NJAS - Wageningen Journal of Life Sciences 68 (2014) 29–39

ELSEVIER

NJAS - Wageningen Journal of Life Sciences

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

Photoperiod sensitivity of local millet and sorghum varieties in West Africa

M. Sanon[a,b], G. Hoogenboom[b,*,1], S.B. Traoré[c], B. Sarr[c], A. Garcia y Garcia[b,2], L. Somé[a], C. Roncoli[b,3]

[a] Institut de l'Environnement et de Recherches Agricoles (INERA), 04 P.O. Box 8645; Ouagadougou 04, Burkina Faso
[b] Department of Biological and Agricultural Engineering, The University of Georgia, Griffin, Georgia 30223-1797, USA
[c] Centre Régional AGRHYMET (CRA), BP.O. Box 11011, Niamey, Niger

ARTICLE INFO

Article history:
Received 1 October 2009
Received in revised form 5 August 2011
Accepted 20 November 2013
Available online 17 January 2014

Keywords:
Pennisetum glaucum (L)
Sorghum bicolor (L) Moench
Daylength
Planting date
Burkina Faso

ABSTRACT

Photoperiod has a strong impact on the development of local millet and sorghum varieties which are two of the most important staple food crops for millions of people in West Africa. Therefore, a better understanding of the response to photoperiod is needed in order to improve production and ultimately increase yield. Several studies have demonstrated the importance of the adaptive capability of local varieties, especially in coping with environmental stress conditions. The objective of this study was to determine the photoperiod sensitivity (PS) characteristics of the most common local varieties of millet and sorghum in Burkina Faso, West Africa. Planting date experiments consisting of 5 or 6 planting dates with complementary irrigation and fertilizer to avoid water and nitrogen stress effect on phenology were conducted at the experiment station of Di in northwestern Burkina Faso during the rainy seasons of 2003, 2004, 2006 and 2007. The study included 7 millet and 11 sorghum varieties from the three main agroecological zones in Burkina Faso to determine their sensitivity to photoperiod. In addition to the various key phenological parameters, panicle initiation date was measured in 2007. Therefore, thermal time from emergence to PI and photoperiod at PI could be experimentally determined. After evaluation of the relation between the PI stage and the other stages that could easily be observed, thermal time from emergence to flag leaf expansion was used to determine the date of panicle initiation (PI) as well as the photoperiod at PI for the experiments conducted from 2003 to 2006. Then, a graphical analysis was conducted to define the critical threshold photoperiod and photoperiod sensitivity for each variety. For both millet and sorghum, the photoperiod sensitivity ranged from 142 to 6184 growing degree days (GDD h^{-1}) per hour of photoperiod extension. The critical photoperiod (Pc) ranged from a daylength of 13.00 to 13.35 h. Although these experiments were only conducted at one location, this study showed that photoperiod response is not only related to latitude, but depends also on the capability of lowlands to maintain soil moisture. There was a positive correlation between the critical photoperiod (Pc) and the latitude of origin of the local varieties and a negative correlation between photoperiod sensitivity and the latitude of origin. Further work will include the implementation of these results in crop simulation models for yield forecasting and the determination of crop management alternatives for millet and sorghum in West Africa

1. Introduction

In Burkina Faso, a landlocked country of West Africa, the rainy season ranges from 2 to 3 months (July to September) in the north, from 3 to 4 months (June to September) in the central region, and from 5 to 6 months (May to October) in the south. Depending on the variability of the rainy season, millet [*Pennisetum glaucum* L.)], sorghum [*Sorghum bicolor* (L.) Moench], maize [*Zea mays* L.], and rice [*Oriza sativa* L.] are the most important cereal crops that are grown, similar to other countries in West Africa. While millet production dominates in the northern part of Burkina Faso, millet and sorghum are both important in the central part, and sorghum and maize dominate in the south. Rice and maize are common in the lowlands of the south, where irrigation is practiced [1]. Millet and sorghum are normally intercropped with cowpea [*Vigna unguiculata* (L.) Walp] and/or groundnut [*Arachis hypogea* (L.)]. The staple

* Corresponding author. Tel.: +1 509 7869371.
E-mail address: gerrit.hoogenboom@wsu.edu (G. Hoogenboom).
1 AgWeatherNet, Washington State University, Prosser, Washington 99350, USA
2 Powell Research and Extension Center, University of Wyoming, Powell, Wyoming 82435, USA
3 Master's in Development Practice, Emory University, Atlanta, Georgia 30322, USA

1573-5214/$ – see front matter © 2013 Royal Netherlands Society for Agricultural Sciences. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.njas.2013.11.004

foods in Burkina Faso are millet and sorghum grain, while their stover is used for livestock feed, for construction, and for various other uses [2,3].

Depending on the planting date, local varieties of millet and sorghum that are sensitive to photoperiod can produce canopies that are between 1.5 and 5 m tall and that have 12 to 41 leaves on the main stem [4]. They are characterized by a very low yield, with tall canopies, and their growing cycle varies according to the climatic zone and the planting date. The low yield is mostly due to the short rainy season with dry spells, a high potential evapotranspiration rate, low soil fertility, and low levels of agrotechnology. One of the most adaptive characteristics of millet and sorghum to West African conditions is their sensitivity to photoperiod, which decreases from the south (low latitude) to the north (high latitude). This photoperiod sensitivity has been observed for many other agronomic crops, including flax, kenaf, oats, rape, rice, rye, soybean and wheat [5–8].

Photoperiod delays the genetic tendency to flower by forcing the plant to wait for a specific signal [9]. Millet and sorghum are short-day photoperiod sensitive crops. Progress towards flowering is accelerated when the daylength decreases below the critical photoperiod. In West Africa, favorable conditions for millet and sorghum production usually extend from May to November. Thus, most of the development occurs under a decreasing daylength, which explains why the duration of their cycle shortens when sowing is delayed during the rainy season in West Africa. The sensitivity to photoperiod is a singular trait for adaptation to environmental constraints. In the Sudano-Sahelian zone, it allows the crop to consolidate flowering towards the end of the rainy season for a wide range of planting dates [2,3,9,10].

Homeostasis refers to the heading date of local varieties occurring at the same period at the end of the rainy season, even if there are large differences among their planting dates. In Nigeria, where a local sorghum variety from Samaru was planted from 9 May to 15 July (range 67 days), all plants headed within the 11-day period between 6 and 17 October [12–15]. The heading date of local varieties in Mali occurs, on average, about 17 days before the end of the rainy season at their respective locations [16]. The same has been reported for millet in Senegal and Mali [3]. These heading dates are, therefore, a compromise between (i) escaping diseases (head moulds) and insects prevalent in the high humidity conditions during the rains and (ii) avoiding drought during seed filling [10,12]. Andrews [13] and Kassam and Andrews [14] concluded that the mechanism of homeostasis was probably determined by photoperiod, since temperature did not vary greatly between sowing dates. Photoperiod affects crop development and offers opportunities and challenges for agriculture, such as breeding for varieties that flower at the most appropriate time for a given environment [17]. Vaksmann *et al.* [10] reported that sensitivity to photoperiod remains necessary, even for improved varieties, in the present grain production systems in the African savannas and the Sahel to be able to optimize natural resource use and minimize the risk of adverse climatic effects.

Several studies have been conducted to determine the photoperiod response of sorghum for either field conditions [14,18–21] or controlled environments [22–24]. Major [5] identified three genetic components to describe the varietal response to photoperiod: (i) the Basic Vegetative Phase (BVP), defined as the minimum thermal time required for panicle initiation under optimum daylength; (ii) the Minimum/Maximum Optimal Photoperiod (MOP), defined as the critical photoperiod (Pc) beyond which the vegetative period is influenced by changes in daylength; and (iii) the Photoperiod Sensitivity Slope (PSS), which, from the MOP, expresses the linear increase of time to flowering for individual varieties. Thus, for short-day plants, under optimum daylength conditions, the duration of the Photoperiod Inductive Phase (PIP) is assumed to be 0 degree-days, and no delay in flowering occurs.

Considerable progress has been made in understanding how the duration from planting to panicle initiation (PI), anthesis (AN) and maturity (M) in sorghum is modulated by photoperiod and temperature. In general, the duration for each growth stage is related to thermal time. The duration to PI comprises a juvenile or pre-inductive phase followed by an inductive photoperiod-sensitive phase, and the rate of progress can be quantified by linear responses to mean temperature and photoperiod [11,22,25]. Results have shown that the sensitivity of sorghum to photoperiod ranges from 0 to more than 40.5 days per one hour increase in photoperiod, with a critical or threshold photoperiod that varies between 12 and 14 hours [26]. In Nigeria, Craufurd and Qi [12] found that the PSS of a local variety was 2115 GDD h^{-1} with a critical photoperiod of 12.9 h. The values found by Chantereau *et al.* [20] ranged from 1546 to 3971 GDD h^{-1} and were higher than the 1160 GDD h^{-1} presented by Folliard *et al.* [27]. The values reported by Alagarswamy et al. [23] for improved varieties were very low compared to the high photoperiod sensitivity varieties of West Africa.

