to achieve optimal grain yields.

During the past six decades, much work has been done to evaluate the effects of plant population on maize grain yield in a wide variety of environments and regions (Duncan, 1958; Pretorius and Human, 1987; Ciampitti and Vyn, 2012; Hörbe et al., 2013; Assefa et al., 2016; Qin et al., 2016). Rainfall is a major determinant of differences in agronomic practices used between regions. In arid and semiarid regions, rainfall is scarce and variable, and soil water is often the most limiting factor for grain production. Climatic conditions affect soil water content throughout the growing season, influencing the number of plants per unit area the soil can maintain throughout this period and, therefore, the optimal plant population. Both plant population and row spacing affect leaf canopy architecture (Sharratt and McWilliams, 2005) and, in turn, affect crop uptake of water and nutrients, as well as and light interception. To justify the establishment of low plant populations, rapid canopy closure is needed for efficient resource use. Hammer et al. (2009) found that at high plant populations, root architecture was more important than canopy architecture and light interception for increasing grain yield. The optimum plant population in low-rainfall regions is not only the function of precipitation, but also a function of the storage capacity of the soil in the rooting zone of crops.

Precipitation can also influence the choice of tillage system, as soil water content affects the level of soil compaction during tillage (Voorhees, 1987). However, the choice of tillage system can also affect soil water dynamics, which in turn influences the optimal plant population. For example, reducing soil tillage, in association with retaining crop residues to increase water infiltration and reduce runoff from the soil surface, will enhance crop yield potential under specific climatic conditions (Findeling et al., 2003; Adekalu et al., 2007; Thierfelder et al., 2015).

Maize producers in many parts of the world, particularly in developing countries where good-quality data from local trials are not available, rely on published information to make agronomic decisions. Many papers have been published on the effects of plant population on yield, but the results are associated with prevailing local environmental conditions and agronomic practices of each study. This could lead to confusion among maize producers regarding the most appropriate agronomic management decision for their specific conditions and farming systems. Thus, there is a need to consolidate these global findings to identify how plant population affects maize grain yield under different climatic and agronomic conditions. To address this, we have conducted a systematic global review of published data from rainfed (nonirrigated) maize production field trials to (i) investigate the effects of plant population on maize grain yield and (ii) determine the influence of mean annual rainfall, soil tillage, and applied N on the relationship between plant population and maize grain yield.

**MATERIALS AND METHODS**

**Selection of Studies**

To collate peer-reviewed articles, a literature search was conducted using the Institute for Scientific Information Web of Science Database (http://apps.webofknowledge.com). The “Web of Science Core Collection” option was used. No timeframe limitation was set, and the last online search was conducted on 5 Sept. 2017. The keywords used included combinations of “corn yield”, “maize yield”, “plant population”, “planting density”, “sowing rate”, “planting rate”, “corn population”, and “maize population”. When articles were unavailable online or from local libraries, a request was made directly to author(s) of the particular article to provide a reprint. Articles were read in full text and examined on the basis of the following eligibility criteria: (i) plant population was evaluated as a treatment to investigate the effects thereof on maize grain yield, (ii) data reported were generated by field experiments with sound statistical designs, and (iii) field trials received no irrigation prior to planting or during the growing season. Any article that was not in English or did not meet the above-mentioned eligibility criteria was excluded. Field trial data generated for modeling purposes were included. To overcome publication bias challenges, studies selected for analysis were not geographically limited. This ensured the inclusion of field trial data from various climatic conditions, combined with different agronomic management systems.

**Data Collection and Extraction**

Data extracted from each eligible article included spatial data (trial location and GPS coordinates), temporal data (trial year), climatic factors (mean annual precipitation), and agronomic information and data (tillage system, plant population, row spacing, applied N rate, and maize grain yield). Data were directly extracted from published tables or from digitized graphs using WebPlotDigitizer (Rohati, 2015). Maize grain yield data were standardized to a moisture content of 15.5%
and expressed in kilograms per hectare. Only treatment mean values were extracted, regardless of the number of replications. If no values were reported in the publication for plant population or if grain yield and rainfall data were reported across varying plant populations, it was recorded as a missing data point in the database.

