Crop Growth and Phenology
–
Species Variability

K. Raja Reddy
Mississippi State University
Mississippi State, MS

Crop Growth and Development and Environment

Species Variability

- ✓ Effects of multiple environmental factors on crop growth and phenology across many important crop species.
- ✓ Can we use environmental productivity index concept across the species to quantify the responses and to develop functional relationships?

Crop Growth and Development and Environment

Major Crops – Global Statistics - 2008

Crop	Area, Million ha	Production, Million Mt.	Productivity, Mt. ha^{-1}
Wheat	224	690	3.0
Maize/Corn	161	823	5.1
Rice	159	685	4.3
Soybeans	97	231	2.4
Barley	57	158	2.8
Sorghum	45	65	1.5
Millets	37	36	0.96
Seedcotton	31	66	2.1
Rapeseed	30	58	1.9
Beans, dry	28	20	0.73

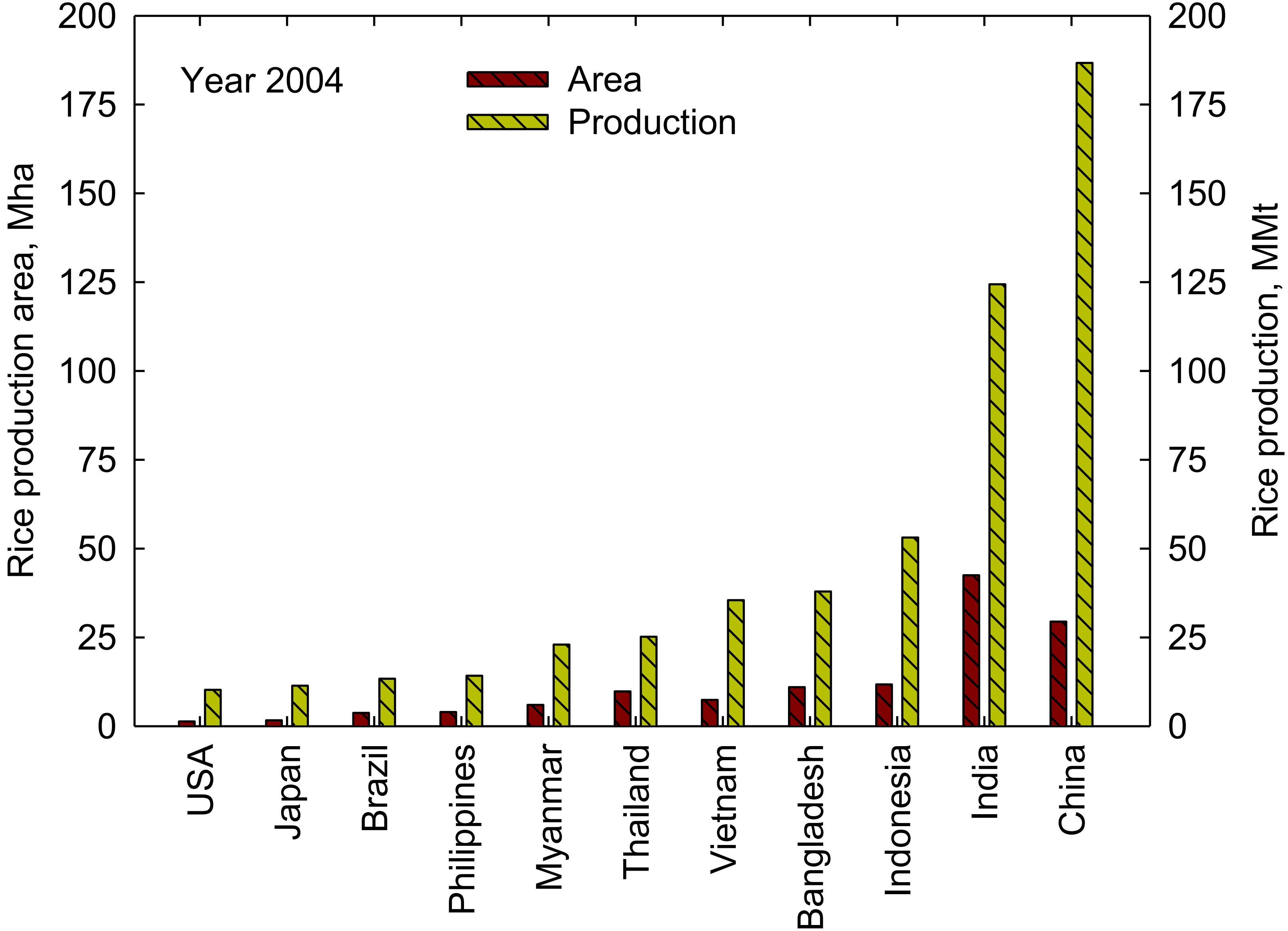
Environmental and Cultural Factors Influencing Crop Phenology

- Atmospheric Carbon Dioxide (indirect)
- Solar Radiation (indirect)
- Photoperiod (direct on flowering, no effect on modern cotton cultivars)
- Temperature (direct)
- Water (indirect)
- Wind (indirect)
- Nutrients (N, P and K) (direct & indirect)
- Growth Regulators (PIX) (indirect)

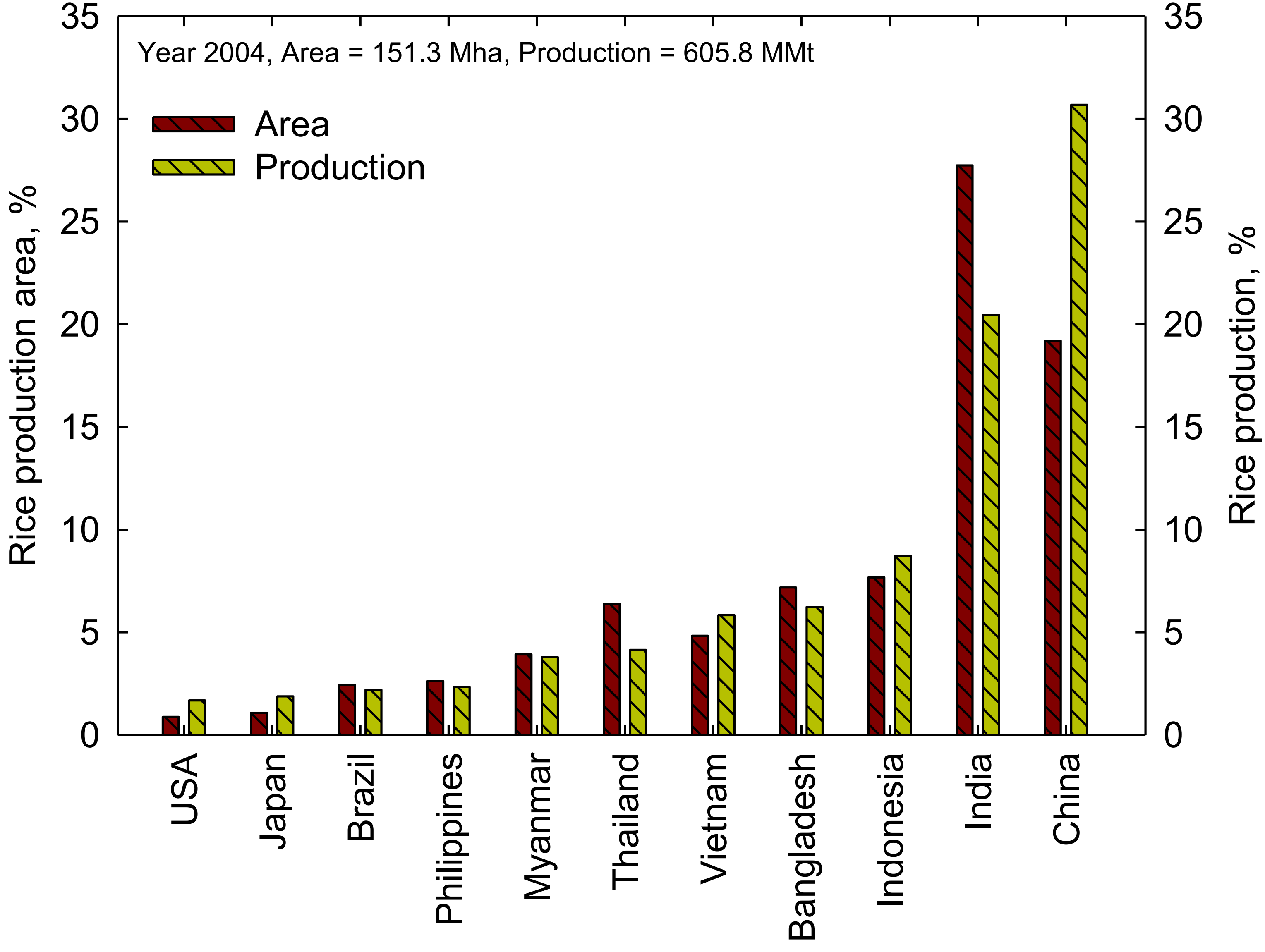
Rice – Some Crop Statistics

- Provides the dietary needs of 1.6 billion with another 400 million rely on rice for one-quarter or one-half of their diet.
- **2004 stats are:** Area = 151 Million ha, production = 606 Million Mt, and average yield = 4.02 t ha^{-1}.
- 53% Irrigated flooded-paddy
- 27% Rainfed lowland
- 12% Rainfed upland
- 8% Deep-water

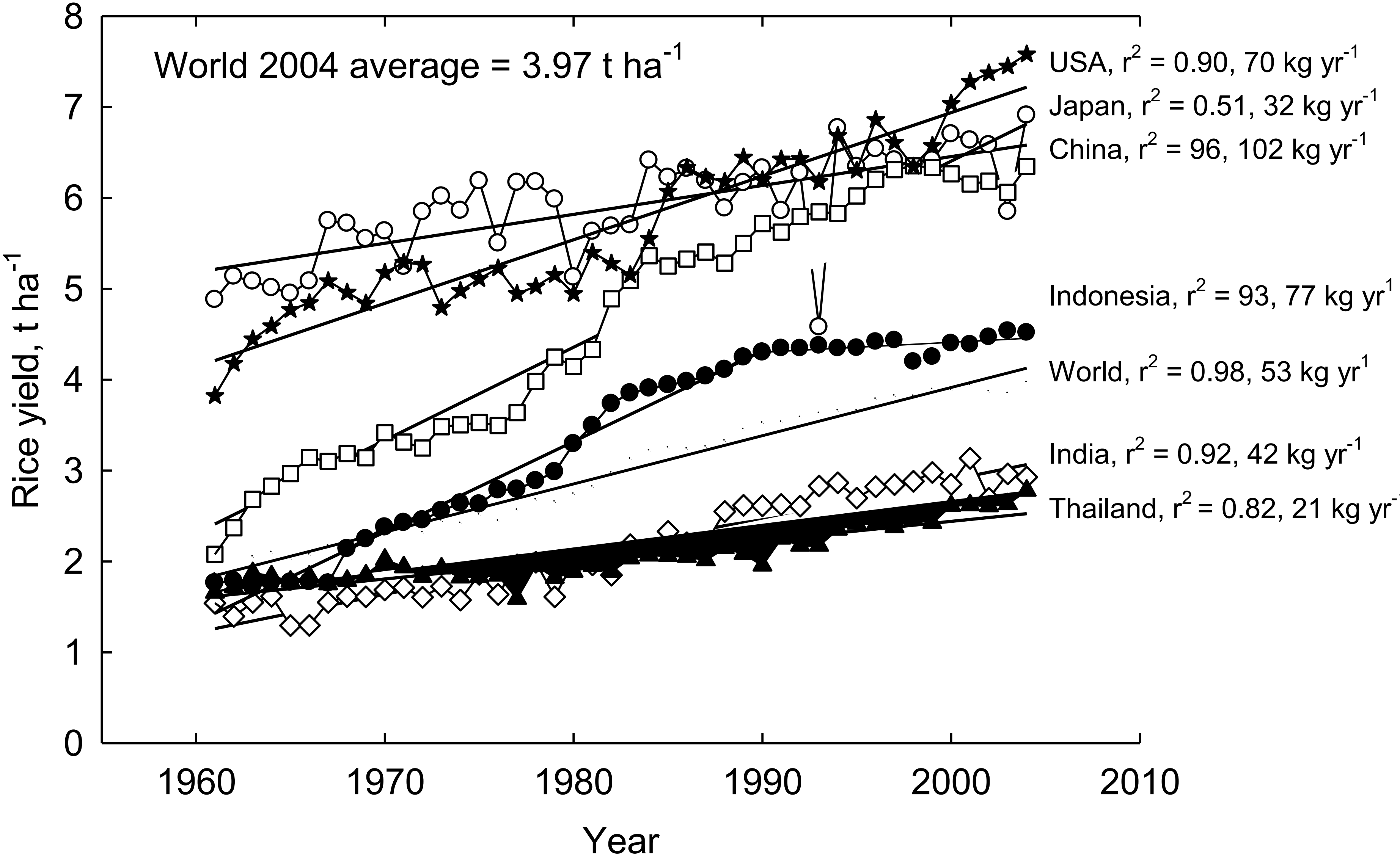
Rice Production Statistics



Rice Production Statistics

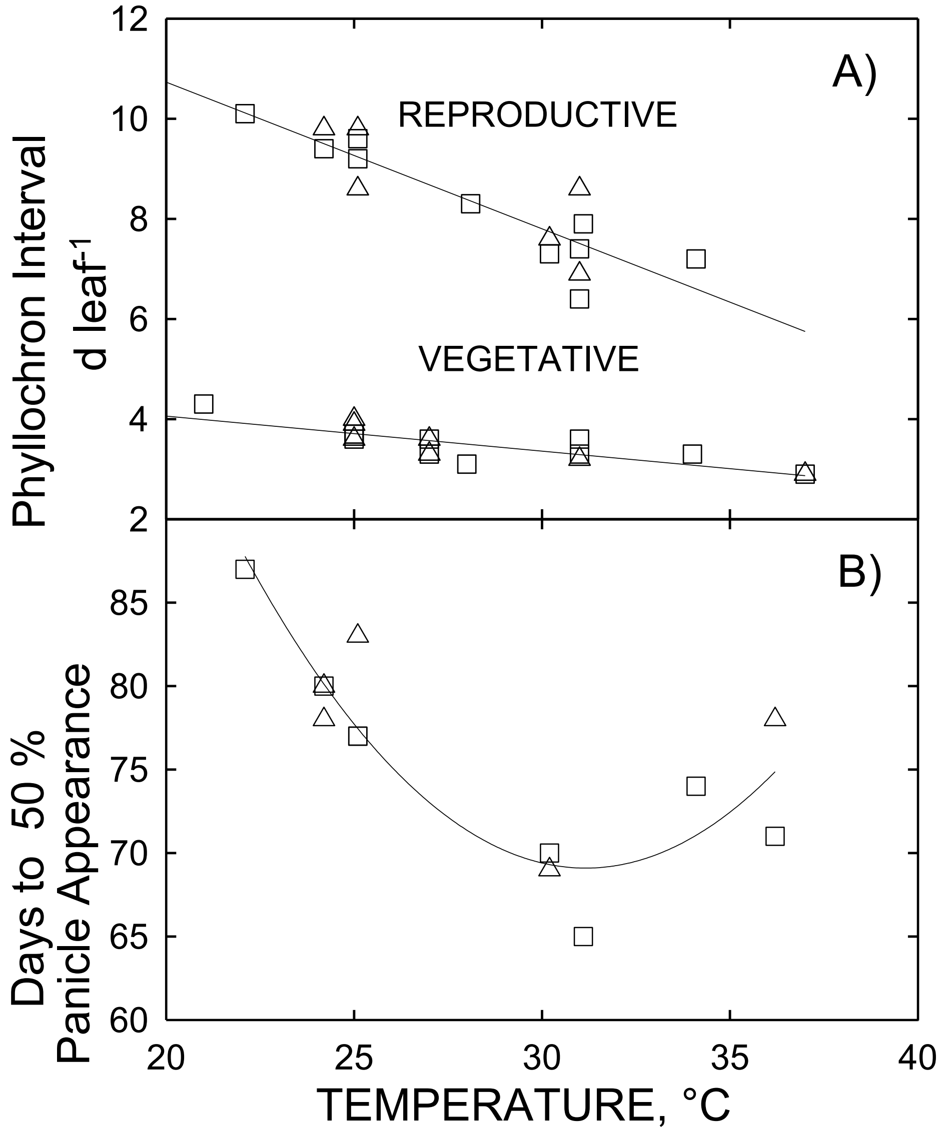


Rice Production Statistics



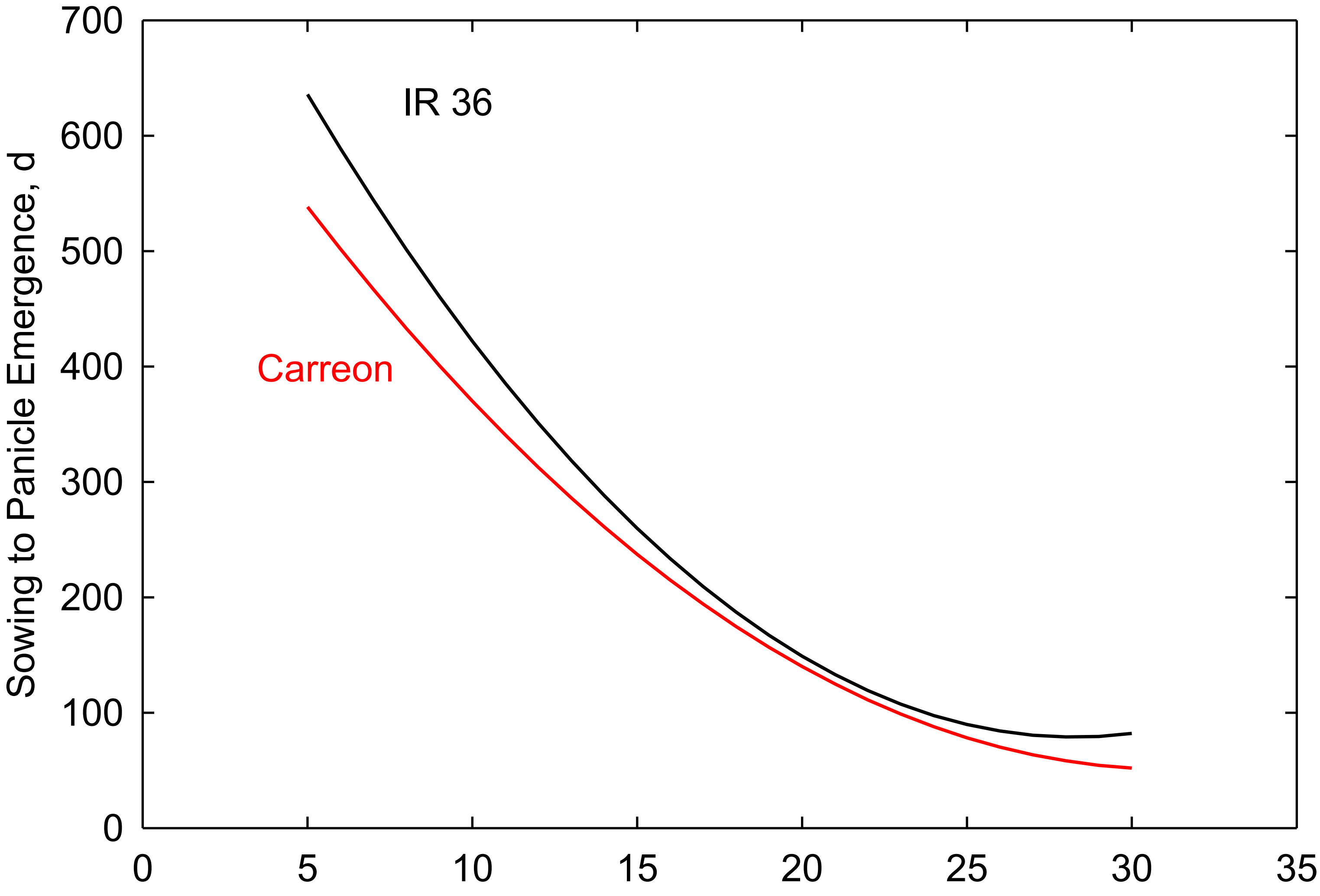
Phenology – Species Variability – Rice

Phenology and Temperature – cv IR 30



Phenology - Species Variability

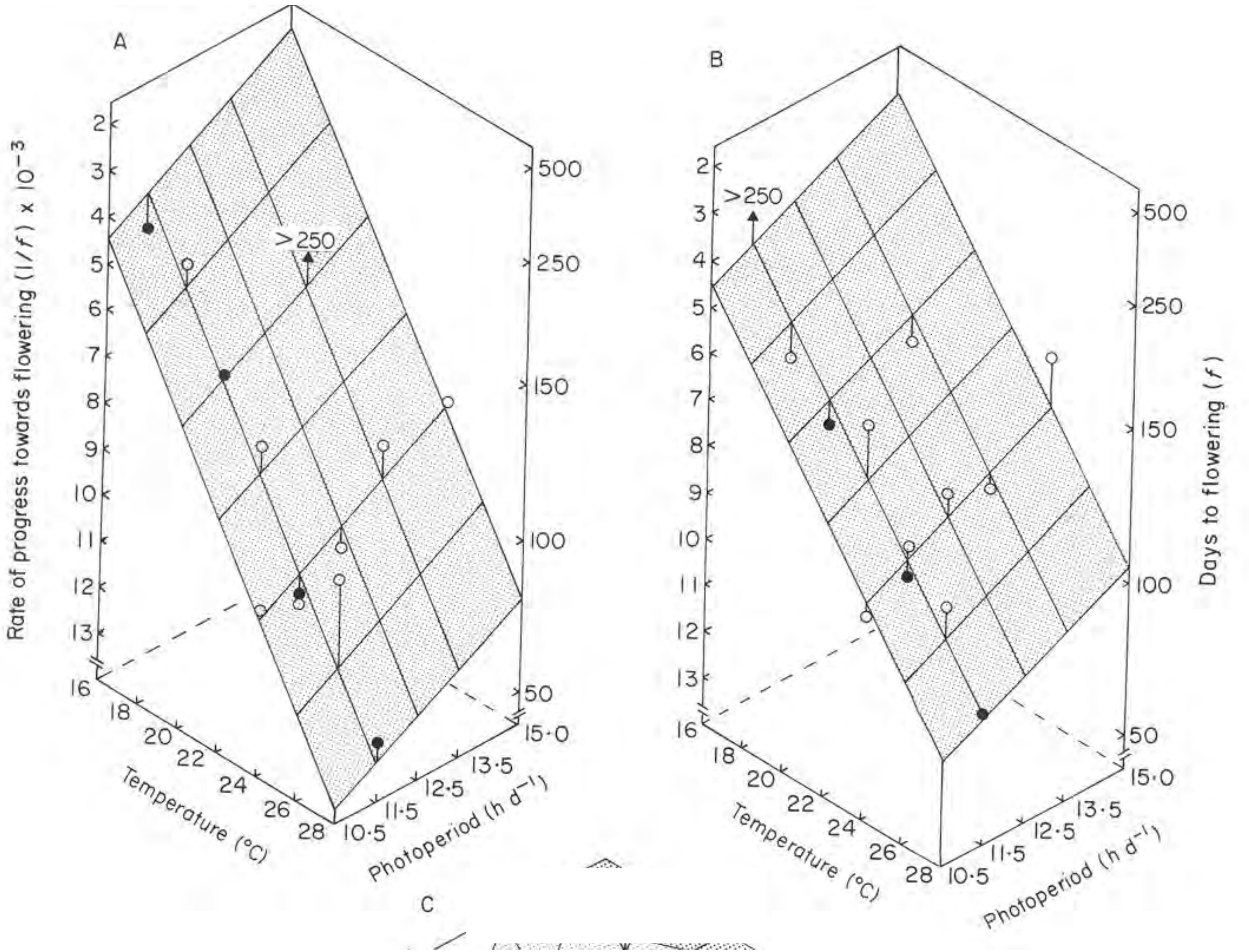
Temperature - Rice



S.K. Leong and C.K.Ong. 1983. J. Expt. Bot. 34: 1551-1561.

