Research

Development of Aeration Plans Based on Weather Data: A Model for Management of Corn Stored in Georgia

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ABSTRACT A model relating daily maximum and daily minimum temperatures based on 30-yr averages from 77 weather stations in Georgia was used to estimate average cooling hour accumulations below specified thresholds of 12.8, 15.6, and 18.3°C from September to November. The dates by which 120, 60, and 40 h of temperature were accumulated below each threshold (1 aeration cycle) were estimated at aeration fan speeds of 0.0013, 0.0026, and 0.0039 $m^3/s/m^3$ (0.1, 0.2, and 0.3 cu ft/min, or CFM/bu, respectively). These temperature accumulations indicate that aeration could be used to cool corn when it is harvested and binned and would be an important addition for insect management plans for corn stored in Georgia. Economic cost of aeration would be comparable to using pirimiphos-methyl, a protectant insecticide. Aeration controllers could be purchased for \$200–\$300 to monitor cooling hours. Airflow rates of 0.0039 $m^3/s/m^3$ may be necessary to shorten the time required to complete an aeration cycle to take advantage of short-duration cold fronts.

STORED RAW AGRICULTURAL COMMODITIES CAN BECOME INFESTED BY a variety of stored-product beetle and moth species. The minimum development temperature for most stored-product insects is 17–21°C, and the optimum range of population growth and development can be 25–35°C (Howe 1965). A variety of management tactics is incorporated into management programs for stored wheat grains including the use of aeration, which involves the mechanical movement of air through a grain mass to cool the internal bin temperature. Cooling stored wheat through low-volume aeration is a recommended practice in the temperate environments of northern Europe (Armitage and Llewellin 1987, Lasseran and Fleurat-Lessard 1990) and the central and northcentral regions of the United States (Cuperus et al. 1986, 1990; Gardner et al. 1988).

Wheat is harvested and stored during the summer months and, as ambient temperatures cool in the fall, the temperature differential between the outside air and the internal wheat mass drives the cooling process. The purpose of aeration is to cool the internal mass to 18°C or less, which is below the minimum developmental temperature for most stored-grain insect pest species. Estimates of the units of air required to cool 1.28 m^3 (1 bu) of grain in general have been given as 600 $m^3/h/1.28\ m^3$ (Jouin 1965), 720 $m^3/h/1.28\ m^3$ (McCune et al. 1963), and 800 $m^3/h/1.28\ m^3$ (Lasseran 1988). Guidelines developed by Noyes et al. (1992) for wheat stored in Oklahoma use the value of 720; therefore, 120 h are required for cooling at 0.0013 $m^3/s/m^3$ (0.1 cu ft/min, or CFM per bushel). The approximate cost to complete 1 cycle at this rate is estimated at \$0.95/bu (Current Management Practices 1994). This cost is primarily for electricity and resulting weight loss due to shrinkage. Increasing the flow rates to 0.0026 and 0.0039 $m^3/s/m^3$ (0.2 and 0.3 CFM per bushel) decreases the time required to complete the cooling cycle to 40 and 60 h, respectively. These higher rates will not increase the electricity costs for a cycle because of the reduced hours required for completion, but larger fan sizes will be required at installation (Noyes et al. 1992). Harner and Hagstrum (1990) showed that airflow rates in excess of 0.02 $m^3/s/m^3$ (1.5 CFM/bu) did not affect grain moisture content or test weight; therefore, the flow rates of 0.0026 and 0.0039 $m^3/s/m^3$ may not increase costs due to shrinkage.

Aeration will inhibit population growth, but may not completely eliminate an existing infestation (Armitage and Stables 1984, Armitage and Llewellin 1987). The increased flow rates enable effective utilization of short-duration cold fronts in late summer and early fall and potentially can cool grain before infestations develop. The Oklahoma recommendations for wheat include an initial cooling in September, based on a temperature threshold of 12.8°C (Noyes et al. 1992). An inexpensive electrical fan controller (\$200–\$300) can be purchased to regulate aeration activation temperature and record hours of fan operation (Noyes et al. 1992).

The recommendations listed above were published for wheat in seasonal climates with cold winters, and comparatively little emphasis has been placed on aeration programs for stored corn. In particular, there are no published guidelines for using aeration in management programs for corn stored in warm temperate climates such as the southeastern United States. Georgia is one of the leading producers of corn in this region, with an estimated production in 1992 of 55,000,000 bushels (Agricultural Statistics 1992). The annual cash value of the corn crop from 1986 to 1992 averaged \$119,500,000 (Georgia Agricultural Facts 1987–1993). The gener-

Fig. 1. Generalized soil regions of Georgia.