One of the least destructive methods to determine photoperiod sensitivity is based on the observation of crop development for different planting dates in the field for a given natural environment, because it does not use artificial lights to extend the daylength or artificial growth chamber conditions. PSS for each cultivar should be obtained through a simple planting date experiment during the normal growing season. Understanding the impact of photoperiod on local millet and sorghum varieties for conditions in West Africa could help improve crop management under severe conditions of growth and development, and contribute to decision making for food security. Primary results have shown that the Photoperiod Sensitivity Slope has a very large range among varieties. Thus, to better understand and to improve millet and sorghum production for a given environment, it is important to determine the response of the main local varieties to photoperiod.

Most of the previous studies have focused on the impact of latitude or daylength on the photoperiod sensitivity of millet and sorghum. However, the long-term adaptation of a variety can include both photoperiod and soil moisture conditions in the lowlands that link with the farmers' production systems. During field experiments conducted in three agroclimatic zones of Burkina Faso, we encountered some difficulties in simulating millet and sorghum production using the available photoperiod coefficients, as they did not simulate the cycle of local varieties grown by producers very well. The objective of this study, therefore, was to determine the response to photoperiod of different millet and sorghum varieties that are commonly grown in three agroecological zones of Burkina Faso, West Africa, and then contribute to databases that can be used in crop simulation models.

2. Materials and Methods

2.1. Experimental site

The experiments were conducted at the Di experiment station, located 42 km northwest of Tougan, Burkina Faso (lat. 13.12° N, long. 3.13° W; 300 m above sea level). The location is characterized by an average annual rainfall of 640 mm, while the rainy season spans from April to October. The field used for the experiment had been cropped continuously since 1999 with a rotation of onion during the dry season and maize or rice during the rainy season. The soil of the experimental area corresponds to a vertic loamy soil, with a pH of 7.5 at a depth of 15 cm. The experiments were conducted at the same site during the rainy seasons of 2003, 2004, 2006 and 2007.

2.2. Experimental design and crop management

Local and improved varieties of millet and sorghum were used for experiments that consisted of either five or six planting dates and were conducted during the 2003, 2004, 2006, and 2007 rainy seasons. The experimental design was a randomized complete block (RCB) in a split-plot design. The main treatment was planting date and the sub-treatment was variety; 4 replicates were used in 2006 and 3 replicates in 2007. To avoid drought stress, supplemental irrigation was applied when needed; the plots were kept free of weeds through cultivation.

2003 and 2004 experiments

For the 2003 and 2004 growing seasons, four millet varieties and eight sorghum varieties were planted. For millet, the varieties Danida, Nadari, Poulpouldi, and Locale Di, were used. Danida, Nadari, and Poulpouldi are local millet varieties from Dori (lat. 13.99° N) in northern Burkina Faso which is an area that is characterized by three to four months of rains that begin late and finish early. Locale Di is a local millet variety from Di, the experimental site. For sorghum, the varieties Pisnou, Sablaga, Yadega, Belko, Magadi, Tiguitanga, Gognimassa, and Locale Di, were used. Pisnou, Sablaga, Yadega and Belko are local varieties from Boulsa (lat. 12.8° N) in central Burkina Faso, which has a rainy season and daylength that is similar to the experiment station in Di.

Six planting dates of millet and sorghum were arranged in blocks and the plantings were 10 days apart. In 2003, planting started on 13 June and ended on 3 August. In 2004, planting started on 14 June and ended on 4 August. The planting density for both millet and sorghum was 0.80 m between rows and 0.40 m between hills in the row. Four to six seeds were planted in each hill and thinned to three plants per hill after seedling emergence for a target population of 93,750 plants ha^{-1}. As the previous crop received a large amount of organic and inorganic fertilizer equivalent to 800 kg ha^{-1} of 14-23-14-6-1 (N:P:K:Br:S), no fertilizer was applied.

2006 experiment

Three millet and three sorghum varieties were planted in 2006. For millet, the varieties consisted of IKMP1, IKMV8201, and Locale Bobo. IKMP1 and IKMV8201 are improved varieties from Kamboinse (lat. 12.75° N.). IKMP1 is characterized by a season duration of 115 to 120 days and is adapted to the southern part of the central plateau of Burkina Faso; IKMV8201 is adapted to both the southern and northern part of the central plateau of Burkina Faso. Locale Bobo is a local variety from Bobo-Dioulasso (lat. 11.17° N), in the southwestern part of Burkina Faso. For sorghum, the varieties Sariaso 11, ICSV 1049, and Locale Bobo were planted. There were five planting dates: 5 June, 20 June, 5 July, 20 July and 4 August. Fertilizer was applied at a rate of 100 kg ha^{-1} as 14:23:14:6:1 (N:P:K:Br:S) for both millet and sorghum at the thinning date, and 50 kg ha^{-1} of urea (46%, or 23 kg of N) was applied 45 days after planting. Each individual plot size was 5.4 m x 4.0 m with a total of 56 hills, 8 border hills and 48 sample hills.

2007 experiment

In 2007, the experiment included only two varieties of sorghum and two varieties of millet, as it focused on detailed growth analysis sampling during the growing season. The sorghum varieties were Sariaso 11 and a local variety from Bobo-Dioulasso. The millet varieties were IKMV8201, an improved variety from Kamboinse, and Locale Bobo, a very sensitive local variety from Bobo-Dioulasso. The five planting dates consisted of 15 June, 30 June, 15 July, 25 July and 4 August. For each planting date and each variety, the experimental design included three replications with a plot size of 44.8 m^2 (8 m x 5.6 m). Other cultural practices were the same as those used in the 2006 experiment.

2.3. Weather data

Daily air temperature, relative humidity, sunshine hours, and rainfall were recorded with a conventional weather station that was operational at the agroclimatic station in Di, located 1000 m from the experimental site. Solar radiation was estimated from sunshine hours and cumulative daily radiation. Daylength was based on civil daylength, which includes the periods when the sun is 6 degrees below the horizon during both sunrise and sunset to account for photoperiod response during the twilight period [28]. Equations [1] and [2] were used to determine daylength:

$$HRLT = 7.639 * ARCOS\left[(-SIN(Lat) * SIN(DEC) - 0.1047)/(COS(Lat) * COS(DEC)\right] \quad [1]$$

$$DEC = 0.4093 * SIN[0.0172 * (DOY - 82.2)] \quad [2]$$

where DEC corresponds to solar declination in radians; DOY is the day of year; Lat is the latitude in radians; HRLT is daylength or photoperiod in hours.

2.4. Crop development observations

In 2003 and 2004, phenology was observed for 12 hills per plot and three 3 plants per hill for a total of 36 plants. In 2006, phenology was observed for 48 hills and 3 plants per hill for a total of 144 plants. For each planting date, crop development was observed one to two times per week. Observations included the date of emergence, number of leaves, canopy height, flag leaf (FL) emergence of the main stem, anthesis date (AN), and physiological maturity (PM). A phenological stage was reached when at least 50% of the plants in a plot had either reached that stage or were beyond it. In 2007, panicle initiation was also observed through dissection of the stem.

2.5. Procedure to Determine the Phenological stages and Photoperiod Parameters

Thermal time (DTT) can be used for predicting plant development if the temperature does not fall below the base temperature (*Tb*) and does not exceed an upper threshold temperature for a significant part of the day [22,29]. Equation 3 was used to determine the cumulative growing degree days (GDD). For the 2003, 2004, and 2006 experiments, PI dates were not observed and were, therefore, derived from Equations [4] and [5]. PI date observations from the 2007 experiment were used for evaluation of Equations [4] and [5]. According to Ritchie and Alagarswamy [30] and Alagarswamy and Ritchie [22], the thermal time to flag leaf appearance (*TTFL*) and thermal time to anthesis (*TTAN*) are related to thermal time to panicle initiation (*TTPI*) as follows:

$$DTT = [(T\max + T\min)/2] - Tb \quad [3]$$

$$GDD = \sum_{i=1}^{n} DTT \quad [4]$$

$$TTPI = \frac{TTAN - 450}{1.199} \quad [5]$$

$$TTAN = TTFL + 150 \quad [6]$$

where *DTT* is daily thermal time, *Tmin* is the minimum daily temperature, *Tmax* is the maximum daily temperature, *Tb* = 10 °C for

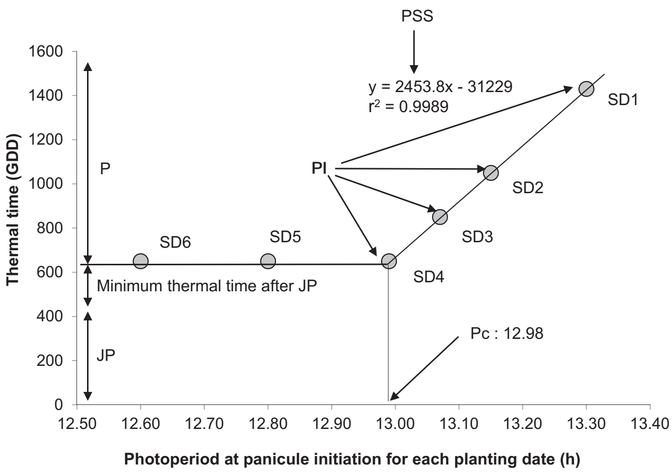

Figure 1. Graphical determination of the photoperiod sensitivity coefficients: PSS (Photoperiod Sensitivity Slope or Photosensitivity coefficient), PI (Panicle Initiation), PIP (Photo Inductive Phase), JP (Juvenile Phase), Pc (critical photoperiod); SD1 is Planting date 1, while SD6 corresponds to Planting date 6.

both millet and sorghum [22], and i = 1,2,3,. . .n days for which GDD is determined. When the minimum temperature drops below *Tb*, or when the maximum temperature exceeds the optimum temperature (*TOPT*), then a different method is developed to calculate degree days [22]. Equation [3] is used when *Tmin* is higher than *Tb* and *Tmax* is lower or equal than *TOPT*. If *Tmin* is lower than *Tb* or *Tmax* is higher than *TOPT*, a temperature correction factor (TMFAC) is used to correct the effects of unfavorable temperatures. The temperature correction function of the Cropping System Model (CSM) [31,32] was used to perform the DD calculation for unfavorable maximum temperature conditions.