Phenology – Species Variability – Rice

Phenology and Temperature –Photoperiod

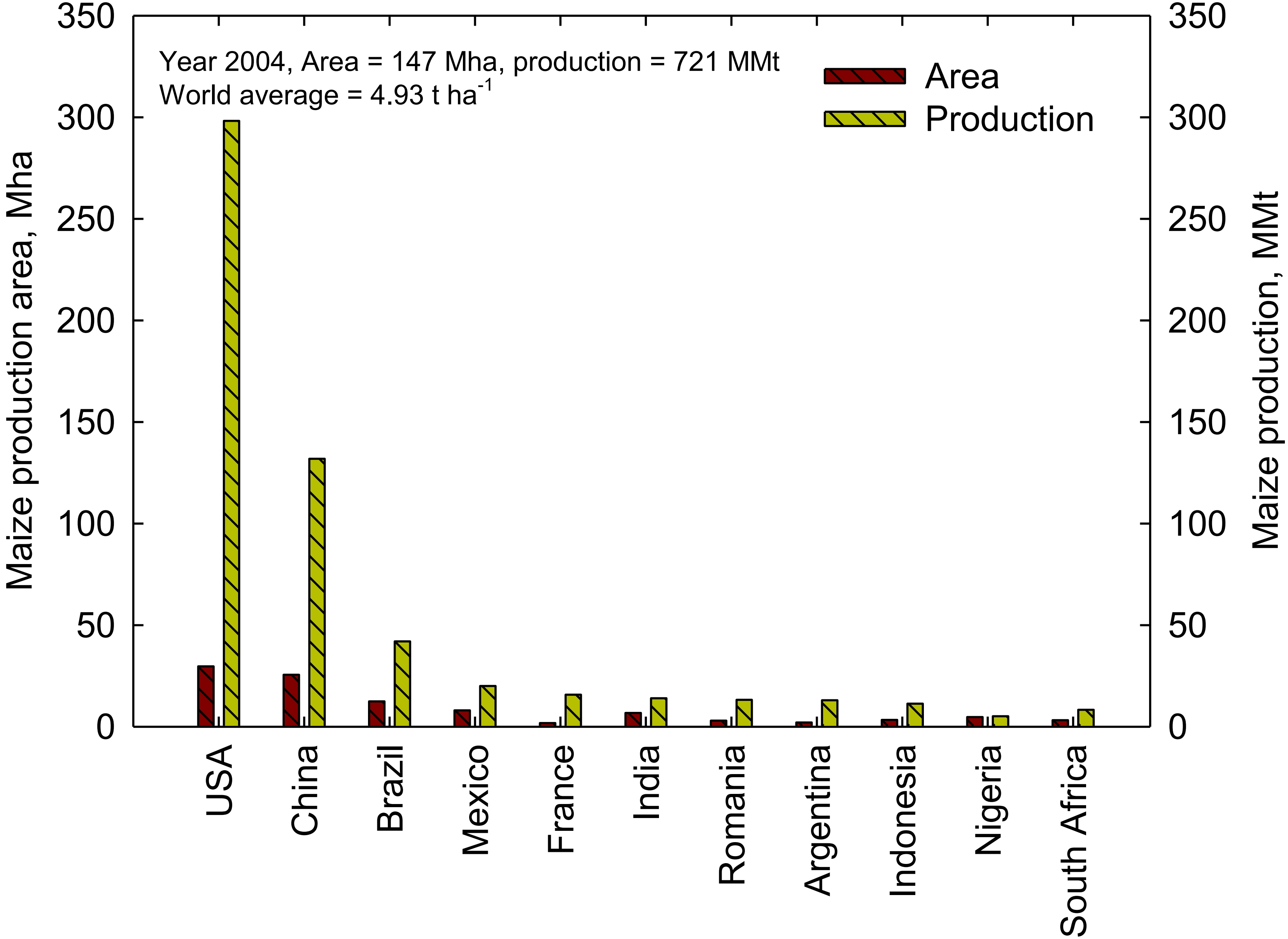


Corn or Maize, *Zea mays* L.

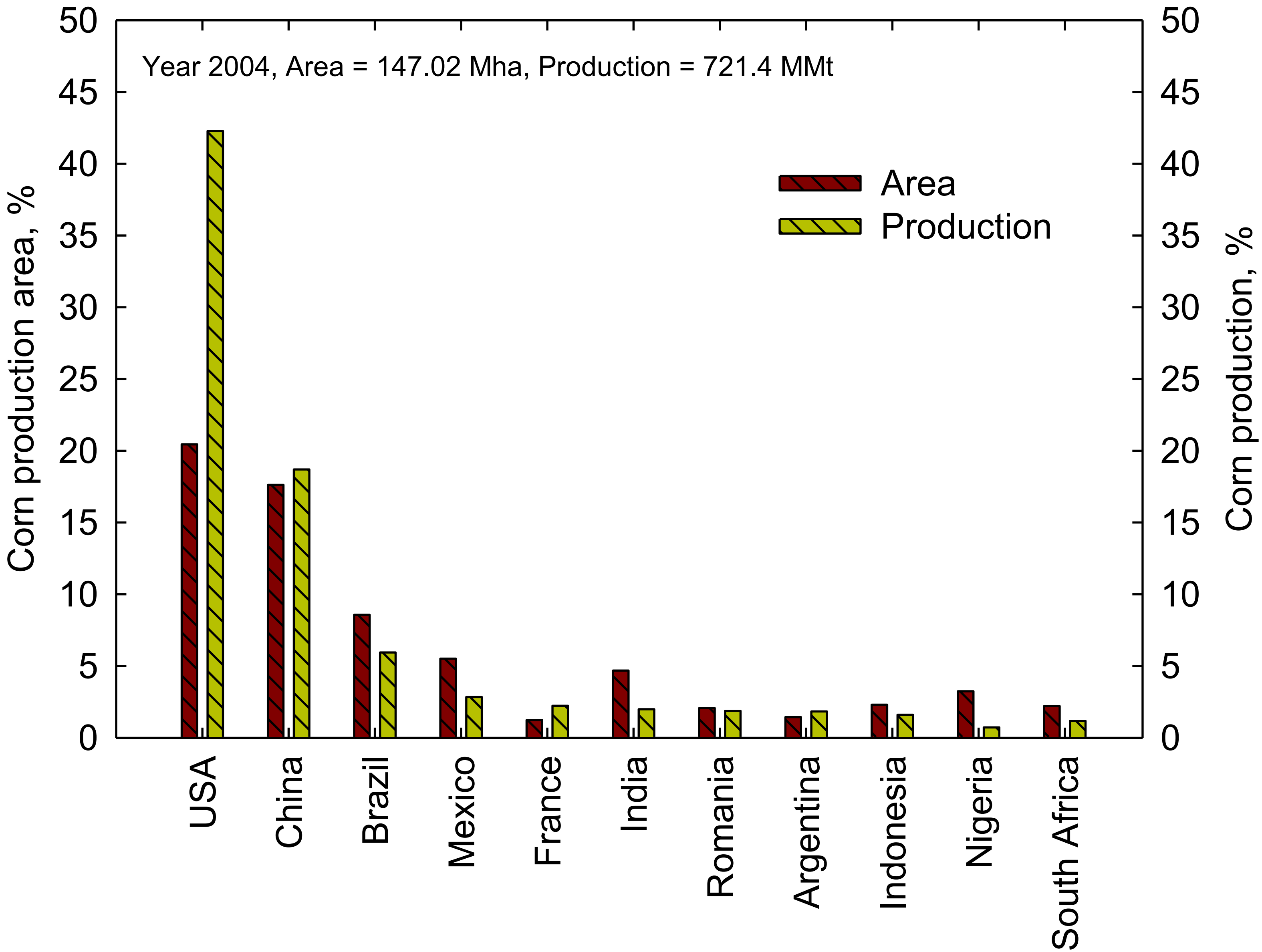
Corn is the 3rd most important food crops globally in terms of energy and protein (FAO, 2004).

Area:	147 Million ha
Total production:	721 Million Mt
Average yield:	4.93 t ha^{-1}

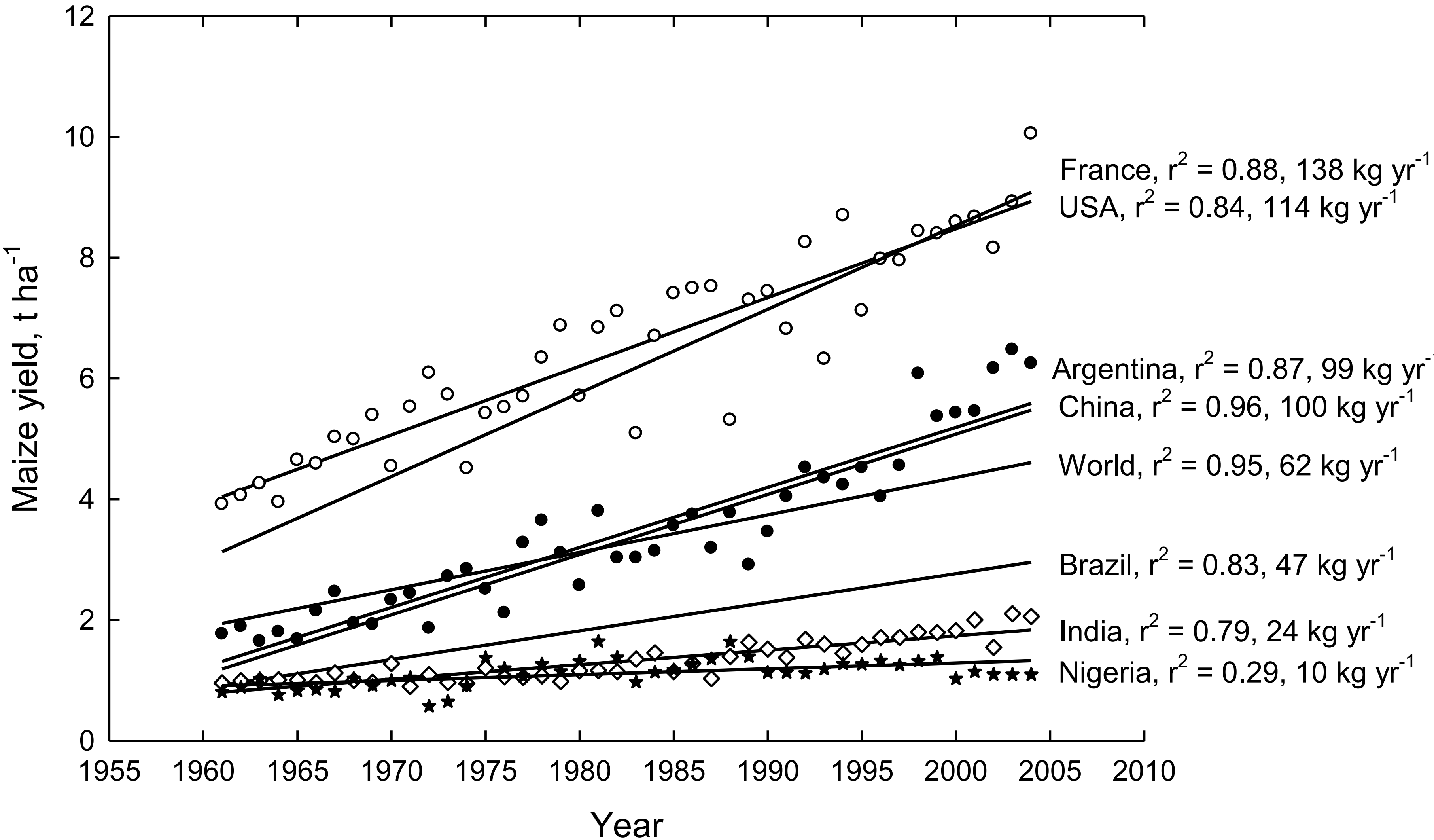
Corn or Maize, *Zea mays* L



Corn or Maize, *Zea mays* L.



Corn or Maize, *Zea mays* L.



Phenology – Species Variability

Phenology – Leaf Appearance Rates (Phyllochrons); Maize or Corn.

- Notice the base temperature which is much different than that of cotton.
- The rate of development is also linear across a wide range of temperatures.

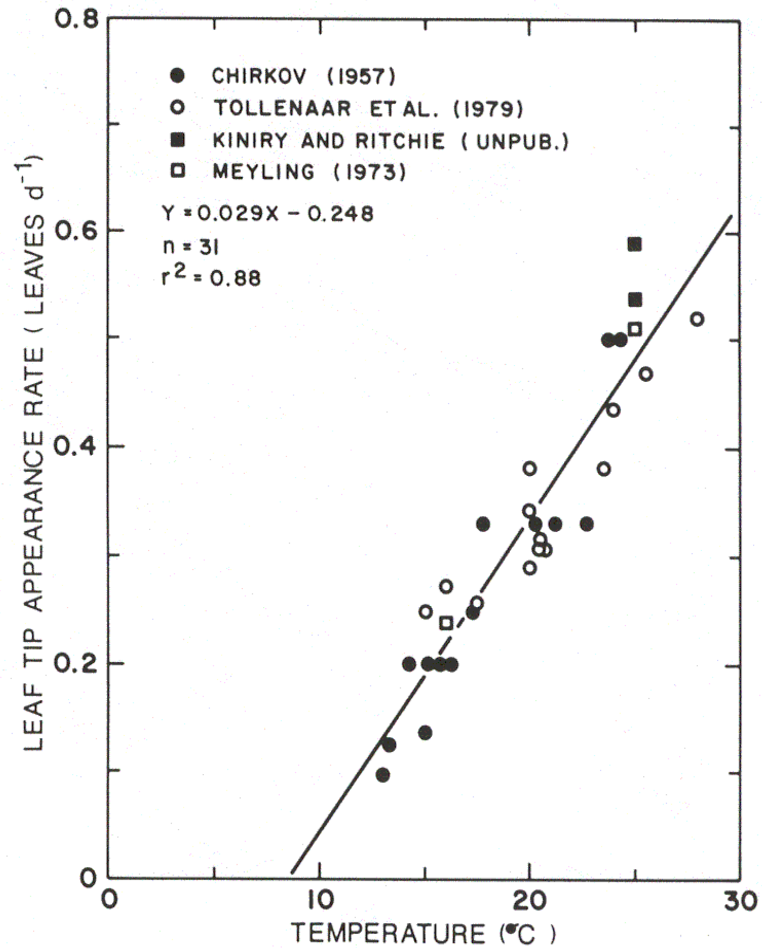


FIGURE 9. Leaf tip appearance rate of maize as a function of temperature with data from four sources.

Phenology – Species Variability

Phenology and Silking to Maturity: Maize or Corn

- Notice the base temperature which is much different than that of cotton, but similar to maize leaf appearance rates.
- The rate of development is also linear across a wide range of temperatures (10 to 30°C).

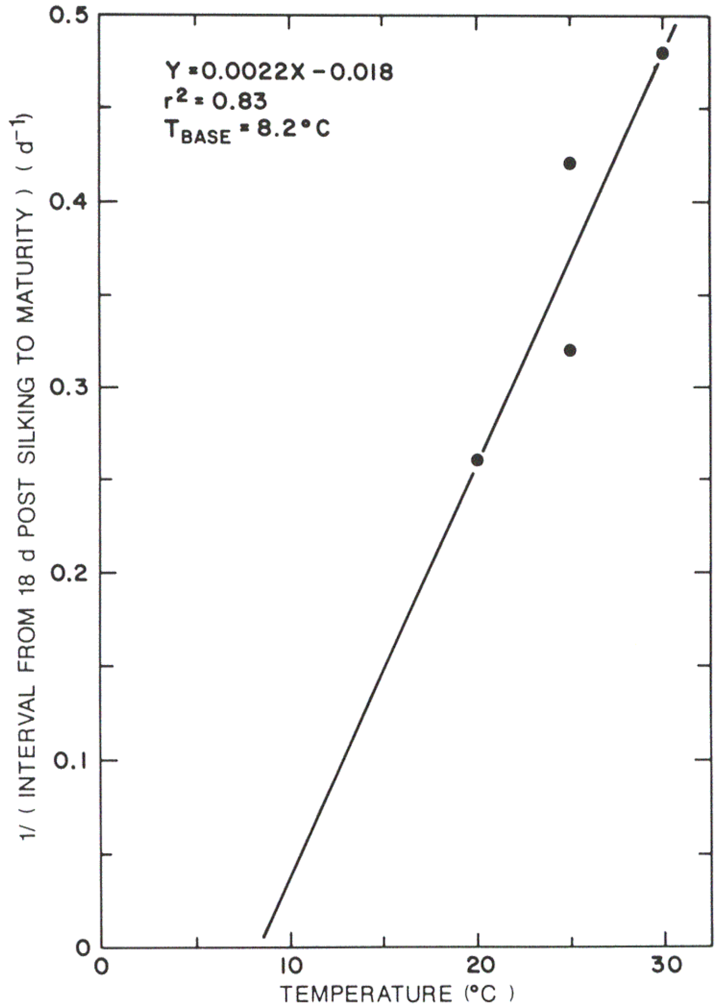
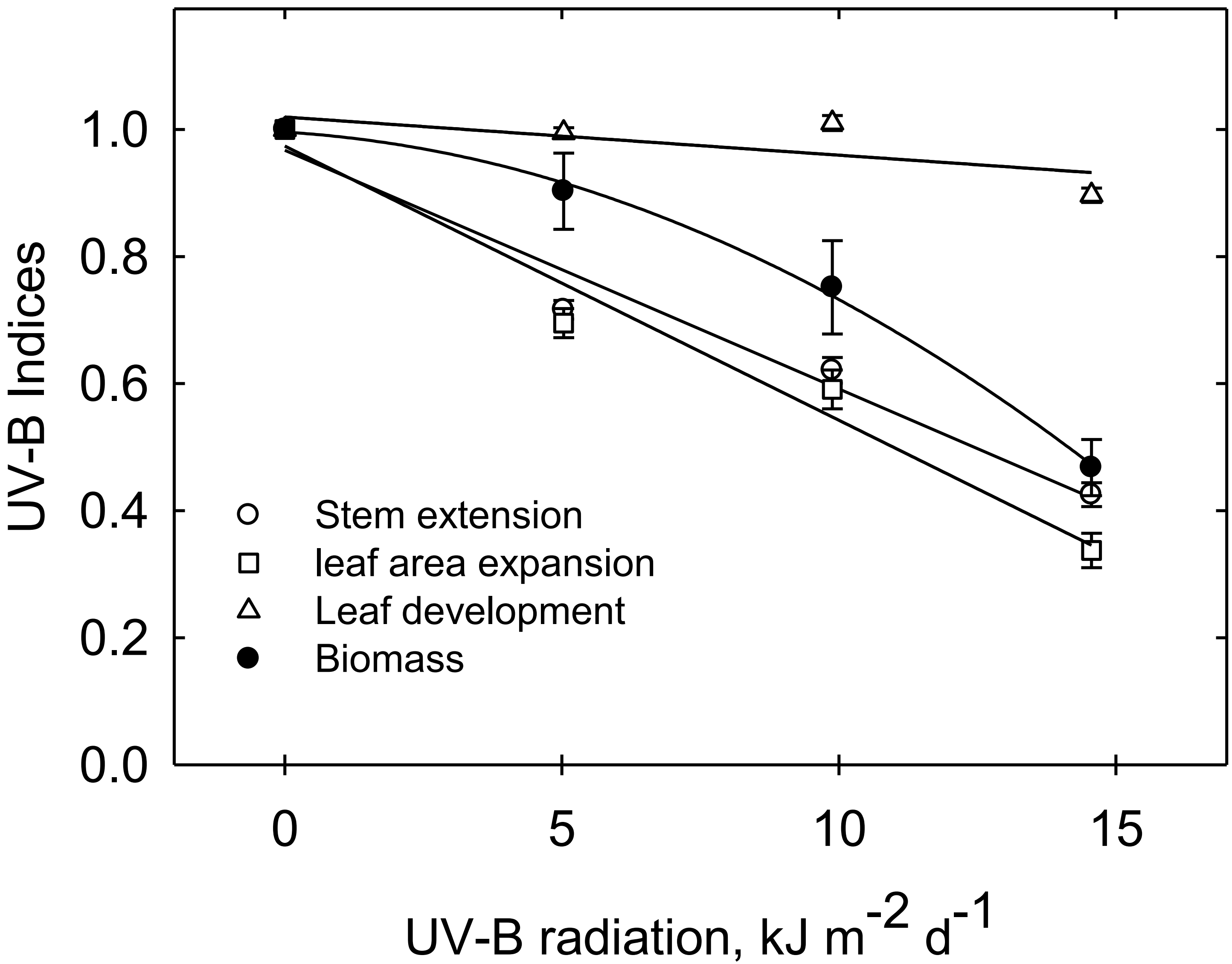


FIGURE 7. Development rate as a function of temperature during the silking to maturity interval of maize. Derived from data of Badu-Apraku et al.[19]



UV-B Indices
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
Stem extension
leaf area expansion
Leaf development
Biomass
UV-B radiation, kJ m-2 d-1

Phenology – Species Variability

Sorghum, *Sorghum bicolor* (L.) Moench

Sorghum is the 4th most important food crops globally in terms of energy and protein (FAO, 2004).