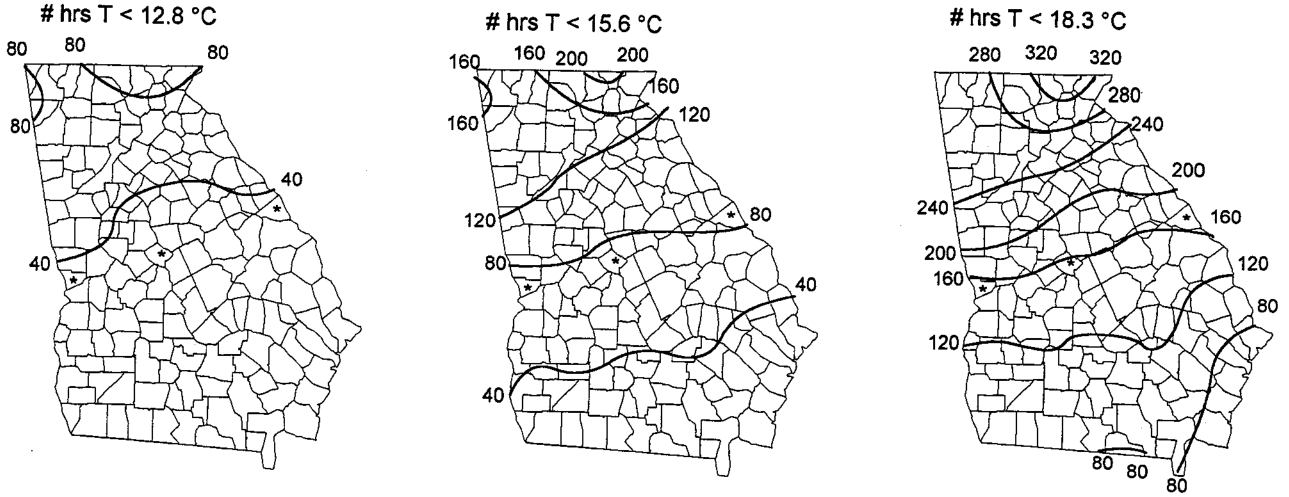


Fig. 2. (top) Estimated hours of temperature below 12.8, 15.6, and 18.3°C in Georgia during September.