For the purpose of this study, the plant population established at planting was extracted, except in cases where the plots were deliberately planted to a higher population and thinned at an appropriate time during the growing season to achieve specific plant populations. In such instances, the final plant populations were extracted. If GPS coordinates of the trials were not reported, the GPS coordinates of the nearest town to the trial location were used.

**Spatial and Temporal Distribution of Research**

A total of 64 articles met the eligibility criteria, which represented 13 countries from five continents. A list of articles included for analysis can be found in Supplemental File S1, with a full reference list provided in Supplemental File S2. A total of 117 trial locations were from the northern hemisphere, but only 10 were from the southern hemisphere. Out of these 127 trial locations, trials from North America were dominant (76%), followed by Asia (14%) and South America (4%) (Fig. 1). The fewest trial locations were from Africa and Europe, which each contributed 3%. Most research locations represented humid environments. Sixteen field trials were conducted in semiarid and super-humid environments, whereas only three were conducted in arid environments. A spatial distribution of research in our study was biased towards the northern hemisphere, with the southern hemisphere being poorly represented (Fig. 2).

From 1966 to 2015, the majority of plant population field trials had been conducted under conventional tillage (CT) practices, with trials under no-tillage (NT) first performed only in 1986 (Fig. 3). Both CT and NT showed an increase in the number of trials conducted during 1996 to 2000, with 19 and 14 trials, respectively. Establishing the optimal plant population is basic agronomic information needed for newly introduced NT systems, and thus trials on NT increased noticeably after 1995, as NT systems increased in popularity around the world. The number of trials involving NT decreased after 2000 and remained fairly constant until 2015, presumably because the optimal plant population was established for NT systems by 2000. However, even though there was an increase in trials under NT after 1995, the number of trials conducted under CT remained higher.

**Dependent Variables of Interest**

In this study, plant population refers to the seeding rate at the start of the growing season (i.e., the intended number of plants per unit area). Producers can alter both plant population and row spacing independently, for example, by keeping the plant population constant while increasing the row spacing, by altering the intra-row spacing (spacing between two plants in the same row) but keeping the row spacing constant, and through different intermediate configurations.

The optimal plant population for a region is dependent on the prevailing soil and climatic conditions. Therefore, comparing studies conducted in regions with dissimilar soil physical characteristics that influence water-holding capacity or with dissimilar mean annual rainfall will lead to erroneous results and conclusions. To avoid this, eligible studies were categorized into five groups according to long-term mean annual rainfall as arid (200–400 mm), semiarid (400–600 mm), subhumid (600–800 mm), humid (800–1000 mm), and super-humid (>1000 mm). The effect of tillage system was analyzed by comparing NT systems with CT systems across different plant populations. For the purpose of this study, any form of tillage or soil disturbance other than direct drilling with seed drills was described as CT, as suggested by Reicosky (2015). Minimum tillage (strip-tillage) was performed in three studies, which were classified as CT (soil cover percentage was either not reported or low). Possible interactions between rainfall and tillage systems could not be investigated because of the absence of NT trials in several rainfall categories.

The effect of plant population and N fertilizer input on maize grain yield was also investigated for studies that reported N fertilizer input. Studies were categorized into three groups according to the total N applied: low (<100 kg N ha$^{-1}$), medium (100–200 kg N ha$^{-1}$), and high N input (>200 kg N ha$^{-1}$). This includes N applied before planting, at planting, and as side-dress applications at various growth stages.

**Fig. 1. Distribution of field trial locations in different countries and continents located in the various rainfall groups.**
Data were also stratified according to soil textural class, organic matter content, soil bulk density, percentage soil cover, and previous crop. However, the abovementioned results are not shown, as there was either no clear response or not enough reports of these factors to reflect a representative situation.

Statistical Analysis

A general regression model (GRM) was used to plot standardized maize grain yield against plant population. Different regression models were tested, and a quadratic regression model provided the best fit to the data, as measured by $R^2$. The $R^2$ was calculated using the proportion of variability around the mean for maize grain yield that was explained by plant population.