2004 stats are:

Area: 43.1 Million ha
Total production: 57.8 Million Mt
Average yield: 1.3 t ha^{-1}

United States = 2.64 Mha, 4.4 t ha^{-1}, 11 MMt
India = 9.4 Mha, 0.8 t ha^{-1}, 7.53 MMt
Nigeria = 7.1 Mha, 1.13 t ha^{-1}, 8.03 MMt
China = 0.57 Mha, 4.1 t ha^{-1}, 2.34 MMt
Mexico = 1.91 Mha, 3.35 t ha^{-1}, 6.4 MMt
Sudan = 6.0 Mha, 4.33 t ha^{-1}, 2.6 MMt

Sorghum – Cultivar Differences

Phenology – Panicle Initiation.

- Notice the base temperature which is almost similar to corn.
- The rate of development can be described by a bilinear model.

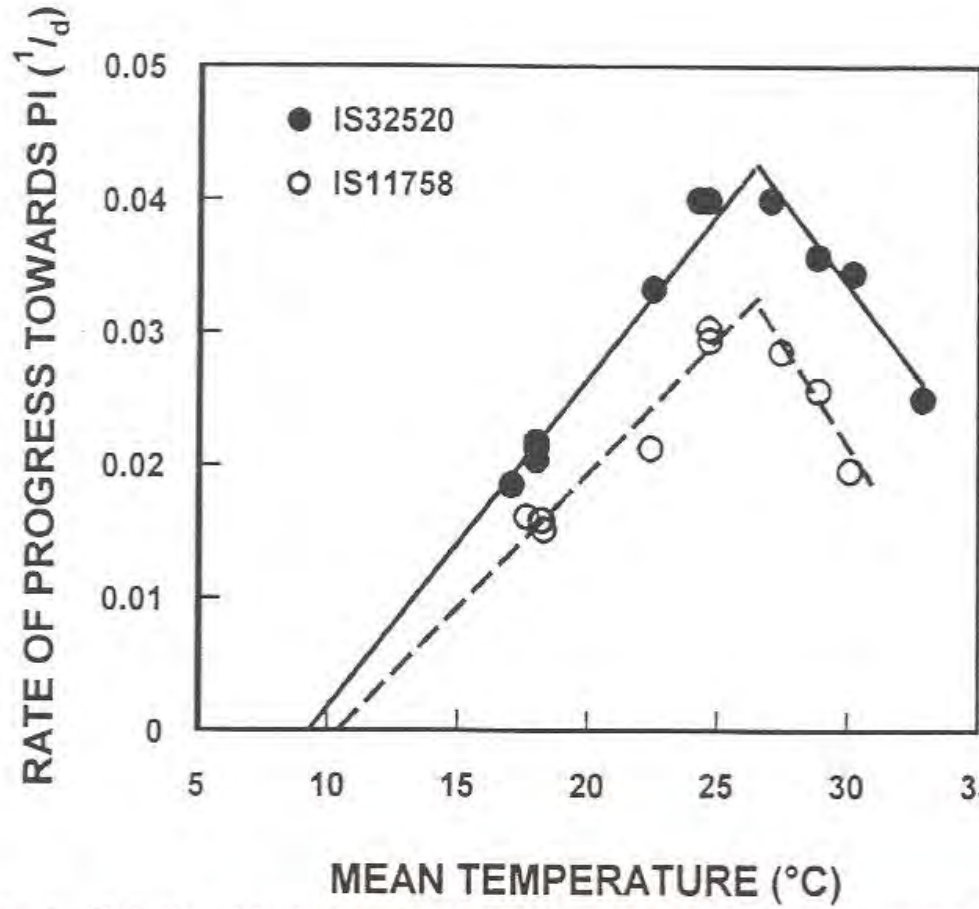


Fig. 1. Relationship between the rate of progress from planting towards PI and mean temperature in sorghum genotypes IS32520 and IS11758 grown in controlled temperature glasshouses under short-days. Fitted lines where $T_b < T \leq T_o$: ○, $y = -0.021 + 0.0020x$; ●, $y = -0.023 + 0.0025x$; and where $T_o < T < T_m$: ○, $y = 0.114 - 0.0031x$; ●, $y = 0.118 - 0.0026x$.

Sorghum – Phenology – Cultivar Differences

Phenology – Leaf development.

- Notice the base temperature which is almost similar to corn.
- The rate of development can be described by a bilinear models. Also, notice the genotypic variability.

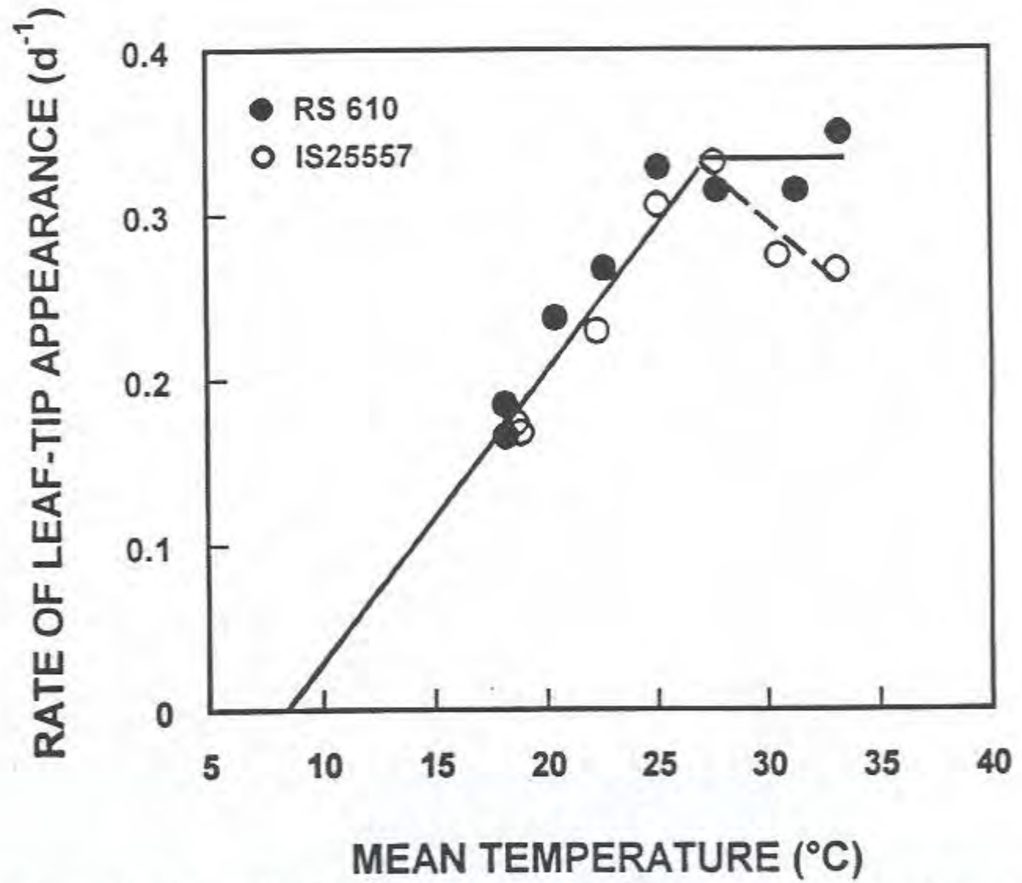
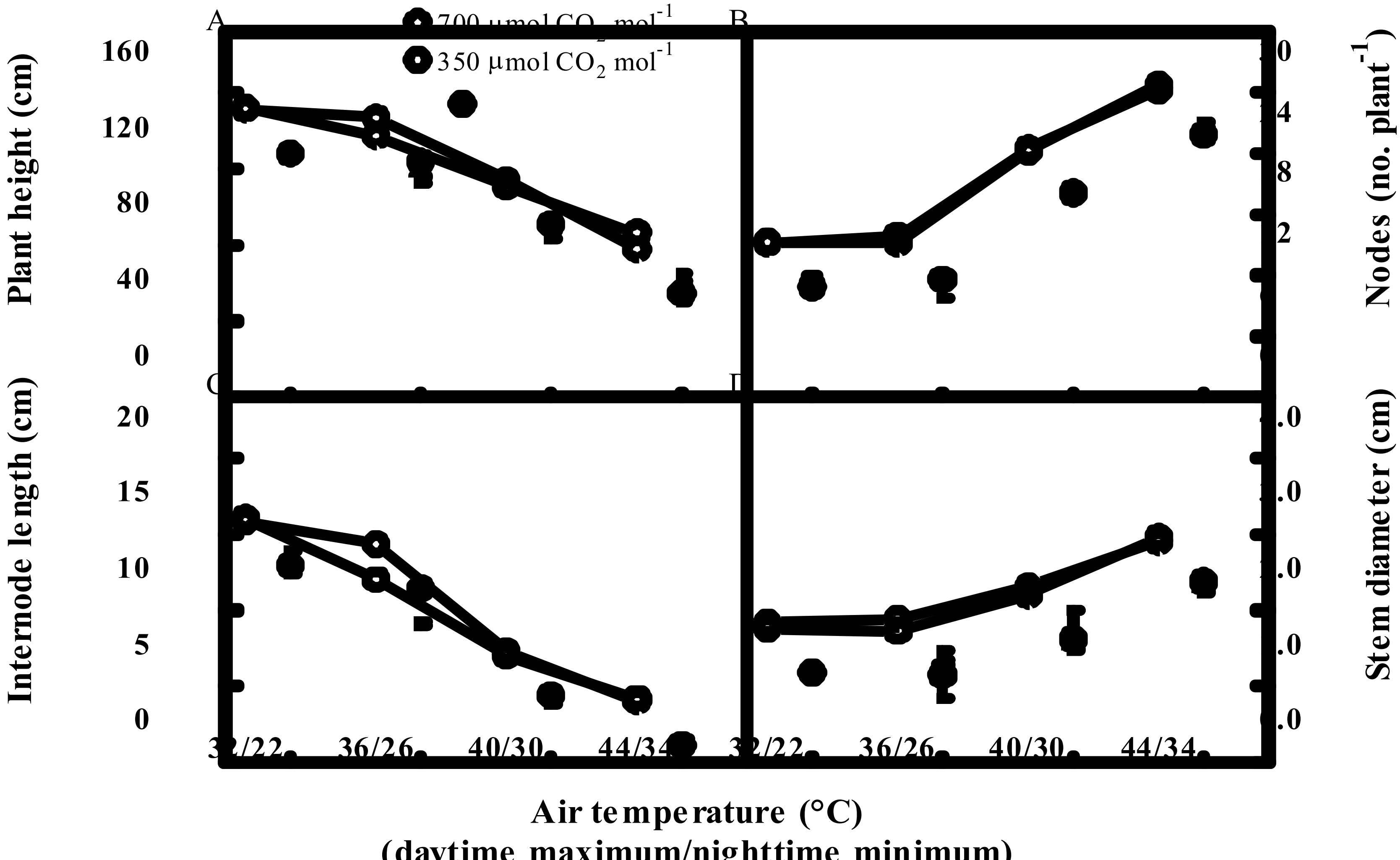
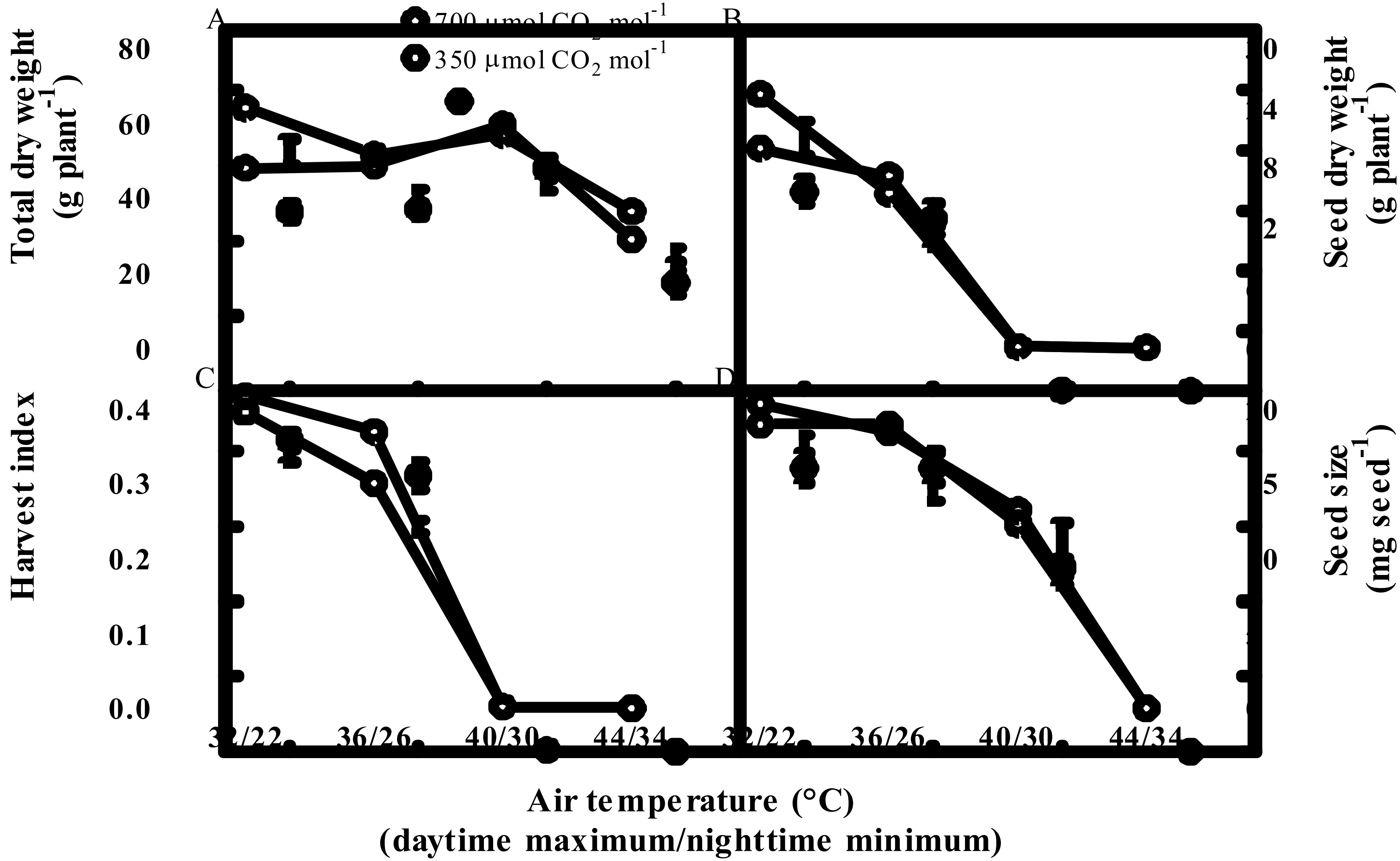


Fig. 4. **Relationship between rate of leaf-tip appearance and mean temperature in sorghum genotypes RS610 and IS25557 grown in controlled temperature glasshouses under short-days. Fitted lines where $T_b < T \le T_o$: ○●, $y = -0.148 + 0.018x$; and where $T_o < T < T_m$: ○, $y = 0.660 - 0.01215x$; ●, $y = 0.335$.**

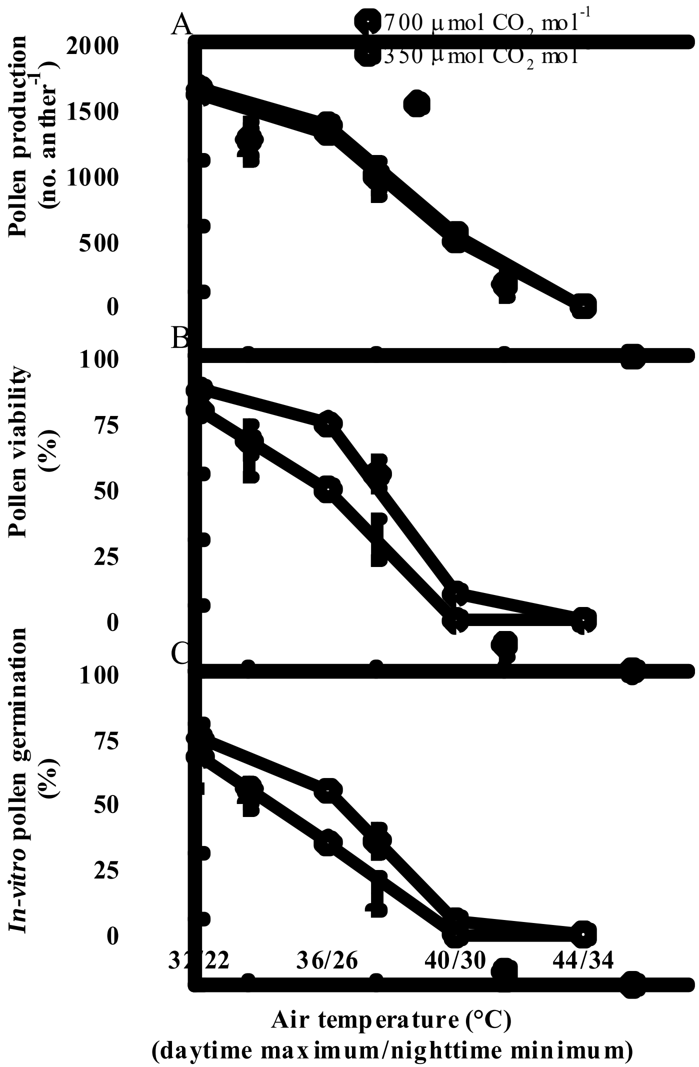
Sorghum – Vegetative Growth and Development