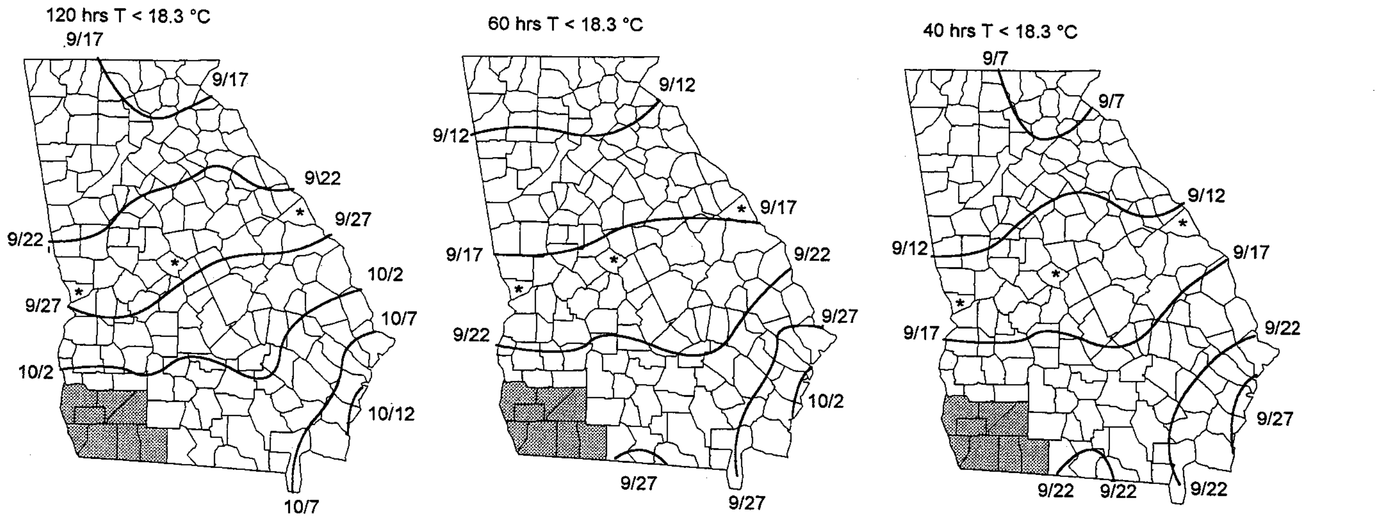
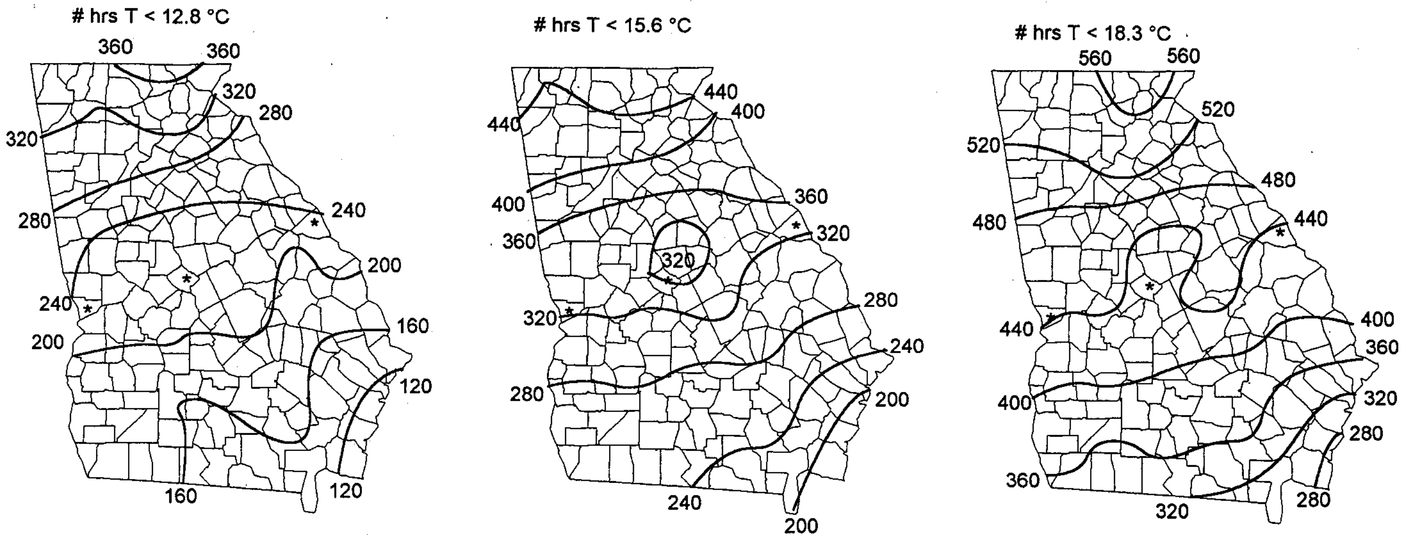


Fig. 3. (bottom) Estimated dates of completion for cooling cycles of 120, 60, and 40 h of temperature at 18.3°C or below in Georgia.

alized harvest period for corn is August–October, depending on planting date, growing temperature, soil fertility, soil moisture, and so forth. On-farm storage is common for corn, but there are several large commercial firms that store corn.

Corn can be treated with a protectant insecticide at storage, but the chemical options are limited. Malathion is scheduled to be withdrawn from use as a corn protectant (Abramson 1991) and the only other labeled protectant is the organophosphate insecticide pirimiphos-methyl. The cost for treatment, based on an approximate market price of \$30/g for malathion and \$240/g for pirimiphos-methyl, is 0.2 and 1.8 cents per bushel, respectively. The economic costs for 2 aeration cycles would be comparable to 1 treatment with pirimiphos-methyl at the time the corn is binned. In addition, because corn is harvested in the fall, the crop would be in the bins for a comparatively short time before temperatures are cool enough to use aeration, as opposed to wheat which is binned earlier in the year. As a preliminary step for developing aeration plans, an empirical model relating daily maximum and minimum temperatures to accumulations of time with temperature below specified thresholds was used to provide estimates of available cooling time during the fall and spring months. This model used recorded temperature data from 77 weather stations in Georgia.

