# Effect of within-season daily rainfall distribution on maize crop yields

Kevin Jan Duffy and Tirivashe Phillip Masere

***Abstract:*** *It is well known that major changes in global food systems are needed when agriculture must meet the challenge of feeding a growing population and at the same time minimize global environmental impacts. Both these aims require optimal crop yields. This need applies crucially to staple foods, such as maize, and in developing parts of the world, such as much of Africa. Within-season rainfall will affect crop yields, and this paper, using simulations, investigates the effects of varying within-season daily rainfall distributions on potential maize yields. The results show that within-season distributions can affect maize yields in low-rainfall seasons, but yields are also dependent on the use of fertilizer. In average and above-average rainfall seasons, within-season variance has little effect on maize yields. If within-season distributions affect crop yields in low-rainfall seasons, as shown here, then this finding could be important for understanding the impacts of possible changes in climate.*

***Keywords****: fertilizer; rainfall distribution; semi-arid environments; soils; crop yields; southern Africa*

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In terms of food security and overall benefit to human society, agricultural yields are, among other important factors, central to the success of farming systems (Foley *et al*, 2011; Grassini *et al*, 2013; Seufert *et al*, 2012). Daily rainfall distribution in the growing season is a critical crop yield determinant because crops need water at each growth stage (Monti and Venturi, 2007). In particular, this factor is even more important in semi-arid environments, which are generally characterized by highly variable and low rainfall, and little or no rainfall is received during critical crop growth stages, resulting in low crop yields (Asseng *et al*, 2001; Kar *et al*, 2007; Monti and Venturi, 2007).

South Africa, like much of southern Africa, is generally characterized as semi-arid, receiving a mean annual rainfall of about 450 mm (Palmer and Ainslie, 2006). Furthermore, South Africa experiences more below-average rainfall than above-average rainfall seasons (Palmer and Ainslie, 2006), and more than 70% of South Africa has a mean annual rainfall of 600 mm or less and is thus classified as being either desert or semi-arid (Schulze, 1997).

Maize was chosen for this study because it is one of the most important staple food crops in South Africa and throughout the southern African region (Akpalu *et al*, 2011). Maize is grown on over 60% of South Africa's cultivated land and constitutes about 70% of grain production (Akpalu *et al*, 2011). Maize grows well in moderate- to high-rainfall areas under deep and well drained soils that have high water-holding capacities (Masere and Duffy, 2014; Smith, 2006). Maize requires rainfall between 500 and 900 mm in a growing season for optimal growth (Ifabiyi and Omoyosoye, 2011; Smith, 2006). Semi-arid conditions make the cultivation of less drought-tolerant crops such as maize very risky. Also, optimal growth for maize occurs in well drained, deep red and yellow-brown soils with high water-holding capacities (Smith, 2006). Such soils are only found in small areas of Africa. Only 10% of Africa is defined as being prime land, composed of highly buffered soils characterized by high organic matter content and excellent water-holding capacities. Over half (57%) of African land is made up of very poor soils containing very low organic matter with low available water capacity (Weight and Kelly, 1998). These poor soils usually fail to infiltrate and store rainwater effectively during high-intensity or infrequent storms

**Table 1.** Input data used to run maize simulations.

| Input data item | Treatment |
|---|---|
| Soil | Two soils conditions, namely: optimal and poor conditions, with PAWC of 309 and 86 respectively |
| Maize variety | SC401, an early maturing variety (applied for all simulations) |
| Sowing density (plants per $m^2$) | 4.7 (applied for all simulations) |
| Fertilizer treatments | No fertilizer (0 kg N/ha), average fertilizer (50 kg N/ha) and high fertilizer (100 kg N/ha) |
| Weeding treatments | No weeding and optimal weeding. For optimal weeding – weeding was set to occur after the weed biomass reached a maximum of 1,000 kg/ha, with the maximum number of in-crop weeding times set at three |

(Barzegar *et al*, 2003). These factors – low rainfall and poor soils – further emphasize the importance of within-season rainfall distribution on crop yields. We hypothesize here that in low-rainfall conditions, the way in which rainfall is distributed within the season should affect crop yields. In this paper, we test this hypothesis by determining the effect of rainfall distribution on simulated maize yield using theoretical seasonal rainfall distribution patterns.

