Agricultural Systems 137 (2015) 24–38

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Production potential of Lentil (*Lens culinaris* Medik.) in East Africa

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ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form 1 December 2014
Accepted 13 March 2015
Available online

Keywords:
East Africa
Lentil
Model
Yield
Sowing date
Phenology

ABSTRACT

Lentil (*Lens culinaris* Medik.) could possibly become a major crop in East Africa due to its many uses as a food and feed. Also, its ability to undertake symbiotic nitrogen fixation is an advantage over cereal crops. This study simulated lentil yield potential in order to determine the geographical areas in East Africa that offer potential for consistent lentil production. Results show that there is potential to further expand the geographical area in which lentil is currently grown in East Africa into Uganda, Kenya, Tanzania and even Somalia. Response to a change in management practices on potential yield of lentil as a result of different sowing dates was also examined. In addition, the effect of phenology on yield potential was examined by comparing a short-season type vs. a long-season type. Delaying sowing alone or in combination with a long-season genotype can result in a high probability of crop yield increase in East Africa. For the long-season genotype, an optimum sowing window was found between June and July (152–229 day of year) for areas to the north of the Rift Valley. Later sowing dates (229–243 day of year) were found to be optimal in southern areas of East Africa. These simulations indicated that selection and breeding for lentil accessions in East Africa should consider changes in plant phenology and/or sowing dates.

1. Introduction

East African countries are dealing with myriads of socio-economic and environmental problems including poverty, alarming population growth, low agricultural productivity, land resource degradation, frequent drought and high-heat episodes, leading to limited crop production. In the last decades, droughts caused widespread famine and economic hardships in many countries of the region. Future climate change may lead to altered frequency or severity of such extreme weather events, potentially worsening water-deficit events.

Cool-season grain legumes are important protein-rich food crops of East Africa. Lentil (*Lens culinaris* Medik.), faba bean (*Vicia faba* L.), and chickpea (*Cicer arietinum* L.) provide a considerable portion of the diet of the people in this region. For example, in Rwanda bean supplies 65% of the national dietary protein, compared to 4% from animal protein, and 32% of the energy (Kelly, 2004). In addition, these crops can play a major role in sustaining soil fertility by symbiotic nitrogen fixation because in this region there are major economic limitations in the use of commercial nitrogen fertilizers. Enhancing and diversifying grain legume production in East Africa would help in alleviating problems of malnutrition and may bring future stability to the region (Siddiq and Uebersax, 2012; Solh, 1996).

Lentil is an annual food legume highly valued for grain in the world. The crop has great significance in cereal-based cropping systems because of its nitrogen fixing ability, the high protein and high micronutrients seeds for human diet, and its straw for animal feed.

Major producing regions of lentil are in South and West Asia, Northern Africa, Canada, Australia and the USA (Chen et al., 2011). Within East Africa, cowpea (*Vigna unguiculata* L.), groundnut (*Arachis hypogaea* L.), common bean (*Phaseolus vulgaris* L.), soybean (*Glycine max* L.), faba bean, and pigeon pea (*Cajanus cajan* L.) are the most important grain legumes crops (Timko et al., 2007). Lentil is now mainly grown in Ethiopia, Sudan, South-Sudan, and Eritrea, but is not a crop in Kenya, Uganda, Somalia, and Tanzania (Bejiga and Degago, 2000). Despite this fact, wild relatives of lentil such as *L. ervoides* have been reported on the slopes of mount Muhavura, in the southwest corner of Uganda (Kisoro region) south of the Equator (Ladzinsky and Smartt, 2000). East African production of lentil is characterized by a low mean yield of 0.1 $t \cdot ha^{-1}$compared to that of Central Asia and North Africa (0.6 $t \cdot ha^{-1}$) and South and Southeast Asia (1.7 $t \cdot ha^{-1}$) (FAOSTAT, 2011). The major reason for these low yields appears to be a result of production on marginal lands in arid and semi-arid environments without irrigation, weeding or pest control (Bejiga and Degago, 2000).

There may be, however, an opportunity of growing cool-season grain legumes like lentil in countries south of Ethiopia such as

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http://dx.doi.org/10.1016/j.agsy.2015.03.005
0308-521X/

Tanzania by replacing the fallow at the end of the rainy season. In this case, lentil would not compete with other crops like maize (*Zea mays* L.), which are grown during the rainy season (Pundir et al., 1996). No reports were found exploring this possibility. This paper explores the possibility for expanding lentil cultivation in East Africa, toward the southern areas (latitude 22° N to 11°50′ S and longitude 21°50′ E to 11°50′ E). This area mainly covers Sudan, South Sudan, Eritrea, Djibouti, Somalia, Uganda, Kenya, and Tanzania. The target region is characterized by widely diverse climates ranging from tropical highlands to semi-arid and arid areas (Nicholson, 2001). Although the focus of this study was on East Africa, Yemen was also included as it is the origin of many lentil landraces.

Sowing date is known to affect plant development and growth which, in turn, affects final yield (Bejiga, 1991). In northern India, Singh and Saxena (1982) obtained the highest yield from lentil sown in the first fortnight of November, while later sowing resulted in lower yield. In Syria, seed yield was maximized by sowing in December, while delaying sowing to January and February reduced seed yield by 25% (Saxena et al., 1983). In Ethiopia, Bejiga (1984, 1991) found that early lentil sown between the last week of June and the second week of July increased yield. Later sowing after mid-July reduced both yield and time to maturity (Bejiga, 1991).

Matching the growth cycle of a crop to the rainfall environment is one of the most important factors affecting crop adaptation to new areas. Differences in phenological development contribute 45–60% of the variation in seed yield in South Asia (Shrestha et al., 2006; Siddique et al., 2003). Kusmenoglu and Muehlbauer (1998) increased seed yield in lentil through the development of cultivars with shorter vegetative and flowering periods. Early flowering is often thought an advantage in enabling long pod-filling period before the onset of drought or high temperatures, during the later stages of crop growth and development (Siddique et al., 2003; Silim et al., 1993). For other conditions, where no serious water scarcity is expected during the critical stages of crop growth and development, a different phenology might be required (Saxena, 2009; Solanki et al., 2007).

Consequently, the first objective of this simulation study was to determine the geographical areas in East Africa that offer potential for consistent lentil production. A mechanistic model was used to calculate grain yields across 30 growing seasons of generated weather data for each location on a 1×1 grid in regions that are candidate areas for expansion of lentil production in East Africa.

The second objective of this study was to examine the change in an agricultural management practice and a possible plant trait to increase grain yield potential of lentil in East Africa. First, the effect of a management practice was examined by exploring the effect of different sowing dates on potential yield of lentil. Second, the effect of phenology on yield potential was examined by comparing short-season, early-flowering lentils to long-season, late-flowering ones. The results of these simulations, therefore, offer information across East Africa in guiding geographically based research in regard to where lentil might be produced, and some research opportunities to increase grain yield potential.

2. Materials and methods

2.1. Model description

Soltani and Sinclair (2012b) recently presented a non-calibrated, mechanistic, comparatively simple model called Simple Simulation Model (SSM) for simulating growth and yield of crops. The robustness of an SSM-Legumes version of the model, generic to grain legume species, has been demonstrated in several studies over a wide range of environments for various legume species including soybean (Sinclair et al., 2010), chickpea (Vadez et al., 2013), and bean (Marrou et al., 2014). Recently, we parameterized a lentil version of the SSM-Legumes model that demonstrated a robust predictive capability in assessing variation in phenological development and yield of lentil in a range of environments, with different rainfall patterns in the Middle East (Michel E. Ghanem, personal communication).

The SSM-Legumes model accounts for leaf area development as a function of temperature that 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 (Sinclair et al., 2014). Radiation use efficiency, like leaf extension, is decreased proportional to soil water content (Soltani and Sinclair, 2012b). Thus, daily growth was calculated based on incident solar radiation, leaf area index, and soil water content. Finally, daily seed growth was calculated as a fraction of total dry matter, considering a linear increase in harvest index.

One of the unique features of the SSM-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 a constant, mechanistically-based transpiration coefficient (Soltani and Sinclair, 2012b). 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 each day so the soil water budget was updated daily by water addition if there was rainfall and water removal from the soil as a result of transpiration and direct evaporation from the soil surface.

