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Soybean production potential in Africa

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ABSTRACT

Soybean (*Glycine max* [L.] Merr.) could possibly become a major crop in Africa due to its many uses as a food, feed, and in industry. Also, its ability to undertake symbiotic nitrogen fixation is a great advantage over cereal crops. This study simulated yield potential across west and east Africa. A number of areas were excluded from soybean production because of inadequate early season rains to allow timely sowing of the crop. Among the remaining areas, average yields greater than 200 g m^{-2} were commonly simulated. Two drought traits were examined as plant modifications to increase yields. These results identified those areas and plant traits in Africa where soybean has the potential to be an important, viable crop.

1. Introduction

Soybean (*Glycine max* (L.) Merr.) offers several major advantages in sustainable cropping systems (Sinclair and Vadez, 2012), including an ability to fix atmospheric nitrogen (N_2) via symbiotic N_2 fixation and, hence, alleviate the need to apply large amounts of nitrogen fertilizer. This advantage could be especially important in crop production in Africa where there are major economic limitations in the use of fertilizer. In addition, the seed of soybean is high in protein and oil content resulting in uses as human food, animal feed, and industrial products. In particular, soybean's nutritional value and its high N_2 fixing potential could result in playing a major role in future cropping systems of Africa.

This paper explores the possibility for soybean cultivation in two large blocks of East Africa (here considered to be latitude 5°N–20°S and longitude 30°E–39°E) and West Africa (here considered to be latitude 15°N–6°N and longitude 17°W–10°E) as candidate regions for expanded agricultural production. Several climatic features in these regions of Africa were explored in considering large-scale soybean production. In addition to rainfall, temperature and photoperiod are key weather variables influencing crop development and growth. Much of West Africa is at low latitudes with relatively high temperature (Fig. 1). However, in East Africa much of the area is at fairly high elevations of 600 m to over 1400 m except for a strip along the east side of this region. These high elevations result in cooler temperatures than might be expected in low latitudes, so that the cool temperatures could slow plant phenological development. On the other hand, the short photoperiods in these low latitudes would normally be expected to accelerate soybean plant development. A key question is the relative influence of photoperiod and temperature on development to determine the parameters for phenological development that may be needed across Africa.

A second major feature of the African climates is the strong annual bimodal pattern in rainfall. Part of the year is essentially completely dry with virtually no rainfall and the remainder of the year is when rainfall occurs. In West Africa, substantial rains only occur in June through September. An additional block in northeast Africa (10°N–5°N latitude and 40°E–45°E longitude) is also subject to rains in the June through September. In East Africa, heavy rains occur only in December through March. In all locations, the rainy period follows several months with little or no rain. Therefore, the soil at the beginning of the rainy season contains little water on which to initiate crop growth. A major consideration in soybean production in Africa will be the response of the crop to soil water availability and the development of plant phenotypes that can remain productive under water-deficit conditions.

The initial objective of this simulation study was to determine the geographical areas in Africa that offer potential for consistent soybean production. Two factors were considered in evaluating potential soybean production in each simulated location. The first was an examination of the adequacy of early season rainfall to allow sowing of a crop. The second factor in determining if soybean was a viable crop in a location was the achievement of a minimum average yield across growing seasons. A mechanistic

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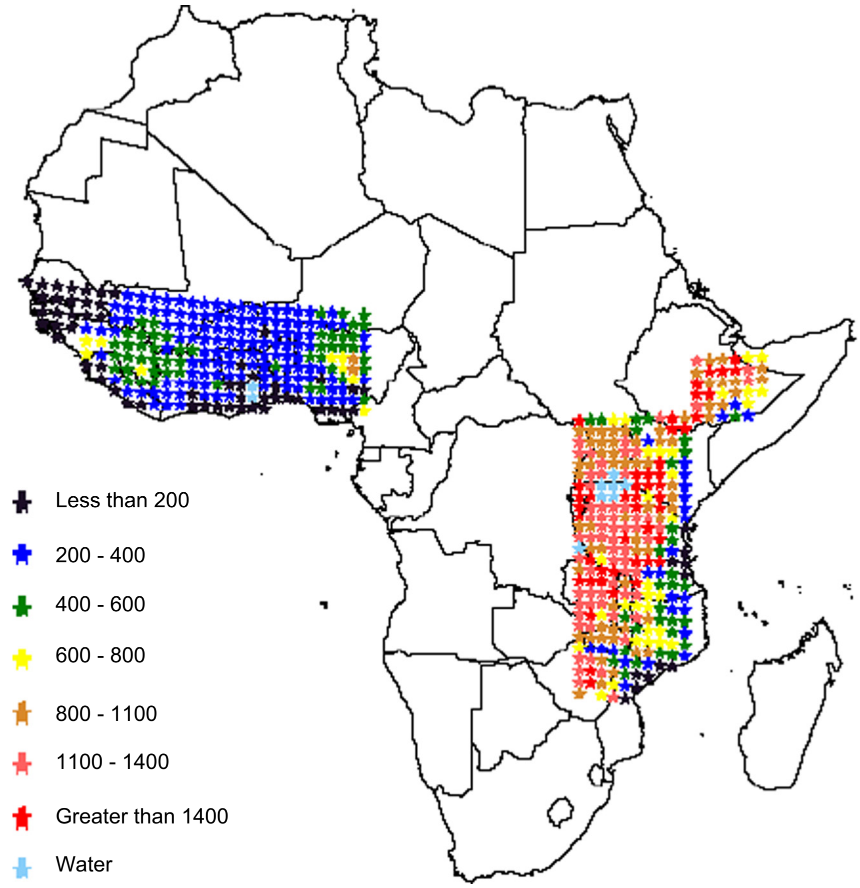

Fig. 1. Elevations (*m*) at simulated locations in West and East Africa.

model used to calculate grain yields across 50 growing seasons of simulated weather data at $1^\circ \times 1^\circ$ grid locations in major regions for expansion of crop production in Africa.