Theoretical daily rainfall distribution patterns were used to assess the effects of within-season rainfall distribution on simulated maize yields under a variety of fertilizer and soil conditions. Seven different patterns of within-season rainfall were developed and three seasonal rainfall totals were chosen to represent low, average and high-rainfall seasons based on maize requirements (Ifabiyi and Omoyosoye, 2011; Smith, 2006) as well as the differences in rainfall received across South Africa (Schulze, 1997).

## Methods

Theoretical daily rainfall distribution patterns were used to assess the effects of within-season rainfall distribution on simulated maize yields under a variety of fertilizer and soil conditions. Seven different patterns of within-season rainfall were developed for total seasonal rainfall amounts of 300 mm, 600 mm and 900 mm, representing low, average and high-rainfall seasons respectively. As a base for all the distributions, we used a pattern of daily rainfall that totalled an amount based on a season measured from Pietermaritzburg, South Africa (latitude 29°37'00" S; longitude 30°22'59" E, altitude 596 m). We then constructed seven different distributions to represent seasons with different characteristics (all adding up to the same total seasonal rainfall). These seven distributions were then reworked by randomly moving the events and altering quantities by random amounts (up to the daily average) to construct 10 replicates for each distribution.

Soil is the base resource for crop production as it determines the crops suitable to grow and also offers a platform for crop, fertilizer and moisture interactions (Masere and Duffy, 2014). Further, soil also determines the amount of water and nutrients that can be available to crops. Thus two soil conditions (poor and optimal) of contrasting plant-available water capacity (PAWC) were chosen to enable comparisons relevant to African conditions (Weight and Kelly, 1998). Optimal soil conditions were represented by a heavy clay Vertisol (72% clay) with a PAWC of 309 mm/m. Conversely, a sandy loam soil composed of 12% clay and 70% sand with a PAWC of 86 mm/m was chosen to represent poor soil conditions.

Three fertilizer options, 0 kg N/ha, 50 kg N/ha and 100 kg N/ha, were selected to enable comparisons representing no, average and optimal fertilizer for maize production (Adesoji *et al*, 2013; Bello *et al*, 2012). The planting date was based on the first opportunity when 20 mm of rain had accumulated in five consecutive days, with a soil water content greater than 30 mm within the sowing window of October to December. Other management variables, including variety, sowing density and weeding times, were optimized based on relevant literature (Masere and Duffy, 2014; Palle and Lauer, 2002; Abuzar *et al*, 2011) and past work experience on farmer practices (Masere, 2011). These variables were uniform across all simulation runs (Table 1).

The crop modelling platform Agricultural Productions Systems Simulator (APSIM) (Keating *et al*, 2003) was used to investigate the effects of within-season daily rainfall distribution on maize yields. APSIM was chosen because it simulates the biophysical crop growth processes based on climate, soil and management variables on a daily basis, thus more closely matching reality, and has been tested extensively in many regions of the world, including Africa (Carberry *et al*, 2004; Dimes *et al*, 2003). Input data in the form of daily climatic data (rainfall, maximum and minimum temperature and radiation), soil description and crop management data (planting, variety, sowing density, weeding, fertilizer) are required to run APSIM to generate outputs related to crop yields and biomass, soil water balance and soil nutrient status. Input data (Table 1 plus the climatic data) are fed into the model through a graphical user interface.

Rainfall for a 14-year period in Pietermaritzburg, South Africa (a representative location of a savanna ecology found throughout Southern Africa) has a within-season daily distribution that is heavily skewed to low values of daily rainfall (Figure 1). The data in Figure 1 can be fitted with a Poisson distribution. This distribution would characterize the rain as falling in discrete events (daily) at an average rate and independently of time, which is a feasible description of a season's rainfall. Thus, it is likely that this type of distribution is representative of southern African rainfall conditions. Thus, we took one of the Pietermaritzburg seasons as a realistic example from this distribution as a base for our theoretical distributions. We then constructed seven different distributions to represent