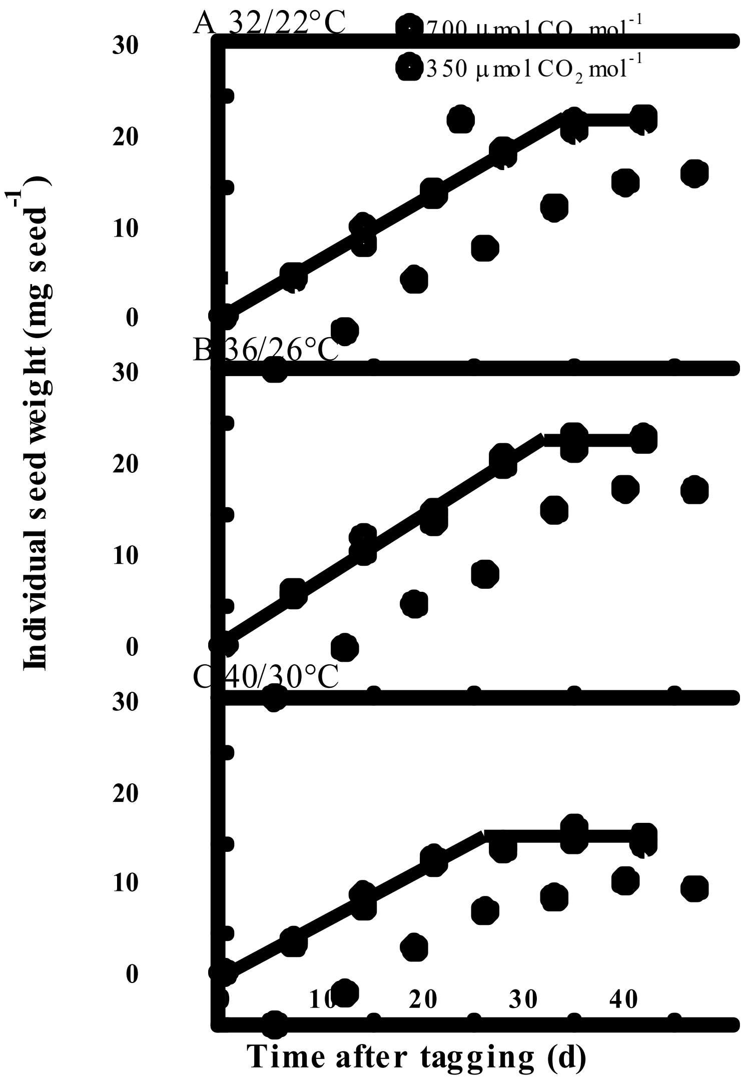


Sorghum – Vegetative and Reproductive Growth and Development



Sorghum – Reproductive Growth and Development





Wheat – Some Crop Statistics

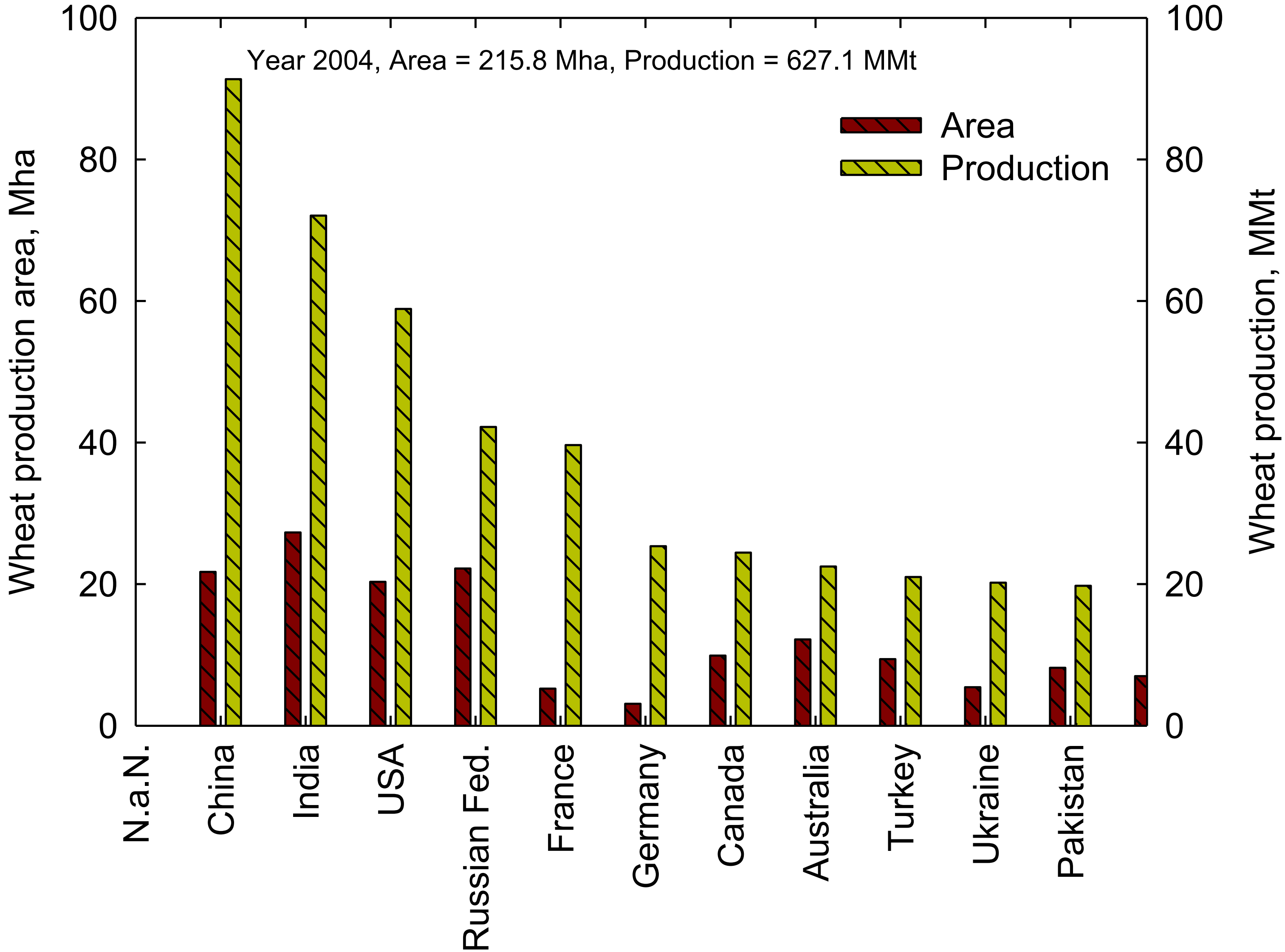
- Provides 20% of the energy and 25% of the protein requirements of over 6 billion population.
- **2004 stats are:**

  Area = 217 Million ha

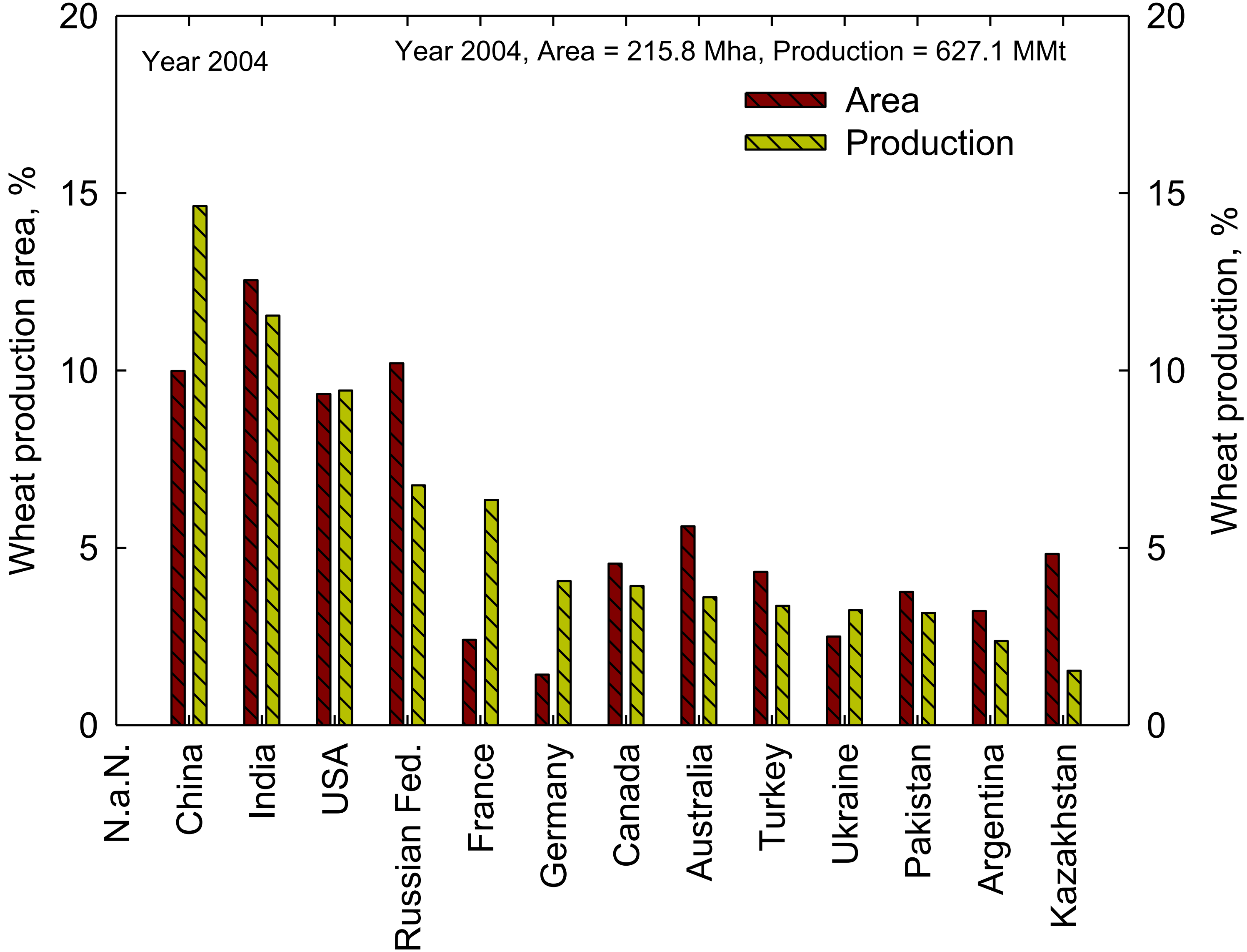
  Production = 633 Million Mt

  Average yield = 2.84 t ha^{-1}.

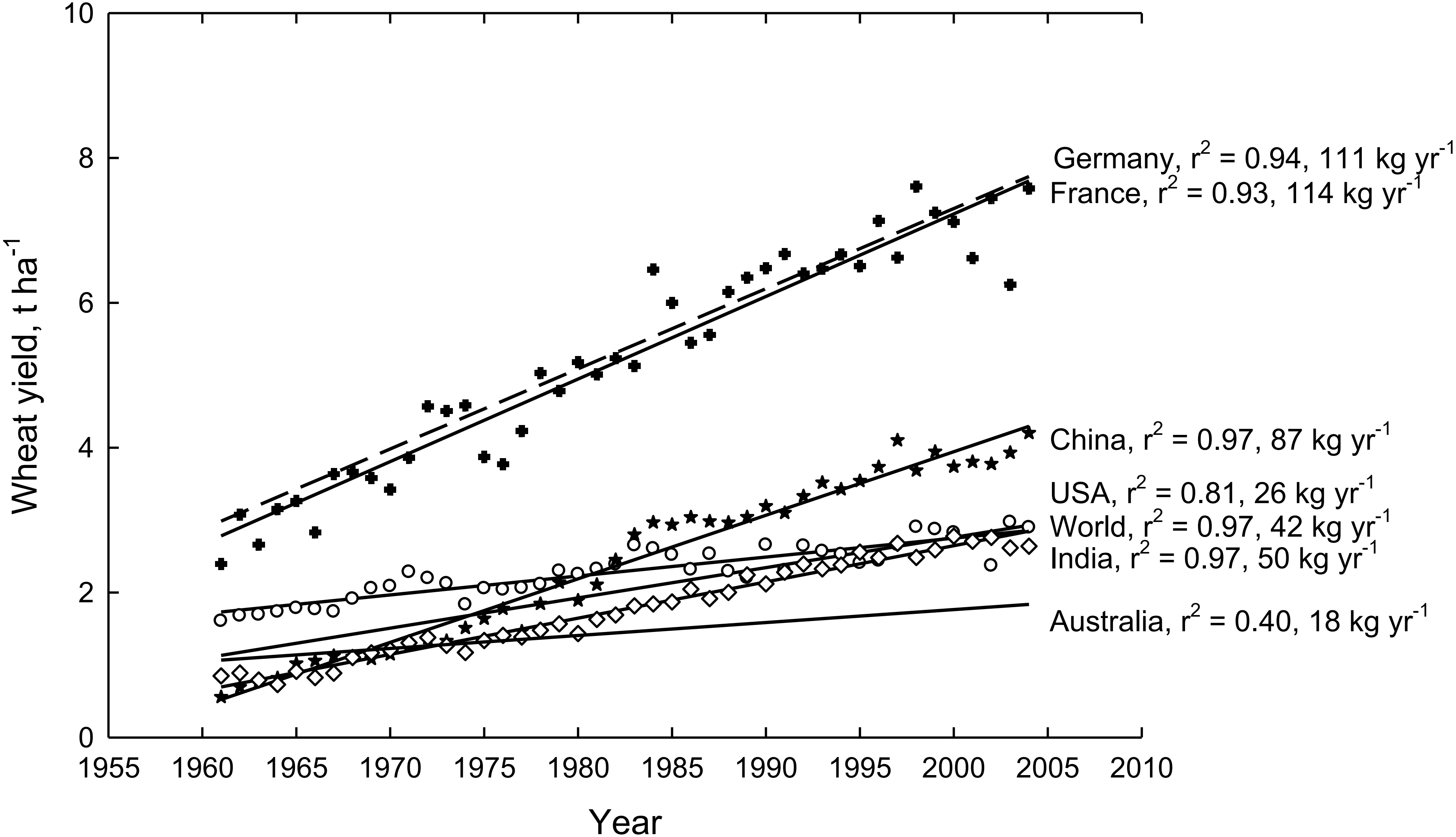
Wheat – Production Trends



Wheat – Production Trends



Wheat – Production Trends



Wheat and Phenology

Temperature Effects on Flowering to maturity

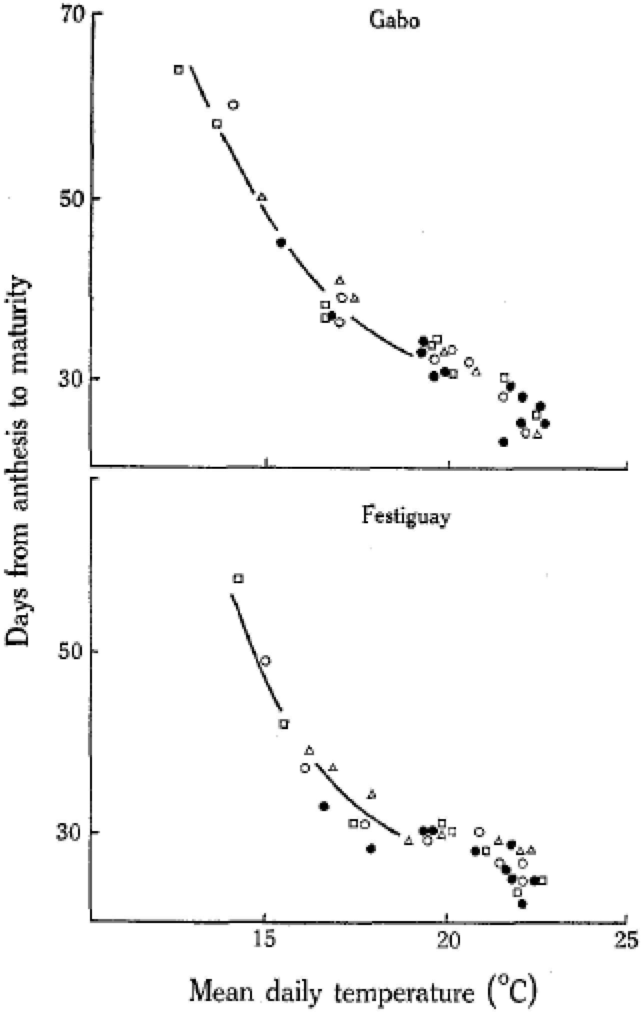


Fig. 3.—Relationship between the duration of the post-flowering phase and temperature for the cultivars Gabo and Festiguay under a range of photoperiods.

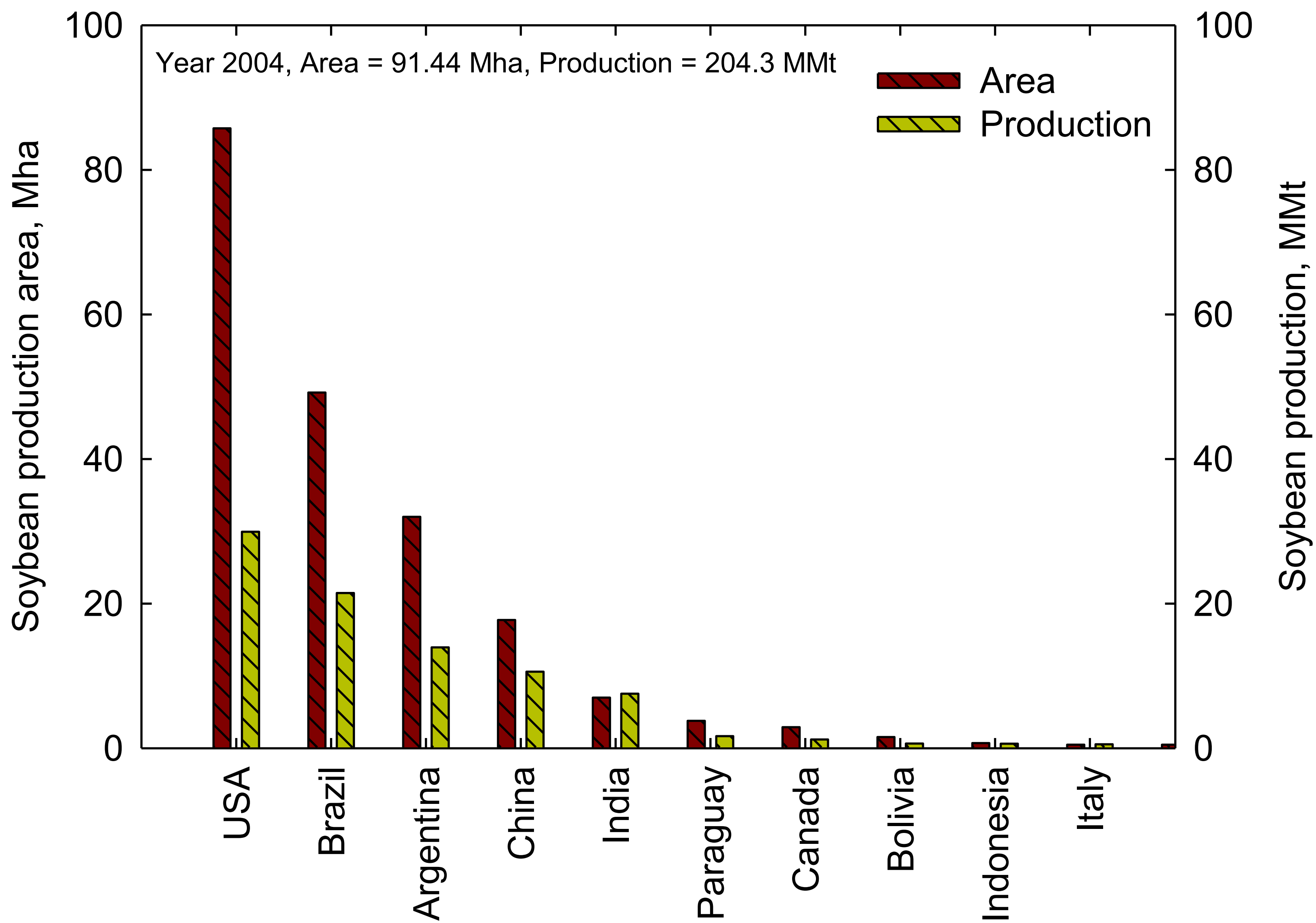
- ● Natural day length.
- □ 15-hr long day.
- △ Natural day length + 1 hr supplemental illumination.
- ○ Natural day length + 2 hr supplemental illumination.

Soybean Production Statistics

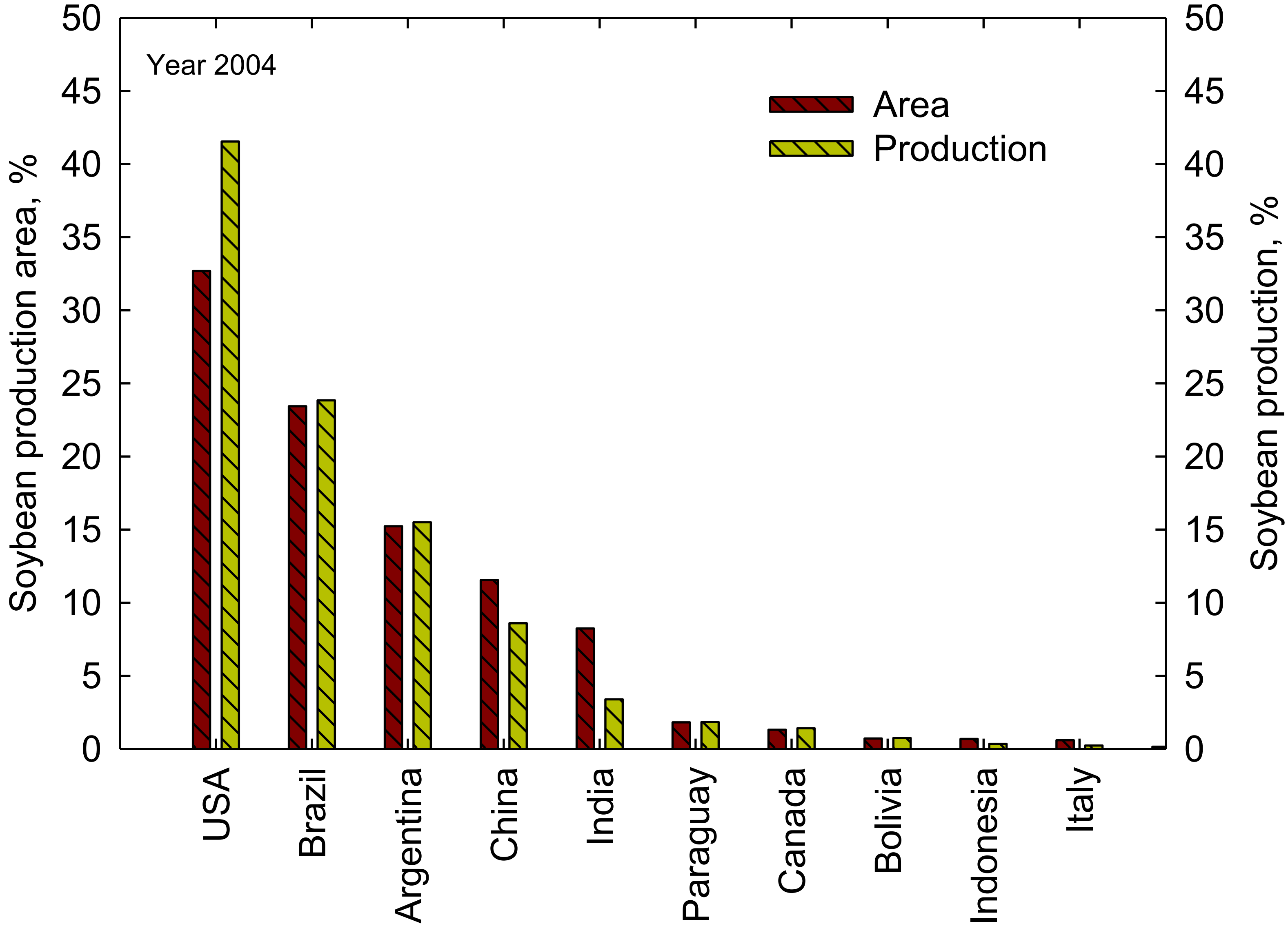
Soybean the most important protein and oilseed crop globally (FAO, 2004).