Description of Temperature Data and Model Development. Archives of continuous temperature observation are available for relatively few locations. Airport observing stations supported by the federal government report hourly measurements of the air temperature. Summarized temperature data for most National Weather Service (NWS) stations are available for study. However, these locations are relatively few in number and their temperature data are subject to a number of distortions, most notably the encroachment of urbanization and its attendant artificial inflation of daily minimum temperatures (Karl et al. 1988). Daily maximum and minimum temperatures are measured routinely throughout the United States by volunteers, mostly in rural locations, cooperating with the NWS. Historical records for the weather stations in Georgia extend back for several decades, providing the primary data base for climatological study. All temperature records for these Georgia weather stations were obtained from databases at the Oklahoma Climatological Survey in Norman, OK. Model diurnal temperature curves were imposed between the daily maximum and minimum temperatures reported by cooperative observers from 1961 through 1990 in the Georgia weather stations. For modelling purposes, the daily minimum and maximum temperatures were assumed to occur at sunrise and midway between solar noon and sunset, respectively. Sunrise and sunset times were determined by formulae obtained from the U.S. Department of Energy (SOLMET 1979). An algorithm based on a sine curve with maximum and minimum temperatures as the maxima and minima of the curve was used to simulate various heat-



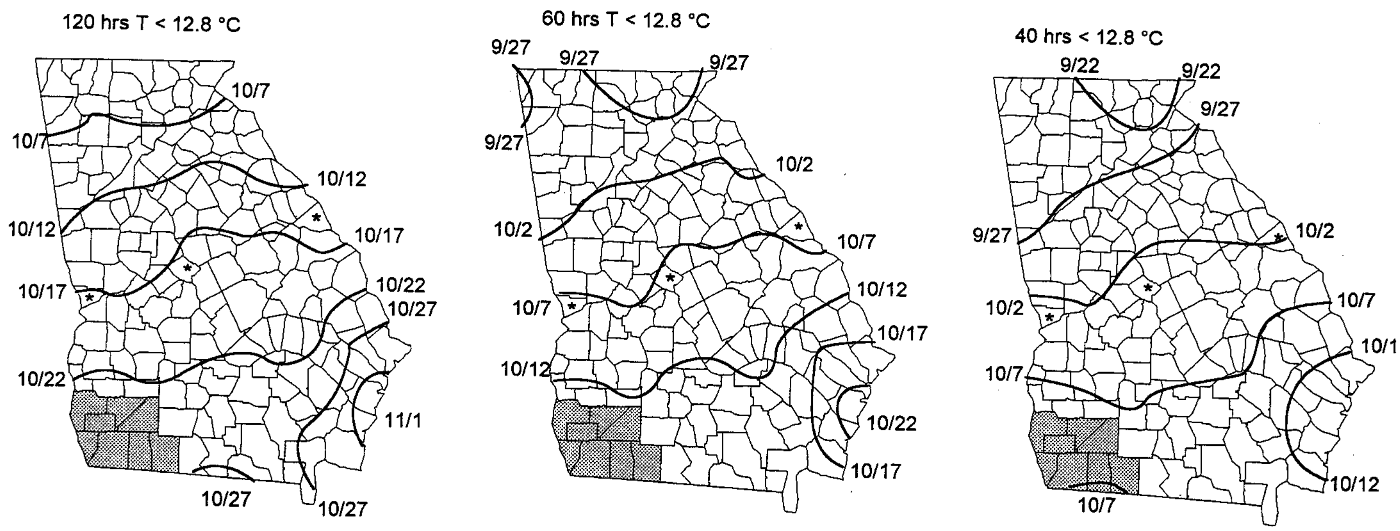


Fig. 4. (top) Estimated hours of temperature below 12.8, 15.6, and 18.3°C in Georgia during October.
Fig. 5. (bottom) Estimated dates of completion for cooling cycles of 120, 60, and 40 h of temperature at 12.8°C or below in Georgia.

ing and cooling rates. Adjustments to the algorithm were based on comparisons with monthly diurnal temperature curves from stations of the Oklahoma Mesonetwork and with published long-term mean temperatures (every 3 h) at Atlanta, Savannah, Macon, and Athens NWS offices (National Climate Data Center 1992). Estimates of hourly temperature at each of the cooperative sites were used to compute estimated mean values of the time-accumulation of below-threshold temperatures and the average dates by which those estimated accumulations reach designated values. The algorithim used to estimate hourly temperatures on any particular day is as follows:

The following information is required: maximum temperature on the previous day; daily maximum and minimum temperature; minimum temperature on the following day; and local mean time of sunrise and sunset: TX, daily maximum temperature; TN, daily minimum temperature; TX_{-1}, maximum temperature on the previous day; TN_{+1}, minimum temperature on the following day; T, hourly temperature; T_{-1},temperature at the previous hour; time, local solar time [hour]; TSR, local solar time of sunrise [hour and decimal]; TSS, local solar time of sunset [hour and decimal]; HOT, time equidistant between local noon and sunset [hours and decimal]; TMID, estimated temperature at midnight; and CR [24 - HOT]/[24 - HOT + TSR].

The algorithm with sine in radians, time in hours, and how the model is used to estimate accumulations for any particular day is illustrated using the average maximum and minimum temperatures for 2 October at Augusta, GA, 33.22° N. Minumum temperatures for 1, 2, and 3 October averaged 14.6, 14.6, and 12.7°C, respectively. Maximum temperatures averaged 27.7, 27.8, and 27.4°C, respectively. Sunrise and sunset on 2 October were at 6.19 (6:11) a.m. and 17.80 (5:48 p.m.) Maximum temperature was assumed to occur midway between noon and sunset (17.80 – 12.00/2) + 12.00 = 14.90. Beginning and ending points for each equation series are shown to illustrate the model. All temperature calculations are in Celcius. If midnight is taken as time 0, 11 h with temperatures <18.3°C and 4 h with temperatures <15.6°C were accumulated at

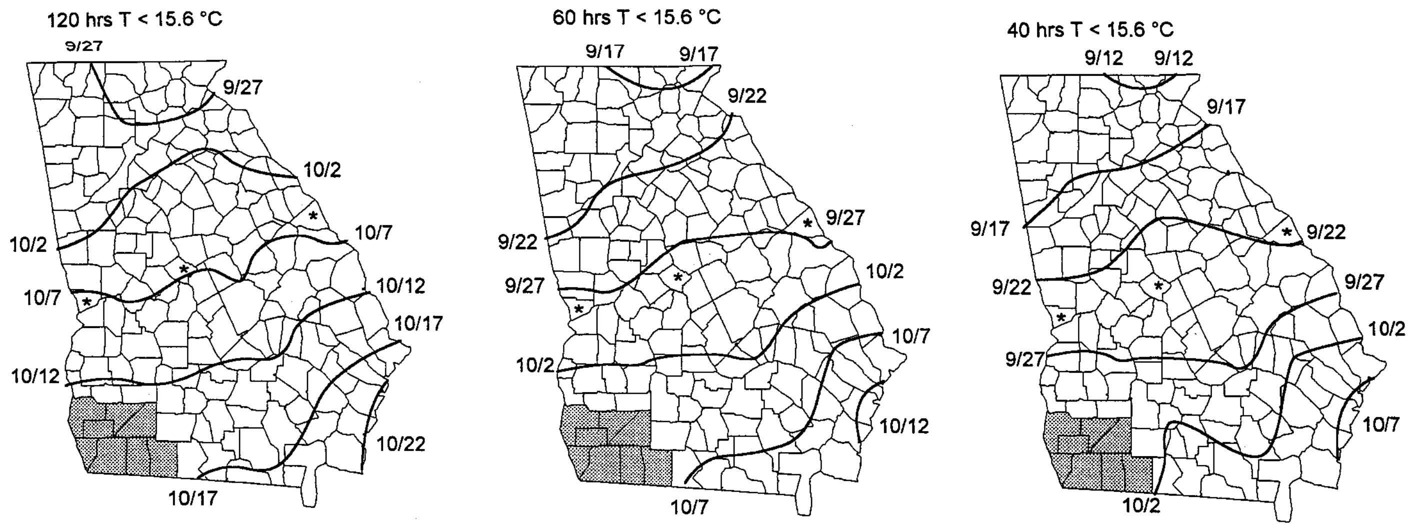


Fig. 6. Estimated dates of completion for cooling cycles of 120, 60, and 40 h of temperature at 15.6°C or below in Georgia.