Calculation of the soil water balance in the lentil model is similar to the original SSM-Legumes of Soltani and Sinclair (2012b). That is, the entire soil volume occupied by roots is considered as a single compartment for calculating the reservoir for crop available soil water. The initial depth of soil water extraction at plant emergence is set equal to 200 mm. Subsequently, the depth of extractable soil water profile is increased steadily per biological day (defined below). The final depth of soil water extraction is limited either by phenological development, the maximum rooting depth capacity of the crop, or by chemical and physical barriers in the soil (limited soil depth). After beginning of seed growth (BSG), increases in rooting depth were terminated.

Soil water status, calculated as the amount of transpirable soil water (ATSW), was calculated daily using the water balance equation for an expanding volume of soil, corresponding to the addition of the new soil layer explored by roots on that given day. Since lentil is cultivated as a rainfed crop in East Africa and Yemen, no irrigation was scheduled in the simulations. Any new accessible water in the soil due to root growth (*NEWAT*) is added to the total water volume component together with daily rainfall (P, mm), and when relevant, irrigation input (I, mm). Water losses from run-off (R, mm), soil evaporation (ES, mm), transpiration (TR, mm) and drainage (D, mm) are subtracted from the soil water. Drainage water is calculated as water that exceeds the total water holding capacity of the volume of soil explored by roots. Run-off is calculated using a modified curve technique as reported by Soltani and Sinclair (2012b).

$$ATSW_d = ATSW_{d-1} + P_d + NEWAT_d - R_d - ES_d - TR_d - D_d \quad (1)$$

In addition, a new algorithm that accounts for crop survival at very low soil water content (Michel E. Ghanem, personal communication) was added to the lentil model based on concepts developed by Sinclair (2000). In low-yielding environments, like East Africa, plant survival under severe drought is crucial for crop performance. The survival phase is characterized by stomatal closure so that continued water loss is considered to be through the entire epidermis based on leaf epidermal conductance (EPCOND). As water is lost from the leaves, leaf relative water content decreases until it reaches a lethal leaf relative water content (LTLRWC). Leaf area was decreased to account for the water loss in reaching LTLRWC for successive leaves of the crop canopy. For lentil, the values of these two physiological input parameters of EPCOND and LTLRWC were set at 0.1 mm s^{-1} and 0.355 g g^{-1}, respectively (Leport et al., 1998; Turner et al., 2001).

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, 2012b). 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 whether actual daily temperature and photoperiod are limiting or not. Therefore, average daily temperature and daily photoperiod were crucial in the model to account for their influence on crop development. In the model, biological days are defined for the following stages: sowing to emergence, emergence to flowering (stage R1 in lentil), R1 to R3 (beginning of pod formation), R3 to R5 (beginning of seed fill), R5 to R7 (end of seed fill) and R7 to R8 (maturity).

2.2. *Model entries: weather generation*

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).

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 (Sinclair et al., 2014). Given that reliable and complete long-term weather datasets are scarce in Africa, it was necessary to generate weather data. The National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) re-analysis baseline data were used to produce a retroactive record of daily data (Dee et al., 2011; Uppala et al., 2005). The surface grids were analyzed in the Weather Research and Forecasting (WRF) tool to extract daily values for the last 30 years at the centroid of a $1° \times 1°$ point grids in each of the regional blocks.

Given the importance of these datasets in the crop simulations, it was necessary to verify whether they do, in fact, represent the patterns of rainfall and temperature distribution. The amount and distribution of precipitation and temperature are among the most important environmental variables that influence the soil water balance, crop growth and other processes. Therefore, an independent comparison was performed for a few locations of similar latitudes, for which historical data were available. The records were checked not only for distribution of precipitation but also for maximum and minimum temperature in order to detect obvious errors. Simulated values were shown to follow the same distribution as the observed ones although the absolute values were not necessarily exactly the same (Ghanem et al., unpublished results).

2.3. *Model parameters: soil and crop parameters*

Simulation were run using fixed sowing date options with no irrigation. Since no extensive soil data were available, in all locations the volumetric transpirable soil water was set equal to 0.13 m^3 m^{-3} and the maximum rooting depth was set equal to 1500 mm. Of course, these two parameters can be varied if such information is available for a specific location. The main crop parameters were extracted from previous published studies or were experimentally measured, and are reported in Table 1.

The same temperature function was used in all simulations with the base temperature equal to 2 °C, an optimum temperature of 20 °C and a ceiling temperature equal to 30 °C. The photoperiod response

Table 1
Crop parameters for lentil, as needed by the SSM-legumes model. Parameter values have been calculated based on experimental results or estimated based on similarities with other grain legumes. Parameters were previously reported in Michel E. Ghanem, (personal communication).

Parameter	Value	Reference
Phyllochron	50.0 °C/leaf	Michel E. Ghanem, personal communication
A coefficient (exponent) in power relationship between plant leaf area and mainstem node number	2.1	Michel E. Ghanem, personal communication
Specific leaf area	0.0069 m^2 g^{-1}	McKenzie and Hill, 1989
Potential radiation use efficiency	2.05 g MJ^{-1}	McKenzie, 1987
Harvest index increase (PDHI)	0.018 d^{-1}	Michel E. Ghanem, personal communication and references therein cited
Transpiration coefficient	0.5 Pa	Michel E. Ghanem, personal communication and references therein cited
FTSW threshold when dry matter production starts to decline (WSG)	0.47	Michel E. Ghanem, personal communication
FTSW threshold when leaf area development starts to decline (WSSL)	0.55	Michel E. Ghanem, personal communication
FTSW threshold when N_2 fixation starts to decline (WSSN)	0.30	Michel E. Ghanem, personal communication
N content in green leaves	2.6 g m^{-2}	McKenzie and Hill, 1989
N content in senescent leaves	1.0 g m^{-2}	Whitehead et al., 2000
N content in green stems	0.019 g·g^{-1}	Ayaz et al., 2004
N content in senescent stems	0.03 g·g^{-1}	Michel E. Ghanem, personal communication
N content in grain	0.043 g.g^{-1}	
Maximum N uptake through fixation	0.50 g.m^{-2}.d^{-1}	

was defined by two variables; the critical photoperiod, which is 11 h for lentil and the photoperiod sensitivity *ppsen*, which is 0.28 for lentil (Michel E. Ghanem, personal communication).

2.4. *Crop yield simulations*

2.4.1. *Sowing date and plant density*

In these simulations, determination of sowing dates were not based on a threshold of accumulated soil water. Instead, simulations were done over a range of defined sowing dates from day 152 (1st of June) till day 264 (21st of September) at 1-wk intervals. Sowing density was fixed at 60 plants m^{-2}, which corresponds to the sowing density used by farmers in Ethiopia (Bejiga, 1991).

2.4.2. *Phenological parameters*

In lentil, genotypes are classified by maturity groups reflecting their adaptability to various latitudinal zones as a result of sensitivity in development to temperature. The expectation was that early-flowering lentil genotypes are often thought to have an advantage in comparison with late-flowering genotypes. While an optimization could be attempted for each phenological cycle, for these initial simulations a single set of development parameters for each of the long-season (late emergence-late flowering) and short-season lentil (early emergence-early flowering) genotypes was explored. The differences in development of the early- and long-season genotypes were defined by the biological days of each development stage (Table 2). Initial simulations were done for short-season, early-flowering, lentil genotypes similar to the ones cultivated in the Middle East and North Africa (Siddique et al., 1998; Thomson et al., 1997). Subsequently, simulations were done for long-season, late-flowering genotypes that are grown in Southern latitudes like Ethiopia and South Asia (Bejiga et al., 1996; Mondal et al., 2013).

Table 2
Developmental parameters for simulation of short-cycle and long-cycle lentil in East Africa including the biological days required for each of the simulated phenological stages.

Parameter	Long-cycle cultivar (Siddique et al., 1998; Thomson et al., 1997)	Short-cycle cultivar (Bejiga et al., 1996; Mondal et al., 2013)
Critical photoperiod (h)	11	11
Photoperiod sensitivity	0.28	0.28
	Biological days	
Sowing to emergence	11.0	7.8
Emergence – R1	43.0	30.0
R1 – R3	5.7	5.7
R3 – R5	13.0	13.0
R5 – R7	16.0	16.0
R7 – R8	14.0	14.0

The two plant types differed mainly in their time from sowing to emergence and emergence to flowering (stage R1 in lentil) (Table 2).