The second objective of the study was to examine two possible plant traits for improving grain yield potential of soybean subjected to water-deficit. The incorporation of drought tolerance traits was targeted for study since nearly all locations in Africa experience water deficits in at least some growing seasons. The two traits simulated for improvement were (1) increased tolerance of N_2 fixation to soil drying, and (2) limited transpiration rate when plants are subjected to high atmospheric vapor pressure deficit. The results of these simulations, therefore, offer information across Africa in guiding geographically based research in regard to where soybean might be produced, and the research opportunities to increase grain yield potential.

2. Materials and methods

2.1. Model description

The SSM-legume model used in this assessment is described fully by Soltani and Sinclair (2012). The robustness of this soybean model has been demonstrated in several studies over a range of environments (Muchow and Sinclair, 1986; Sinclair et al., 2007; Salado-Navarro and Sinclair, 2009). In brief, leaf area is developed as a function of temperature and can be restricted by inadequate nitrogen and soil water. The leaf area index of the crop is used to intercept solar radiation, which in turn is used to calculate crop growth as a function of radiation use efficiency. Radiation use efficiency, which was assumed to be 2.0 g MJ^{-1} photosynthetically active radiation under well-watered conditions, was decreased at low soil water contents. Therefore, daily growth was calculated based on incident solar radiation, leaf area index, and soil water content. Finally, daily seed growth was calculated as a function of crop mass.

Daily N_2 fixation during development was calculated to meet the daily needs of new growth on each day. However, inadequate soil moisture as defined by fraction of transpirable soil water (FTSW) results in decreases in the N_2 fixation rate, which causes decreased nitrogen accumulation in the plants. N_2 fixation is commonly the most sensitive process to water deficit in soybean plants so that even modest soil drying (FTSW < 0.5; Soltani and Sinclair, 2012) results in decreased crop nitrogen accumulation. Therefore, on days when FTSW decreases to less than 0.5 a linear decrease in the N_2 fixation rate as a function of FTSW is invoked in the simulations. In addition, during seed fill a restriction on N_2 fixation is simulated by requiring adequate photosynthate to support N_2 fixation activity. If there is no excess daily photosynthate after supporting seed growth, N_2 fixation activity is set equal to zero.

A unique feature of this model was that the daily crop transpiration rate is intimately linked to daily crop growth. That is, the transpiration rate is calculated as a function of crop growth multiplied by the atmospheric vapor pressure deficit, divided by the constant transpiration coefficient for soybean of 4.5 Pa. The parameters defining the transpiration coefficient have been shown to be stable across a wide range of conditions within a crop species (Tanner and Sinclair, 1983). The transpiration rate was calculated on each day so that water was removed from the soil along with direct evaporation from the soil surface. Calculation of daily soil water status was completed by adding rainfall to the soil that was not lost due to runoff and deep percolation. Since no extensive soil data were available, in all locations the volumetric transpirable soil water was set equal to 0.13 and the maximum rooting depth was equal to 1000 mm.

Development of the crop was calculated daily as a function of photoperiod and daily mean temperature. The photoperiod response is especially important in soybean and is a key to adapting the crop to various environmental zones. When the photoperiod (PP) is shorter than a critical photoperiod (CPP) for this short-day species, the scalar for the plant photoperiod function (*ppfun*) is set equal to a value of 1. However, when the photoperiod is greater than CPP, then the following equation is invoked (Soltani and Sinclair, 2012):

$$ppfun = 1 - ppsen * (PP - CPP) \tag{1}$$

The strong sensitivity of soybean to photoperiod can be critical in defining the latitudinal zones in which cultivars of differing development characteristics can be grown. In addition, plant development is sensitive to temperature. The scalar function for temperature was based on development response to mean daily temperature. The same temperature function was used in all simulations with the base temperature equal to 7 °C, an optimum temperature in the range from 27 to 34 °C and a ceiling temperature equal to 45 °C.

The duration of each development stage of the plants was defined by the biological days required for completion of the phenological stage (Soltani and Sinclair, 2012). Biological days represent the total number of days required to complete a development stage when plants are grown under optimum photoperiod and temperature conditions. The actual number of days to complete a development stage is greater than the biological days depending on limiting temperature and photoperiod. In the model, biological days are defined for the development stages of sowing to emergence, emergence to flowering (stage R1 in soybean), R1 to R3 (beginning pod), R3 to R5 (beginning of seed fill), R5 to R7 (end of seed fill) and R7 to R8 (maturity).

The model requires daily input of minimum and maximum temperature, solar radiation, and rainfall. These data were obtained from the weather generator described below. The weighted daily vapor pressure deficit, which is required in the calculation of transpiration rate, was calculated from minimum and maximum temperature based on the approach suggested by Tanner and Sinclair (1983).

2.2. Weather generation

To understand the variability in the range of crop response to weather, it is necessary to simulate crop yield for at least 20 growing seasons at each location. Given that such weather datasets are not available in Africa, it was necessary to generate them. The weather generator MarkSim (Jones and Thornton, 2000; Dixit et al., 2011), which was developed for tropical latitudes, was used to generate daily weather for 50 years at $1^\circ \times 1^\circ$ locations in each of the regional blocks to be simulated. In the generation of weather, elevation at each location was considered in the MarkSim calculations. MarkSim is a stochastic model so that no simulated year was the same, but over 50 years it was expected that the range of weather scenarios for a location was represented. However, it was not anticipated that MarkSim necessarily generated daily weather that exactly represented any specific growing season at any specific location, but rather indicated the range of weather possibilities in the vicinity of each grid location.

2.3. Crop yield simulations

2.3.1. Sowing

A condition to initiate the sowing of a crop was that sufficient water had accumulated in the soil following the dry season to support seed germination and early seedling growth. To avoid sowing with an isolated early rain, no sowing was allowed before day of year 180 in the latitudes greater than 4°N and before day 310 in the other latitudes. The actual date of sowing was determined based on accumulated soil water content in each growing season by calculating soil water budget on each day following the dry season. In these simulations, the threshold for accumulated soil water for sowing of soybean was 40 mm (soil wetted to a depth of approximately 30 cm). However, if the 40 mm of water was not accumulated in the soil within the first 50 days following the earliest possible sowing date, then that growing season was aborted for a lack of water to support sowing.