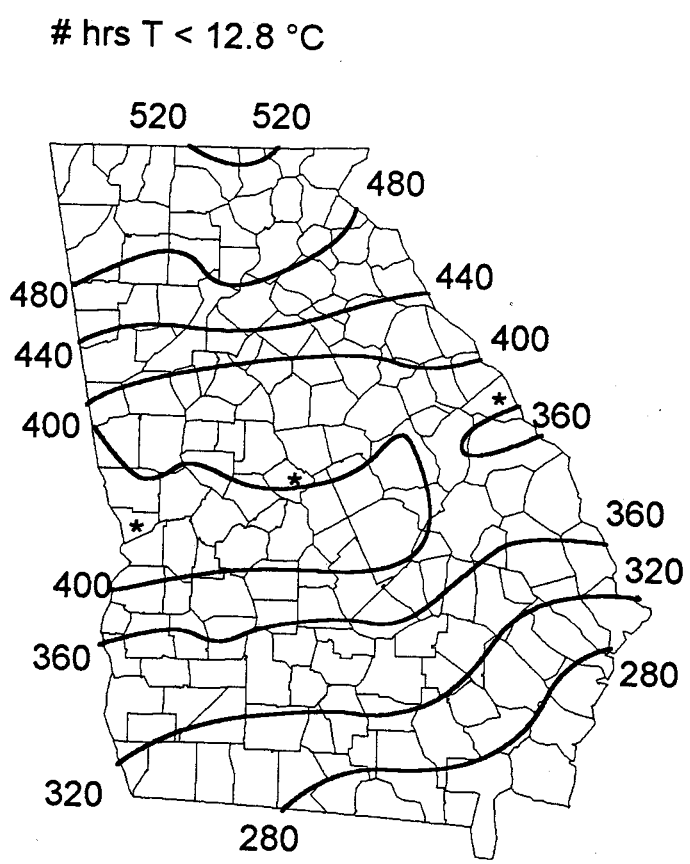


Fig. 7. Estimated hours of temperature below 12.8°C in Georgia during November.

the Augusta site on 2 October.

Temperature at midnight beginning day (2 October):

$$T = TMID = TX - 1 + \{[(TN - TX - 1) * \sin(CR * \pi)]/2\}$$

$$27.7 + \{(14.1 - 27.7) * \sin[(24 - 14.90)/(24 - 14.90 + 6.19) * \pi]/2\}$$

$$27.7 + [-13.6 * \sin(1.87/2)] = 16.7.$$

Hourly temperature each hour from midnight until TSR

$$T = TMID + \{(TN - TMID * [\sin2(time * \pi)/2 * TSR)]\}$$

$$16.7 + \{(14.1 - 16.7) * [\sin2(1.00 * \pi)/(2 * 6.19)]\} = 16.5 \text{ at 1:00 a.m.}$$

$$16.7 + \{(14.1 - 16.7) * [\sin2(6.00 * \pi)/(2 * 6.19)]\} = 14.1 \text{ at 6:00 a.m.}$$

Temperature at time = TSR

$$T = TN\ (14.1).$$

Temperature at each hour from time = TSR to time = HOT

$$T = TN + \{(TX - TN) * \sin[(\pi/2) * (time - TSR)/(HOT - TSR)]\}$$

$$14.1 + \{(27.8 - 14.1) * \sin[(\pi/2) * (7.00 - 6.19)/(14.90 - 6.19)]\}$$

$$14.1 + \{(13.7) * \sin[(\pi/2) * (7.00 - 6.19)/(8.71)]\} = 16.1 \text{ at 7:00 a.m.}$$

$$14.1 + \{(13.7) * \sin[(\pi/2) * (8.00 - 6.19)/(8.71)]\} = 18.5 \text{ at 8:00 a.m.}$$

$$14.1 + \{(13.7) * \sin[(\pi/2) * (14.00 - 6.19/(8.71)]\} = 27.6 \text{ at 2:00 p.m.}$$