3. Results

3.1. Rainfall spatial distribution

Eastern Africa's diverse topography and large water bodies such as the Indian Ocean and Lake Victoria contribute to a high variance in spatial distribution of rainfall. Fig. 1 shows variation in yearly precipitation over the region. Ethiopian highlands, Uganda, as well as southern parts of South Sudan, and eastern parts of Tanzania show the highest annual rainfall: between 1500 and 2000 mm/year (Fig. 1). The Greater Horn of Africa, Somalia, Kenya, as well as eastern parts of Ethiopia and western parts of Tanzania show lower cumulative rain. Most parts of Sudan and northern parts of South Sudan are a very arid zone with an annual precipitation less than 200 mm per year (Fig. 1).

East Africa can be divided into four more or less homogenous rainfall regions (Fig. 1): Region A (Greater Horn of Africa); Region B (Ethiopian Highlands); Region C (Central East Africa); and Region D (Southern East Africa). The annual cycle of rainfall in East Africa is generally characterized by two rainy seasons: the "long rains" in March-May (MAM) and the "short rains" which typically start mid-October and continue until mid- December (OND) (Black et al., 2003; Clark et al., 2003). In general, East African climate is normally dry between the "long and short rains" seasons. The exception to this is in the high plateau regions in the northern Great Rift Valley (central and northern Ethiopia) (Fig. 1, Region B), which has a third and stronger rainy season (Kiremt) during June to September (Segele and Lamb, 2005).

3.2. Baseline simulated yield and production risk

The initial objective of this simulation study was to assess geographical viability of lentil production in East Africa. The model, which included the new algorithm accounting for crop survival at very low soil water content, was run for all locations and years using the baseline parameters, phenology, and sowing date most commonly found in the literature for lentil in Ethiopia, i.e. a short-season phenology (parameters in Table 2) sown in June on day of the year 152 (Fig. 2). As shown in Fig. 2B, the Ethiopian highlands were simulated to have the highest average grain yields ranging between 1.2 to 2.0 t ha^{-1} (120 and 200 g m^{-2}) dry weight. Portions of south Uganda, north eastern Tanzania and a pocket in south Kenya and Tanzania were simulated to have average grain yields ranging between 1.2 to 1.6 t ha^{-1} dry weight. South Sudan and most of Tanzania had a simulated average yield ranging between 0.8 to 1.2 t ha^{-1}. Many of the locations in the Great Horn of Africa (Somalia and eastern Ethiopia) had a low simulated average yield ranging between 0.4 to 0.8 t ha^{-1}. Most of the locations in Sudan and Yemen had a very low simulated average yield (less than 0.4 t ha^{-1}). There were some locations in the northern parts of Sudan where the lack of rainfall resulted in no simulated crop growth (i.e., no germination or early crop termination every year) (Fig. 2B).

The risk of being unable to obtain yield (expressed as number of years where yield could not be obtained) can be a stronger criteria for acceptability for industrial and commercial development of a crop in a region than average yield alone. Setting this threshold at two or more years of failure out of 30, large areas of East Africa appear not to be suitable to lentil growth under the prevailing current cropping practices (i.e., a short-season phenology crop sown in June). As shown in Fig. 2A, lentil production is not appropriate in a large band in the northern tier of East Africa (Sudan, Eritrea, Yemen, and northern Ethiopia). In addition, much of the Great Horn of Africa region (Somalia and eastern Ethiopia) and large parts of western Tanzania are not appropriate for lentil production. Even with a more relaxed threshold criterion at three or more years of failure out of the 30 growing seasons, there are still large areas in Tanzania, Somalia, Uganda, and Kenya that seem unlikely to be suited for consistent production of lentil (Fig. 2) under the simulated conditions. On the contrary, Ethiopian highlands, South Sudan, eastern Kenya and Tanzania appear suitable for lentil production (Fig. 2A).

3.3. Change in sowing date

One management practice for potential increase in lentil yield is to change sowing date. Farmers in Amhara and Oromia regions in Ethiopia usually sow lentil in June to July on well-drained soil, while farmers of waterlogged black soil can sow as late as the end of September (Bejiga, 1991). Simulations were done over a range of sowing windows from day of year (doy) 152 (1 June) until 264 doy (21 September) at 1-week intervals. The sowing date of early June (152 doy) was taken as the basis for assessing the impact of the change in sowing date on potential yield.

Neither the absolute values nor the distribution pattern of simulated average grain yield changed when sowing date was shifted to early July (182 doy). Of the remaining dates, the results for 201, 229, 243 and 264 doy are presented to illustrate the full range of results. The probabilities of yield increase as a result of the delaying sowing date are shown in Fig. 3. Except for a very few locations in northern Sudan, delaying sowing until late July (201 doy) resulted in a higher probability of average yield increase for many simulated locations in East Africa (Fig. 3A). The most consistently large yield increases with delayed sowing were in the central portion of East Africa, especially in Ethiopia, South Sudan, Uganda, and some of the areas of in central and southern Somalia, where most of the locations had more than 85% probability of yield gain. On the other hand, there were locations between these two areas and around them (like in Tanzania and Sudan), where the probability of yield increase was less than 55%, i.e. there was a likelihood of a yield decrease (Fig. 3A). A similar pattern was observed when sowing was delayed until mid-August (229 doy) (Fig. 3B). For this date, the highest probability of yield gain (more than 85%) was extended eastwards in Ethiopia and Somalia. Delaying sowing to September (both early (243 doy) and late (264 doy)) (Fig. 3C and D) showed the highest probability of yield gain (85% increase) in Kenya, Uganda, northern parts of Tanzania and central parts of Somalia (Fig. 3C and D).

3.4. Change in phenology

The standard lentil model simulated yield based on the definition of the development stages of a short-season lentil genotype (early emergence-early flowering). Simulations were done, for each sowing date, for an altered late-maturity long-season genotype (late