2.3.2. Phenological parameters

In soybean, genotypes are classified by maturity group classifications reflecting their adaptability to various latitudinal zones as a result of sensitivity in development to photoperiod and temperature. Based on the low latitude of much of Africa, the expectation was that soybean genotypes with extended development characteristics under short photoperiods would be required. While an optimization could be attempted for each location, for these initial simulations a single set of development parameters for each of the blocks of East and West Africa was explored. The initial simulations were done by inputting to the model biological days for each phenological stage of a maturity group VII soybean (Table 1). The value of CPP for a MG VII soybean is 12.3 h and *ppsen* is −0.32 (Soltani and Sinclair, 2012). As described later, simulations in West Africa were done using phenological parameters for MG VIII soybean and these are also presented in Table 1.

2.3.3. Nitrogen fixation

As discussed previously, the N_2 fixation rate in soybean commonly declines when FTSW decreases to less than 0.5. The N_2 fixation rate decreases linearly with decreasing FTSW below the 0.5 threshold. This response is consistent with observations of N_2 fixation decline reported by Sinclair (1986) and confirmed in subsequent observations including the most recent ones reported by Devi and Sinclair (2013) for variety 'Benning'. The initial simulations with the threshold for N_2 fixation decrease set at FTSW = 0.5 were identified as the 'standard' soybean.

An improved, drought-tolerant cultivar was simulated by simply shifting the N_2 fixation threshold to a low value of FTSW equal to 0.25. This value is at or somewhat greater than that identified in eight genotypes found to have N_2 fixation drought tolerance in a screen of over 3000 genotypes by Sinclair et al.

Table 1
Developmental parameters for simulation of soybean maturity group VII (MG VII) in East Africa and maturity group VIII (MG VIII) in West Africa, including the biological days required for each of the simulated phenological stages.

Parameter	MG VII	MG VIII
Critical photoperiod (h)	12.3	12.1
Photoperiod sensitivy	−0.32	−0.33
Biological days		
Sowing – emergence	4	4
Emerg – R1	20.67	20.97
R1–R3	10.07	11.07
R3–R5	6.38	6.03
R5–R7	34.82	35.47
R1–R7	51.27	52.57

(2000). This threshold is also consistent with the recent discovery by Devi and Sinclair (2013) of N_2 fixation drought tolerance in the slow-wilting genotype 'PI 471938'.

The impact of making N_2 fixation more tolerant of soil drying in the simulations was calculated in each of the 50 growing seasons at each location by comparing grain yield with the standard soybean. This comparison gave the amount of yield increase or decrease in each season as a result of the trait modification. The mean yield change was calculated across growing seasons for each location. In addition, a probability of yield increase was calculated as the fraction of growing seasons in which a positive yield increase was obtained as a result of the change in the N_2 fixation sensitivity to soil drying.

2.3.4. Limited-transpiration trait

Most soybean cultivars express a continually increasing transpiration rate with increasing atmospheric vapor pressure deficit (VPD) (Sinclair et al., 2008; Sadok and Sinclair, 2009). However, the slow-wilting genotype 'PI461937' was found to have a breakpoint in transpiration with increasing VPD such that there was little or no further increase in the transpiration rate at VPD greater than about 2.0 kPa (Fletcher et al., 2007; Sinclair et al., 2008). Therefore, this trait prevents excessive transpiration under conditions of high midday VPD and soil water is conserved for use by the crop later in the growing season. Devi et al. (2014) identified several genotypes with thresholds as low as 1.4–1.5 kPa. A moderate threshold of 1.8 kPa was chosen for these simulations to not impose the most severe constraint on gas exchange, which could result in a major limitation on the photosynthetic productivity of the crops.

The standard model was run on daily time steps. However, to simulate the impact of the limited-transpiration trait, it was necessary to track VPD through the daily cycle on an hourly basis to determine when VPD exceeded the threshold. Therefore, it was necessary to estimate hourly weather values on an hourly basis from the daily input values. Hourly solar radiation and temperature were estimated as outlined by Goudriaan and van Laar (1994) and hourly VPD was obtained as the difference between saturated vapor pressure calculated for that hour and the saturated vapor pressure calculated from minimum temperature of the day (Sinclair et al., 2005). At any hourly time step when VPD exceeded 1.8 kPa, water loss was held to the rate calculated for a VPD of 1.8 kPa, which also required an adjustment in growth.

The mean and probability of yield increase over growing seasons was calculated as described previously.

3. Results and discussion

3.1. Sowing

The initial objective of this simulation study was to assess geographically the viability of soybean production. The first factor considered was simply the adequacy of early season rainfall to allow sowing of a crop. As shown in Fig. 2, there were locations in both West and East Africa where there was sufficient rainfall to support sowing in every growing season. In West Africa, Nigeria and countries in the southwest area consistently had adequate initial rainfall for sowing. If the criterion for adequate early-season rainfall for sowing is expanded to include locations in which sowing occurred in 49 out of 50 seasons, then the number of locations for soybean production is greatly expanded. Much of West Africa becomes open to soybean production except for a band of locations across the northern tier and a pocket in the south central area mainly in southern Ivory Coast and Ghana. In East Africa, the areas for soybean production include western Tanzania, Zambia, Malawi, Zimbabwe, and a few locations in Mozambique.

The acceptability of the fraction of growing seasons in which soybean could not be grown will likely be assessed based on a number of factors. If commercial production has a criterion of unacceptability of an inability to sow in two or more growing seasons out of 50, then large areas of Africa appear not to be suitable. In West Africa, soybean production is not appropriate in a large band in the northern tier and in southern Ivory Coast and Ghana (Fig. 2). In East Africa, many locations are not suited for soybean based on the rainfall requirement for sowing. Only locations in western Tanzania, Zambi, Malawi, Zimbabwe, and a few locations in Mozambique appear suitable for soybean production. Even with a relaxed unacceptability criterion of a failure to sow in four or more years out of the 50 growing seasons, there are still large areas in Uganda and much of Somalia, Kenya and Tanzania that seem likely to be unsuited for consistent production of soybean.