Data were optimized by profiling the desirability of maize grain yield responses to plant population and row spacing simultaneously according to procedures described by Derringer and Suich (1980). This technique is commonly used for analysis of industrial data where multiple operating conditions must be optimized at the same time (Silva et al., 2013). The procedure involved two steps. First, the responses of maize grain yield ($Y_n$) were predicted by fitting the observed responses in maize grain yield using Eq. [1] that was produced from a GRM:

$$Y_n = 0.15(PP) + 8261(RS) − 3000(RS)^2 − 2880 \quad [1]$$

where PP is plant population (plants ha$^{-1}$) and RS is row spacing (m). Second, the plant population and row spacing that simultaneously produced the most desirable (highest) predicted maize grain yield were then obtained. This transformation was performed by the desirability ($d$) function in Eq. [2]:

$$d_n = \begin{cases} 0 & \text{if } \hat{Y} < Y_{\min} \\ \frac{\hat{Y} - Y_{\min}}{Y_{\max} - Y_{\min}} & \text{if } Y_{\min} \leq \hat{Y} \leq Y_{\max} \\ 1 & \text{if } \hat{Y} > Y_{\max} \end{cases} \quad [2]$$

where $\hat{Y}$ is mean maize grain yield, $Y_{\min}$ is the minimum maize grain yield, and $Y_{\max}$ is the maximum maize grain yield.

Scores were assigned to predicted maize grain yield ranging from 0 (very undesirable, i.e., low maize grain yield) to 1 (very desirable, i.e., high maize grain yield). The individual desirability scores were then combined to obtain an overall desirability ($D$) as a geometric mean:

$$D = \left(d_1 \times d_2 \times \cdots \times d_n\right)^{1/n} \quad [3]$$

The regression coefficients of Eq. [1] were standardized to a mean of 0 and SD of 1 to evaluate the relative contribution of plant population and row spacing to the overall prediction of maize grain yield. The standardized coefficients were 1.35, −0.86, 0.39, and −0.30 for plant population, (plant population)$^2$, row spacing, and (row spacing)$^2$, respectively. The computer package Statistica version 13 was used for all statistical analyses (TIBCO Software, 2017).

RESULTS

Impact of Plant Population on Maize Grain Yield

The responses of maize grain yield to plant population in rainfall groups are presented in Fig. 4. In arid environments (Fig. 4a), maize grain yield was low across all plant populations ($r^2 = 0.05$, $p < 0.05$, $n = 87$), with no clear response to plant population. Maize grain yield was
Plant population were conducted in humid environments (Fig. 4d, \(n = 1794\)). An increase in maize grain yield was recorded up to a plant population of 120,000 plants ha\(^{-1}\), after which yield declined. The polynomial regression indicated a maize grain yield of 11,000 kg ha\(^{-1}\) at a plant population of 120,000 plants ha\(^{-1}\) (\(r^2 = 0.233, p < 0.001, n = 1794\)).

In super-humid environments (Fig. 4e), a positive response of maize grain yield to plant population was highly variable across the reported plant populations in the semiarid, subhumid, and humid environments. In semiarid environments, the polynomial regression (\(r^2 = 0.131, p < 0.001, n = 951\)) had a maximum point at \(\sim140,000\) plants ha\(^{-1}\), which reflected a maize grain yield of 9000 kg ha\(^{-1}\) (Fig. 4b). In subhumid environments (Fig. 4c), maize grain yield could not be explained by plant population (\(r^2 = 0.07, p < 0.001, n = 937\)). Most studies on plant population were conducted in humid environments (Fig. 4d, \(n = 1794\)). An increase in maize grain yield was recorded up to a plant population of 120,000 plants ha\(^{-1}\), after which yield declined. The polynomial regression indicated a maize grain yield of \(\sim11,000\) kg ha\(^{-1}\) at a plant population of 120,000 plants ha\(^{-1}\) (\(r^2 = 0.233, p < 0.001\)). In super-humid environments (Fig. 4e), a positive response of maize grain yield to plant population was...
found \( r^2 = 0.48, p < 0.001, n = 133 \) with a maximum yield \( (12,000 \text{ kg ha}^{-1}) \) at \( \sim 110,000 \text{ plants ha}^{-1} \).