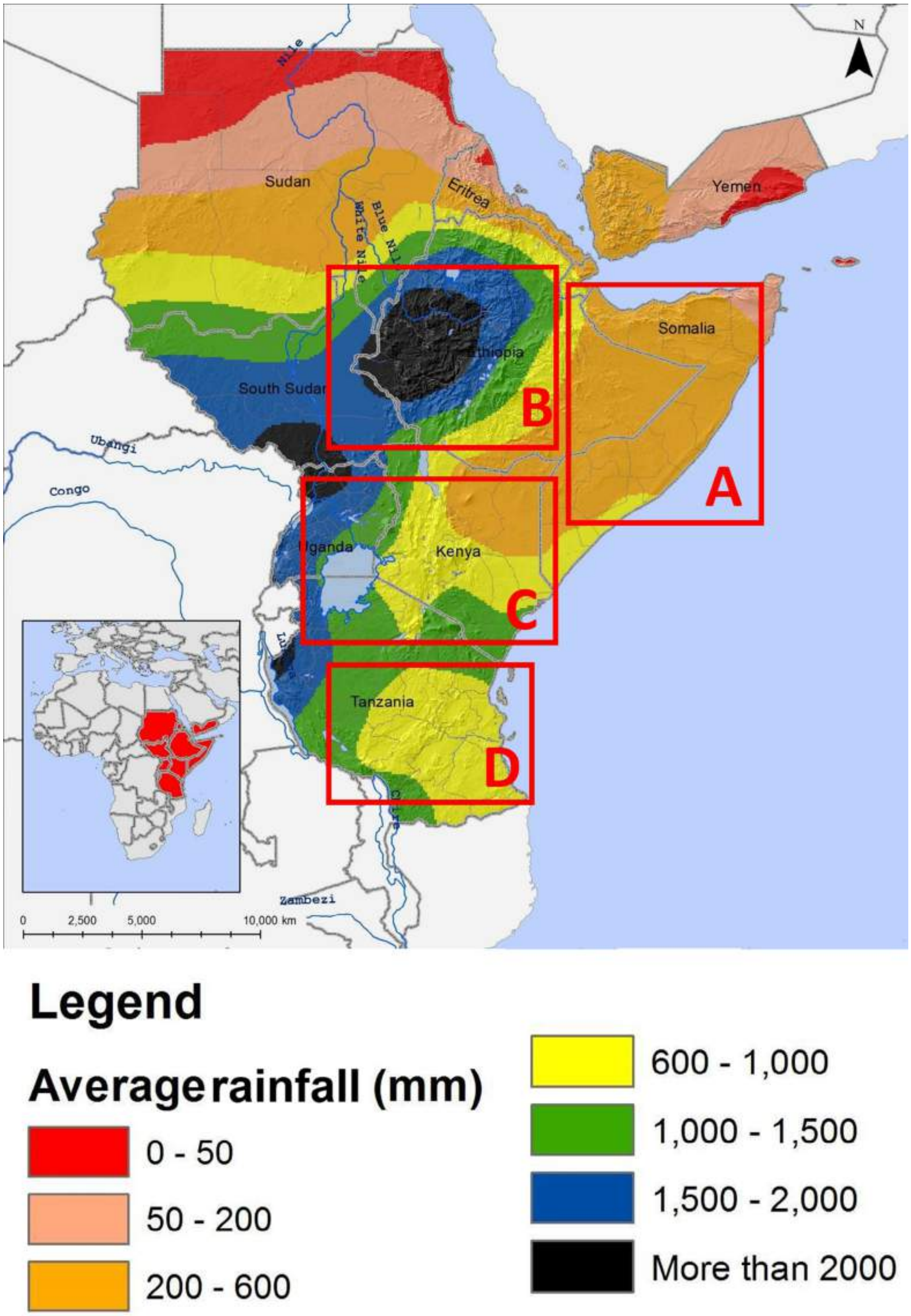

Fig. 1. Annual rainfall distribution at simulated locations in East Africa.

emergence-late flowering) in which the number of days to emergence and the number of days from emergence to flowering were greater (Table 2). Fig. 4 shows the probabilities of yield increase as a result of a long-season genotype (201, 229, 243, and 264 doy).

A late-emerging, late-flowering crop sown early June (152 doy) had a positive impact on yield in nearly all locations in South Sudan and Ethiopia, Uganda as well as southern parts of Somalia and coastal areas of Kenya (Fig. 4A). On the contrary, in most parts of Sudan, Yemen and Tanzania, the probability of yield increase by prolonging the crop cycle was less than 55%. Further delaying the sowing until July (201 doy) or mid-August (229 doy) for a long-season genotype of lentil restricted the extent of the area where the highest probability of yield increase (85%) was expected to the Ethiopian highlands, South Sudan and Uganda (Fig. 4B and C) compared to the baseline scenario of sowing at day 152 with the same phenology. When sowing was performed later in September (243 or 264 doy), the area where the highest probability of yield increase moved further to the south of East Africa covering only a few locations of southern

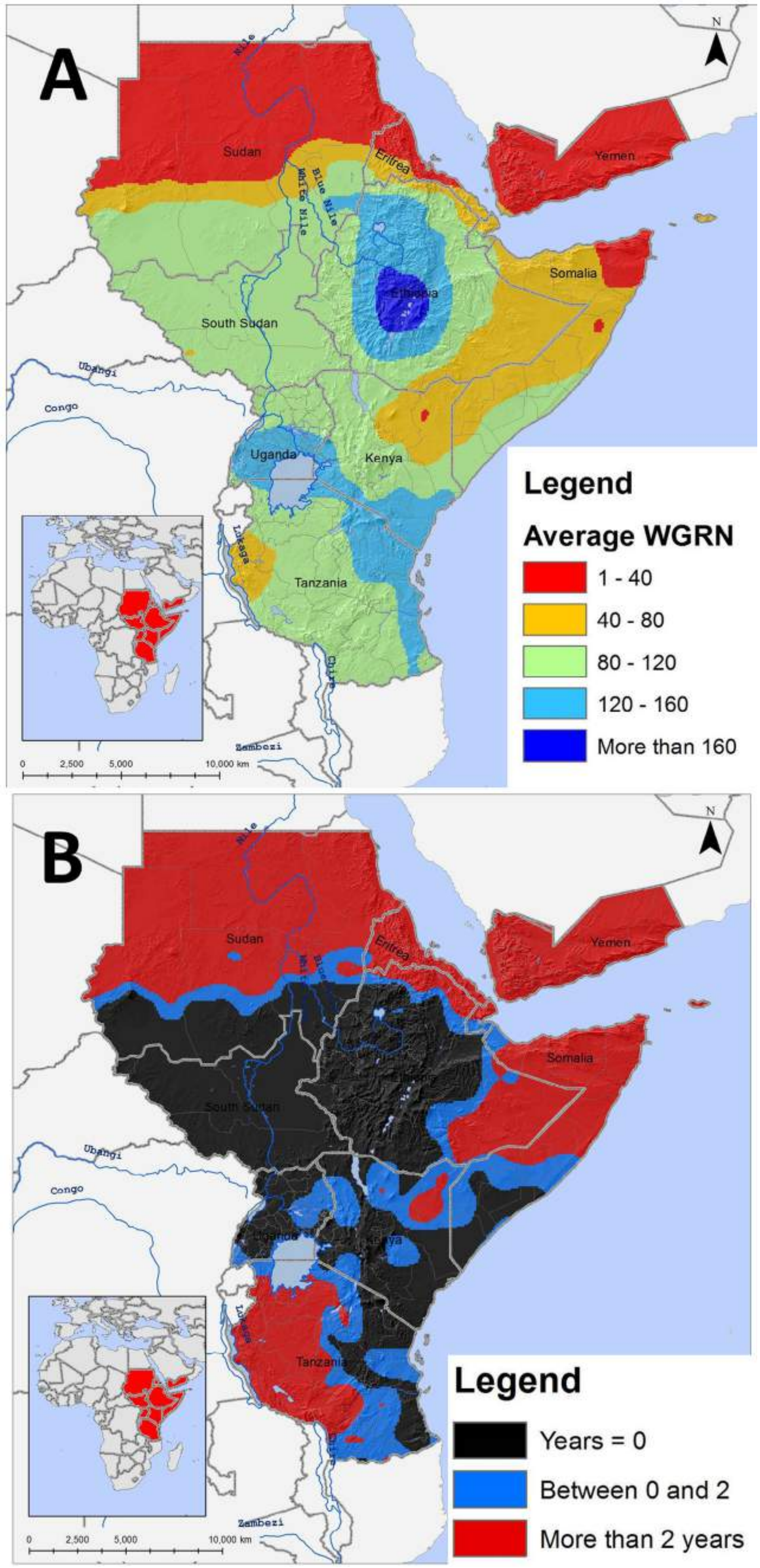

Fig. 2. Average grain yield (WGRN, g dry weight m-2) (A) and number of years without yield (B) for standard short cycle lentil simulated at each location for a fixed sowing date at 152 day-of-year (doy).