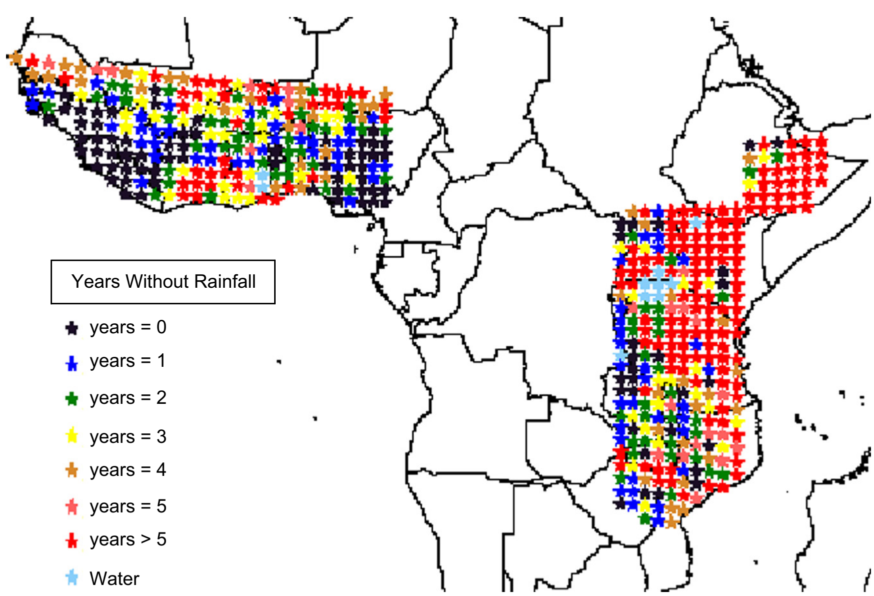

Fig. 2. Number of growing seasons out of 50 in which inadequate soil water was accumulated to meet the criteria of 40 mm accumulated water in the soil during the 50 d window for sowing.

The above simulation results indicate that the amount of accumulated soil water required for sowing a crop appears to be a critical factor in the suitability of locations for soybean production. The accumulation of 40 mm soil water within the 50 d window for sowing was assumed necessary for soybean to support germination of its relatively large seeds, to provide water for rapid establishment of its large leaves resulting in fairly high transpiration rates, and to avoid the occurrence of early-season severe drought for which soybean appears to be poorly adapted (Sinclair and Ludlow, 1986). However, there well may be genetic variability within the soybean germplasm so that requirement for soil water at sowing might be less restrictive.

In addition to the possibility of identifying soybean genotypes with more tolerance to early season water deficits, a greater potential may exist in the selection of other grain legume species that are better adapted for germination and early plant growth on lower soil water reserve. Small-seeded species with initial slow development of leaf area will likely require a lower amount of soil water in the early stages of development. Also, plant traits that allow prolonged survival of severe stress would allow the crop to persist in seasons in which early rains are followed by a drought period. In pigeon pea, for example, initial leaves are small in area and the leaves have a high capacity for survival of severe water deficit due to a low threshold water content for senescence (Sinclair, 2000). The apparent importance of the criterion of initial soil water accumulation for sowing indicates that studies are needed to assess germination and early transpiration rates of various soybean genotypes and grain legume species, as well as determining the ability of seedlings to survive periods of severe soil water deficit.

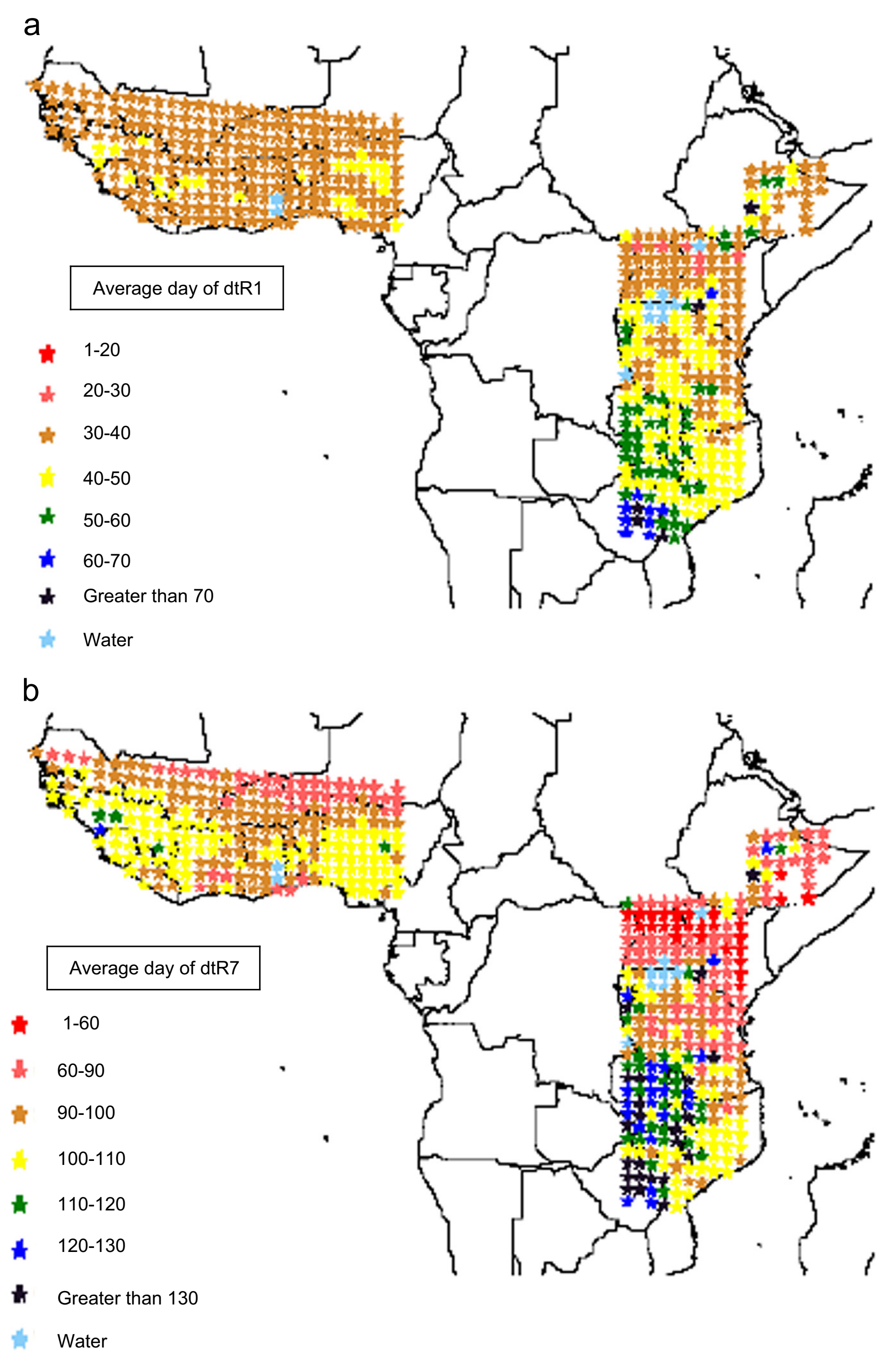

Fig. 3. Simulated days to (a) anthesis (stage R1) and (b) physiological maturity (stage R7) for maturity group VII soybean.