**Relationship between Plant Population and Row Spacing**

A desirability function was used to express the relationship between plant population and row spacing (Fig. 5), where 0 indicated a very undesirable score (i.e., a low maize grain yield) and 1 indicated a very desirable score (i.e., a high maize grain yield). The desirability contours ran mostly in parallel to row spacing, indicating that row spacing had a small effect on maize grain yield, explaining only 23.8% of variance in maize grain yield, according to the GRM. Plant population had the most influence on maize grain yield, explaining 76.2% of the variance. The highest desirability scores were achieved at plant populations of \( \geq 80,000 \text{ plants ha}^{-1} \). The lowest desirability was obtained when plant population was low in combination with narrow row spacing.

**Soil Tillage Systems**

Maize grain yield increased for both CT and NT systems as plant population increased (Fig. 6a and 6b). The polynomial regressions showed maximum points at \( \sim 120,000 \) and 110,000 plants ha\(^{-1}\) for CT \( (r^2 = 0.19, p < 0.001, n = 2542) \) and NT \( (r^2 = 0.66, p < 0.001, n = 381) \), respectively. Maximum points on the regression line corresponded to maize grain yields of \( \sim 9000 \) and 11,000 kg ha\(^{-1}\) for CT and NT systems, respectively. A decrease in maize grain yield for both systems was evident for plant populations of \( \geq 110,000 \text{ plants ha}^{-1} \). More variation in the data was found across all plant populations for CT systems than for NT systems. Grain yield varied from 110 to 18,800 kg ha\(^{-1}\) for plant populations of between 60,000 and 90,000 plants ha\(^{-1}\) in CT systems (Fig. 6a) and between 700 and 16,100 kg ha\(^{-1}\) in NT systems (Fig. 6b).

Low yields at the higher plant populations were reported for both CT (Fig. 6a) and NT (Fig. 6b) systems. The severe constraints on maize grain yield might be unrelated to plant population and could have been the effects of poor agronomic management or soil factors in combination with the tillage system. For example, NT in a poorly drained or easily compacted soil could cause low maize grain yield regardless of the plant population. We examined whether soil textural class may be contributing to the variable yields for the CT and NT systems by stratifying the data by soil texture class. However, there were too few data points for the tillage systems in each of the soil texture classes to identify a significant impact of textural class.

---

**Fig. 5.** The relationship between predicted responses of maize grain yield on plant population and row spacing and the desirability of responses \((0 = \text{very undesirable}, 1 = \text{very desirable})\).

**Fig. 6.** Maize grain yield as affected by plant population in (a) conventional tillage \( (r^2 = 0.19, p < 0.001, n = 2542) \) and (b) no-tillage \( (r^2 = 0.66, p < 0.001, n = 381) \) across various rainfall groups.
Response of Plant Population to Applied Nitrogen

The response of plant population to applied N is presented in Fig. 7a to 7c. Large variation was found in all N input systems, particularly in low-N-input systems. As a result, no clear-cut responses of plant population to applied N in these systems were noted ($r^2 = 0.07, p < 0.001, n = 525$) (Fig. 7a). As plant population increased in medium-N-input systems, maize grain yield increased and reached a maximum point at $\sim 110,000$ plants ha$^{-1}$, corresponding to an average maize grain yield of 10,000 kg ha$^{-1}$ ($r^2 = 0.49, p < 0.001, n = 680$) (Fig. 7b). For maize plant populations $>110,000$ plants ha$^{-1}$ in medium-N-input systems, maize grain yield penalties could be expected. In high-N-input systems, the response to applied N was weaker than in medium-N-input systems (Fig. 7c), although not as weak as in the low-N-input systems. The quadratic regression ($r^2 = 0.19, p < 0.001, n = 2018$) showed a maximum point at 150,000 plants ha$^{-1}$, reflecting a maize grain yield of $\sim 10000$ kg ha$^{-1}$. Beyond this maximum point, maize grain yields declined. For all N input production systems, it was clear that N fertilization did not explain much of the variation in maize grain yield in studies in which effects of plant population were evaluated.