This methodology allowed for the determination of TTPI from observed data using Equations [5] and [6], where TTPI = (TTFL-300)/1.199 [22]. This means that TTPI depends on TTFL, and thus on the number of days from emergence to flag leaf. During the rainy season, the maximum temperatures ranged from 32 to 38 °C and the minimum temperature ranged from 22 to 25 °C. These are optimum temperatures for both millet and sorghum development. For this study, therefore, the simple Equation [3] was used with 10 °C as base temperature for calculating GDD for each individual growth stage.

The BVP includes both the juvenile and the preinductive photoperiod phase. According to Ritchie and Alagarswamy [29], the BVP can be used to determine the developmental stages of millet and sorghum. The vegetative phase includes BVP and photoperiod inductive phase (PIP). If the photoperiod is below Pc, then the duration of the vegetative stage is a function of temperature only and is the same as the duration of BVP [22]. When photoperiod was higher than Pc, then the linear relationship between thermal time to panicle initiation (TTPI) and photoperiod was used to determine photoperiod sensitivity (PSS) and the critical photoperiod (Pc). PSS is the slope of the linear relationship between TTPI and photoperiod. If there is no effect of photoperiod on TTPI, the slope is equal to zero and the relationship is a parallel line with the X-axis, in which the intercept with the Y-axis is BVP. Pc is the value for photoperiod for the date that the slope becomes zero. This date is determined by the intersection between the line with a zero slope and the line with a positive or negative slope between photoperiod and TTPI (Figure 1). For the four growing seasons (2003, 2004, 2006 and 2007), the 13 June, 14 June, 5 June and 15 June planting dates, respectively by year, corresponded to the period with the longest daylength and were assumed to cause the longest vegetative phase. The planting dates prior to 15 July corresponded to the most common planting dates normally used by local farmers. The 23 July planting date was considered the latest planting date for farmers, although some producers continued to plant if the dry spells did not allow them to do so before 20 July. For this experiment, either the two or three latest planting dates were used to determine the critical photoperiod (Pc) and to adjust the BVP. The three or four early planting dates were used to determine PSS according to the linear relationship defined earlier (Figure 1). For field experiments, the BVP is the average TTPI for the two or three latest planting dates when there is no effect of photoperiod.

2.6. Evaluation of the PI date determination

TTPI was calculated using Equation [5] and then the date of PI and the photoperiod at PI were determined by iterative procedure for the experimental data collected in 2003, 2004, and 2006. Before using Equation [5], the data collected in 2007 were used to evaluate the method we utilized to calculate TTPI and to determine the PI date and photoperiod values. Equation [5] was employed to calculate TTPI, PI dates, and PP at PI in 2007. We observed the PI dates by dissection in 2007, and those observed PI dates were used to obtain the observed TTPI and the observed PP at the observed PI date. The evaluation consisted of a comparison of the calculated values of TTPI, PI dates and PP at PI dates in 2007 with the observed TTPI, PI dates and PP at PI dates in 2007.

2.7. Statistical analysis

The rainy seasons for the four years were compared using the Rainfall Index [33]. This index is an indicator of the amount of rainfall with respect to long-term or normal climate data and was determined with the following formula:

$$Rain\,fall\,index = (Rx - Rm)/S \qquad [7]$$

where Rx = Annual total rainfall for a given year x; Rm = long term mean (30 years); S = long term standard deviation (30 years) The mean and standard deviation were within a reference period of 1978-2007 (30 years). Annual rainfall was the total rainfall for the period June-July-August-September (JJAS). The rainfall totals for 2003, 2004, 2006 and 2007 were compared to the long-term rainfall average using TTEST [34]. The same approach was used to determine the JJAS rain frequency index. Assuming that the temperature distribution was normal, the paired TTEST [34] was used to determine whether the mean temperature values for two years were equal only for certain periods during the growing season or for the entire rainy season. The planting, emergence, flag leaf appearance, and anthesis dates were used to determine TTPI, BVP, and photoperiod at the PI date. The linear relationship between TTPI and photoperiod was used to calculate PSS and graphically determine Pc.

The Index of Agreement (d) (Equation 8) was used to compare the calculated data with the observed data for 2007. According to the d-statistic [35], the closer the index value approaches one, the better the agreement between the observed and calculated variables.

$$d = 1 - \left[\frac{\sum_{i=1}^{i} (Ci - Oi)^2}{\sum_{i=1}^{n} ((Cci) - (Ooi))^2} \right] \qquad [8]$$

In Equation [8], n is the number of observations, *Ci* is calculated values, *Oi* is observed values. *Cci* = *Ci*–*M* and *Ooi* = *Oi*–*M* where *M* is the average of observed values.

The Index of Agreement (d) is used both for TTPI and number of days from emergence to PI, the Root Mean Square Error (RMSE) (Equation 9) between observed and calculated values of TTPI or number of days from emergence. A small value for RMSE, according to Loague and Green [36] is an expression of a good agreement between the calculated and observed values:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Pi - Oi)^2}{n}} \quad [9]$$

where Pi is the calculated value, and Oi is the observed value.

3. Results

3.1. Weather conditions

The June-July-August-September (JJAS) mean rainfall total for 30 years (1978 to 2007) was 569.1 mm, with a standard deviation of 124.3. The mean frequency of the JJAS rain was 47 days, with a standard deviation of 5. From June to September, total rainfall was 736.1 mm for 2003, 469.8 mm for 2004, 543.9 mm for 2006, and 708.2 mm in 2007. According to the rainfall index, the 2003 and 2007 seasons were very wet, the 2004 season was dry, and the 2006 season was slightly dry and close to normal. The 2003, 2004 and 2007 seasons were significantly different from normal, while there was no significant difference between the 2006 rainfall and normal. The number of rainy days during the 2004 season was close to normal, while in 2003 (50), 2006 (54) and 2007 (54) the number of rainy days was significantly different from normal (47). For the 2006 cropping season, rainfall had a more even distribution (Figure 2).

The temperature trend varied from June to October with the progress of the rainy season; the variability of the maximum temperature is usually more important than the variability of the minimum temperature (Figure 2). For the period from June to October, the average maximum temperature in 2003 was 33.9 °C and was significantly different ($P < 0.001$) from the average maximum temperatures in 2004 (34.9 °C), 2006 (34.9 °C) and 2007 (34.6 °C). For the period from 15 June to 31 July, the average maximum temperature (35.7 °C) in 2006 was significantly different from the average maximum temperature in 2003 (33.7 °C), 2004 (33.9 °C) and 2007 (34.6 °C), while there was no significant difference between 2003 and 2004. From 1 August to 31 October, the average maximum temperature was significantly different between years: the average maximum temperature for 2004 (35.1 °C) was significantly different from 2003 (33.8 °C), 2006 (34.0 °C) and 2007 (33.8 °C). However, there were no significant differences between 2003, 2006 and 2007.

For the period from 1 August to 31 October, the average minimum temperature for 2007 (21.7 °C) was different from the average minimum temperature for 2003 (23.6 °C), 2004 (23.5 °C), and 2006 (23.6 °C). The average daily mean temperature in 2003 was 28.9 °C and was significantly ($P < 0.001$) different from the average mean temperature in 2004 (29.5 °C), 2006 (29. 5 °C) in, and 2007 (28.3 °C). For the same period, 2007 was different from 2004 and 2006. For the period from 15 June to 31 July, the average mean temperature (30.2 °C) in 2006 was significantly different ($P < 0.001$) from those observed in 2003 (28.8 °C), 2004 (29.3 °C) and 2007 (28.1 °C), while no significant difference between 2003 and 2004 was found (Figure 2). From 1 August to 31 October, the average mean temperature (28.7 °C) in 2003 was almost the same as for 2004 (29.3 °C) and 2006 (28.8 °C). For 2007 the mean average temperature (27.8 °C) was significantly ($P < 0.001$) lower than for the other years.

In general, we can state that the 2004 and 2006 seasons were warmer than 2003 and 2007 seasons during the growing period from June to October. During the growing season from 20 June to 10 October, which was the period from sowing to maturity, the photoperiod ranged from 12.59 h (10 October) to 13.69 h (20 June). The daylength for the first planting date in June was longer, corresponding to the beginning of the rainy season, and decreased progressively with the advancement of the rainy season (Figure 2).