3.2. Phenological parameters

Investigation of the appropriate phenological parameters for soybean was initiated by examining the results for all locations in Africa using maturity group VII parameters (Table 1; Soltani and Sinclair, 2012). For much of East Africa, MG VII resulted in flowering (stage R1) in 40–50 days (Fig. 3a). However, locations in the south and west were simulated to have inappropriately long durations to R1, indicating that a somewhat earlier maturity group soybean may be needed for these locations. Much of the north of East Africa were simulated to have short durations of 30–40 days to R1 indicating that somewhat higher maturity group soybean may be needed in this region assuming that early-season rainfall allowed sowing in this area.

The duration to physiological maturity (stage R7) indicates somewhat more restrictive areas for MG VII production (Fig. 3b). Assuming development stage R7 should be delayed until at least 100 days, then again much of the northern locations of East Africa are not suited for soybean production. Introduction of a longer season soybean in the northern regions of East Africa is likely not a solution for this area since the longer season genotype would likely aggravate the problem of achieving consistent sowing and production in these areas.

In West Africa, MG VII appears to be too short in many locations based on both early flowering of less than 40 days (Fig. 3a) and physiological maturity in less than 100 days (Fig. 3b). Therefore, simulations were redone for West Africa using MG VIII parameters (Table 1). The change resulted in flowering occurring between 40 and 50 days after sowing for virtually all locations in West Africa (Fig. 4a). Also, the date to stage R7 was delayed to 100–120 days in many locations (Fig. 4b). Therefore, all subsequent simulations for West Africa were done by using MG VIII development parameters while MG VII parameters were used for East Africa.

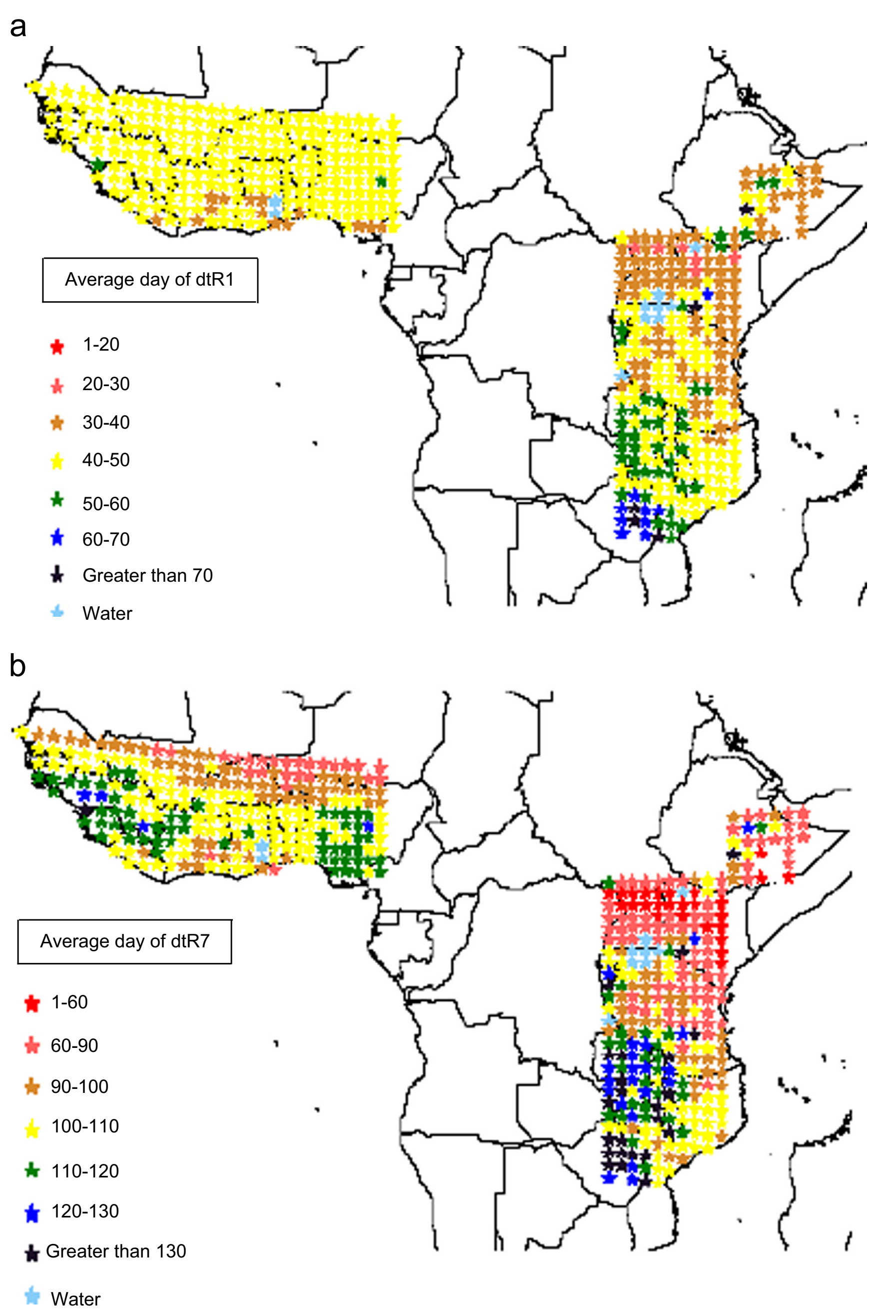

Fig. 4. Simulations of development for maturity group VII soybean in East Africa and maturity group VIII soybean in West Africa. Days to (a) anthesis (stage R1) and (b) physiological maturity (stage R7) are presented.