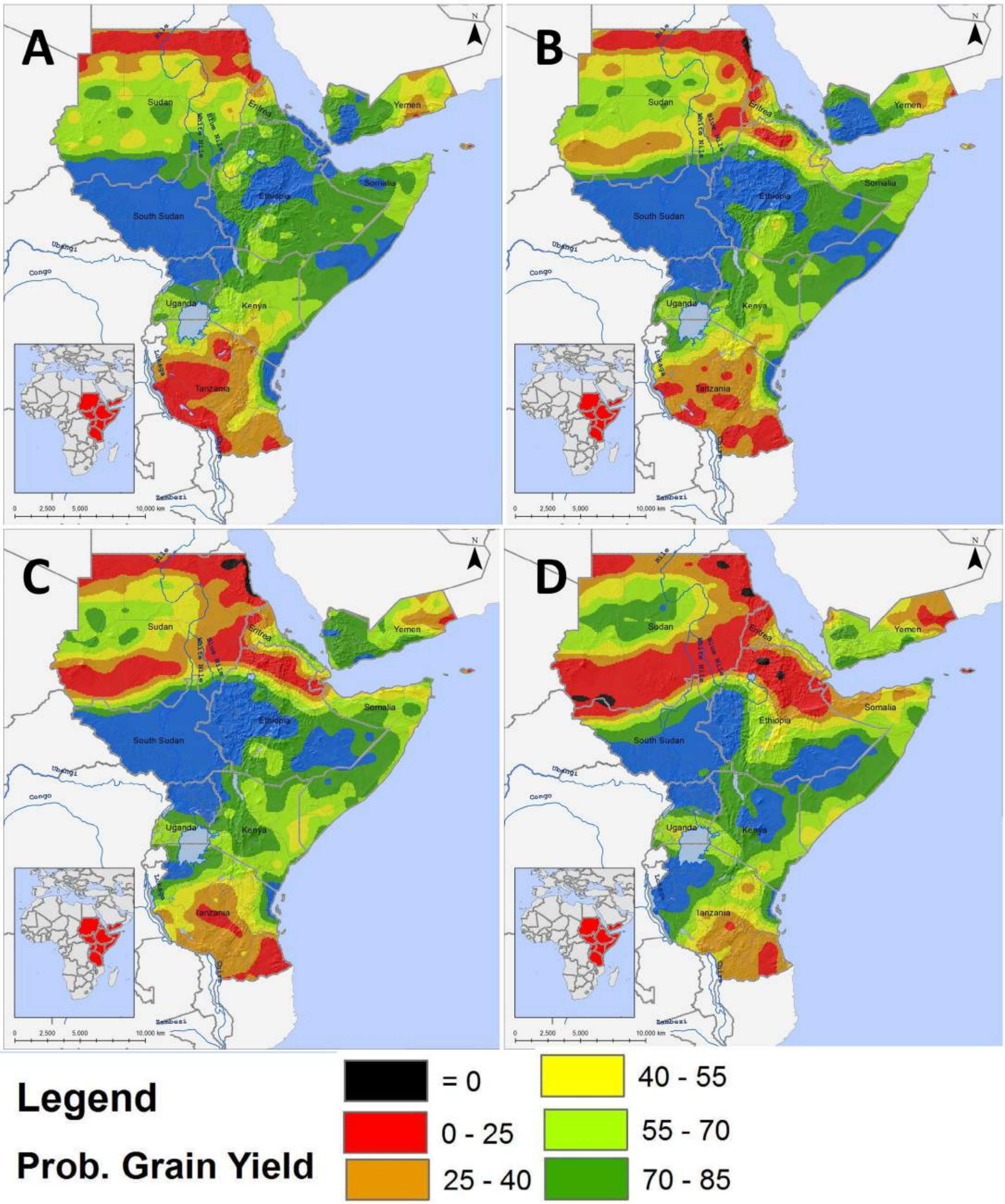

Fig. 3. Probability of grain yield increase of simulating different sowing day-of-year (SD) (A) 201, (B) 229, (C) 243, and (D) 264 as compared to a sowing date of 152 doy.

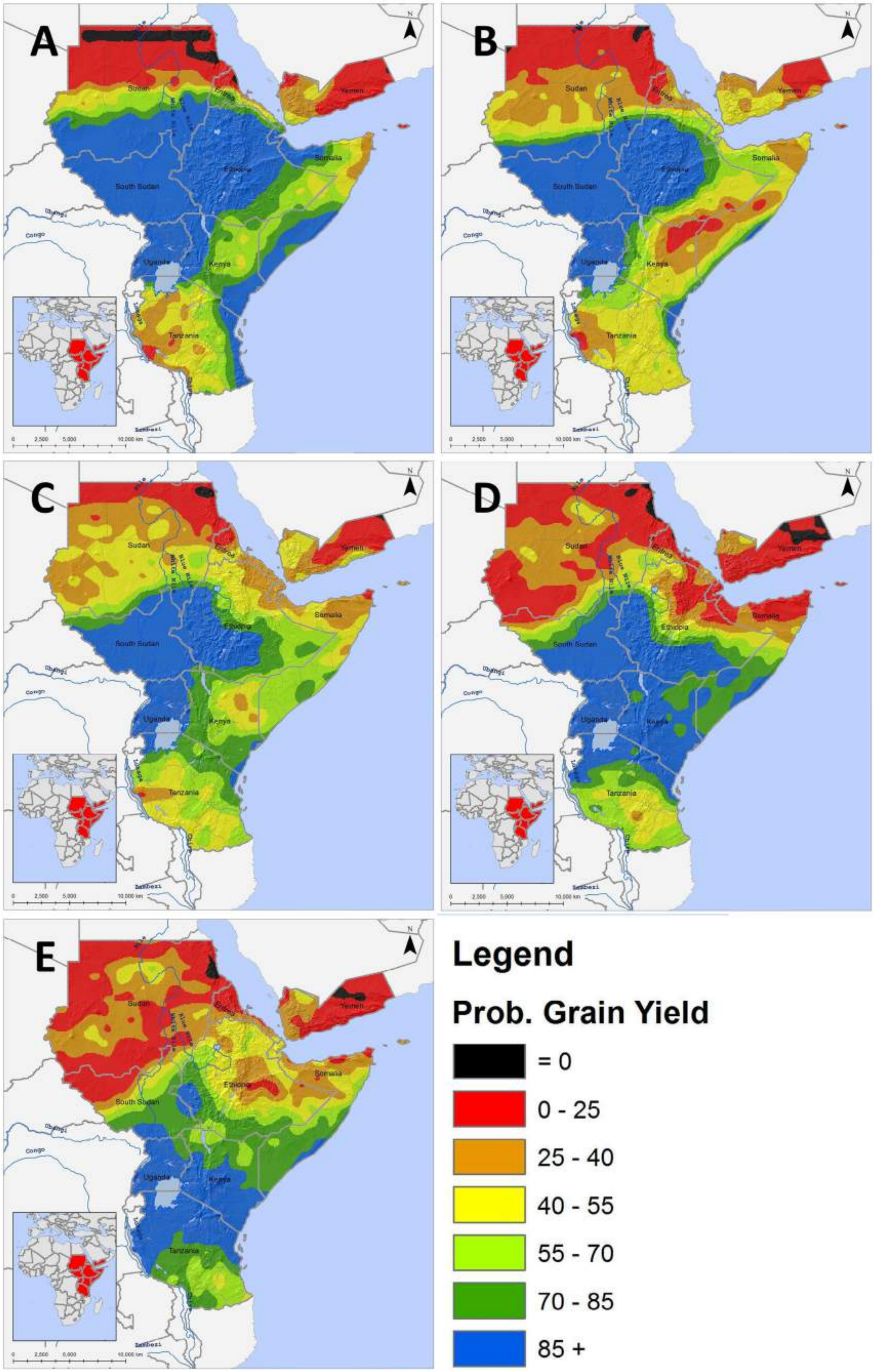

Fig. 4. Probability of grain yield increase of simulating long-cycle lentil as compared to a short-cycle lentil for different sowing day-of-year (SD) (A) 152, (B) 201, (C) 229, (D) 243, and (E) 264.