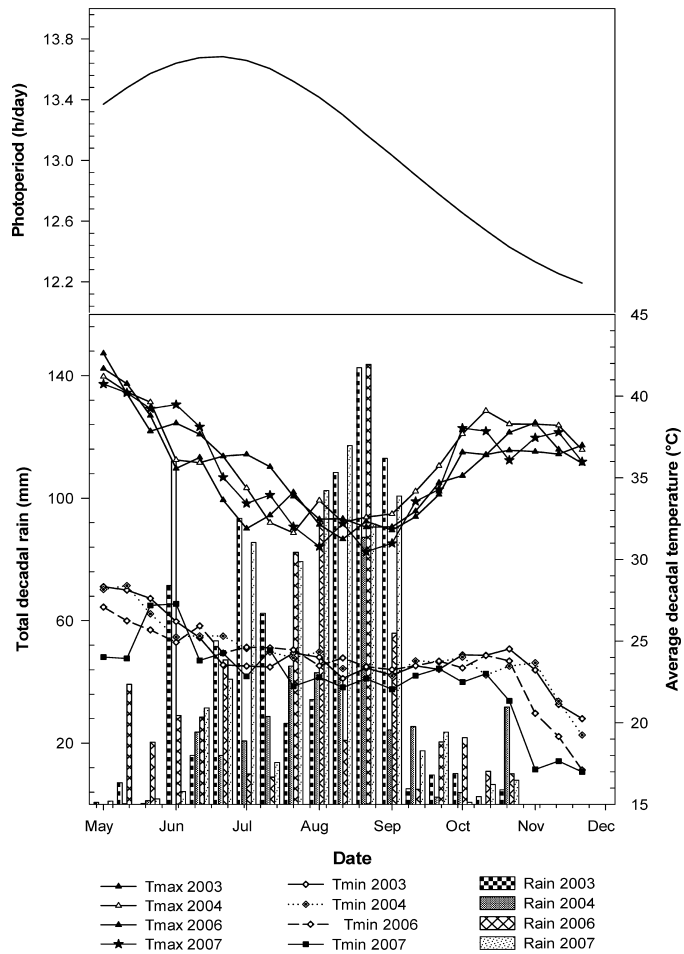

Figure 2. Weather conditions during the 2003, 2004, 2006, and 2007 cropping seasons. Values for air temperature are an average and for rainfall are a cumulative total for 10-day periods (decadal).

3.2. Evaluation of the TTPI determination in 2007

3.2.1. TTPI for sorghum

For 2007, there was a good agreement between the calculated and observed values of TTPI (Figure 3 for sorghum), the number of days from emergence to PI (TPI), and photoperiod (PP) at panicle initiation. The d coefficient for the calculated and measured TTPI was 0.98, 0.95 for TPI (days) and 0.92 for PP. This was also supported by reasonable values for RMSE for TTPI (49.4), TPI (3.85) and PP (0.068) for sorghum.

3.2.2. TTPI for millet

For millet there was a better agreement between the calculated and observed values for thermal time (TTPI), number of days (TPI), and photoperiod (PP) from emergence to panicle initiation as compared to sorghum. The d coefficient was 0.98 for TTPI, 0.97 for TPI and 0.95 for PP. The values for RMSE for TTPI (46.7), TPI (3.15) and PP (0.06) were higher than those obtained for sorghum.

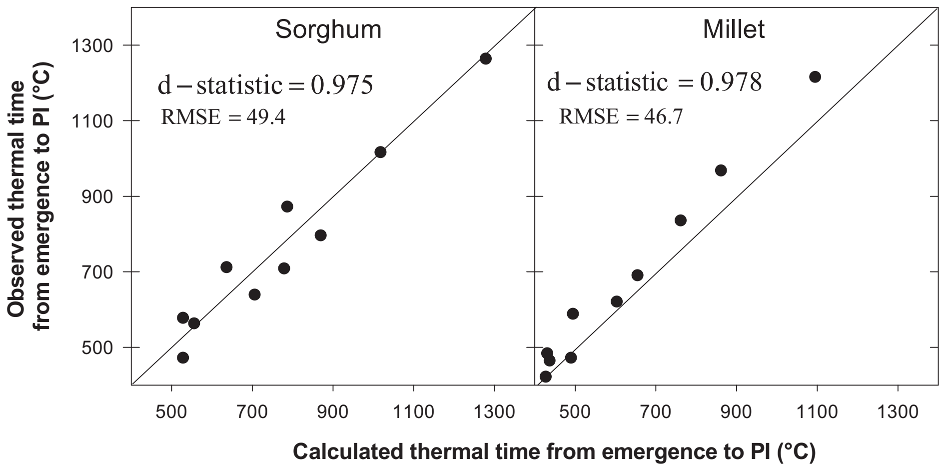

Figure 3. Relationship between calculated and measured thermal time to Panicle Initiation (PI) for sorghum and millet in 2007.

3.3. Sorghum development and photoperiod sensitive traits

Basic Vegetative Phase

The variety Pisnou had the lowest TTPI (410 GDD) in 2003 for the latest planting date. In this case, BVP was assumed to be 410 GDD. The highest BVP was found for Tiguitanga (606 GDD) in 2003 and Locale Bobo (598 GDD) in 2006. Varieties that had a low BVP included Pisnou, Sariaso 11 and ICSV 1049, while the varieties Sablaga, Magadi, Locale Di, Yadega, Belko and Gognimassa had BVP values between 410 and 606 GDD. In 2007, BVP determined through direct observation was 639 GDD for Locale Bobo and 472 GDD for Sariaso 11. These values were slightly higher than those obtained in 2003, 2004 and 2006 as derived with Equation [5]. However, for Locale Bobo, the difference was only 40 GDD or about 2 real days.

Relation between Thermal Time to Panicle Initiation and Time to Flag Leaf

In 2003, the TTPI for all varieties ranged from 410 GDD for the latest planting date to 1093 GDD for the first planting date, with an average of 702 GDD. This corresponded to a range of 51 to 92 real days from emergence to flag leaf, with an average of 68 days. There was a good correlation between TTPI and days to flag leaf.

In 2004, the TTPI for the same 8 varieties ranged from 483 to 1044 GDD and the number of days to flag leaf ranged from 51 to 86 days with an average of 65 days. The fact that TTPI and days to flag leaf were higher in 2003 than in 2004 was consistent with the weather conditions. The paired t-test between 2003 and 2004 for TTPI showed a significant difference. Wetter conditions probably increased the cycle in 2003 as compared to 2004. A t-test for the number of days to flag leaf showed a significantly large ($P < 0.001$) difference between 2003 and 2004. In 2003, the average TTFL was 69 days, while in 2004 it was 66 days. This was also consistent with the weather data, showing that it took fewer days to reach the flag leaf stage under warmer conditions. In 2006, TTPI ranged from 467 to 1538 GDD and the average was 806 GDD. The number of days to flag leaf varied from 51 to 115, with an average of 71 days. In 2007, TTPI ranged from 472 to 1263 GDD, and the number of days from 29 to 73. During the four years there was a good correlation between TTPI and the number of days to flag leaf for all varieties.

Relationship between TTPI and photoperiod

For each variety, TTPI varied as a function of the planting date. In general, the early planting date had the highest TTPI, and the value for TTPI was lowest at the PI date for the fourth planting date. With respect to the variation of TTPI from the first to the last planting date, the varieties Pisnou and Magadi, which are considered to constitute the first group, had the smallest variation in TTPI. For these two varieties, the minimum value for TTPI was 410 GDD and the maximum was 700 GDD. For the second group of varieties, i.e., Yadega, Tiguitanga, Sariaso 11 and ICSV 1049, TTPI varied from 600 GDD to 900 GDD from the first to the last sowing date. The variety Locale Bobo (fourth group) had the largest variation in TTPI, which ranged from 600 to 1550 GDD. The values for photoperiod at PI ranged from 13.45 h for the early planting date to 13.00 h for the later planting dates. The varieties Pisnou, Magadi, Sariaso 11 and ICSV 1049 were the first varieties to reach PI, but they remained sensitive to photoperiod until the daylength dropped below 13.05 h. The varieties Locale Di, Yadega and Tiguitanga were part of the second group, with a daylength of 13.30 h at the PI date for the first planting date, while the Pc was 13.05 h. For the variety Locale Bobo, the PI started at a daylength of 13.20 h for the first sowing date and a daylength of 13.05 h for the final sowing date.

The relation between photoperiod and TTPI for the 11 varieties, including the same 8 varieties in 2003 and 2004 and 3 different varieties in 2006, is shown in Figure 4. Most of the relationships were linear [5], except for the variety Locale Bobo, which had a hyperbolic relationship [27]. The t-test showed that there was a highly significant ($P < 0.003$) difference between 2003 (700 GDD) and 2004 (678 GDD) for the values of TTPI. Despite the difference due to weather conditions, the overall relation between TTPI and photoperiod was the same for each variety in 2003 and 2004, and between Locale Bobo and Sariaso 11 in 2006 and 2007 (Figure 4).