DISCUSSION

Impacts of Plant Population on Maize Grain Yield

Across all plant populations, very few observations were obtained for arid environments (Fig. 4a), as rainfed maize production is uncommon in arid regions because of low and erratic rainfall. Plant population appeared to have no effect on maize grain yield in arid environments, even when plant population increased from 30,000 to $>120,000$ plants ha$^{-1}$. Arid regions are usually characterized by high annual and seasonal rainfall variability. Low plant populations in arid environments would usually be expected to carry less risk of crop failure, even though a yield penalty could be expected in years with good rainfall (Birch et al., 2008). This could be a reason for data showing that plant populations as high as 150,000 plants ha$^{-1}$ could have similar yields to populations of 30,000 plants ha$^{-1}$. Another factor

![Fig. 7. Maize grain yield as affected by plant population in (a) low-N-input ($r^2 = 0.07, p < 0.001, n = 525$), (b) medium-N-input ($r^2 = 0.49, p < 0.001, n = 680$), and (c) high-N-input ($r^2 = 0.19, p < 0.001, n = 2018$) systems across various rainfall groups.](image-url)
that could explain yields obtained at high plant populations in arid environments could be soil characteristics such as texture and organic matter content that affect soil water-holding capacity. Usually, in environments with such low mean annual rainfall, irrigation practices are followed to ensure crop growth throughout the growing season.

A few studies reported very low yields at plant populations of >80,000 plants ha⁻¹ (Fig. 4b and 4d). In one study, where plant populations of 180,000 and 250,000 plants ha⁻¹ were evaluated under semiarid conditions, a soil water deficit was observed during the silking stage in one of the trial years (Westgate et al., 1997). It has been shown that water stress during this critical growth stage decreased kernel set in the apical ear region, as well as kernel dry matter yield (Setter et al., 2001). Apart from varying plant populations, hybrid choice to match the duration of the growing season and to avoid water and heat stress during critical growth stages should also be a strategy that producers use to minimize risk of crop failure.

Rainfed maize production in semiarid environments plays an important role in grain production in various countries, such as the United States, China, Hungary, and South Africa (Bennie and Hensley, 2001; Blumenthal et al., 2003; Lente, 2009; Li et al., 2011). Our findings indicate that maize grain yield varied substantially in these environments (Fig. 4b), which can be attributable to inconsistency in rainfall (Blumenthal et al., 2003; Allen, 2012). Blumenthal et al. (2003) suggested that, if possible, producers could use long-range weather forecasts to estimate potential grain yield at planting and alter the plant population accordingly to limit the chance for grain yield losses.

The highest maize grain yields were found in more humid environments at plant populations of between 90,000 and 120,000 plants ha⁻¹. maize grain yield typically decreased when plant population reached >120,000 plants ha⁻¹ (Fig. 4d). In these environments, variation in maize grain yield can be caused by factors such as competition for water, nutrients, sunlight, and space, as well as agronomic factors such as planting date, hybrids, weed and pest control, and tillage (Begna et al., 2001; Shrestha et al., 2001; Pedersen and Lauer, 2003; Van Roekel and Coulter, 2011; Crozier et al., 2014). For example, when water stress occurs, crop responses to applied N are poor and lead to yield decreases (Clay et al., 2005). Split applications of N fertilizer would be recommended to apply proportionally more fertilizer during times when soil water is still available. Therefore, various factors modify the effects of plant population on maize grain yield and should be managed according to the prevailing conditions and resources.

Modern maize hybrids exhibit tolerance to drought, pests, and diseases, contributing to the well-documented increase in maize yields over time. From a comprehensive review of maize yield advances through breeding by Duvick (2005), it is clear that most maize hybrids has a similar production potential when grown in a stress-free environment (i.e., very low plant populations). However, modern hybrids’ tolerance to stress, which is induced by greater plant to plant competition, has increased as a result of breeding for yield under higher plant populations. Maize breeding has therefore resulted in an increased production potential when interplant competition occurs but has not increased production potential per plant (Duvick et al., 2004). Manipulating plant population is therefore an important consideration for producers to realize maize production potential.