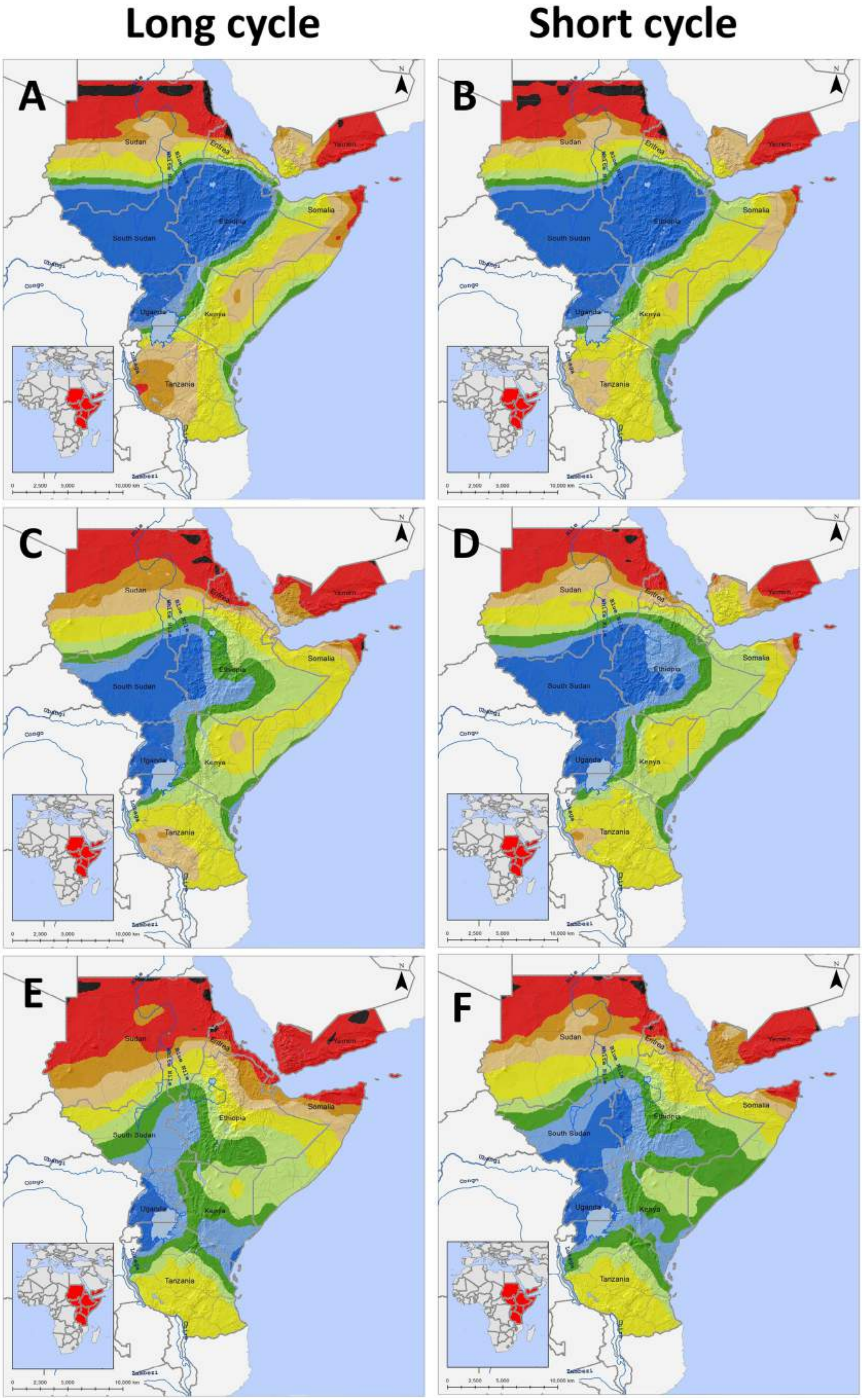

Fig. 5. Simulation of actual transpirable soil water (ATSW) in mm of water left in the soil after harvest for short-cycle and long-cyclel lentil sown on different sowing day-of-year (SD) (A and B) 152, (C and D) 201, (E and F) 229, (G and H) 243, (I and J) 264.

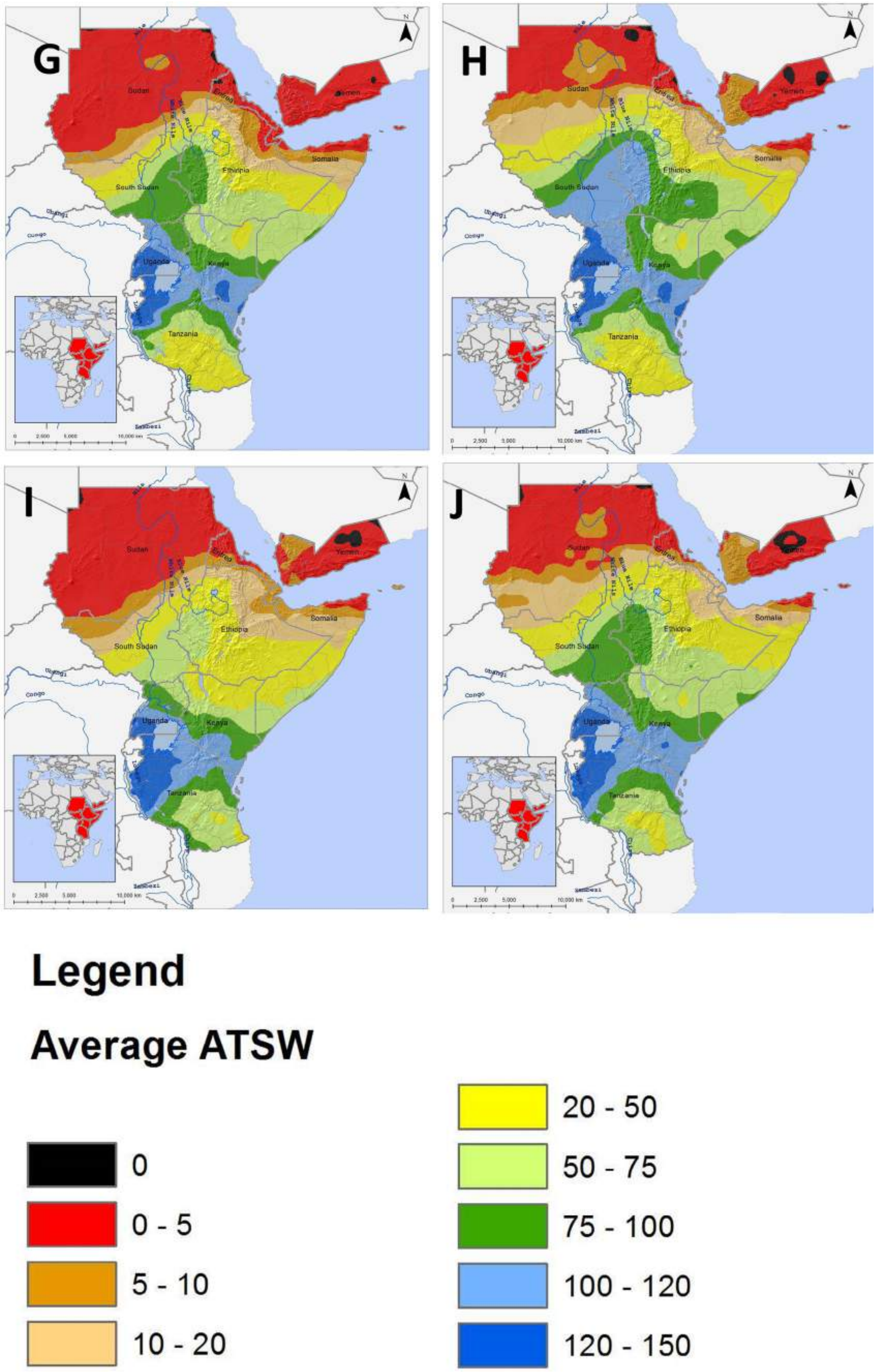

Fig. 5. (*continued*)

parts of Ethiopia and South Sudan but almost entirely Uganda and Kenya as well as the northern locations in Tanzania (Fig. 4D and E).

3.5. Soil water content at the end of the crop cycle

The amount of actual transpirable soil water (ATSW, mm) that was in the root zone at the end of the crop cycle was examined as an indicator of the extent of water use by the crop. A low value of ATSW indicates that the crop cycle was better synchronized with rainfall which allowed more effective use of the available water. Fig. 5 represents the ATSW for both the long-season (Fig. 5A, C, E, G, I) and short-season (Fig. 5B, D, F, H, J) lentil genotypes for each of the sowing dates. For all sowing dates, northern locations of Sudan showed the lowest ATSW values (zero) especially on the earliest sowing date (152 doy) for both phenologies (Fig. 5A, B). For a crop sown in June (152 doy), the highest simulated ATSW values were found in Ethiopia, South Sudan and Uganda (more than 120 mm of water) for both phenologies. For the same sowing date, low simulated ATSW values (less than 50 mm) were shown for most parts of Sudan, the Great Horn of Africa, Kenya and Tanzania for short-season phenology.

Later sowing dates moved the area where simulated ATSW was the highest southwards toward Kenya, Uganda and Tanzania (Fig. 5). In general, the same spatial pattern of ATSW is observed for the same sowing date, on long- and short-season genotypes. However, for the highest simulated ATSW values, long-season lentil genotypes left less water in the soil (lower ATSW) than the short-season genotypes, especially for sowing dates following 201 doy (Fig. 5C–J).

4. Discussion

4.1. Areas for lentil production

The SSM-legume model used in this assessment was based on the parameters presented for lentil by (Michel E. Ghanem, personal communication). The simulation results presented here using the baseline parameters, phenology and sowing date most commonly found in the literature for lentil in southern latitudes in East Africa showed that the model was able to predict regions of higher yield potential. The simulations predicted the highest yield potential for lentil in the Ethiopian highlands (Fig. 1). This area of higher yield coincides with Amhara, Oromia, Tigray and the “Southern Nations Nationalities and Peoples” (SNNP) regions, known to be the main lentil producing regions in Ethiopia (Regassa et al., 2006).