Temperature at time = HOT

$$T = TX = 27.8.$$

Temperature at midnight at end of day

$$TMID = TX + [(TN + 1 - TX) * \sin(CR * \pi/2)]$$

$$27.8 + \{(12.7 - 27.8) * \sin[(24 - 14.90)/(24 - 14.90 + 6.21) * \pi]/2\}$$

$$27.8 + [(-15.11) * \sin(1.87/2)] = 15.7.$$

Temperature at each hour from HOT until TSS

$$T = TX + \{(TMID - TX) * \sin3/2[(\pi/2) * (time - HOT)/(24 - HOT)]\}$$

$$27.8 + \{(15.7 - 27.8) * \sin3/2[(\pi/2) * (15.00 - 14.90)/(24 - 14.90)]\}$$

$$27.8 + (-12.1) * \sin3/2(0.017) = 27.7 \text{ at 3:00 p.m.}$$

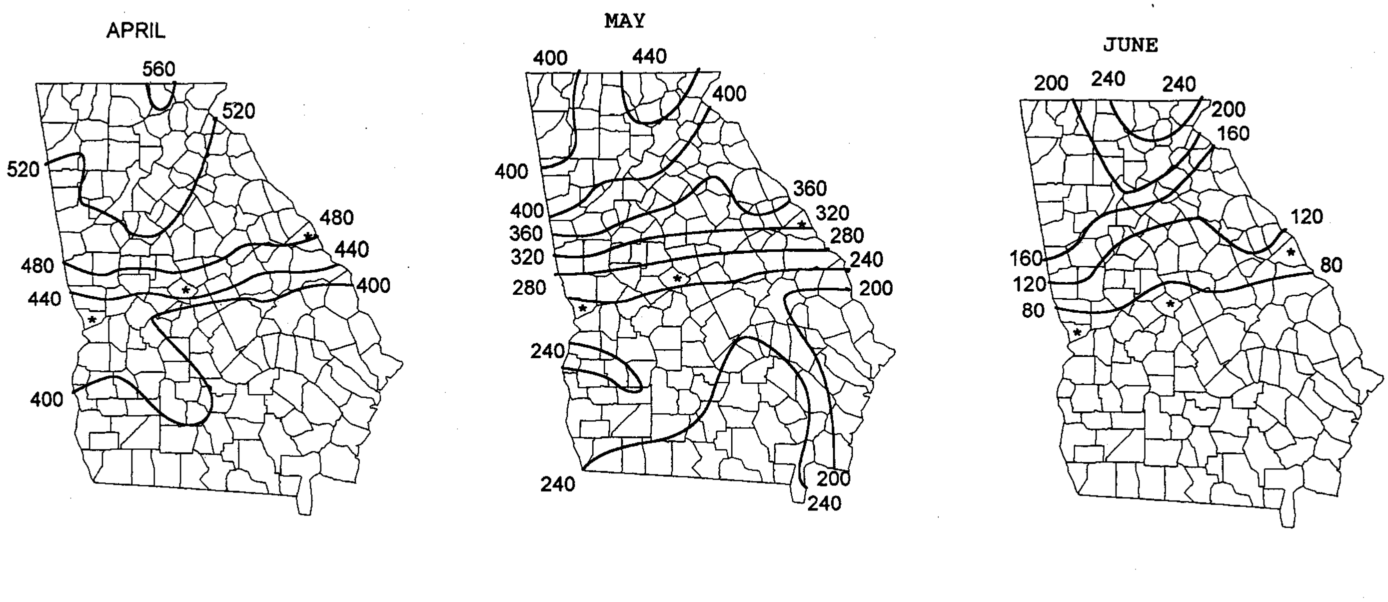


Fig. 8. Estimated hours of temperature below 18.3°C in Georgia during April, May, and June.

$27.8 + (-12.1) * \sin 3/2(0.362) = 25.2$ at 5:00 p.m.

Temperature at each hour from TSS until midnight

$T = T - 1 + [(TMID - T - 1) * \sin 3/4[(\pi/2) * (time - TSS)/(24 - TSS)]]$.

$25.2 + \{(15.7 - 25.2) * \sin 3/4[(\pi/2) * (18 - 17.8)/(24 - 17.8)]\}$

$25.2 + [(15.7 - 25.2) * \sin 3/4(0.051)] = 24.2$ at 6:00 p.m.

$24.2 + [(15.7 - 24.2) * \sin 3/4(0.300)] = 20.7$ at 7:00 p.m.

$20.7 + [(15.7 - 20.7) * \sin 3/4(0.557)] = 17.6$ at 8:00 p.m.

$17.6 + [(15.7 - 17.6) * \sin 3/4(0.811)] = 16.1$ at 9:00 p.m.

$16.1 + [(15.6 - 16.1) * \sin 3/4(1.065)] = 15.7$ at 10:00 p.m.