Area:	91.4 Million ha
Total production:	204.4 Million Mt
Average yield:	2.23 t ha^{-1}

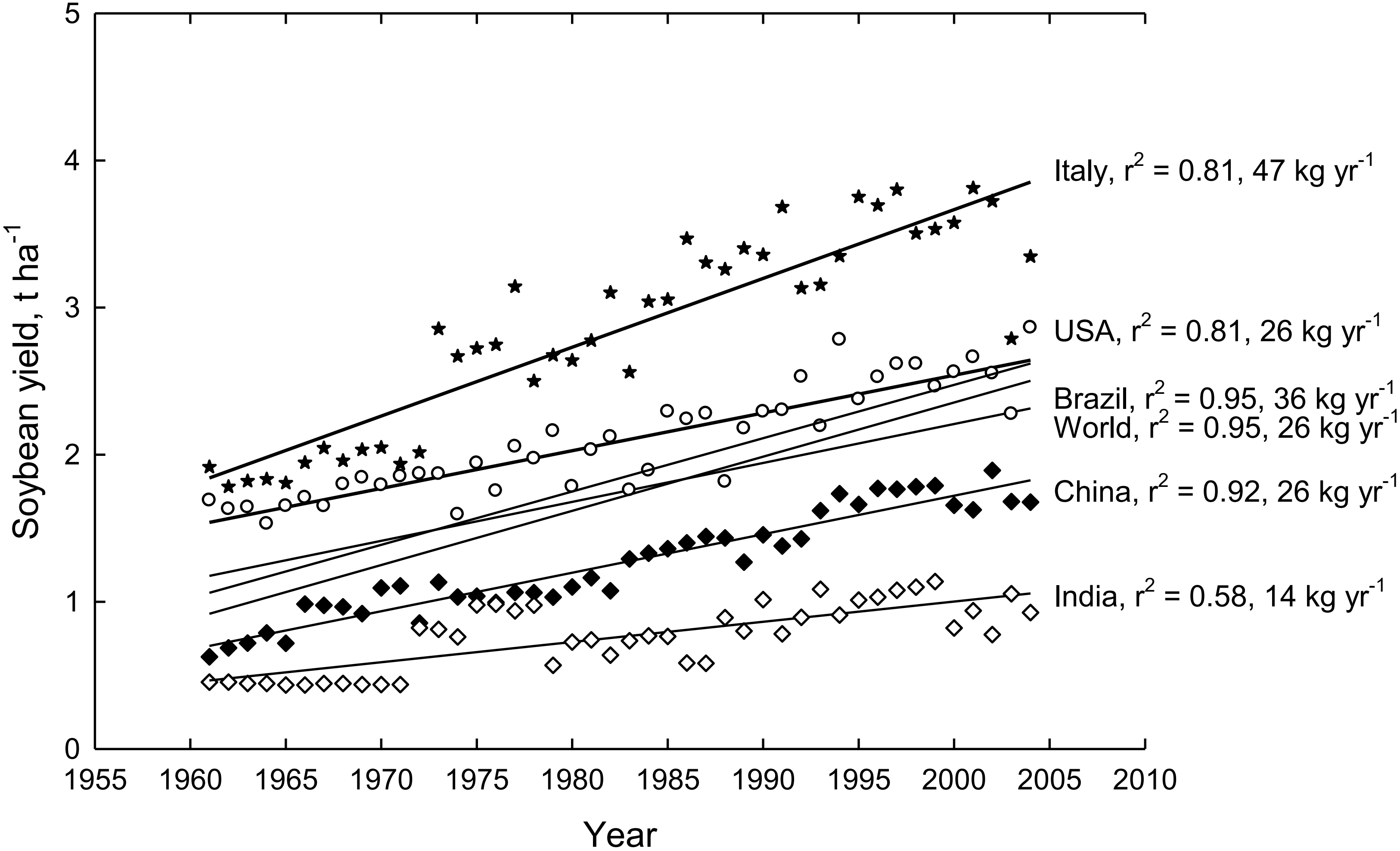
Soybean Production Statistics



Soybean Production Statistics



Soybean Production Statistics

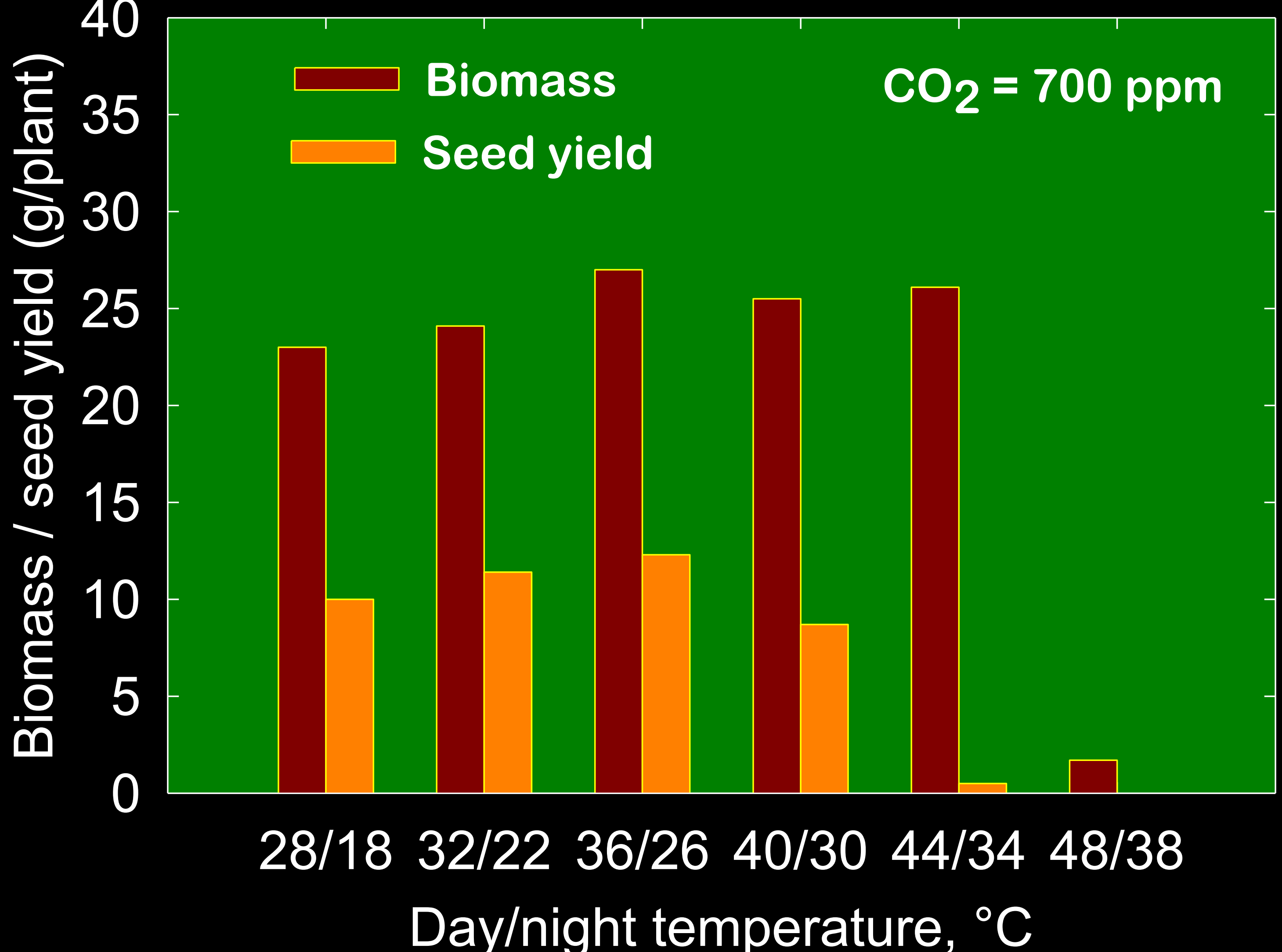


Temperature and CO_2 Effects on Soybean Developmental Rates

CO_2, ppm	Temp. °C	Plastochron interval, d $leaf^{-1}$	Final node number, no. $plant^{-1}$
300	26/19	4.2	10.3
	31/24	3.3	11.5
	36/29	3.2	12.0
600	26/19	3.9	11.2
	31/24	2.7	11.4
	36/29	2.6	12.1

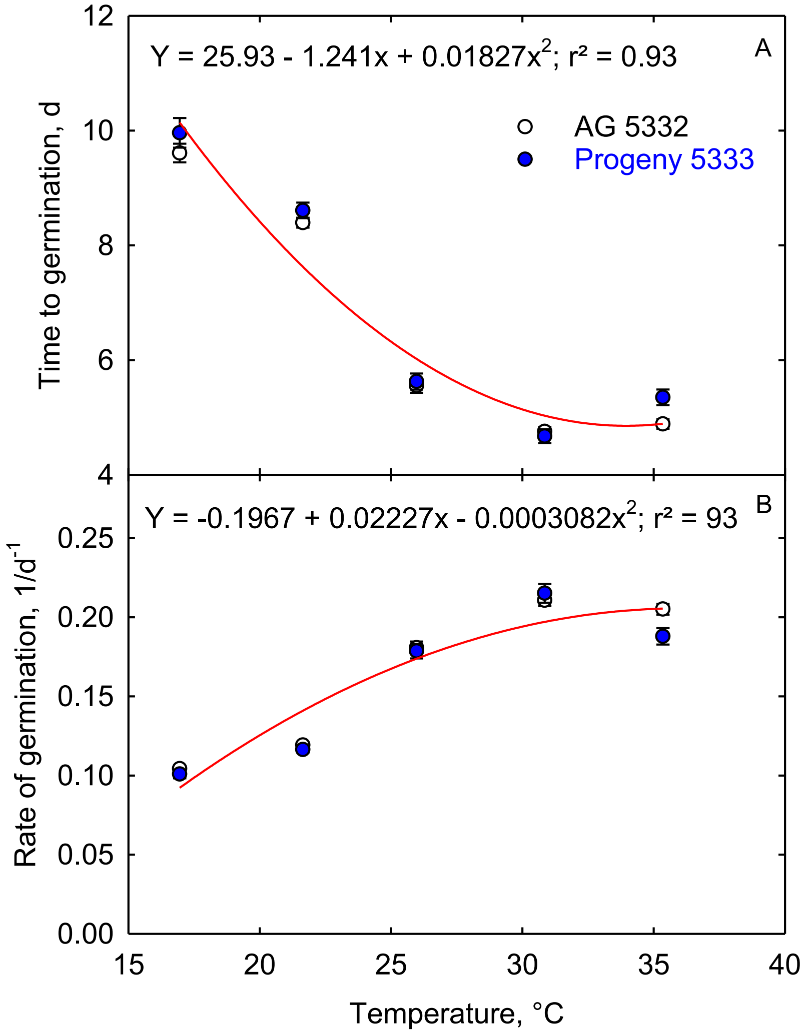
Crop Growth and Development - Environment

Response to temperature - Soybean biomass and seed yield

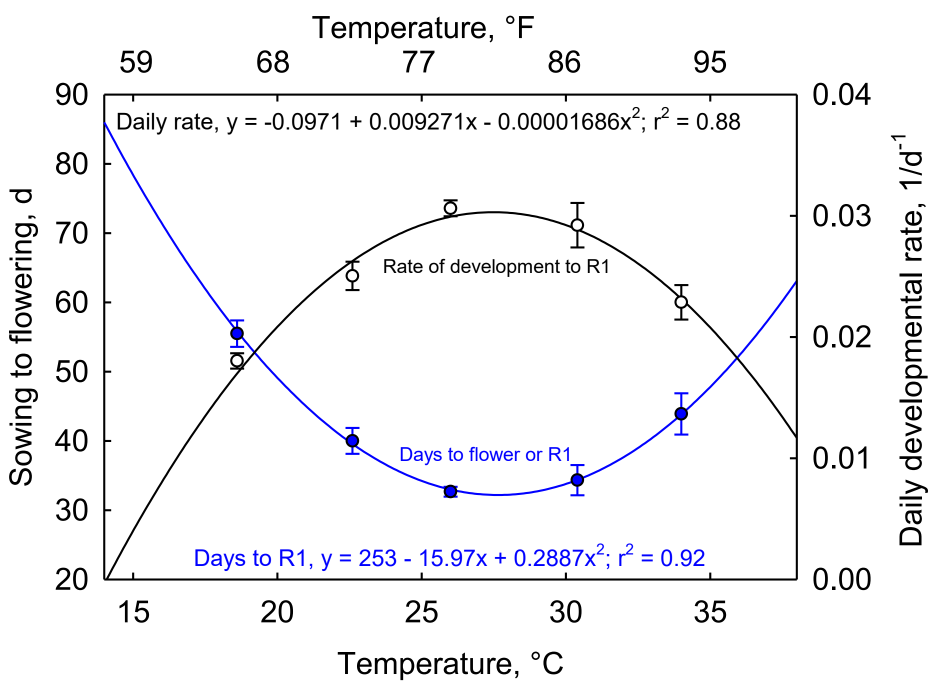


Temperature and Soybean Developmental Rates

Seed Germination

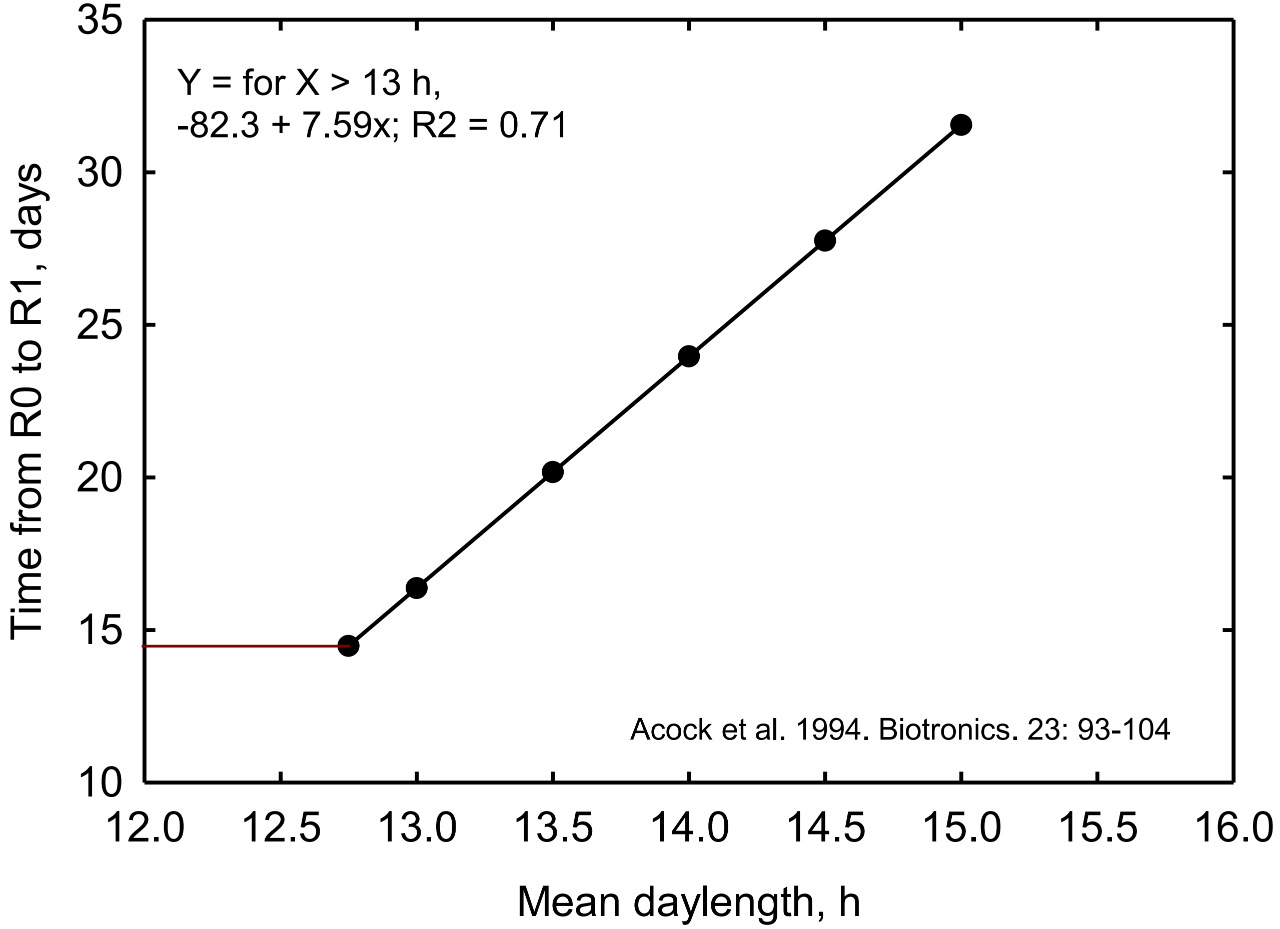


Sowing to Flowering



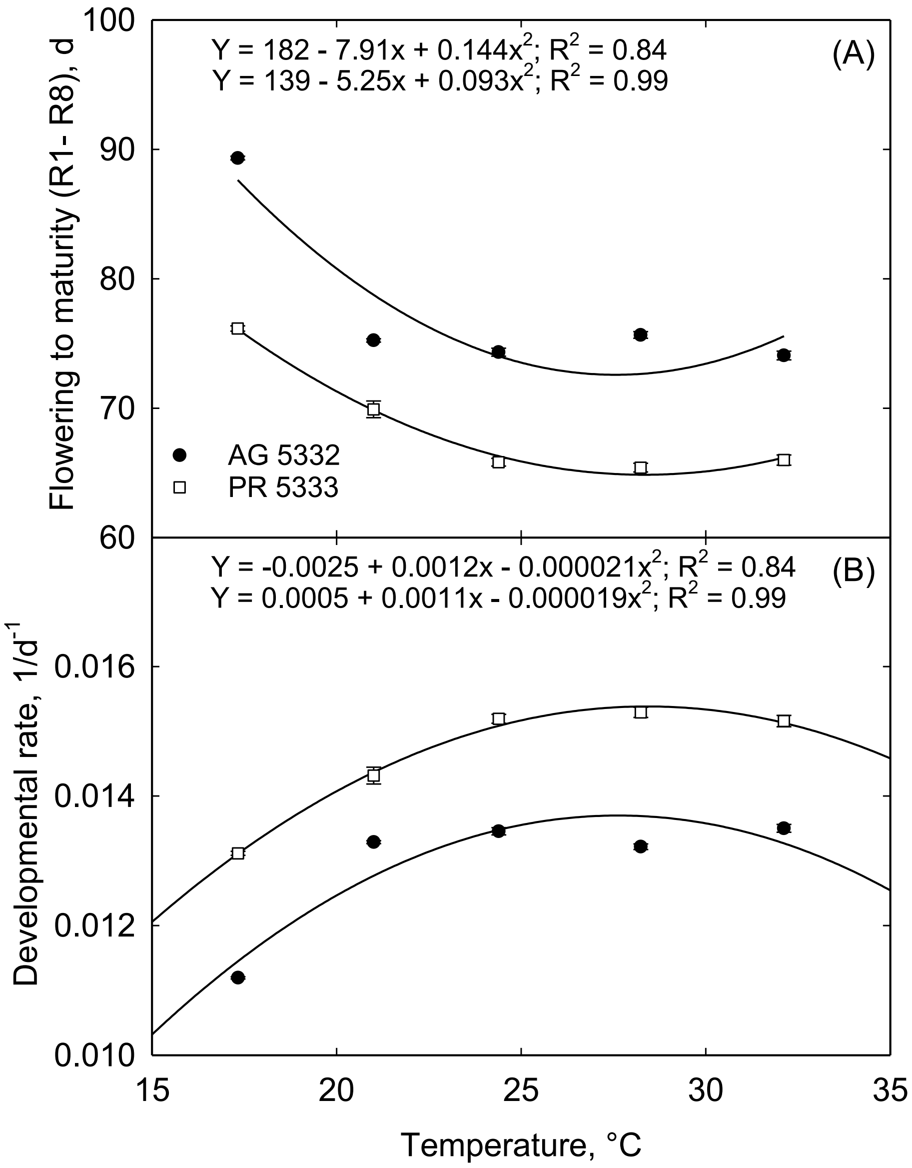
Temperature and Soybean Developmental Rates