3.3. Standard model yields

Average grain yields for the standard soybean, using MG VII characteristics for East Africa and MG VIII characteristics for West Africa, were calculated based only on the growing seasons in which a crop was sown. That is, the zero yield in those growing seasons when a crop could not be sown was not included to avoid skewing the average yields to a lower level. As seen in Fig. 5, substantial areas in both West and East Africa were simulated to have average grain yields of greater than 200 g m^{-2} (2 t ha^{-1}) dry weight, and a substantial number of locations with yield averages greater than 240 g m^{-2}. In West Africa, except for a few locations, only the northern tier of location was simulated not to have achieved at least 200 g m^{-2} average yield. Similarly, much of the southern portion of East Africa achieved average grain yields of greater than 200 g m^{-2}.

3.4. Nitrogen fixation drought tolerance

One trait for potential increase in soybean yield is to decrease the sensitivity of N_2 fixation to drying soil. The usual threshold of 0.50 FTSW in the standard model for the initiation of decrease in the soybean N_2 fixation rate was changed to a much more tolerant threshold of 0.25 FTSW. Except for a very few locations, the increased tolerance of N_2 fixation resulted in average yield increases (Fig. 6a). The most consistently large yield increases were in the southern portion of East Africa, especially in Mozambique, where many locations had average yield increases of more than 15 g m^{-2}. These levels of yield increase are approaching a 10% yield gain for many locations.

In West Africa, the larger increases in yield as a result of the N_2 fixation drought tolerance trait were simulated for southern Ivory Coast and Ghana. This area had somewhat lower amounts of rainfall and consequently somewhat lower yields (Fig. 5). The result for this area contrasts with the southwestern and southeastern areas of West Africa. These areas experience high amounts of rainfall and less soil water deficit so that the N_2 fixation drought tolerance offers less benefit in these areas.

The decision by farmers to adopt cultivars with drought traits needs to consider also the probability of yield increase rather than simply the average yield increase over a number of growing seasons. That is, the immediate question for farmers needs to include the probability of yield increase in the coming growing season. If there is a reasonable probability of yield increase, e.g. at least a 50% probability of yield increase, then the cultivar with the altered trait could be attractive depending on the level of yield loss in those seasons where increase is not achieved.

The probabilities of yield increase as a result of the incorporation of the drought tolerance nitrogen fixation characteristic are shown in Fig. 6b. In fact, in many locations across all simulated locations in both East and West Africa the probability of yield increase from the improved N_2 fixation drought tolerance was 70% or greater. There were locations where the probability of yield increase was greater than 85%. On the other hand, there were a few locations where the probability of yield increase was less than 55%, and hence areas in which the drought tolerance nitrogen fixation trait is likely not to be useful. The high rainfall locations in southwest and southeast West Africa are areas where the probability of yield increase showed little consistent benefit found from this drought tolerance trait.

3.5. Limited-transpiration trait

The standard soybean model calculated the transpiration rate to increase linearly as the atmospheric VPD increased. Simulations were done for an altered cultivar in which the transpiration rate was limited to a maximum rate at any time in the day when vapor pressure deficit exceeded 1.8 kPa. In nearly all locations the limited-transpiration trait resulted in an increase in average yield (Fig. 7a). In many locations in both West and East Africa the average yield increase was greater than 15 g m^{-2}. The exceptions to the larger yield increases were the areas of high rainfall in West Africa. In East Africa, areas of yield increase were scattered across the region with consistently high increases in Mozambique.

The probability of yield increase as a result of the limited-transpiration trait in East Africa was very similar to the distribution resulting from the nitrogen fixation drought tolerance trait. That is, many locations had probabilities of yield increase of greater than 70%. However, the high rainfall regions of southwest and southeast of West Africa again showed only a small benefit of the limited-transpiration trait.

3.6. Comparison of two drought traits

Two plant traits for water deficit environments were explored in the simulations as approaches either expand the regions

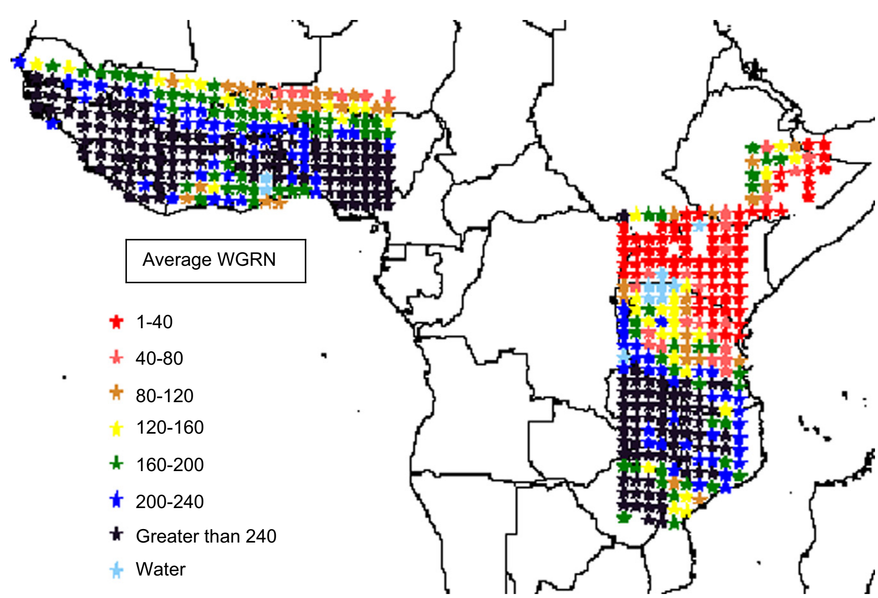

Fig. 5. Average grain yield (WGRN, g dry weight m^{-2}) for standard soybean simulated at each location based only on yield from growing seasons in which yield was greater than zero.