Critical photoperiod

For all varieties, the Pc ranged from 13.05 to 13.30 h. Locale Bobo, a variety from the southern region of Burkina Faso, had the lowest value for Pc. The variety Magadi from Dori, located in the north, had the largest value for Pc. In general, the varieties from the northern region had the largest values for Pc, while the varieties from the southern region had the lowest values for Pc. The improved varieties, such as Sariaso 11 and ICSV 1049 from Saria, had a Pc of 13.05 h and 13.08 h, respectively. The variety Sariaso 11 had the same Pc as the variety Locale Bobo (Figure 4).

Photoperiod sensitivity

The values for PSS ranged from 751 for variety Pisnou to 4145 GDD h^{-1} for Locale Bobo. Based on the values for PSS, three groups of varieties could be defined. The group with the lowest PSS consisted of Pisnou, Magadi, Sariaso 11 (1052 GDD h^{-1}) and ICSV 1049 (1099 GDD h^{-1}). The second group of varieties included Yadega (1804 GDD h^{-1}), Locale Di (1832 GDD h^{-1}), Gognimassa

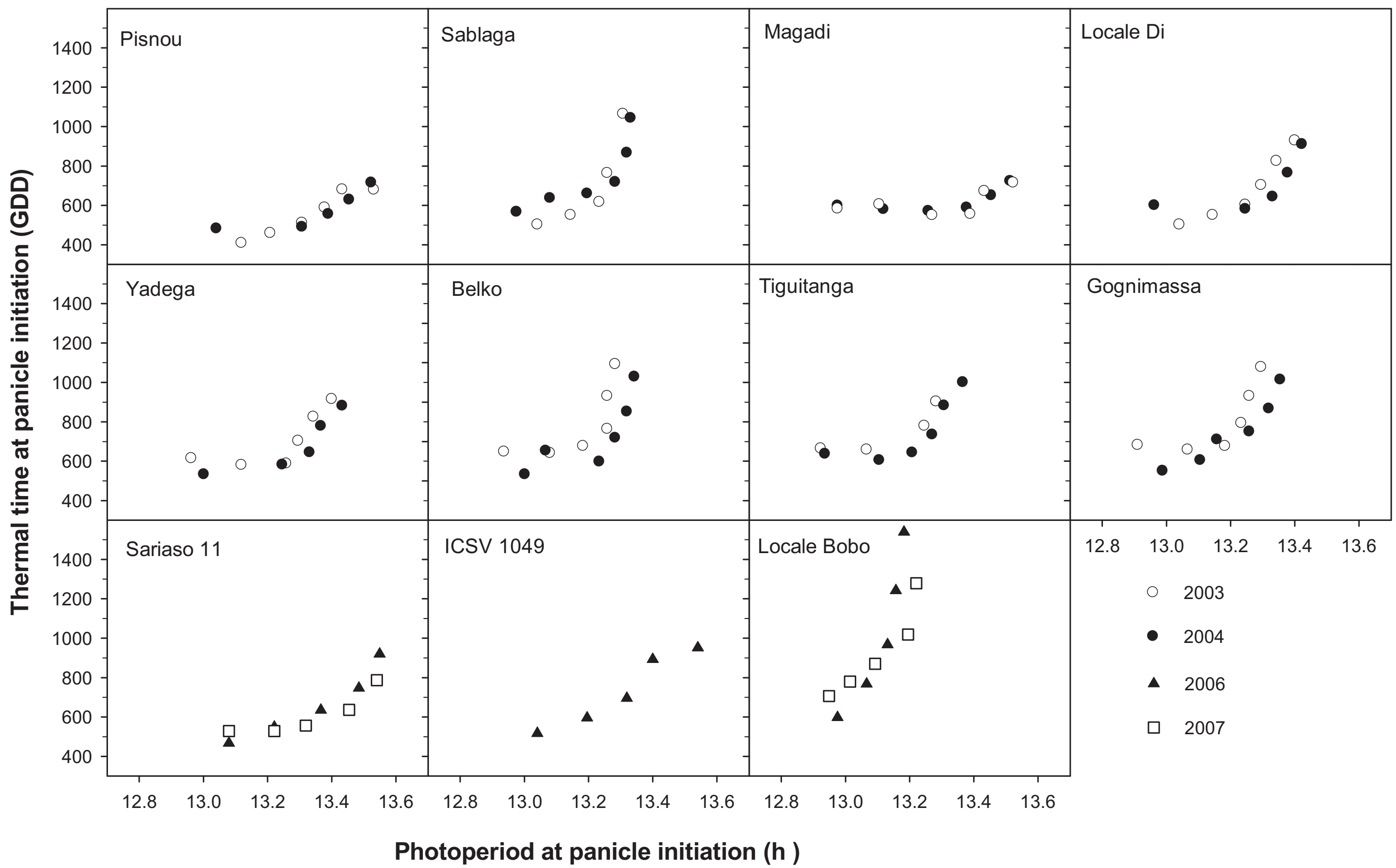

Figure 4. Relationship between photoperiod at Panicle Initiation (PI) and thermal time (or GDD) at PI for the sorghum varieties Pisnou, Sablaga, Magadi, Locale Di, Yadega, Belko, Tiguitanga, and Gognimassa in 2003 and 2004; for the varieties Sariaso 11, ICSV 1049 and Locale Bobo in 2006, and the varieties Sariaso 11 and Locale Bobo in 2007.

Table 1
Origin, critical photoperiod (Pc), and slope of the photoperiod sensitivity (PSS) for the millet and sorghum varieties of this study.

Crop	Cropping Season	Variety	Origin	Latitude (°)	Pc (h)	PSS (GDD/h)
Sorghum	2003 - 2004	Pisnou	Boulsa	12.80	13.12	751
	2003 - 2004	Sablaga	Boulsa	12.80	13.15	2522
	2003 - 2004	Magadi	Dori	13.99	13.30	1039
	2003 - 2004	Locale Di	Di	13.12	13.15	1832
	2003 - 2004	Yadega	Boulsa	12.80	13.20	1804
	2003 - 2004	Belko	Boulsa	12.80	13.15	2251
	2003 - 2004	Tiguitanga	Dori	13.99	13.18	2218
	2003 - 2004	Gognimassa	Di	13.12	13.10	1931
	2006	Sariaso 11	Saria	12.16	13.05	1052
	2006	ICSV 1049	Saria	12.16	13.08	1099
	2006 - 2007	Locale Bobo	Bobo	11.17	13.05	4145
Millet	2004	Danida	Dori	13.99	13.30	142
	2004	Nadari	Dori	13.99	13.30	837
	2004	Poulpouldi	Dori	13.99	13.30	436
	2003 - 2004	Locale Di	Di	13.12	13.18	1742
	2006 - 2007	IKMV8201	Kamboinse	12.75	13.22	2287
	2006	IKMP1	Kamboinse	12.75	13.35	1239
	2006 - 2007	Locale Bobo	Bobo	11.17	13.00	6184

(1931 GDD h^{-1}), Tiguitanga (2218 GDD h^{-1}), Sablaga (2522 GDD h^{-1}). The third group was limited to Locale Bobo, with a high PSS of 4145 GDD h^{-1} (Table 1).

3.4. Millet development and photoperiod sensitive traits

Basic Vegetative Phase

The emergence of millet took approximately three days; the duration of the vegetative phase was computed starting at emergence. The value for BVP for most of the varieties ranged from 400 to 520 GDD, except for the variety Locale Bobo, which had a value of 664 GDD for BVP for the fifth planting date. In 2007, when BVP was determined through direct observation, the BVP was 621 GDD for Locale Bobo (Yeregalo Sininon) and 421 GDD for IKMV8201. These values seem a little lower than those obtained in 2003, 2004 and 2006 as derived from equation [5]. For Locale Bobo, the difference was 42 GDD or about 2 days.

Relation between TTPI and Time to Flag Leaf

The relation between TTPI and the time to flag leaf for millet was the same as for sorghum (Figure 3B). For 2003, TTPI ranged from 494 to 946 GDD and TTFL ranged from 51 to 83 days. In 2004, TTPI ranged from 516 to 956 GDD and TTFL ranged from 51 to 80 days. There were no significant ($P < 0.20$) differences between 2003 (66 days) and 2004 (63 days) for TTFL. The average TTPI was 704 GDD in 2003 and 674 in 2004 and there was also no significant difference ($P < 0.47$) between these two years. In 2006 and 2007, the range of TTPI and TTFL was larger than for 2003 and 2004 because of the local variety from Bobo that exhibits high photoperiod sensitivity. However, the relation between TTPI and TTFL was the same for 2003 and 2004 as for 2006 and 2007 (Figure 3B).