Sowing to Flowering

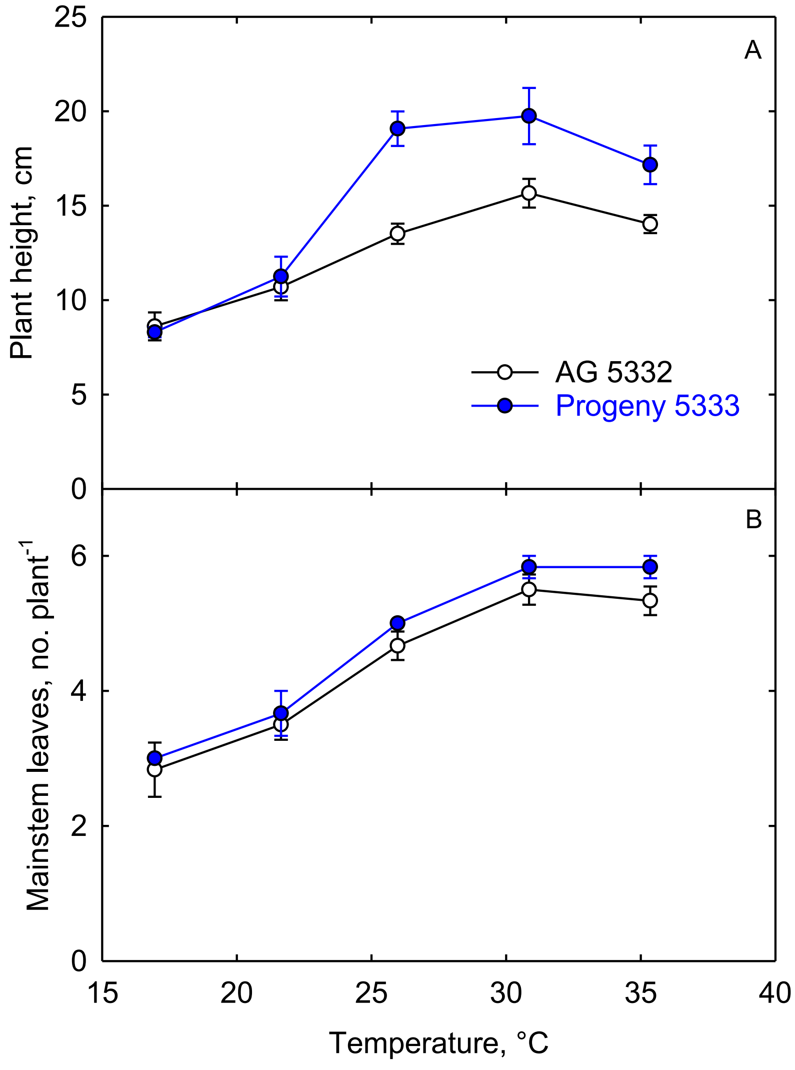


Temperature and Soybean Developmental Rates

Flowering to seed maturity (R1 to R8)



Temperature and Soybean Growth Rates

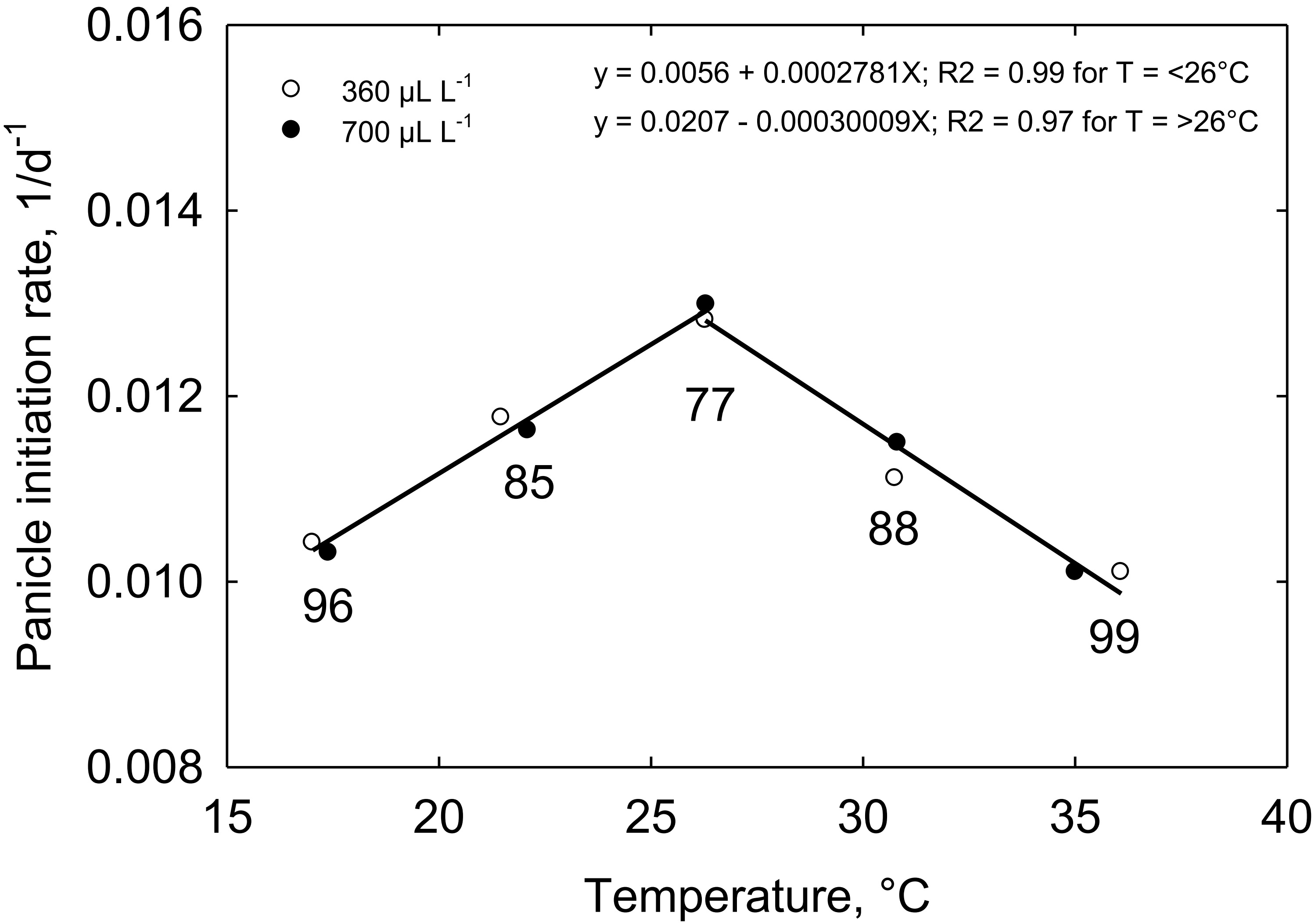


Rangeland grass – Big bluestem (*Andropogon gerardii*)

- C4 photosynthetic pathway
- Clump forming perennial grass
- Grows 3 to 6 feet tall but occasionally up to 9 feet.
- Lower stems are a purplish or bluish color
- Leaves are 1/2 inch wide and up to 20 inches long.
- Arrangement of the flowers in three dense elongate clusters is the reason for the common name of turkey-foot grass.
- Grows best in moist well drained soil in full sun and is a major component of the tallgrass prairie.

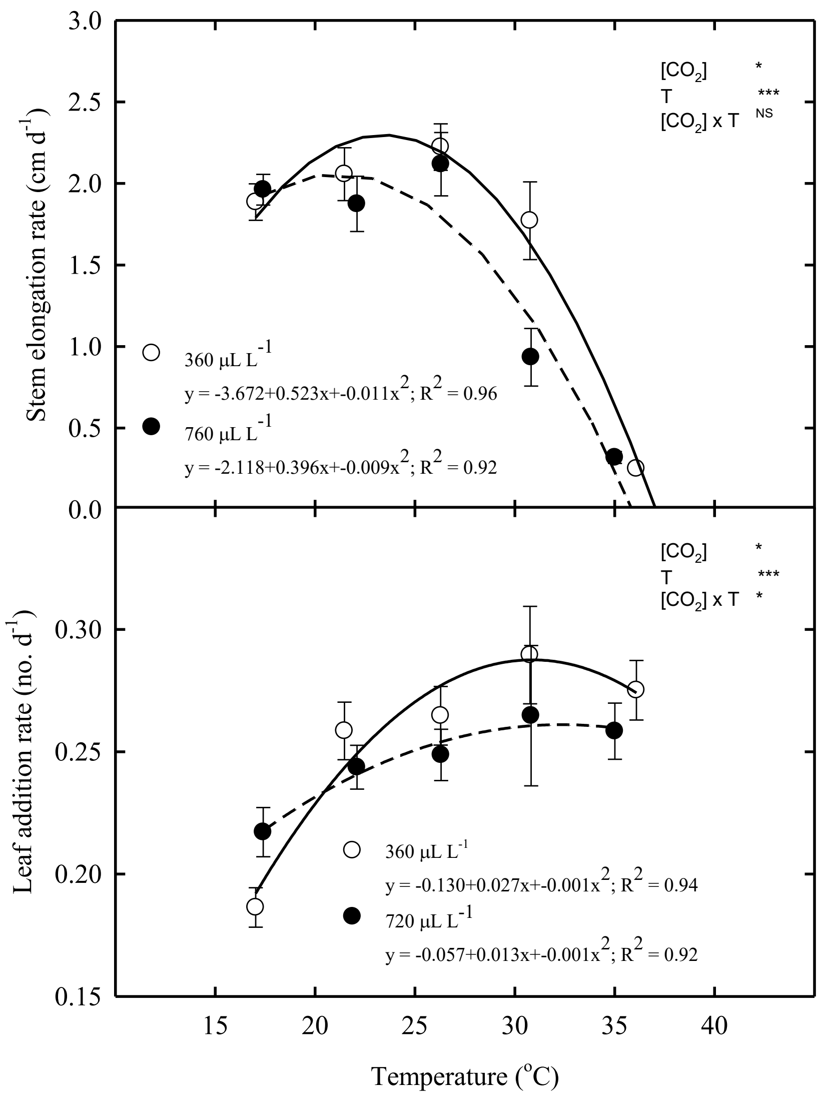
Rangeland grass – Big Bluestem, *A. girardii*

Reproductive Response – Panicle initiation



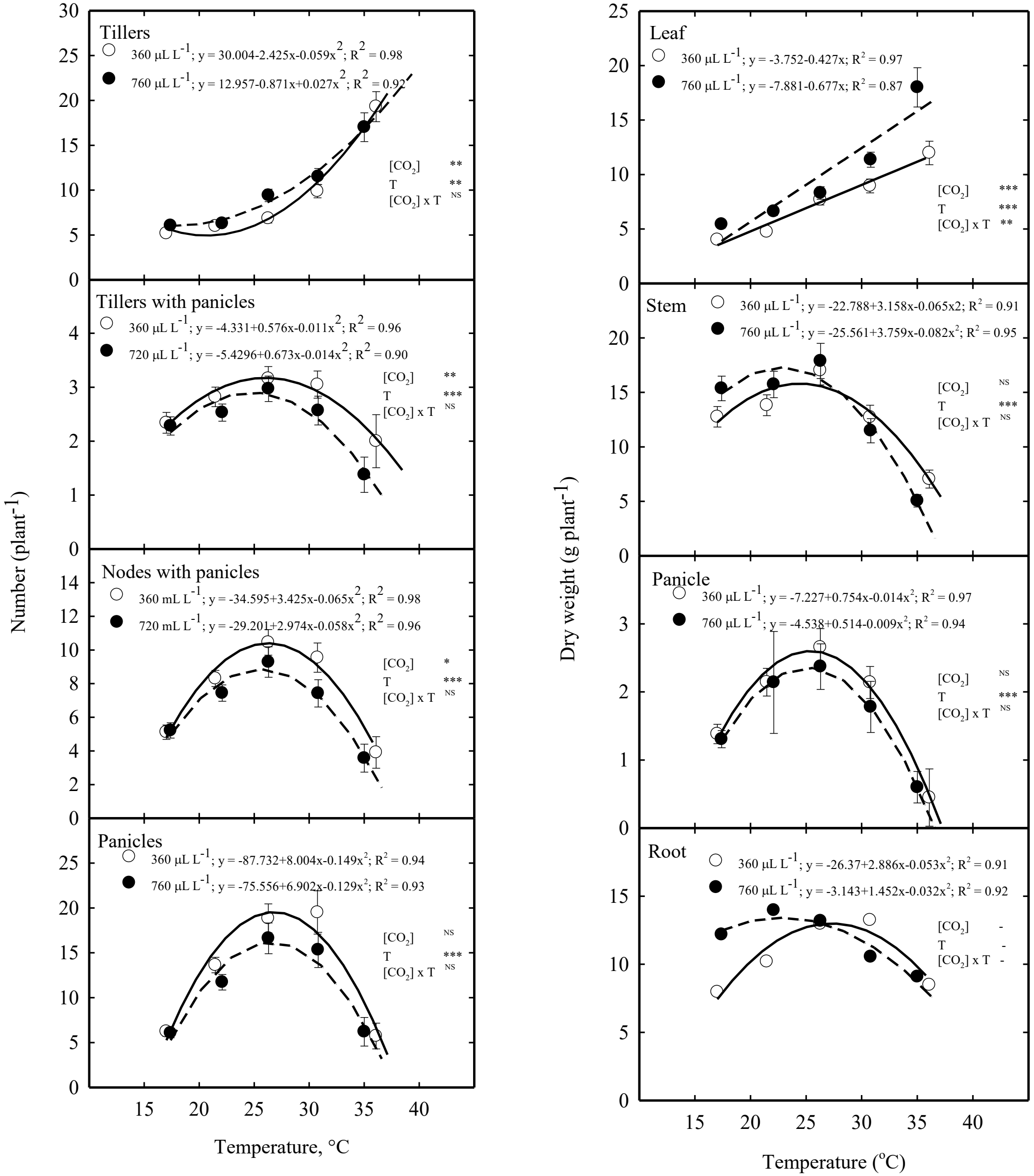
Rangeland grass – Big Bluestem, *A. girardii*

Growth and Developmental Responses



Rangeland grass – Big Bluestem, *A. girardii*

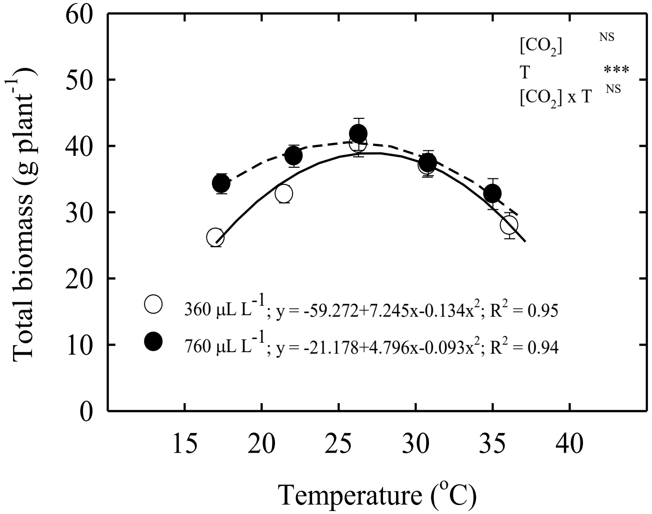
Growth and Developmental Responses

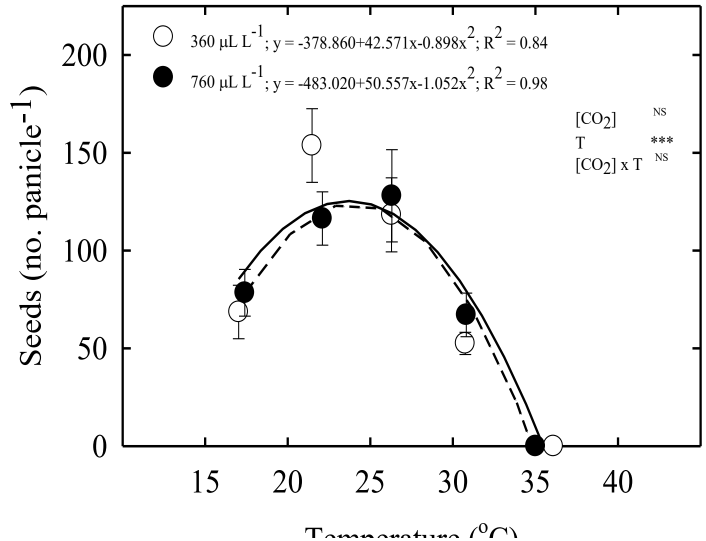


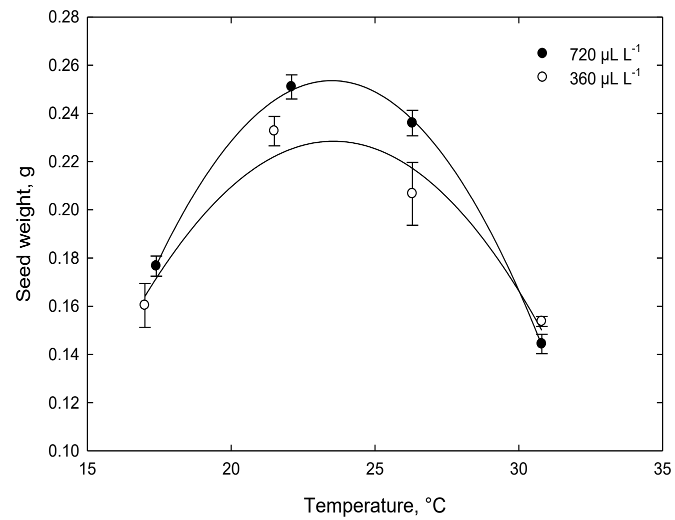
Rangeland grass – Big Bluestem, *A. girardii*

Seed number and weight response

Total weight response







Chickpea is a cool-season crop grown substantially in South and West Asia, the Mediterranean region, and South and Central America.

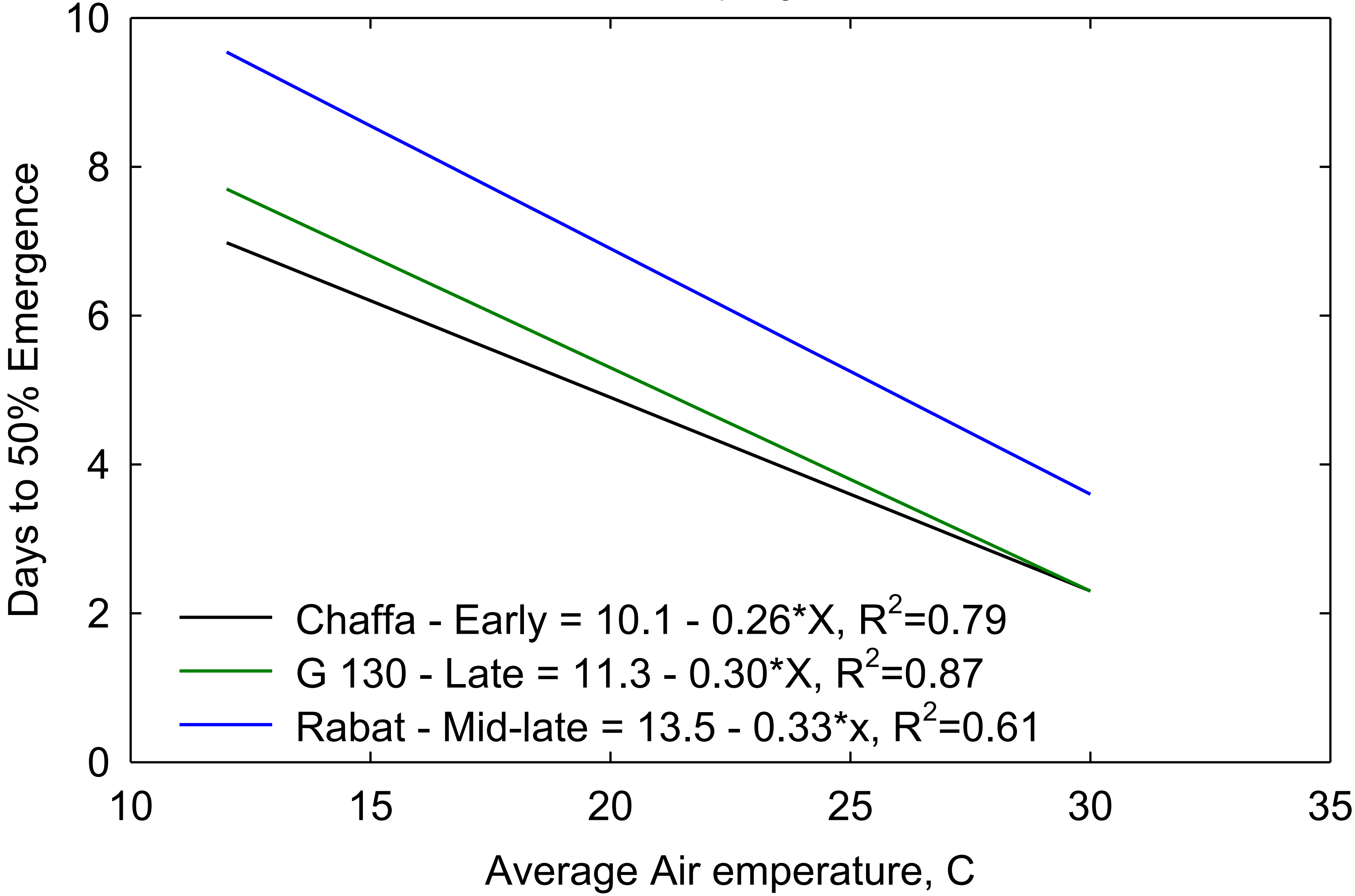
Chickpea - C*icer arietinum* L.