The average observed seed yield of lentil in farmers’ field in Ethiopia is generally about 0.6–0.8 t ha^{-1} (Regassa et al., 2006). Not surprisingly, the simulation results in this study predicted a higher maximum average grain yield for the same areas with yield ranging between 1.6 and 2.0 t·ha^{-1} (Fig. 1). Yields of about 2.0 t ha^{-1} have been reported from experiments performed under controlled field experimental conditions in Ethiopia (Erkossa et al., 2006).

Lentil is dominantly produced by smallholder farmers and most of them follow a traditional farming system based on indigenous knowledge. Risk decisions by farmers in regard to the introduction of a change in management practices or a new plant trait may cause the probability of yield increase to be at least as important as the long-term average yield increase. Very likely, risk-averse farmers may want to avoid the changes that result in a substantial fraction of the growing season with yield decreases even if the long-term average yield is higher. Since in one location nearly all management practices or traits can result in a given season, either an increase or a decrease in yield depending on the weather of that individual growing season, it is important for crop breeders and farmers to understand the probability of yield increase (Sinclair et al., 2014).

The inability to obtain yield in two or more growing seasons out of 30 was a criterion used to identify the geographical areas in East Africa for consistent low-risk, lentil production. Simulation results showed under the current conditions of short-season genotypes sown in June that large areas of East Africa appear not to be suitable for lentil production. Fig. 2A, shows that large parts of the northern tier of East Africa and much of the Great Horn of Africa, as well as western Tanzania are high risk areas for lentil production. On the contrary, the Ethiopian highlands, South Sudan, Uganda, eastern Kenya and Tanzania appear suitable for lentil production (Fig. 2A). Lentil is not currently a crop in Kenya, Uganda and Tanzania (Bejiga and Degago, 2000). However, the simulation results showed that even under the actual parameters, phenology, and sowing date most commonly used in southern latitudes, lentil can potentially become a crop in large areas in these countries.

4.2. Sensitivity to sowing date

Changing sowing dates could be an option for increasing yield in future climates (Ludwig and Asseng, 2010). In general, delaying sowing until mid-August (229 doy) resulted in a higher probability of average yield increase across many simulated locations in central East Africa covering the countries of Ethiopia, South Sudan and Uganda (Fig. 3). The probability of yield increase as a result of delayed sowing was simulated to always be higher than 85% (for all dates) for Uganda. In the northern tier of East Africa, except a small pocket in Sudan, delaying sowing beyond mid-August does not seem useful as it did not improve the probability of yield increase.

Delaying sowing to September (243 or 264 doy) shifted the highest simulated yield gain (85% increase) to the south toward Kenya, Uganda, northern parts of Tanzania and central parts of Somalia (Fig. 3C and D). This coincides with the end of the rainy season in this area and would therefore offer a potential of growing lentil in this area by replacing the fallow. This would not compete with other crops like maize, which are grown during the rainy season in this area of East Africa. Of course, this hypothesis must be explored experimentally. Shifting sowing dates until the end of September (264 doy) is likely not to be useful in Ethiopia (Fig. 3D).

These results contrast with common advocacy of early sowing as a means to avoid rising temperatures and drought during the reproductive phase and maximize lentil yield. With a defined growing season, the early sowing of lentil is reported to produce the highest seed yield in Mediterranean type of environments such as Italy, Syria, Western Australia (Materne et al., 2007). Under these conditions, an early sowing lentil crop makes better use of seasonal precipitation than the crop from a later date of sowing (Saxena et al., 1983). However, when lentil is sown early, depending on the performance of varieties and soil type, increased weed competition, biotic stresses, and waterlogging incidences may occur and affect its productivity (Materne et al., 2007). Late sowing in the Middle-East is reported to alter the vegetative and phenological development of the crop through changes in temperature and photoperiod (Erskine and Saxena, 1993; Erskine et al., 1994).

In Ethiopia, lentil is predominantly grown during the main rainy season (Kiremt) (June to September). The simulation results for Ethiopia contrast with some experimental conclusions from that of late June to mid-July sowing in both mid- to high-altitude areas (Bejiga, 1991; Regassa et al., 2006). Bejiga et al. (1996) reported that later sowing after mid-July reduced yield in Ethiopia. However, there was a large yield variation in yield in the data presented by Bejiga et al. (1996), highlighting the challenge in using conventional experimentation conducted over limited number of seasons (five in the study of Bejiga et al., 1996) to screen for an appropriate sowing date in a location (Sinclair and Muchow, 2001). In chickpea, Soltani and Sinclair (2012a) reported also that calculations of mean yield based on 10-year periods did not match the overall simulated long-term mean in many cases, indicating that even ten years of experimentation may be insufficient to reflect the overall crop behavior in a location.

4.3. Sensitivity to phenology parameters

Matching the phenology of a crop to an environment is key to improving adaptation and increasing crop yield. The simulations results showed that lengthening the time to flowering and crop growing cycle was very similar to the distribution resulting from the change in sowing date. That is, many locations had probabilities of yield increase greater than 70% in nearly all locations in South Sudan and Ethiopia, and Uganda for all sowing dates (Fig. 4). However, many locations in Sudan, Yemen and Tanzania showed only a small benefit from increasing the duration of the crop season (less than 55%) for almost all sowing dates. Like the distribution of probability of yield gain resulting from a late sowing alone (Fig. 3D), a combination of late sowing (September 243 or 264 doy) and long-season genotypes shifted the area of highest probability of yield increase to the south of East Africa toward Uganda and Kenya as well as northern locations of Tanzania (Fig. 4D and E).

These simulation results generally indicated higher yield with a long-season crop. These results are consistent with some experimental results in Ethiopia, reporting that late-maturing genotypes were found to be favored when rainfall occurred over a longer period (Bejiga et al., 1995). In Australia, late sowing improved the relative performance of the late-flowering genotypes that perform poorly in drought years (Materne, 2003).

Conversely, these results are in contradiction with experimental findings on lentil grown in the dry areas of Syria where the highest yielding lentil genotypes produced a large amount of mass, flowered early, and had a brief, rapid seed-filling phase (Silim et al., 1993). Time to flowering accounted for 49% of the variation in the seed yield, indicating that drought avoidance through early flowering was key to minimize the effects of drought stress (Silim et al., 1993). The opposite was observed for the same genotypes in wetter years. Similarly, early flowering and maturing genotypes were high yielding at low-rainfall, low-yielding environments in Australia but the yields of these genotypes were low compared to the best medium-rainfall, mid-flowering genotypes over eight locations and five years (Materne, 2003). A possible explanation for these discrepancies between sites would be that, although early flowering is important for drought escape, it is not effective if genotypes have a relatively low mean yield over many seasons and sites, due to an inability to respond to increasing available soil moisture (Materne, 2003; Materne and Siddique, 2009; Turner et al., 2001). Additionally, avoidance may not be the only mechanism for drought tolerance in lentil (Leport et al., 1998; Shrestha et al., 2006).

Comparing the water available in the soil at crop maturity by examining the ATSW (Fig. 5) clearly shows the deficiency of the short-season phenology, compared to the long-season one. Fig. 5 shows that for most sowing dates (except 152 doy) short-season lentil genotypes left more water in the soil (higher ATSW values) than the long-season genotypes. This indicates that for areas of higher probability of yield increase (located in the north and center of East Africa for early sowing and in the southern locations of East Africa for later sowing), there is still water in the soil that can be used as a resource to maximize mass accumulation and yield formation. Short-season phenology shows a disadvantage compared to long-season phenology in the potential use of the water resource.