Relation between TTPI and photoperiod

There was no evidence of a correlation between TTPI and photoperiod for the varieties Danida, Nadari, and Poulpouldi, especially in 2003, due to the wet weather conditions that year. The variety

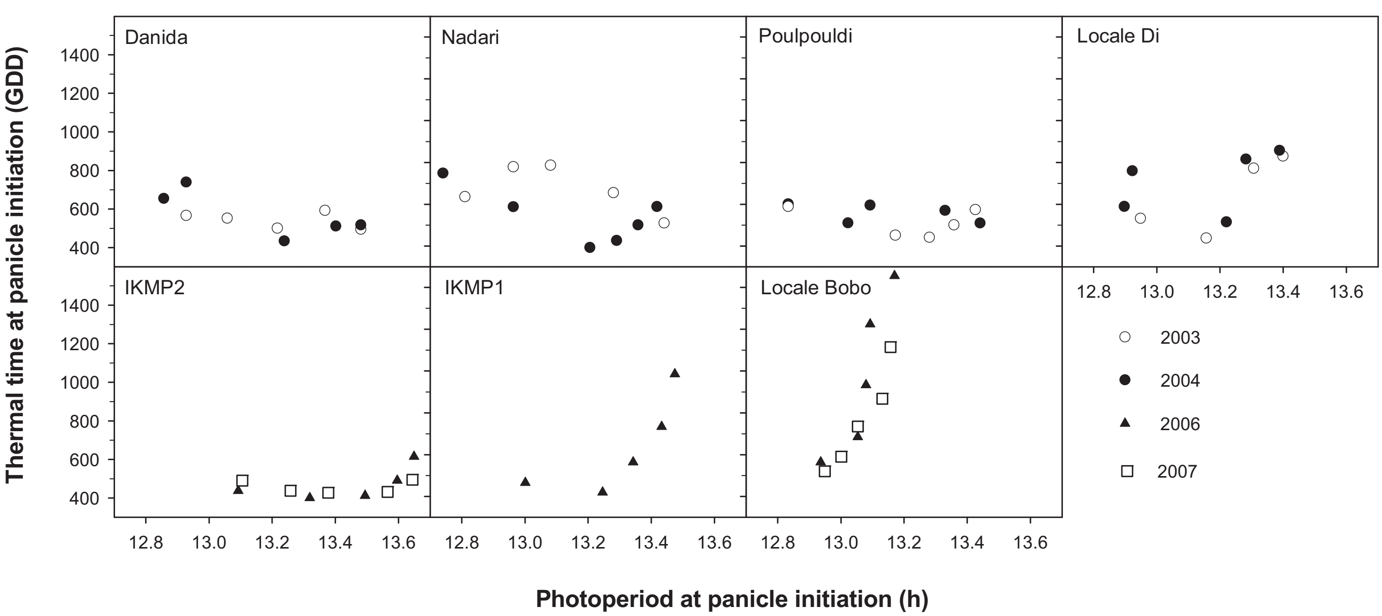

Figure 5. Relationship between photoperiod at Panicle Initiation (PI) and thermal time (or GDD) at PI for the millet varieties Danida, Nadari, Poulpouldi, and Locale Di in 2003 and 2004; with varieties IKMV8201 I, IKMP1 and Locale Bobo in 2006, and with varieties IKMV8201 and Locale Bobo in 2007.

Poulpouldi had the most constant value for TTPI regardless of the planting date. The range of values for TTPI for the variety IKMV8201 was the smallest. For the varieties Locale Di and IKMP1, TTPI ranged from 400 to 1000 GDD, while TTPI ranged from 600 to 1550 GDD for the variety Locale Bobo, which was the largest variation. In 2003 and 2004, the varieties Danida, Nadari, and Poulpouldi from Dori, had the lowest values for TTPI. The variety Locale Bobo required more thermal time to reach flowering during the 2006 and 2007 rainy seasons, compared to the other varieties (Figure 5).

Critical photoperiod

It was more difficult to determine the Pc for the varieties Danida, Nadari and Poulpouldi in 2003 because of the very wet season. These varieties were originally from Dori, which is a dry region, and Pc ranged from 13.00 to 13.35 h. Pc for the variety Locale Bobo was smaller (13.00 h), as it is originally a variety from the wetter southern part of Burkina Faso. The variety IKMP1 had a higher value for Pc, as it is an improved variety from Saria. IKMV8201, also an improved variety, had a Pc of 13.20 h. The three varieties from Dori, Danida, Nadari, and Poulpouldi had a Pc of 13.30 h day^{-1} (Figure 5, and Table 1).

Photoperiod sensitivity

The photoperiod sensitivity coefficient was the smallest for the varieties Danida (142 GDD h^{-1}), Poulpouldi (436 GDD h^{-1}) and Nadari (837 GDD h^{-1}), which are all varieties from Dori. The PSS for variety Locale Di was 1742 GDD h^{-1}, while the PSS for variety IKMP1 was 1239 GDD h^{-1} and 2287 GDD h^{-1} for variety IKMV8201; these latter two are improved varieties that are adapted to the central part of Burkina Faso. For the variety Locale Bobo, from southern Burkina Faso, PSS was 6184 GDD h^{-1}. Locale Bobo had one of the highest values for PSS and the plants from all five sowing dates reached flowering almost at the same time (Table 1).

3.5. Relation between location and photoperiod components

In order to understand the importance of the sensitivity of short-day plants to daylength, one must look at their regions of origin. For both millet and sorghum, the most sensitive varieties to PP are those which have a low value for Pc and a high value for PSS. Using this classification, the most sensitive varieties were those from Bobo-Dioulasso in the southern part of Burkina Faso, while the least sensitive varieties were those from Dori in the northern part of Burkina Faso (Figure 6). The results from the 2003, 2004, 2006 and 2007 experiments did not allow us to conclude that sorghum is either more or less sensitive to photoperiod than millet.

4. Discussion

4.1. Weather conditions

Excessively wet conditions observed in 2003 reduced the temperature, while many dry spells were observed in 2004. However, this was not a constraint for the experiment because of the supplemental irrigation that reduced the impact of dry periods on crop growth. In 2003, because of the wet season and excess rain, the early planting dates for the short cycle varieties could not complete flowering and grain filling. The differences in temperature which were very great at the beginning of the growing season caused variations in growth and development among the 2003, 2004, 2006, and 2007 seasons. During the growing season, which lasted from 20 June to 10 October, the photoperiod ranged from 12.59 h on 10 October to 13.69 h on 20 June. The daylength for the first planting date in June was longer, corresponding to the beginning of the rainy season, and decreased over time with the progress of the rainy season.

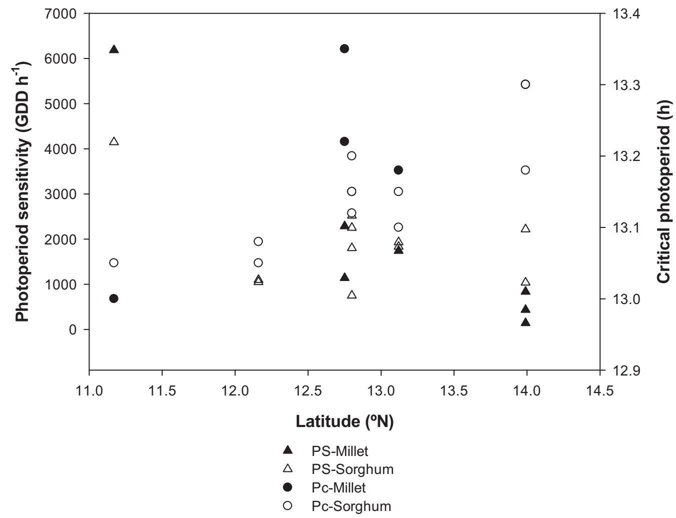

Figure 6. Relationship between latitude and the photoperiod components (Threshold-photoperiod or critical photoperiod, photosensitivity slope) for sorghum and millet in 2003, 2004, and 2006.

4.2. Evaluation of the TTPI determination in 2007

The evaluation of Equation [5] for the calculation of TPPI with observed data for 2007 showed that Equation [5] and the iterative procedure can be used to calculate TTPI, date of PI and the number of days from emergence to PI with good accuracy. Due to the intensive data collection requirements, this procedure could only be evaluated for two varieties. This equation was then used to determine TPPI and PPI for 2003, 2004 and 2006 (Figure 4 and Figure 5). Equation [5] provided a good agreement with observed data (Figure 3).

4.3. Sorghum development and photoperiod sensitivity characteristics

In many studies, the BVP is expressed as the number of days from emergence. Our results showed a large variability in photoperiod-sensitive characteristics. The BVP ranged from 410 for the least photosensitive variety to 639 GDD for the variety with the greatest photosensitivity, values that are higher than those found by the previous studies. These values were higher than those found by Clerget et al. [37] in a controlled environment. Interaction between photoperiod sensitivity and environmental conditions can explain this difference between results from these different studies. Low latitude adapted local varieties are characterized by a long BVP. Our results showed that during the four-year experiments, the TTPI ranged from 410 GDD to 1538 GDD. These results were similar to those found in the literature [27,38–40]. For an experiment conducted in Australia under irrigated conditions with one hybrid and five planting dates, the TTPI ranged from 299 GDD to 625 GDD [19]. The values for the number of days for flag leaf and flowering obtained in this study had the same range as those that have been reported for similar climatic conditions [27,38–40].

For most varieties (Figure 4), the relationship between photoperiod and TTPI was linear [5], except for the local varieties of sorghum from Bobo, which exhibited a hyperbolic relationship between photoperiod and TTPI [4,27].