Production and distribution

- Chickpea is a cool season food legume crop grown on >10 million ha in 45 countries of the world.
- Chickpea is either the first or the second most important, rainfed, cool season food legume, grown mainly by small farmers in the semi-arid tropics (SAT) and West Asia and North Africa (WANA) regions.
- The crop is also grown in southern and eastern Africa (particularly important in Ethiopia), Europe, the Americas and, more recently, Australia.
- World production is 7 million tones.
- International trade in chickpeas has increased over the years.

Phenology - Species Variability
Temperature - Sowing to 50% Emergence
Chickpea Cultivars

Roberts et al., 1980. Expt. Agric.16:343-360.

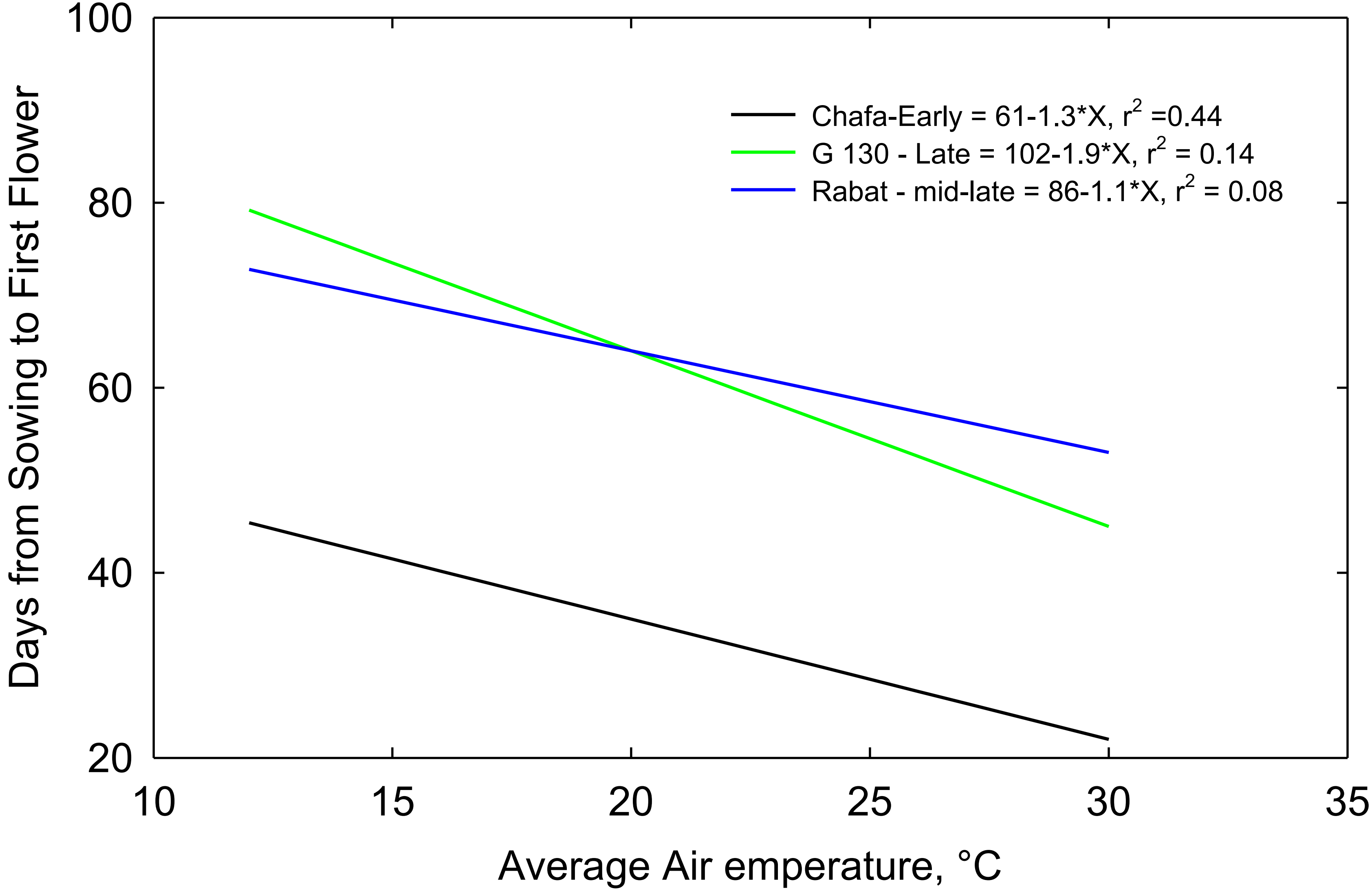


Phenology - Species Variability

Temperature - Sowing to First Flower

Chickpea Cultivars

Roberts et al., 1980. Expt. Agric.16:343-360.

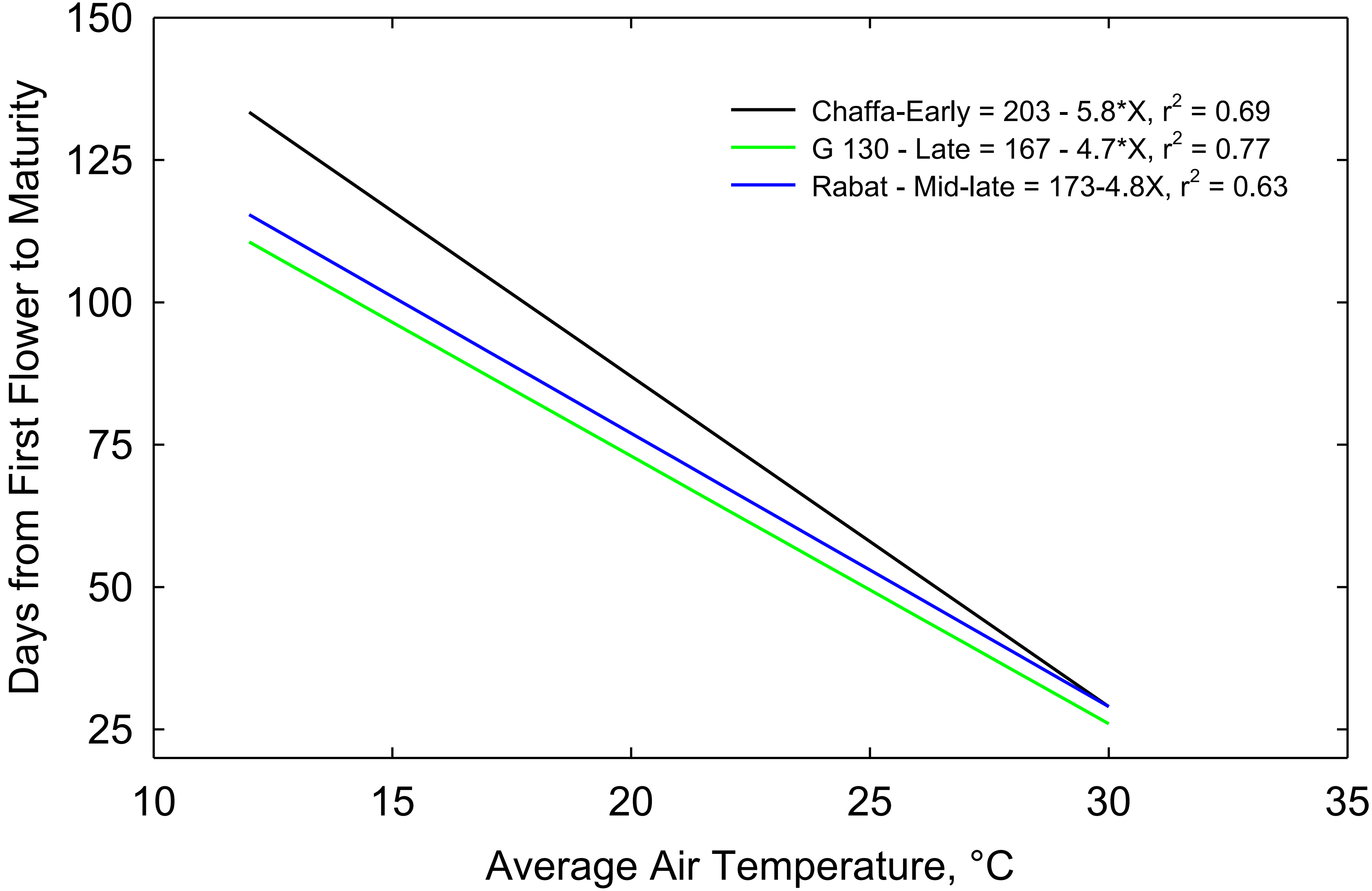


Phenology - Species Variability

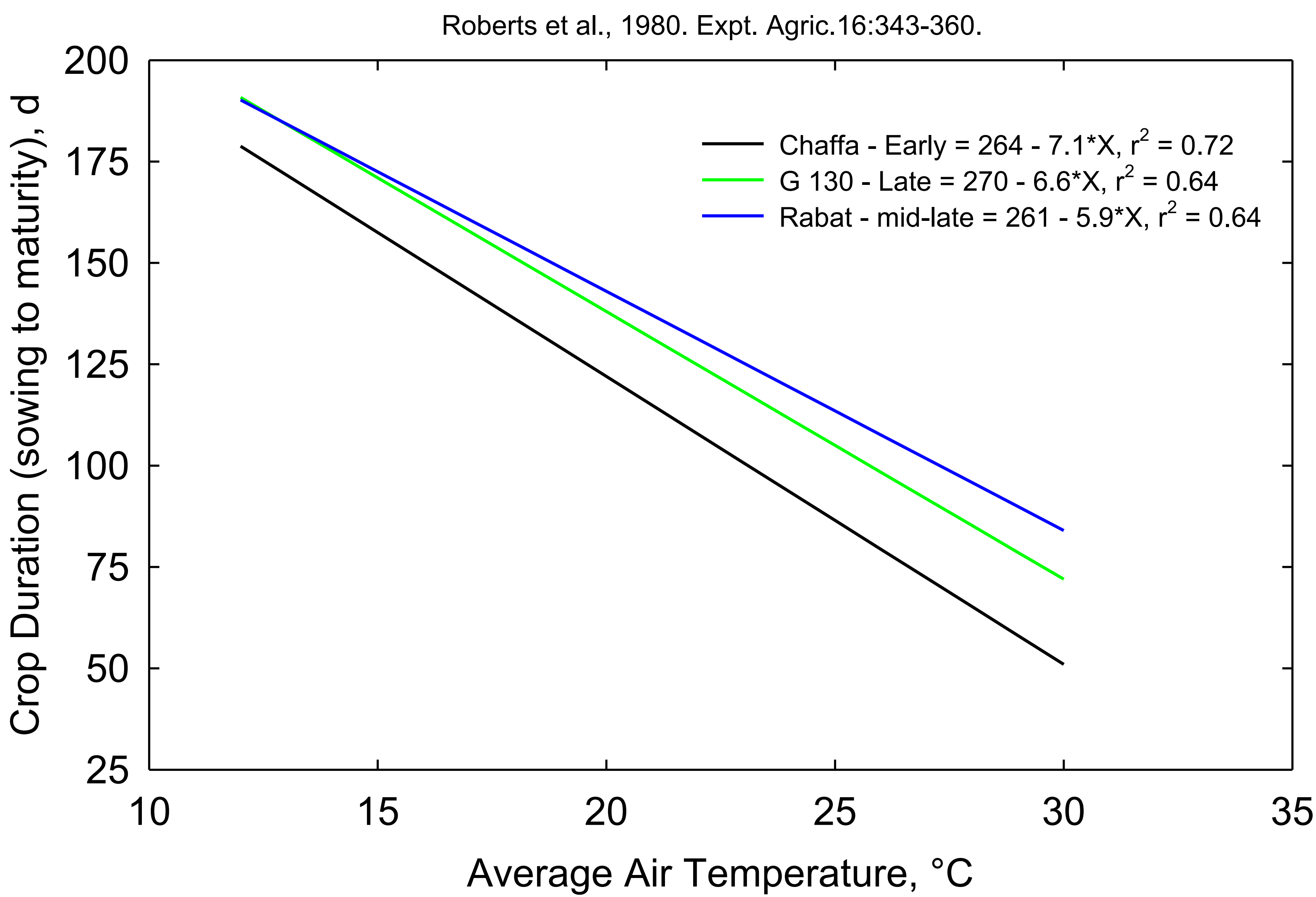
Temperature - First Flower to Maturity

Chickpea Cultivars

Roberts et al., 1980. Expt. Agric.16:343-360.



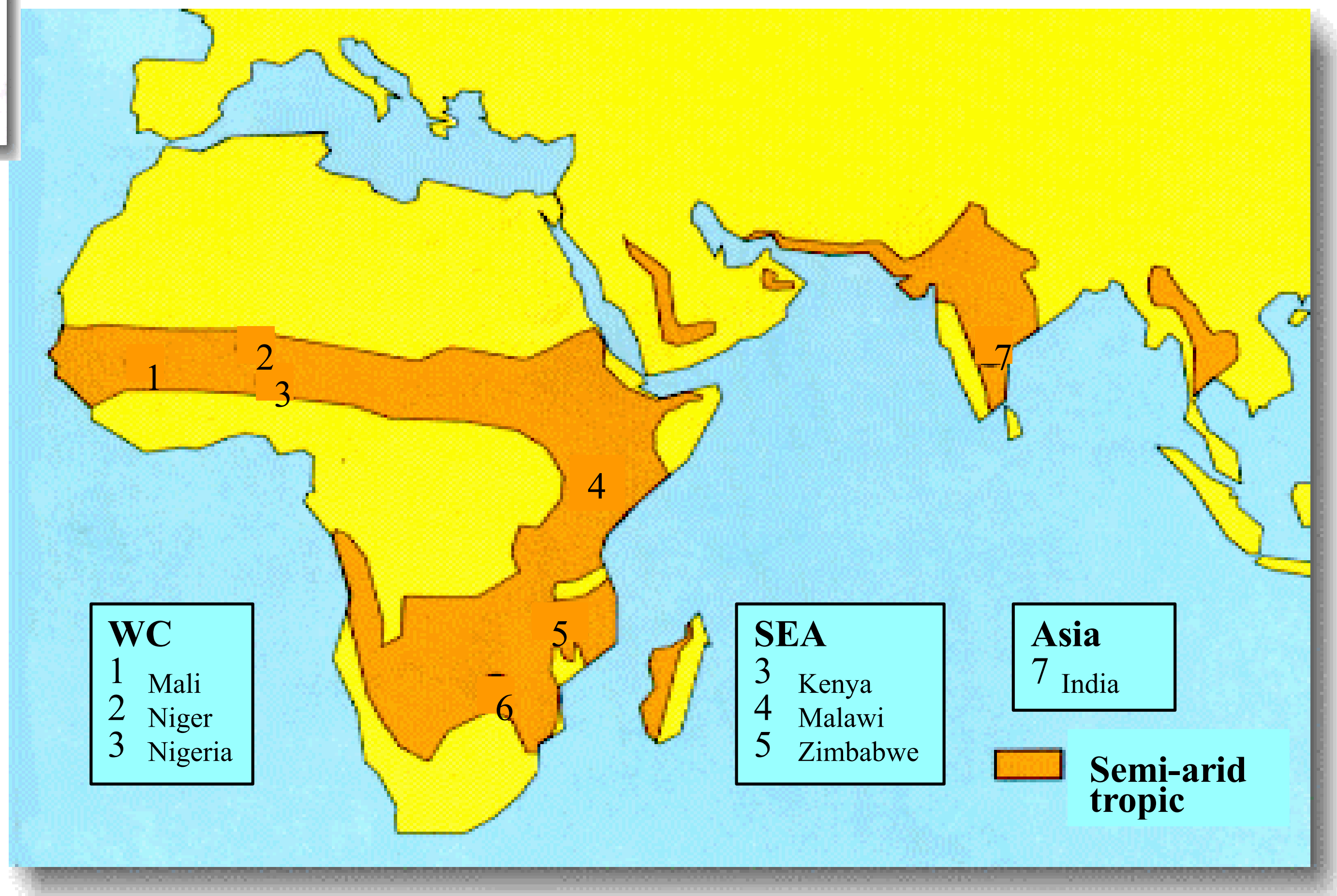
Phenology - Species Variability
Temperature - Sowing to Maturity
Chickpea Cultivars



Groundnut or Peanut (*Arachis hypogaea* L.)

Groundnut, an important cash crop, is an annual legume. Its seeds are a rich source of edible oil (43-55%) and protein (25-28%). About two thirds of world production is crushed for oil and the remaining one third is consumed as food. Its cake is used as feed or for making other food products and haulms provide quality fodder.

Groundnut or Peanut
(*Arachis hypogaea* L.)



The semi-arid tropics of Asia and Africa (WC = western and central Africa; SEA = southern and eastern Africa (Source: http://www. cgiar.org/icrisat/)

Distribution:

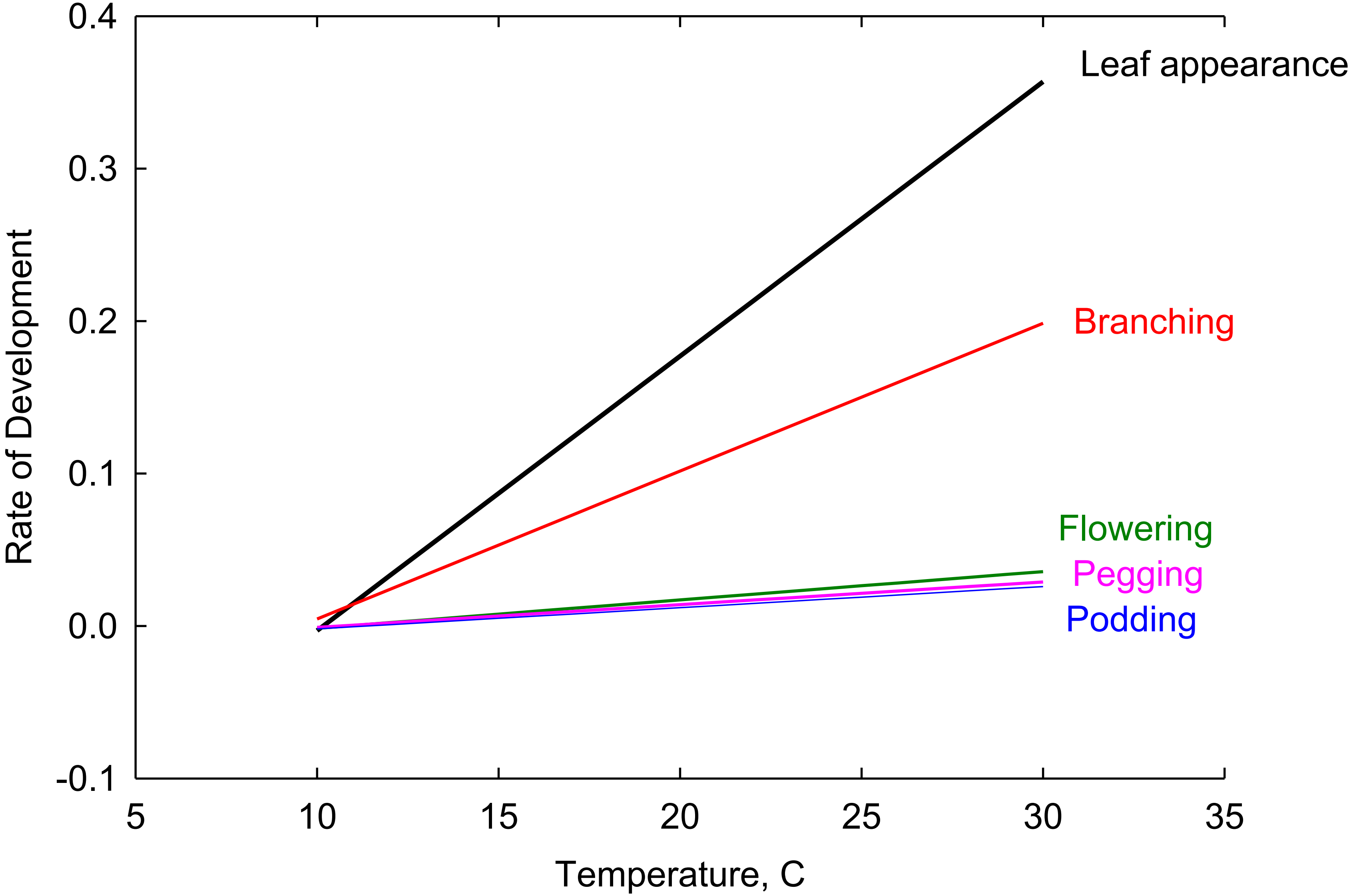
Groundnut originated in the southern Bolivia/north west Argentina region in south America and is presently cultivated in 108 countries of the world.

Asia with 63.4% area produces 71.7% of world groundnut production followed by Africa with 31.3% area and 18.6% production, and North-Central America with 3.7% area and 7.5% production.

Important groundnut producing countries are China, India, Indonesia, Myanmar, Thailand, and Vietnam in Asia; Nigeria, Senegal, Sudan, Zaire, Chad, Uganda, Cote d'Ivory, Mali, Burkina Faso, Guinea, Mozambique, and Cameroon in Africa; Argentina and Brazil in South America and USA and Mexico in North America.

Phenology - Species Variability

Temperature - Groundnut (Peanut, cv. Robut 33-1)



S.K. Leong and C.K.Ong. 1983. J. Expt. Bot. 34: 1551-1561.