4.4. Combining changes in sowing date and phenology

Generally, delaying sowing and a longer phenology tended to have similar distribution patterns of probability of yield increase in East Africa. However, the relative value of the change in management

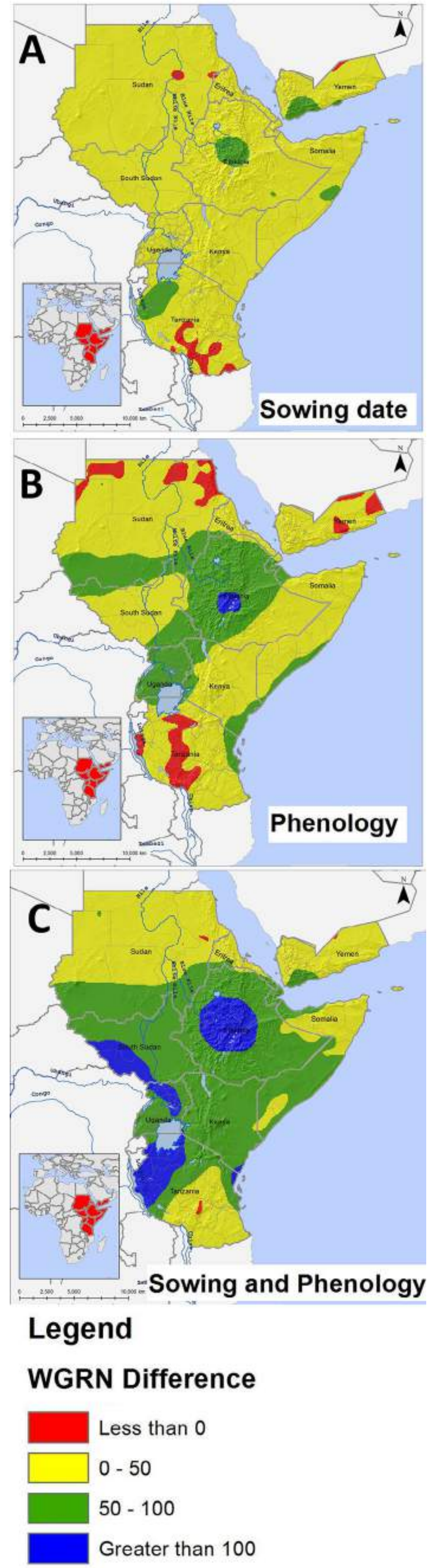

Fig. 6. Simulation of average yield gain (WGRN, g dry weight m-2) at each grid location by changing (A) sowing date, (B) phenology, and (C) changing both sowing date and phenology.

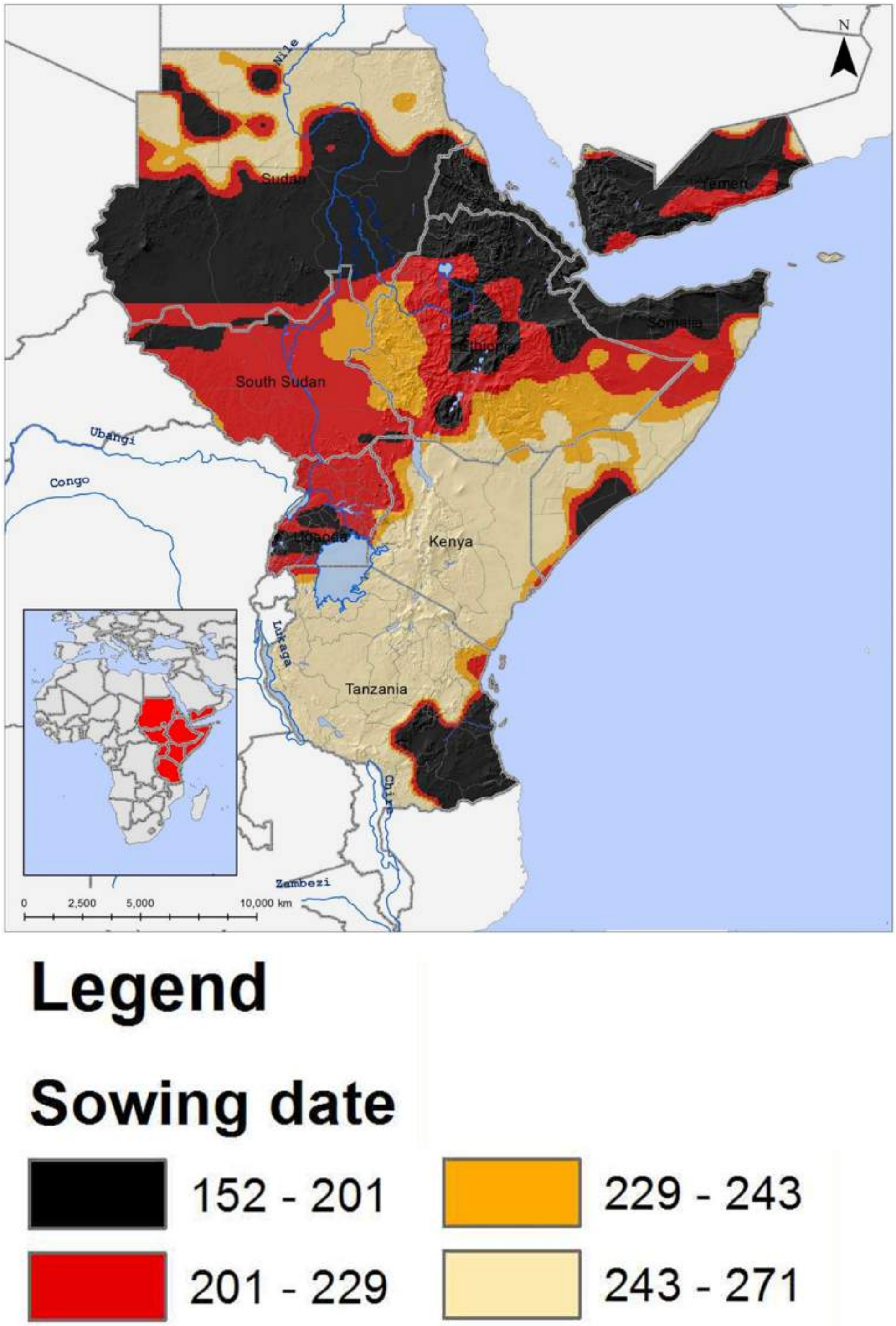

Fig. 7. Simulation of optimum sowing window for long-cycle lentil genotypes.

practice and/or trait differed by locations. As shown in Fig. 6, the simulated average yield gain that can be reached by changing sowing date alone (Fig. 6A) is less than the yield gain through lengthening lentil phenology (Fig. 6B). This can been explained by the fact that, in very dry areas, shifting the cycle position, without substantially changing cycle duration, won't allow escape of extreme drought and subsequent significant yield reduction, or early crop termination. In the case of changing sowing date, major gains (above 50 g m^{-2}) were mainly limited to Ethiopia and eastern Tanzania, while changing sowing date was unlikely to be beneficial in southern Tanzania (Fig. 6A). Under the effect of a longer-season genotype, yield gain was further extended (Fig. 6B) to many locations of Ethiopia and Uganda and some locations in South Sudan. However, the maximum extent of average yield gain was reached by combining changes in both sowing date and a longer phenology to cover Ethiopia, South Sudan, Uganda and Kenya, as well as some parts of Tanzania and Somalia (Fig. 6C).

The simulation results allowed a determination of the optimum sowing windows for each location for long-season genotypes of lentil. Fig. 7 represents the optimum sowing windows when average grain yield was simulated highest across the 30 growing seasons. For long-season genotypes of lentil, an optimum sowing window was found between June and July (152–229 doy) for areas to the north of the Rift Valley (Fig. 7). Indeed, in the Northern part of Eastern Africa there is limited opportunity for the crop to benefit from rainfall in the second rainy season since the dry season is very long. Except for some locations in Tanzania, later sowing dates (229–243 doy) were found to be optimal in southern areas of East Africa. This is consistent with the high possibility for the crop to capture water from the second rainy season if they are not sown too early. In Tanzania, substantial rainfall is commonly experienced from the end of September.

5. Conclusions

The results of these simulations offer information across East Africa in guiding geographically based research in regard to where lentil might be produced, and some research opportunities to increase grain yield potential that can be explored. The results of these simulations offered several crucial insights into developing lentil production in East Africa:

1 One of the key findings of this study is that there is a potential to further expand the geographical area in which lentil is currently grown in East Africa into Uganda, Kenya, Tanzania and even Somalia. Obviously, local experiments are needed to evaluate the possibility of growing lentils and evaluating the genetic material available.
2 Delaying sowing alone or in combination with long-phenology genotypes can result in a higher probability of crop yield increase in lentil producing areas of East Africa. However, the benefit of the change in this management practice or trait needs to be evaluated both by the increase in average yield and by probability of yield increase.
3 These simulations show that response to management practice or trait modification in a breeding effort strongly depends on the location of deployment. Certainly, these results do not support the concept of cultivar development for "wide adaptation".

Acknowledgment

This work was supported by the CGIAR Research Program on Grain Legumes and the USAID/CGIAR-US Universities Linkage Program.

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