**Soil Tillage and Crop Management**

The optimum plant population was lower for NT than CT systems, but at a given plant population, maize yields were higher in NT than in CT systems. When cultivating maize in soils sensitive to compaction and poor drainage, tillage may be advantageous by increasing drainage and root growth to deeper soil layers. This may, in turn, enable these soil types to sustain higher plant populations and narrower row spacings. Conversely, soils managed under NT practices can have higher water-holding capacity in variable climates than soils managed under CT (Thierfelder et al., 2015). Improved water storage, infiltration, and movement in soil, due to higher aggregate stability and organic matter content, are among the most important characteristics of NT soils (Yimer et al., 2008; Verhulst et al., 2010).

No-tillage is often, though not always, practiced as part of a conservation agriculture (CA) management system. Conservation agriculture is based on a combination of agronomic practices, including (i) reduced tillage or NT, (ii) permanent soil cover by either crop residues or cover crops, and (iii) crop rotations with three or more different crops. When assessing the effects of NT, it is important to keep in mind that NT alone may not be sufficient in achieving positive grain yield results. Higher grain yields attributed to NT may be the combined effect of multiple factors, such as retention of crop residues, crop rotation, and improved technology. This, in turn, may lead, to reduced pest infestation, improved soil quality, specifically increased organic matter content, and increased water use efficiency, among other things (Rusinamhodzi et al., 2011).

Our results show the number of plant population trials involving NT increased significantly after 1995 (Fig. 3). As expected, trials conducted under CT remained high throughout all eras, with an increase in the number of trials performed after 1995. These results correspond with the findings of Derpsch (1998), Triplett and Dick (2008), Derpsch et al. (2010), and Derpsch and Friedrich (2010). Derpsch (1998) and Derpsch et al. (2010) attribute the rise of NT adoption since the 1990s to expansion into climates and soil types earlier thought to be unsuitable for crop production. However, CT remains popular where the adoption of NT is inhibited by several environmental factors, such as low soil fertility, high rainfall, and high temperatures.
as climatic conditions, soil types, and crop requirements. Socioeconomic factors can also play a strong role, as Giller et al. (2009) concluded that the critical constraints for CA adoption in sub-Saharan Africa are competition for crop residues, labor issues, and the lack of external inputs.

In recent decades, maize grain yields improved with unchanged N inputs, clearly showing more effective N use by modern hybrids (Duvick, 2005; DeBruin et al., 2017). The application rate and timing of N may be altered by the producer according to the prevailing soil and environmental conditions. In regions where heavy downpours are frequent, side-dress N applications may reduce N leaching and losses and improve N uptake by the crop. Crozier et al. (2014) found yield increases when N application was delayed until side-dress, with an interaction between row spacing and N timing. Furthermore, Ciampitti and Vyn (2011) found that both plant population and N rate had a large influence on maize grain yield, highlighting the significance of agronomic management practices to maximize maize grain yields.

Spatial and Temporal Distribution of Data
The distribution of trial locations in this study was biased towards the northern hemisphere (Fig. 1 and 2). Most trial locations were located in the United States, China, and Canada, each contributing 91, 18, and 12 trial locations, respectively. This could be ascribed mostly to the large number of trial locations in the major maize production zone of the United States, where favorable weather conditions for maize production combined with deep, well-drained soils result in high maize yield potentials. Interestingly, there is a shortage of research focusing on the impact of plant population on maize grain yield in countries that depend heavily on grain maize as a primary food source. According to FAO (2017), the food supply quantity (maize and its products) for Africa was 121.87 g capita\(^{-1}\) d\(^{-1}\) during 2013. During the same year, it was 75.88, 35.34, 26.85, and 19.75 g capita\(^{-1}\) d\(^{-1}\) for South America, North America, Asia, and Europe, respectively (FAO, 2017). The populations of the latter three regions do not depend as heavily on grain maize for their daily diet as the former two regions, but still most research is conducted in North America and Asia. Maize grain is primarily used as livestock feed in China and the United States, with some also used for ethanol production more recently (Foley, 2013; IATP, 2014). Many of the countries that rely on maize for human diets are developing countries. The lack of national capacity in these countries to provide the necessary tools and materials such as fertilizer, improved cultivars, and machinery, among other things, likely significantly limits maize grain yields.