$15.7 + [(15.7 - 15.7) * \sin 3/4(1.318)] = 15.7$ at 11:00 p.m.

Results and Discussion

Most of the corn crop in Georgia is produced in the Coastal Plain, which can be delineated from the Piedmont region by the topographic fall line, which runs from Columbus through Macon to Augusta (Fig. 1) (Bergeaux 1962, Seegars 1993). Only 3 counties outside the Coastal Plain reported an average annual corn harvest of >100,000 bushels from 1986 to 1992 (Georgia Agricultural Facts 1987–1993).

Analyses of the 30 yr of temperature data from Georgia indicate that none of the counties in the Coastal Plain accumulates 40 h of temperatures below 12.8°C (55°F) in September, and only a few counties in the northern portion of this region accumulate at least 40 h of temperature below 15.6°C (60°F) (Fig.2). At least 80 h of temperature accumulation below 18.3°C (65°F) would be possible for the entire Coastal Plain (Fig. 2).

If corn is binned in late August or early September, any initial cooling may have to be based on a threshold of 18.3°C, which is near the minimum developmental temperature for most of the common insect pest species. The effect of increasing fan speeds to shorten the cooling cycle from 120 to 60 or 40 h yields an earlier calendar date for completing the cycle (Fig. 3). The practical implications can be illustrated using the 8 counties in the extreme southwest portion of the state, which produce an average corn crop of 1,000,000 bu or more per year. A cooling cycle of 120 h below 18.3°C can be completed by 7 October using a flow rate of 0.0013 $m^3/s/m^3$ (0.1 CFM); increasing the fan speed to 0.0026 and 0.0039 $m^3/s/m^3$ (0.2 and 0.3 CFM) to shorten the cycle to 60 and 40 h yields completion dates of 27 and 22 September, respectively.

Most of the counties in the Coastal Plain will accumulate 120–160 h below 12.8°C and 240 to 320 h below 15.6°C in October (Fig. 4). The effect of increasing fan speeds to shorten the cooling cycle is again shown by earlier temperature accumulation dates at each temperature, as illustrated by the 8 southwestern counties. At cooling cycles of 120, 60, and 40 h, temperature accumulation dates are 27, 17, and 12 October for a threshold of 12.8°C (Fig. 5). If the threshold temperature is increased to 15.6°C, accumulation dates for 120, 60, and 40 h are 17, 7, and 2 October (Fig. 6). By November, lower ambient temperatures have cooled to produce sufficient temperature hours below the specified thresholds to achieve a 2nd cooling cycle at a lower temperature than the once used for the 1st cycle (Fig. 7).

The temperature in the center of the grain mass will probably remain fairly constant throughout winter and spring, but the temperatures at the surface and along the interior bin walls will eventually increase in response to the increasing ambient temperatures (Arthur 1994). These peripheral zones with elevated temperature will become favorable for population growth and development if infestations occur when temperatures warm in the spring. Insect infestations may be controlled by fumigating the bin with phosphine, at an approximate cost of \$1.15/bu (Current Management Practices 1994), which would be incurred each time the bin is fumigated.

Fumigations would probably be necessary to control infestations in the peripheral regions of a grain bin because of the difficulty of using additional aeration cycles. Because most aeration fans are in the bottom of the bin and air is pulled in at the bottom and pushed to the surface, a cooling front would have to pass through the bulk mass, which may be at or below the specified temperature, to reach the surface. In addition, there would be an increased cost of \$0.95/bu for each additional cycle. There may be enough availible hours of temperatures below 18.3°C in April and May to use aeration, but little cooling could be accomplished in June (Fig. 8). In addition, there may be increased risks of shrinkage and moisture loss with additional aeration.

Temperature data presented in this study indicate that aeration may be an alternative to grain protectants for corn stored in the major agricultural regions of Georgia. Aeration plans suitable for corn storages in adjacent southeastern states could be developed using models of temperature accumulation for those states. September and October can be quite warm in the deep South, as compared to the midwestern and north central states. Increased or variable-aeration fan speeds may be required to take advantage of short-duration cold fronts to cool the corn mass and manage insect populations before infestations can become established. After the 1st cycle of 12.8, 15.3, or 18.3°C, a 2nd cycle at a lower temperature could be used to further cool the corn. Corn stored into the summer would be vulnerable to insect attack, and because phosphine is not a residual pesticide, repeat fumigations would be required to eliminate subsequent infestations.

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