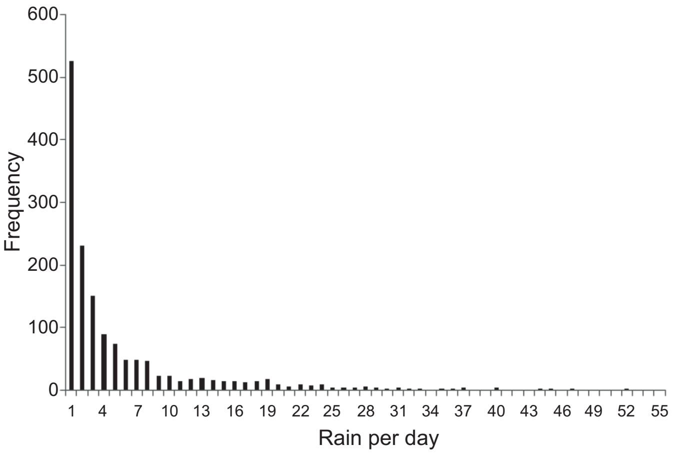


**Figure 1.** Distribution of daily rainfall for Pietermaritzburg, South Africa, over 14 seasons from 2000 to 2014. Days with no rainfall were the most frequent: 3,538 days (not shown because of scale).

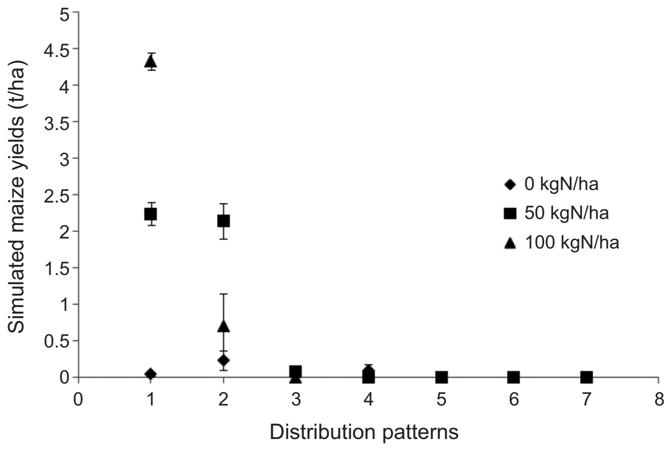


**Figure 2.** Effects of within-season rainfall distribution on simulated maize yields in optimal soil conditions under three fertilizer levels for a low-rainfall season.

seasons with different characteristics, but each with the same total seasonal rainfall:

(1) a distribution taken from an actual South African season; this original distribution was used as a base for all the other constructed distributions;
(2) the same original distribution with large storm events added in randomly;
(3) a distribution with most of the rainfall events moved to the first half of the season (first three months of a six-month season);
(4) a distribution with most of the rainfall events moved to the last half of the season;
(5) a uniform distribution with the same rainfall every day;
(6) a distribution with most rainfall received mid-season (central two months); and
(7) a distribution with good early rains followed by a mid-season dry spell (central two months) and good rains at the end of the season.

Although they are quite crude, these distributions do appear to cover the extreme rainfall distributions that are possible. These seven distributions were then reworked by randomly moving the events and randomly altering amounts to make up 10 replicates for each distribution, all of which were used for different simulation runs.

## Results and discussion

Simulation results indicate that within-season rainfall distributions can have an effect on maize yields. For example, on optimal soils and for low-rainfall seasons (300 mm/season), yields range from 0 tons/ha to 4.3 tons/ha (Figure 2). Also, fertilizer application can improve these yields and the higher application of fertilizer gives the best yields (Figure 2). These results are consistent with maize yields reported by Masere (2011) and Adesoji *et al* (2013). In fact, without fertilizer the original distribution does not provide yields. The reason for this must be that without fertilizer the low daily rainfall events do not allow enough crop growth for crop survival. However, no fertilizer with more intense rain in the form of storms (distribution 2) results in some yields (Figure 2). These yields are also improved by the application of fertilizer, but an average fertilizer application is shown to give the best yields. All other distributions result in no yields regardless of fertilizer application (Figure 2). The simulation outputs for poor soil conditions with low rainfall were similar overall, but with more variability (not shown here).

Thus, in low-rainfall seasons, it appears that it is important for rainfall days to be spread out, with rainfall events not concentrated for time periods; nor should the daily rainfall events be strictly uniform (the same every day). These results are probable in that minimum amounts of rain should be required for all plant growth stages, although for maize the first month is known to be the most crucial (Monti and Venturi, 2007).