Limitations and Challenges
In the current study, it was found that there is a need for better metadata in plant population studies to help explain anomalous data points in a compiled dataset. Poor reporting of trial protocols made it challenging to understand methods used in trials, and consequently erroneous conclusions could result when comparing data. In a meta-analysis on NT and crop yield by Pittelkow et al. (2015), several critical management factors such as N rate and residue management were not reported adequately, which limited the utility of the extracted data for explaining the impact of plant population on maize grain yield. Derpsch et al. (2014) suggested that there should be a set of questions that need to be answered in research protocols. Poor reporting of trial protocols is considered to be of particular concern with regard to the ambiguity with the role of NT in CA research (Derpsch et al., 2014). For example, in our review, only two out of the 10 articles reporting on field trials evaluating plant population under NT management recorded the type and/or amount of soil cover in the fields used for the trials. Many authors have highlighted the importance of adequate soil cover in an NT system (Wall, 1999; Sayre et al., 2006; Verhulst et al., 2010; Derpsch et al., 2014). Maintaining a permanent soil cover can be advantageous, with reduced water and wind erosion in combination with a decrease in evaporation and runoff from soil surfaces as benefits. These benefits contribute to a more sustainable cropping system and improved crop growth. Therefore, the effects of NT with CT on crop growth cannot be rigorously compared if all practices associated with NT management were not implemented.

Because of the geographical bias in the distribution of trial locations towards North America, most of the field trials included in this study were conducted at agricultural research stations. As reported by Pittelkow et al. (2015), research stations are often located on more fertile soils when compared with on-farm soils and conditions. This may affect the results regarding the effects of NT and CT under different plant populations or row spacings at the farm level. To reduce challenges posed by the above-mentioned bias, it is recommended that more field trials should be conducted in poorly represented environments, particularly in the southern hemisphere. This should improve our understanding of the effects of agronomic management practices on crop growth in challenging environments. This can help elucidate those practices contributing to improved maize grain yields and more sustainable maize production systems.

CONCLUSION
This global systematic review was conducted to investigate the effects of plant population on maize grain yield. It was shown that the optimal plant population is dependent on rainfall, and that maize grain yield varies significantly across environments with different climatic conditions. Overall, our results suggest that plant populations of 90,000 to 120,000 plants ha\(^{-1}\) are optimal to
maximize maize grain yield across most rainfall regions. When the effects of plant population on maize grain yield were investigated for CT and NT systems, we found that optimum plant population was lower for NT than CT systems, but that, at a given plant population, maize grain yields were higher in NT than in CT systems. With regard to N fertility, the response of maize grain yield to plant population was weaker at high rates of N (>=200 kg N ha^{-1}) than at N rates from 100 to 200 kg N ha^{-1}.

The large variability among studies and the small number of studies in certain environments and tillage systems indicate that these conclusions should be applied cautiously. It is evident that there is a shortage of research in more arid environments across the world, a knowledge gap that should be addressed rapidly, given the dependence of many semiarid regions on rainfed maize production.

Recommendations for plant populations in these environments must be derived from field trials conducted under the same conditions, because of the specific challenges posed by low and inconsistent rainfall. More research is also needed to understand the response of maize grain yield to NT alone compared with NT as part of a CA system, where practices such as crop diversification and maintaining crop residues on the soil surface are integrated. Finally, there is a need for more metadata to provide better recommendations for optimizing plant populations in various climatic conditions and rainfed maize production systems.

**Conflict of Interest**

The authors declare that there is no conflict of interest.

**Supplemental Material Available**

Supplemental material for this article is available online. The dataset for this article can be found at doi:10.5061/dryad.dq91858.

**Acknowledgments**

We thank authors who provided their articles per request when articles were not available online. The help and guidance provided by Dr. Corrie Swanepoel during the preparation stages of this review is much appreciated. Drs. André Nel and Chloe MacLaren are thanked for their considerable comments and editing, which improved this manuscript to its current form. Mr. Anton Kunneke is thanked for constructing Fig. 2. This work is based on the research supported in part by the National Research Foundation of South Africa (Grant no. 109446).

**References**