The results showed that Pc varied from 13.00 h d^{-1} to 13.45 h d^{-1}, and the most sensitive varieties to photoperiod had the lowest values. Alagarswamy and Ritchie [22] found that the values for Pc for sorghum ranged from 12.5 to 13.5 h. The Pc values found in a previous study were: 12.9 to 13.40 h for the variety Sariaso 11 at Saria in the central part of Burkina Faso [39], 13.05 h day^{-1} for the variety CSM388 in Mali [27]; for Nigeria 12.9 h d^{-1} [12] and 12.00 h according to Muchow and Carberry [19].

In our current study, the photoperiod sensitivity varied from 751 to 2522 GDD for most varieties, and 4000 GDD for one variety from Bobo-Dioulasso. These values were higher than those found in Nigeria by Craufurd and Qi [12] and by Chantereau et *al.* [40] in Saria (Burkina Faso) with values ranging from 600 to 1800 GDD h^{-1}. The varieties Sariaso 11 and ICSV 1049 were among the varieties that were used by Chantereau et al. [40] in their experiments. The values for PSS were also higher in our study than those found by others [19,22–24].

4.4. Millet development and photoperiod sensitivity characteristics

The BVP values that were found for millet in this study were compared to the BVP values obtained from previous studies. For the shortest photoperiod in India, Craufurd and Bidinger [41] found a value of 386 GDD; this value was similar to the BVP of 405 GDD that we found in our experiment for the varieties that were not sensitive to photoperiod. In Mexico, Maiti and Soto [42] found that BVP varied among varieties with an average of 450 GDD for millet grown at a daylength that was less than 13 h; the BVP was about 19 days for sowing conditions with a daylength of 13.5 h. For the same conditions, Carberry and Campbell [8] found a BVP of 16 days. The range of the values of BVP obtained by Maiti and Soto [42] was the same as what our experiment demonstrated.

As the photoperiod decreased from 13.69 h (20 June) to 12.59 h (10 October), the time required for PI decreased drastically. Several studies also found a correlation between time/days, or thermal time to PI, and photoperiod [39,41–44].

Limited information is available with respect to the critical photoperiod for millet development. Most studies have concentrated on photoperiod and phenological phases [8,39,41,42,44] using minimum daylength with 13 h as the shortest daylength at planting, but no specific value for critical photoperiod has been defined. Matthews and Pilbeam [45] and Hundal and Joy [46] used 12.0 h as the critical photoperiod for simulating millet production in Nepal. However, the millet varieties from West Africa are very sensitive to photoperiod, which ranges from only 12.6 h to 13.68 h during the growing season from June to October. In our study, the critical photoperiod ranged from 13.00 to 13.35 h. Thus, a small error in the determination of the critical photoperiod could affect the overall understanding of phenological development.

Very limited data are available about photoperiod sensitivity for millet. In our study we found a large difference in PSS that ranged from 142-436 GDD h^{-1} for the least sensitive varieties to 2287 GDD h^{-1} for the most sensitive varieties; a very high PSS of 6184 was observed in a local variety from Bobo-Dioulasso. The range of values from our study was larger than those reported by Hundal and Joy [46], e.g., 130 GDD h^{-1}. The very high values of PSS obtained with the varieties of sorghum and millet from Bobo-Dioulasso could be explained by the fact that these varieties are very sensitive to photoperiod, and the curve described by plotting PP against TTPI is hyperbolic (Figure 4 and Figure 5 for Locale Bobo).

4.5. Relation between location and photoperiod components

In order to understand the importance of the sensitivity of short-day plants to daylength, one must look at their regions of origin. For both millet and sorghum, the most sensitive varieties to photoperiod were those that had a low value for Pc and a high value for PSS. Using this classification, the most sensitive varieties were those from Bobo-Dioulasso, located in the southern part of Burkina Faso, while the least sensitive varieties were those from Dori, located in the northern part of Burkina Faso (Figure 6). The results from the 2003, 2004, 2006 and 2007 experiments did not support the conclusion that sorghum is either more or less sensitive to photoperiod than millet. The values for Pc ranged from 13.00 to 13.35 h, with the higher values for the varieties from the north, suggesting that their PI date is relatively early and adapted to a short period of rain in that region. This high value for Pc is a long-term adaptation of local varieties for a region that allows a crop to reach anthesis and maturity before the end of the rainy season. For conditions in the southern part of the country, Pc is also adjusted based on the end of the rainy season; the onset of flowering occurs six to eight weeks before the end of the rainy season. In the south, the value for Pc has been adjusted to avoid an unsuitable maturity period and to guarantee a satisfactory grain-filling period that is in "agreement" with the rainfall after flowering.

Plants sown on different dates will often flower on the same or nearly the same date. These results are consistent with Major and Kiniry [26], who reported that for northern latitudes the juvenile phase of a short-day plant increases as the latitude of the growing site decreases. For most short-day plants in West Africa, the locally adapted genotypes exhibit a 1-day lag in flowering for every 2-day lag in planting date during the rainy season from June to August [26]. This study emphasized the fact that for a given latitude, photoperiodism ensures that plants will flower close to the same day of the year, every year.

Using several varieties, the results from this study demonstrated that the sensitivity to photoperiod also depends on crop management. Considering the high photoperiod sensitivity of the variety Tiguitanga (2218 GDD h^{-1}), which is usually grown in the lowlands of Dori, the adaptation takes into account both photoperiod and available soil water in the lowlands. Because of the accumulation of water in the lowlands in Dori with the first rains in April and May, the increase in soil moisture allows the farmers to sow very early in May, two months before the start of the normal cropping season in this area. After the rainy season at the end of September, the available water in the lowlands allows the crop to grow until October. For these conditions of a guaranteed extended period of available soil water, the phenology of the varieties in Dori for these lowlands is adjusted for a longer cycle similar to the varieties that are adapted to southern conditions. Because of the lowland cropping system, the varieties selected are able to grow from May to October by adjusting BVP to 606 DD, Pc to 13.18 h day^{-1}, and PSS to 2218 GDD h^{-1}. For the varieties that are normally grown in the north, Tiguitanga had the lowest value for Pc and the highest values for BVP and PSS. This is an adaptation characteristic that integrates genetics with local topographic and soil moisture conditions.

In this study, we determined the photoperiod sensitivity for millet and sorghum varieties adapted to the ecological conditions of Burkina Faso by reducing water and nitrogen stress with supplemental irrigation and optimum fertilization. The coefficients that define photoperiod sensitivity corresponded to the range of values that are more realistic in West Africa during the rainy season, where photoperiod sensitivity is a major trait of most of varieties used by farmers. Using these coefficients after evaluation for the rainy season allows for a more realistic simulation of the actual cropping cycle, and, therefore, a better assessment of the impact of climate change and climate variability on food security in the region. The results allow for the development of alternate management options based on improved variety selection for a given environment.

Acknowledgements

This study was supported in 2003 and 2004 by the Climate Forecasting for Agricultural Research (CFAR) Project funded by National

Oceanic and Atmospheric Administration (NOAA), and in 2006-2007 by the AGRHYMET Regional Center. Thanks are also due to the Visiting Scholar Program of the Fulbright Program that allowed the first author to visit the University of Georgia.

References

[1] US AID.–FEWS NET–Famine Early Warning Network. http://www.fews.net/pages/livelihoods-country.aspx?gb=bf&loc=6&l=en. Verified 12/08/2013.

[2] S.B. Traoré, F.N. Reyniers, M. Vaksmann, B. Kone, A. Sidibe, A. Yorote, K. Yattara, M. Kouressy, Adaptation a la sécheresse des écotypes locaux de sorghos du Mali, Sécheresse 11 (2000) 227–237.

[3] M. Diop, F.N. Reyniers, B. Sarr, Apport du photopériodisme à l'adaptation du mil à la sécheresse en milieu soudano-sahélien, Sécheresse 16 (2005) 35–40.

[4] M. Dingkuhn, M. Kouressy, M. Vaksmann, B. Clerget, J. Chantereau, A model of sorghum photoperiodism using the concept of threshold-lowering during prolonged appetence, European Journal of Agronomy 28 (2008) 74–89.

[5] D.J. Major, Photoperiod response characteristics controlling flowering of nine crop species, Canadian Journal of Plant Science 60 (1980) 777–784.

[6] P. Hadley, E.H. Roberts, R.J. Summerfield, F.R. Minchin, (1984). Effects of temperature and photoperiod on flowering in soya bean [Glycine max (L.) Merrill]: a quantitative model, Annals of Botany 53 (1984) 669–681.

[7] B.S. Vergara, T.T. Chang, The Flowering Response of the Rice Plant to Photoperiod. A Review of the Literature. Fourth Edition. The International Rice Research Institute, Los Baños, Laguna, Philippines, 1985.

[8] P.S. Carberry, L.C. Campbell, The growth and development of pearl millet as affected by photoperiod, Field Crops Research 11 (1985) 207–217.

[9] M. Dingkuhn, B.B. Singh, B. Clerget, J. Chantereau, B. Sultan, Past, present and future criteria to breed crops for water-limited environments in West Africa, Agricultural Water Management 80 (2006) 241–261.

[10] M. Vaksmann, S. Traoré, O. Niangado, Le photopériodisme des sorghos africains, Agriculture et Développement n 9 (1996) 13–18.