In better rainfall conditions (600 mm/season) with optimal soils, rainfall distribution has little effect, but the application of fertilizer has an overwhelming effect (Figure 3). Again, this supports the requirement for a minimum amount of rain throughout the season, which is more likely in seasons with higher rainfall. However, with good rains, some effect of within-season variation on maize yields was expected, and so this lack of effect is interesting. Very similar results were obtained for high-rainfall conditions (900 mm/season) and on poor soils (not shown here). However, for poor soils there was again increased variability in yields. This variability could be due to nutrient leaching. For example, with no fertilizer, higher-rainfall events (distribution pattern 2) resulted in approximately 30% more nitrate leaching than for distribution pattern 1. With fertilizer, optimal maize yields are shown for the original rainfall distribution (Figures 2 and 3). This rainfall distribution falls in the overall distribution shown in Figure 1. As with most rainfall, this distribution represents a situation with daily rainfall falling in random and independent events. Plants in general might have adapted to such distributions, growing best in conditions with many low-daily-rainfall events and fewer higher-rainfall days. Even in low-rainfall seasons (300 mm), better maize yields can be obtained when rainfall is distributed in random events throughout

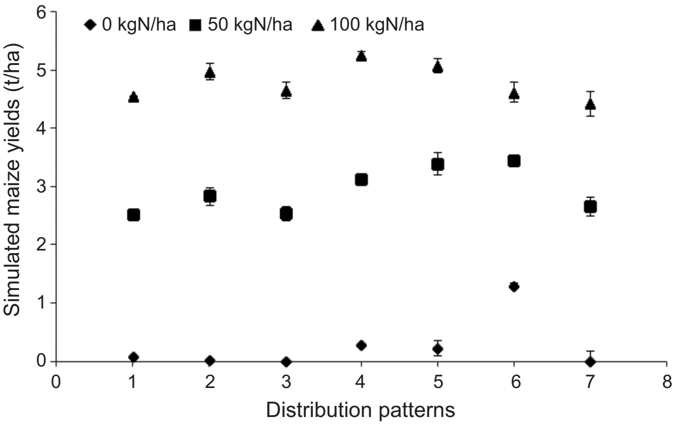


**Figure 3.** Effects of within-season rainfall distribution on APSIM simulated maize yields (t/ha) in optimal soil conditions under three fertilizer levels for a high-rainfall season.

the growing period, which is consistent with other findings (Ifabiyi and Omoyosoye, 2011; Monti and Venturi, 2007). Also, if storms are randomly introduced (distribution pattern 2), yields are better than for the other distributions (Figure 2).

In general, the simulation results show that maize yields are dependent on total seasonal rainfall for both low- and high-fertilizer treatments, regardless of soil conditions. This is consistent with the findings of Akpalu *et al* (2011), who showed that a change in rainfall amount was the primary driver of maize yields. However, here we show that the within-season rainfall distribution can have an influence on maize yields regardless of the total seasonal rainfall. This might explain why there has been no simple correlation between total rainfall and crop yields (Phillips *et al*, 1998; Keating *et al*, 2010; Masere and Duffy, 2014; Monti and Venturi, 2007).

## Conclusion

In a semi-arid environment such as Africa, it is important to understand all the factors that could affect crop yields. Our results indicate that in these conditions the within-season daily rainfall distribution can have an important effect on maize yields. On poor soils, these distributions can influence how effective the use of fertilizers will be, with an important bearing on farming risk. For small-scale African farmers with few resources, the risk of buying fertilizer could be financially crippling if yields were small (Masere and Duffy, 2014). It appears that no fertilizer (or perhaps manure) will result in small yields. However, in semi-arid environments, the simulation results from this study highlight the importance of considering the daily rainfall probability distributions. The effects of within-season rainfall variability could be used to construct risk models to help optimize management decisions. This could be very important for high-risk low-income farmers in developing countries, but could also apply more subtly and perhaps with larger financial implications to commercial farmers. Also, the effects of within-season variability could have an important bearing in terms of possible climate change. Climate change could affect within-season variability or could alter the overall rainfall received in the future. This study indicates that these effects could affect potential crop yields, and highlights the importance of further research on within-season rainfall variability.

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