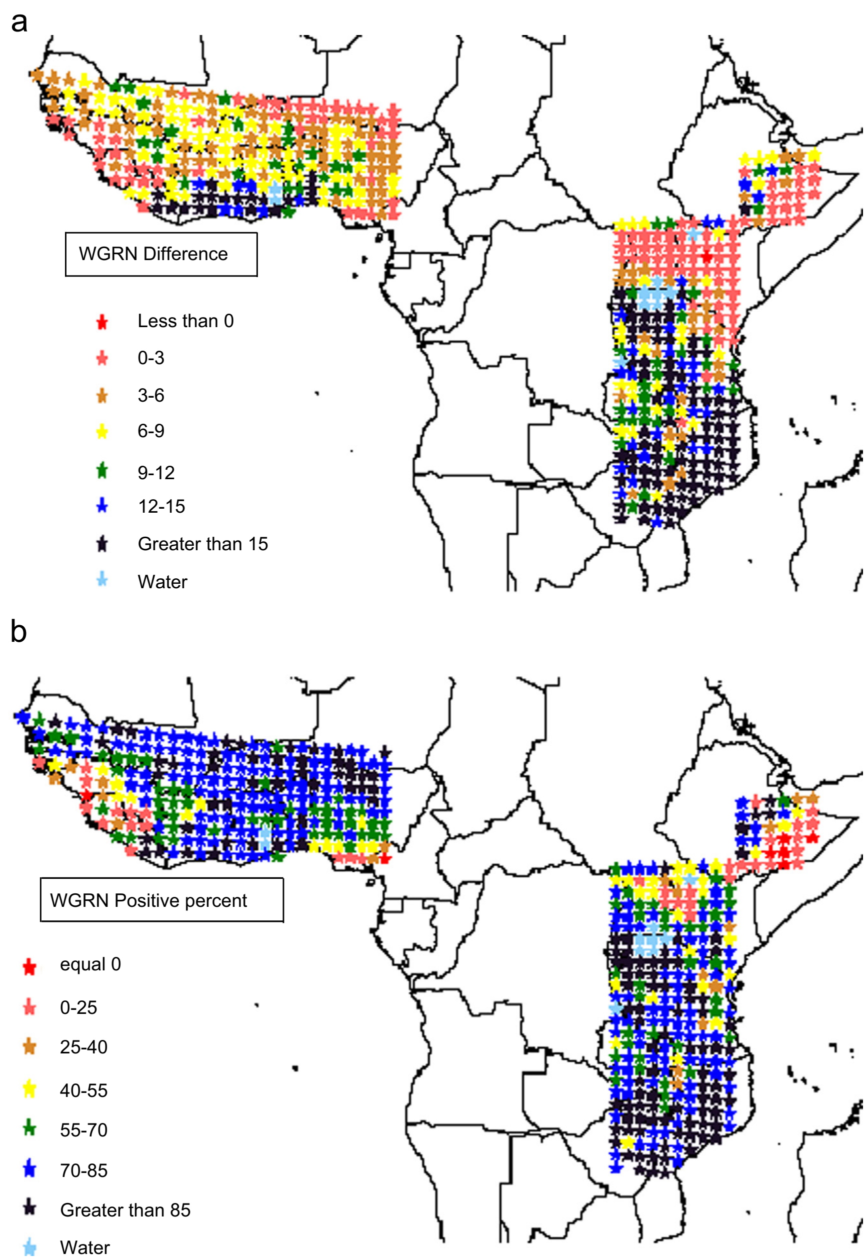

Fig. 6. Results of simulating drought tolerant nitrogen fixation (threshold for decrease at FTSW=0.25) as compared to standard soybean (threshold for decrease at FTSW=0.50) on (a) grain yield increase (g dry weight m^{-2}) and (b) probability of grain yield increase.

in Africa where soybean might be produced, or increase the yields in regions where the standard soybean now seems viable. Both traits tended to result in increased yields in nearly all locations across Africa. A substantial number of locations, particularly in south East Africa, had yield increases of greater than 15 g m^{-2} for both traits. However, the relative value of the two traits differed by locations. Nitrogen fixation drought tolerance resulted in greater yield increases than the limited transpiration trait in southern parts of the Ivory Coast, Ghana, Togo, and Benin of West Africa. On the other hand, soil water conservation by the limited transpiration rate under high VPD tended to result in greater average yield increase (Fig. 7a) than drought tolerant N_2 fixation (Fig. 6a) in all other regions. While Sinclair et al. (2010) simulated an advantage of the limited transpiration trait for the very driest regions of the US, the greater benefit was generally achieved in all locations as a result of increased N_2 fixation drought tolerance. The much drier conditions and lower yield level in Africa appears to have favored the water conservation trait due to its advantage in conserving soil water for seed fill resulting in sustained crop development in many growing seasons. Therefore, these simulations indicate that selection and breeding for the limited transpiration trait should likely receive the higher priority in most regions of Africa. This trait has now been well documented to exist in PI 416937 (Fletcher et al., 2007; Sinclair et al., 2008).

Risk decisions by farmers in regard to the introduction of a new drought trait, however, may cause the probability of yield increase to be at least as important as the long-term average yield increase. That is, risk-averse farmers may likely want to avoid the situation where a substantial fraction of the growing season will result in yield decreases even if the long-term average yield is higher. Since in one location nearly all drought traits can result in either an increase or a decrease in yield depending on the weather of an individual growing season, it is important for crop breeders and farmers to understand the probability of yield increase.