[11] P.Q. Craufurd, V. Mahalakshmi, F.R. Bidinger, S.Z. Mukuru, J. Chantereau, P.A. Omanga, A. Qi, E.H. Roberts, R.H. Ellis, R.J. Summerfield, G.L. Hammer, Adaptation of sorghum: characterization of genotypic flowering responses to temperature and photoperiod, Theoretical and Applied Genetics 99 (1999) 900–911.

[12] P.Q. Craufurd, A. Qi, Photothermal adaptation of sorghum (*Sorghum bicolor*) in Nigeria. Agricultural and Forest Meteorology 108 (2001) 199–221.

[13] D.J. Andrews, Effects of date of sowing on photosensitive Nigerian Sorghums, Expl. Agric 9 (1973) 337.

[14] A.H. Kassam, D.J. Andrew, Effects of sowing dates on growth, development and yield of photosensitive sorghum at Samaru, Northern Nigeria. *Experimental Agriculture* 11 (1975) 227–240.

[15] V.B. Ogunlela, Different yield response of photo-sensitive and photo-insensitive sorghum varieties to delayed sowing in semi-arid Nigeria, Indian J. Agric. Sci. 55 (1985) 634–637.

[16] M. Ouattara, M. Vaksmann, F.N. Reyniers, O. Niangado M. Kouressy, Diversité phénologique des sorghos du Mali et adaptation à la diversité des agro-écosystèmes. Mise en valeur d'un savoir: Gestion des ressources génétiques des plantes en Afrique des savanes, 1998, pp. 73–84.

[17] P.W. Morgan, S.A. Finlayson, K.L. Childs, J.E. Mullet, W.L. Rooney, Opportunities to improve adaptability and yield in grasses: lessons from sorghum. Crop Science 42 (2002) 1791–1799.

[18] G.L. Hammer, R.L. Vanderlip, Genotype-by-environment interaction in grain sorghum, I. Effects of temperature on radiation use efficiency. Crop Sci. 29 (1989) 370–376.

[19] R.C. Muchow, P.S. Carberry, Phenology and leaf-area development in atropical grain sorghum, Field Crops Research 23 (1990) 221–237.

[20] J. Chantereau, M. Ag Hamada, A. Bretaudeau, S.O. Tembely, Etude de nouvelles variétés de sorgho en milieu paysan dans la zone cotonnière Cmdt du Mali (1995–1996): Amélioration du sorgho et de sa culture en Afrique de l'Ouest et du Centre. Actes de l'atelier de restitution du programme conjoint sur le sorgho Icrisat-Cirad, 1998, pp. 199–210.

[21] G. Trouche, J. Chantereau, J.-D. Zongo, Variétés traditionnelles et variétés améliorées de sorgho dans les régions sahéliens. In: L. BACCI, F.-N. REYNIERS (éd) Le futur des céréales photopériodiques pour une production durable en Afrique tropicale semi-aride. Actes du séminaire international, 27–30 avril 1998, Florence, Italie. Ed. CeSIA, Florence, Italie, CIRAD, Montpellier, France.

[22] G. Alagarswamy, J.T. Ritchie, Phasic development in CERES sorghum model, in: T. Hodges (Ed.), Predicting Crop Phenology, CRC Press, Boca Raton, 1991, pp. 143–152.

[23] G. Alagarswamy, D.M. Reddy, G. Swaminathan, Durations of the photoperiod-sensitive and -insensitive phases of time to panicle initiation in sorghum, Field Crops Research 55 (1998) 1–10.

[24] B. Clerget, Le rôle du photopériodisme dans l'elaboration du rendement de trois variétés de sorgho cultivées en Afrique de l'Ouest (Effect of photoperiod-sensitivity on yield and yield components of three sorghum varieties grown in West Africa). PhD thesis, Institut National Agronomique Paris Grignon, Grignon, France, 2004.

[25] E.H. Roberts, R.J. Summerfield, Measurement and prediction of flowering in annual crops, in: J.G. Atherton (Ed.), Manipulation of flowering., 1987, Butterworths, London, 1987, pp. 17–50.

[26] D.J. Major, J.R. Kiniry, Predicting daylength effects on phenological processes, in: T. Hodges (Ed.), Predicting Crop Phenology, CRC Press, Boca Raton, pp. 15–28.

[27] A. Folliard, P.C.S. Traoré, M. Vaksmann, M. Kouressy, Modeling of sorghum response to photoperiod: a threshold-hyperbolic approach, Field Crops Research 89 (2004) 59–70.

[28] J.W. Jones, J.R. Kiniry, CERES-Maize a Simulation Model of Maize Growth and Development. Texas A & M University Press, College Station, Texas, 1986.

[29] J.T. Ritchie, G. Alagarswamy, Simulation of sorghum and pearl millet phenology, in: S.M. Virmani, H.L.S. Tandon, & G. Alagarswamy (Eds.), Modeling the Growth and Development of Sorghum and Pearl Millet. Research Bulletin no. 12, ICRISAT, Patancheru, 1989, pp. 24–26.

[30] J.T. Ritchie, G. Alagarswamy, Genetic coefficients for CERES Models, in: S.M. Virmani, H.L.S. Tandon, & G. Alagarswamy (Eds.), Modeling the Growth and Development of Sorghum and Pearl Millet. Research Bulletin no. 12, ICRISAT, Patancheru, 1989, pp. 27–29.

[31] J.W. Jones, G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, J.T. Ritchie, The DSSAT Cropping System Model, European Journal of Agronomy 18 (2003) 235–265.

[32] G. Hoogenboom, J.W. Jones, P.W. Wilkens, C.H. Porter, W.D. Batchelor, L.A. Hunt, K.J. Boote, U. Singh, O. Uryasev, W.T. Bowen, A.J. Gijsman, A. Du Toit, J.W. White, G.Y. Tsuji, Decision Support System for Agrotechnology Transfer Version 4.0 [CD-ROM], University of Hawaii, Honolulu, Hawaii, 2004.

[33] S.E. Nicholson, J. Kim, J. Hoopingarner, Atlas of African rainfall and its interannual variability. Department of Meteorology, Florida State University Tallahassee, Florida, USA, 1988.

[34] SAS Institute Inc. SAS OnlineDoc® 9.1.3. Cary: USA. SAS Institute Inc, 2004.

[35] C.J. Willmott, S.G. Ackleson, R.E. Davis, J.J. Feddema, K.M. Klink, D.R. Legates, J. O'donnell, C.M. Rowe, Statistics for the evaluation and comparison of models. Journal of Geophysical Research, 90(C5) (1985) 8995–9005.

[36] K. Loague, R.E. Green, Statistical and graphical methods for evaluating solute transport models: overview and application, J. Contam. Hydrol. 7 (1991) 51–73.

[37] B. Clerget, M. Dingkuhn, J. Chantereau, J. Hemberger, G. Louarn, M. Vaksmann, Does panicle initiation in tropical sorghum depend on day-to-day change in photoperiod? Field Crops Research 88 (2004) 11–27.

[38] A. Tenkouano, J. Chantereau, P. Sereme, A.B. Toure, Comparative response of a day-neutral and photoperiod-sensitive sorghum to delayed sowing or transplanting, African Crop Science Journal 5 (1997) 259–266.

[39] L. Bacci, C. Cantini, F. Pierni, G. Maracchi, F.N. Reyniers, Effects of sowing date and nitrogen fertilization on growth, development and yield of a short day cultivar of millet (Pennisetum glaucum L.) in Mali, European Journal of Agronomy 10 (1999) 9–21.

[40] J. Chantereau, G. Trouche, J.F. Rami, M. Deu, C. Barro, L. Grivet, RFLP mapping of QTLs for photoperiod response in tropical sorghum, Euphytica 120 (2001) 183–194.

[41] P.Q. Craufurd, F.R. Bidinger, Potential and realized yield in pearl millet (Pennisetum americanum) as influenced by plant population density and life-cycle duration, Field Crops Research 22 (1989) 211–225.

[42] R.K. Maiti, G.G.L. Soto, Effect of four sowing date environments on growth, development and yield potentials of 15 pearl millet cultivars (*Pennisetum americanum* L Leeke) during autumn-winter seasons in Marin N.L., Mexico, Journal of Experimental Botany 41 (1990) 1609–1618.

[43] G. Alagarswamy, F.R. Bidinger, The influence of extended vegetative development and d2 dwarfing gene in increasing grain number per panicle and grain yield in pearl millet, Field Crops Res. 11 (1985) 265–279.

[44] E.J. Van Oosterom, G.J. O'leary, P.S. Carberry, P.Q. Craufurd, Simulating growth development, and yield of tillering pearl millet: iii. biomass accumulation and partitioning, Field Crops Research 79 (2002) 85–106.

[45] E.J. Van Oosterom, G.J. O'leary, P.S. Carberry, P.Q. Craufurd, Simulating growth development, and yield of tillering pearl millet: iii. biomass accumulation and partitioning, Field Crops Research 79 (2002) 85–106.

[46] P.K. Hundal, J. Joy, Application of CERES-Millet model to crop yield predictions in Punjab, Journal of Agrometeorology 6 (2004) 171–176.