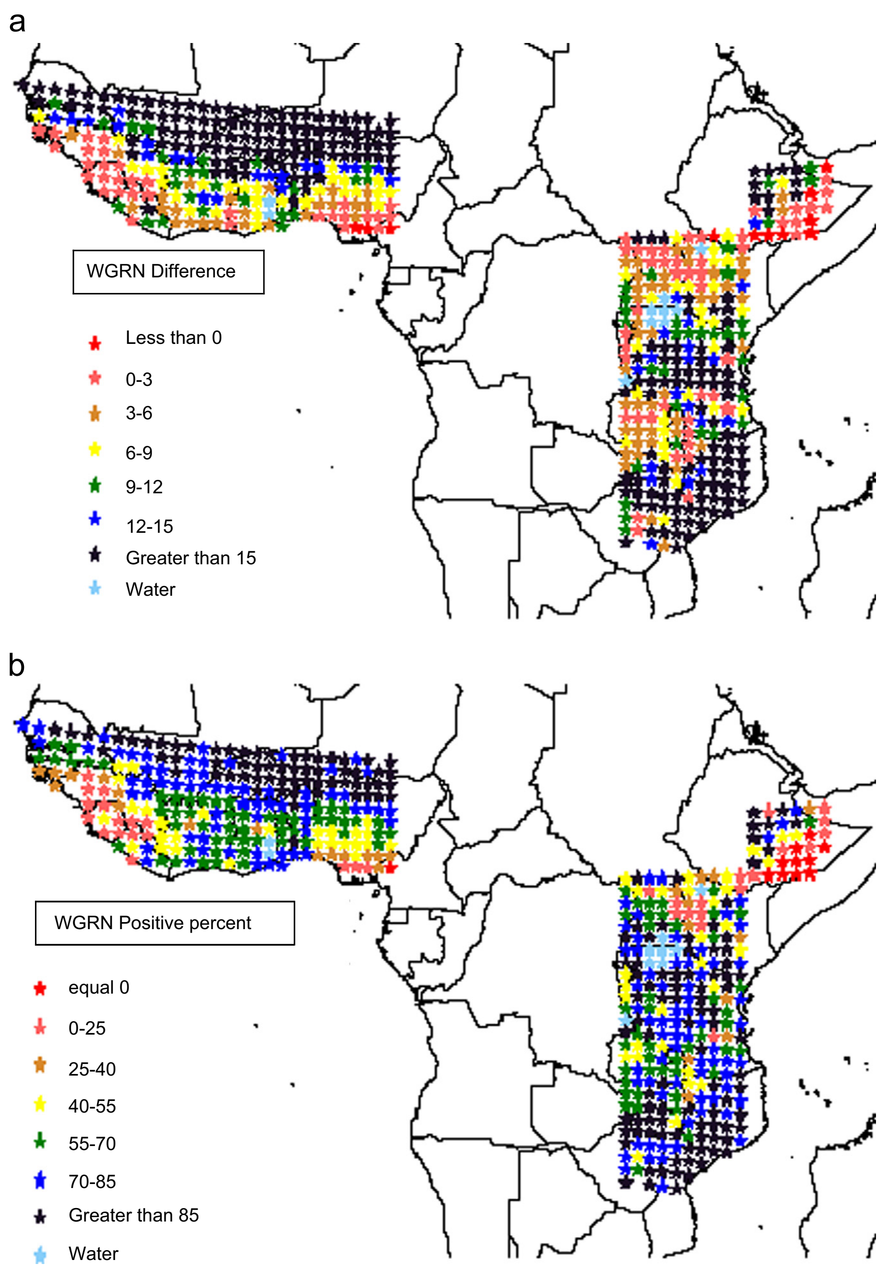

Fig. 7. Results of simulating limited transpiration rate at high atmospheric vapor pressure deficit (breakpoint at 1.8 kPa) as compared to standard soybean with no breakpoint on (a) grain yield increase (g dry weight m^{-2}) and (b) probability of grain yield increase.

Figs. 6b and 7b present the probability of yield increase across growing seasons for drought tolerant nitrogen fixation and for the limited-transpiration trait, respectively. The probabilities of yield increase are very similar for the two traits in East Africa. Much of East Africa has probabilities of yield increase that are greater than 70% indicating that these traits are likely to be advantageous.

In West Africa, however, the probability of yield increase appears to be somewhat higher in many locations for the N_2 fixation drought tolerance trait than for the limited transpiration trait. The temporal dynamics of drought in this northern tier of West Africa allow the early season conservation of water to have a larger impact on average yield. However, in the remainder of West Africa, the probability of yield increase is greater for N_2 fixation drought tolerance than for the limited-transpiration trait. Therefore the priority in breeding for drought traits will have to be balanced between higher average years across growing seasons achieved with the limited transpiration trait, or greater probability of yield increase in individual growing seasons obtained with the N_2 fixation drought tolerance trait.

4. Conclusions

Currently, there is no geographical assessment of soybean suitability for the range of climates in Africa. This study was undertaken to provide perspective about the possibilities in regard to geographical regions in Africa that might be considered for soybean production and to evaluate plant traits to improve soybean adaptability in Africa. Therefore, the two specific objectives of this simulation study were (1) to determine the geographical locations where soybean can be considered, and (2) to assess the potential benefit of incorporation drought-traits into soybean cultivars. The results of these simulations offered several crucial insights into developing soybean production in Africa.

(1) Water accumulation in the soil to allow sowing is a critical variable. The criteria used in these simulations of 40 mm of accumulated soil water during a 50 d window of sowing dates greatly restricted the locations where soybean could be consistently growing. This trait alone appears to be critical in defining the regions where soybean production can be considered. A key outcome of these simulations is the recommendation that experiments and sensitivity analyses are needed to evaluate possible genetic and species variation in the requirement for soil water at the time of sowing. Key questions may be the rate of seedling leaf area development and water use, and the survival capacity of seedlings if severe water deficit develops at early stages.

(2) The simulations presented here indicate that maturity group VII genotypes are generally appropriate for much of East Africa where soybean can be grown. Southern areas of East Africa will likely need lower maturity group cultivars. On the other hand, West Africa needs cultivars that have more extended development offered by MG VII cultivars. In these simulations, MG VIII parameters appeared appropriate for much of West Africa. Use of the appropriate phenology characteristics resulted in average simulated yields greater than 240 g m^{-2} in many locations in West and East Africa. A threshold annual yield of 200 g m^{-2} further expands the area where soybean production would be acceptable.

(3) Both a limited-transpiration trait and N_2 fixation tolerance to drought were found to be beneficial. However, the benefit of each trait needs to be evaluated both by the increase in average yield and probability of yield increase in each region. Neither drought trait was superior across all regions of Africa. However, there were more locations that obtained more positive response from the limited-transpiration trait than the N_2 fixation drought tolerance. The emphasis given to each trait in a breeding effort depends on the average yield increase and the probability of increase in the locations for which a cultivar is being developed.

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