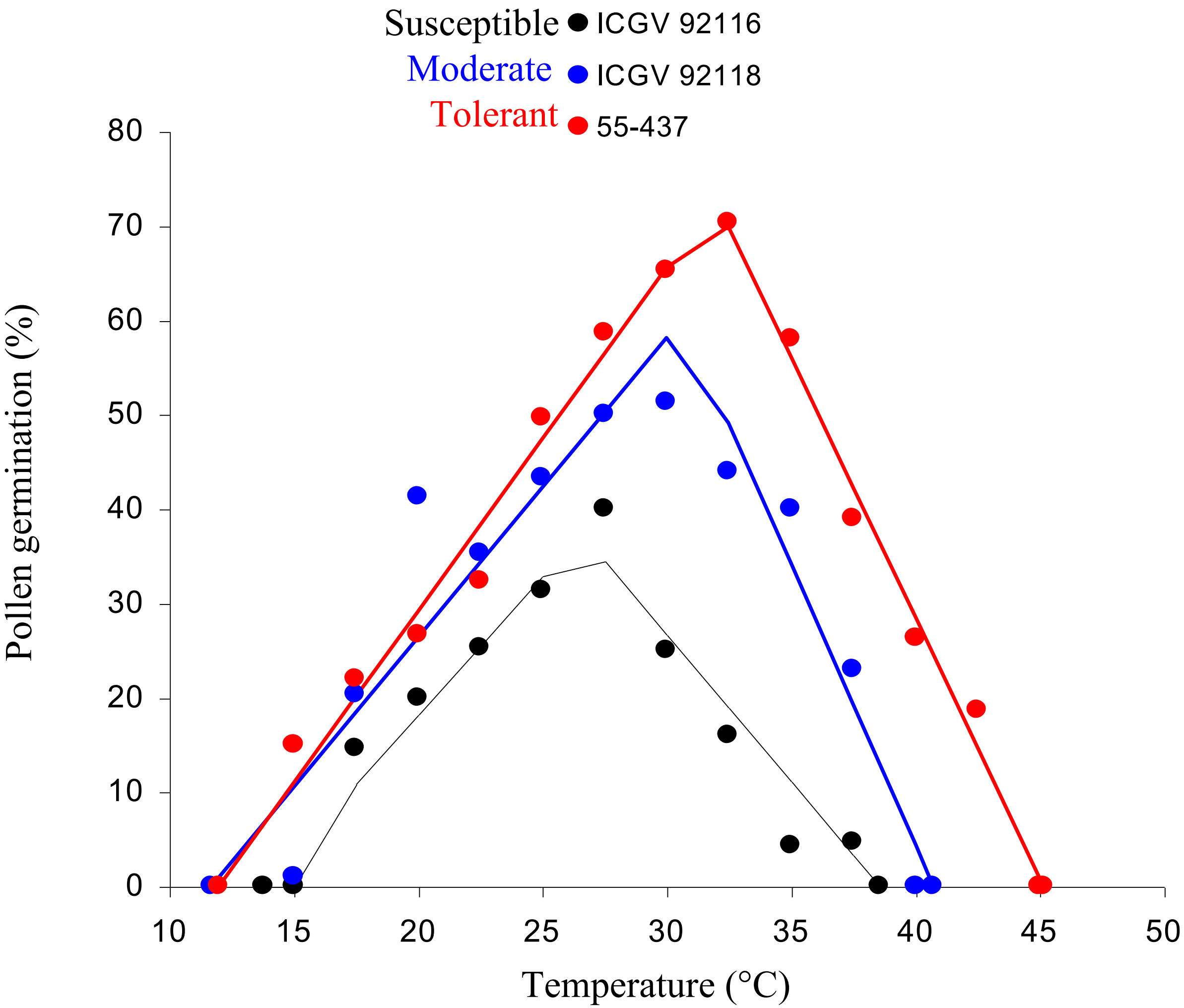
Phenology - Species Variability

Temperature - Groundnut (Peanut, cv. Robut 33-1)

Event	Equation	CGDD	Tbase
Leaf appearnce	= 0.018*T - 0.183, r^2 =0.79,	56	10.0
Branching	= 0.0097*T - 0.0924, r^2 =0.89,	103	9.5
Flowering	= 0.00186*T - 0.0201, r^2 =0.96,	538	10.8
Pegging	= 0.00149*T - 0.0158, r^2 =0.90,	669	10.6
Podding	= 0.00139*T - 0.0158, r^2 =0.98,	720	11.4

S.K. Leong and C.K.Ong. 1983. J. Expt. Bot. 34: 1551-1561.

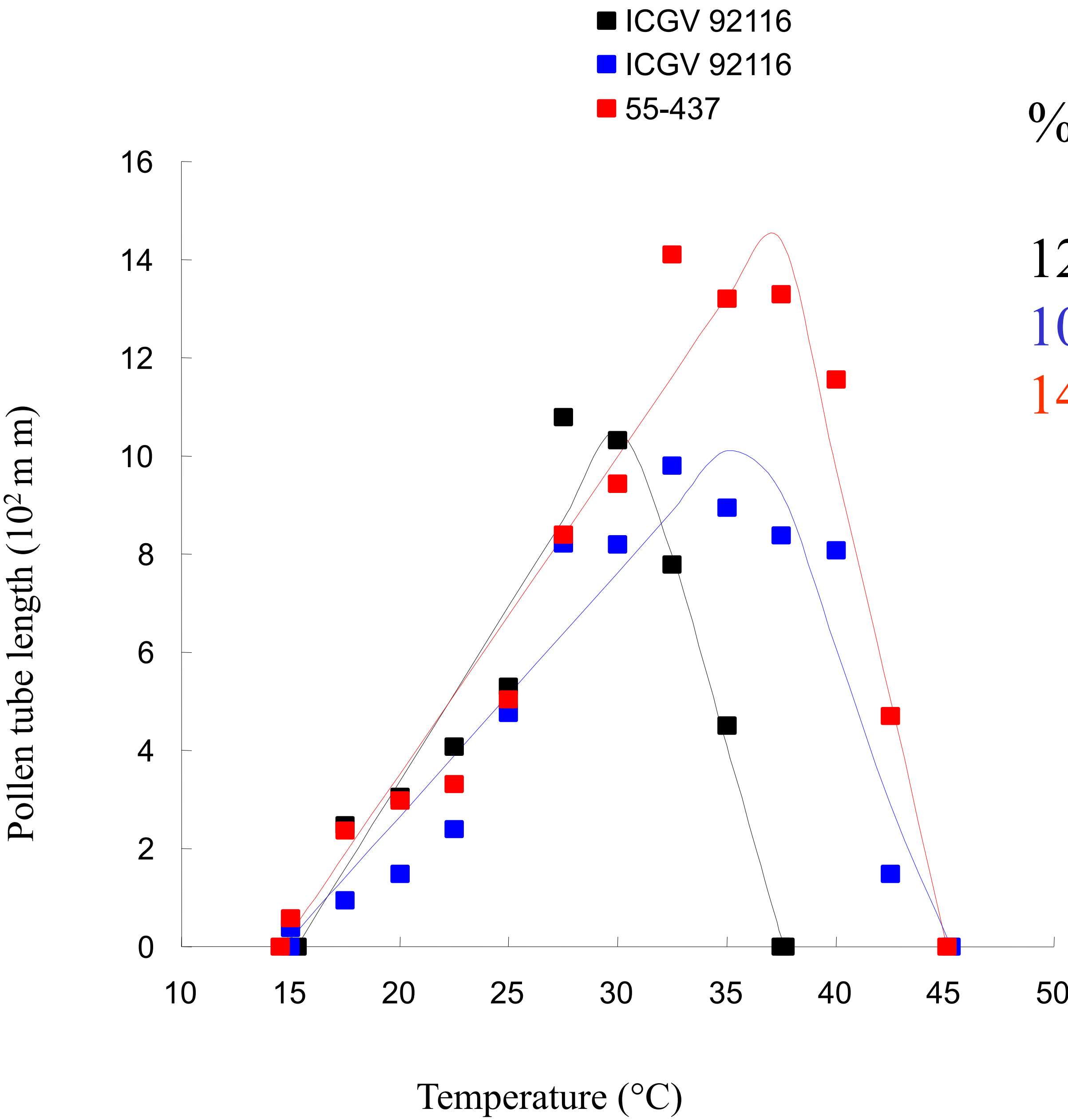
Temperature – Pollen Germination



%	T_b	T_{opt}	T_{max}
40	13.8	26.5	38.5
51.5	11.7	30.6	40.7
70.3	11.9	31.9	45.2

Effect of temperature on percentage pollen germination of susceptible (T_{opt} < mean-LSD), moderately tolerant (T_{opt} = ±mean) and tolerant (Topt > mean+LSD) genotypes. Symbols are observed values and lines are fitted values.

Temperature – Pollen Tube Growth



%	T_b	T_{opt}	T_{max}
1280	16.0	36.4	45.5
1080	15.3	30.5	37.7
1410	14.5	37.6	45.1

Cowpeas (*Vigna unguiculata belong to the family Fabaceae.*

Cowpeas were originally native to Asia and are now an important forage and cover crop in the southern United States. The seeds, usually called black-eyed peas or black-eyed beans, are cooked and eaten.

Phenology – Species Variability – Cowpea Lines

Sowing to Flowering

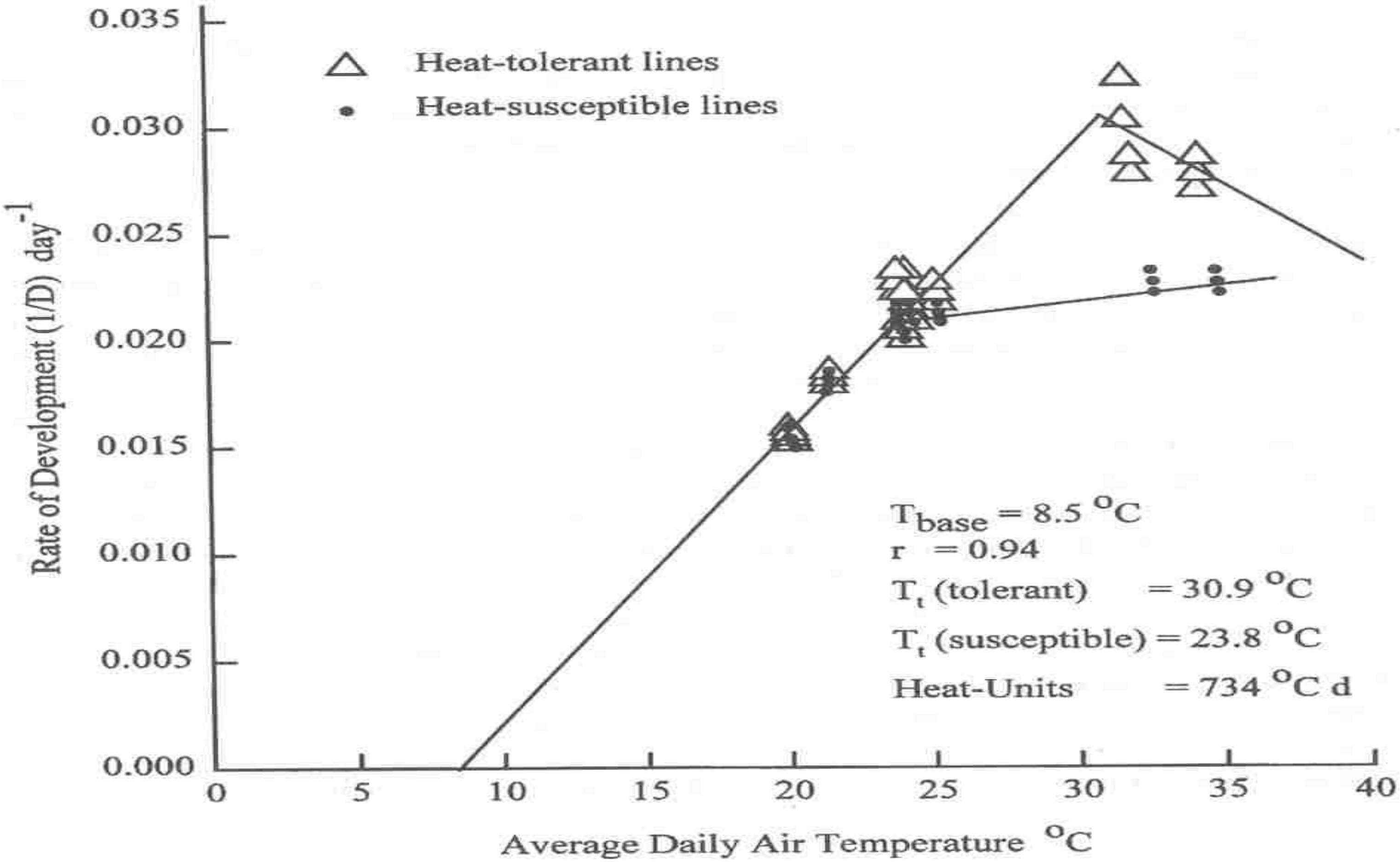
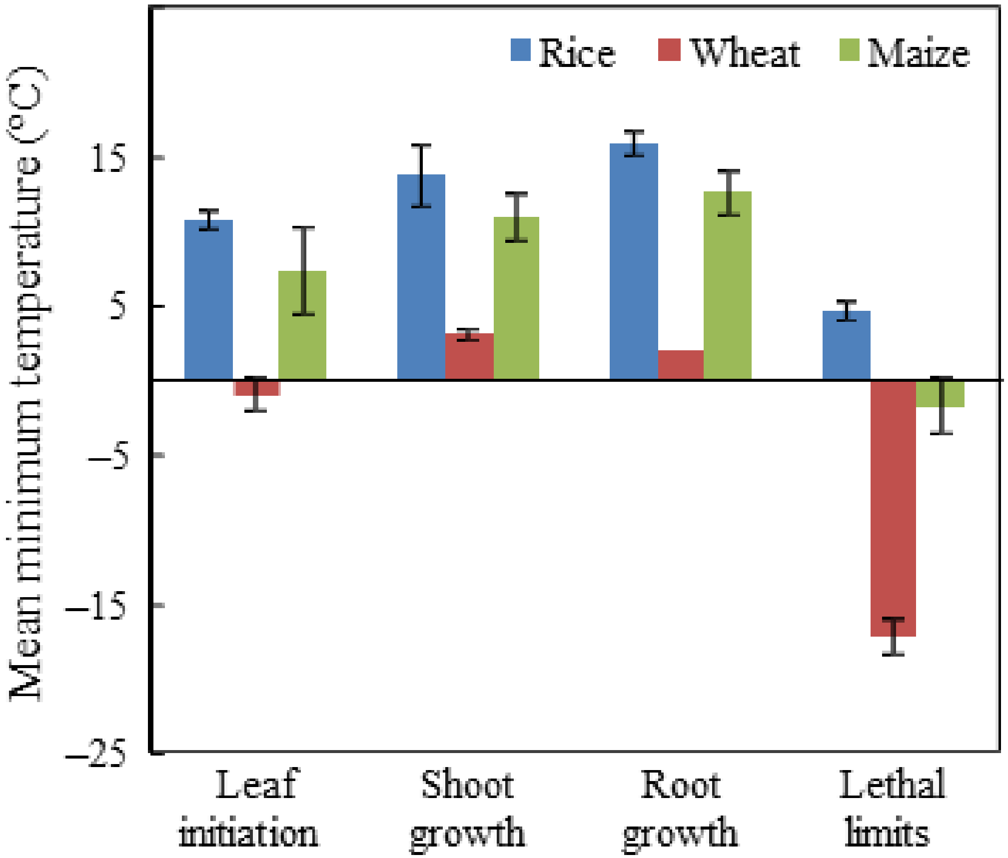


FIGURE 6.1 Rate of development (1/D) of heat-tolerant and heat-susceptible cowpea lines, where D is the period between sowing and first flowering as a function of average air temperature. The heat-unit and r values are based on the linear part of the curve. Ismail, A.M., and A.E. Hall, Positive and potential negative effects of heat-tolerance genes in cowpea. *Crop Sci.* 38: 381–390.

Phenology and Growth - Species Variability

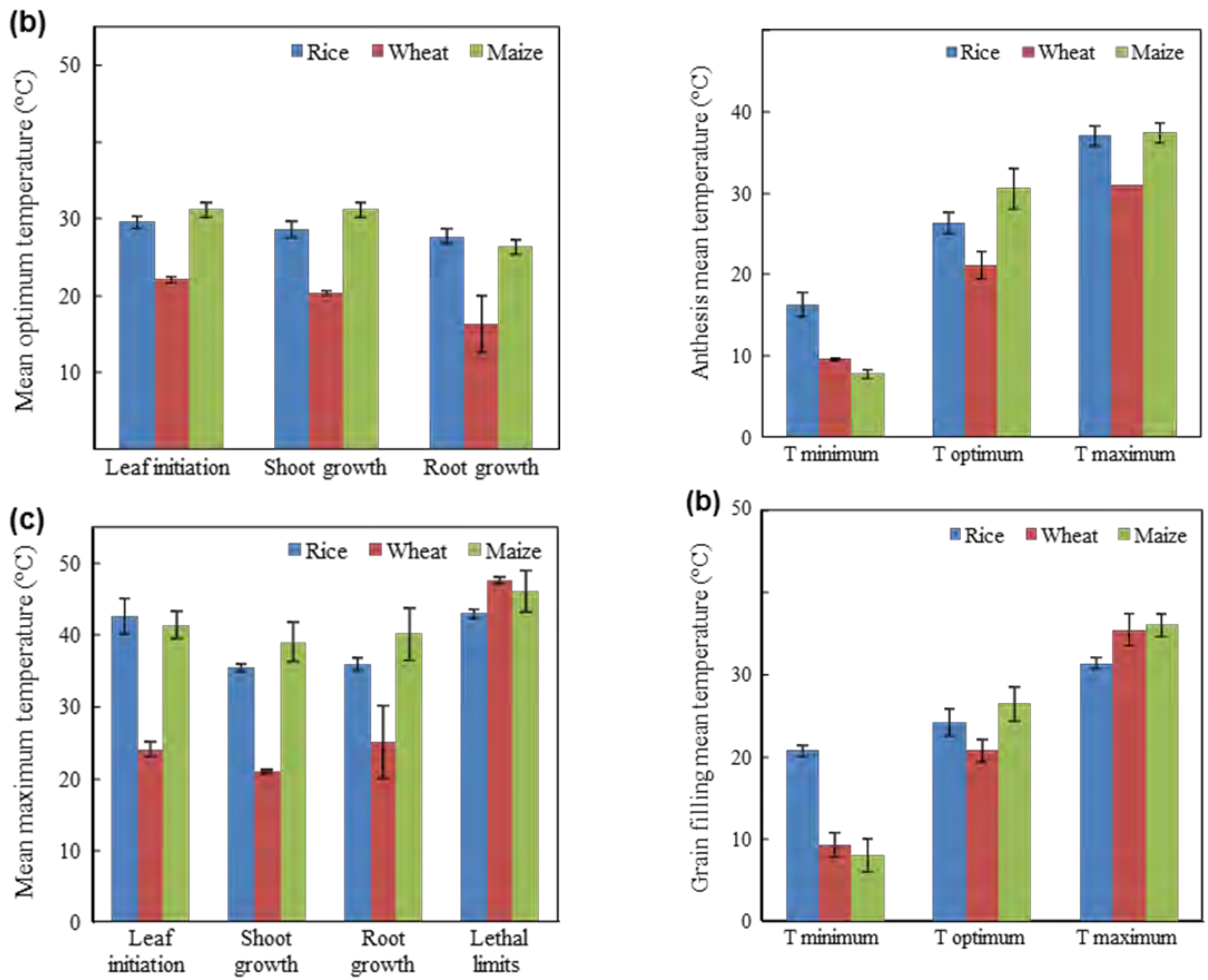
Cardinal Temperatures - Major Crops



Sanchez et al. (2014), Global Change Biology, 20:408-417

Phenology and Growth - Species Variability

Cardinal Temperatures - Major Crops



Sanchez et al. (2014), Global Change Biology, 20:408-417

Phenology and Growth - Species Variability

Cardinal Temperatures - Major Crops

Table 2 Summary of mean (± SE) of: lethal minimum (TLmin) and lethal maximum (TLmax) temperatures; base (Tmin), optimum (Topt) and maximum (Tmax) temperatures for relevant processes and development phases in maize; *n*, number of literature sources

Processes	Mean Temperature (± SE)(°C)	*n*
Lethal limits		
TLmin	- 1.8 (1.9)	8
TLmax	46.0 (2.9)	6
Leaf initiation		
Tmin	7.3 (3.0)	8
Topt	31.1 (1.7)	11
Tmax	41.3 (1.9)	3
Shoot growth		
Tmin	10.9 (1.5)	3
Topt	31.1 (0.8)	3
Tmax	38.9 (2.8)	4
Root growth		
Tmin	12.6 (1.5)	3
Topt	26.3 (1.8)	5
Tmax	40.1 (3.6)	3
Phenological phases		
Sowing to emergence		
Tmin	10.0 (2.2)	3
Topt	29.3 (2.5)	3
Tmax	40.2 (2.1)	1
Sowing to tassel initiation		
Tmin	9.3 (2.7)	12
Topt	28.3 (3.8)	11
Tmax	39.2 (0.6)	4
Anthesis		
Tmin	7.7 (0.5)	3
Topt	30.5 (2.5)	3
Tmax	37.3 (1.3)	4
Grain filling		
Tmin	8.0 (2.0)	2
Topt	26.4 (2.1)	5
Tmax	36.0 (1.4)	4
Whole plant		
Tmin	6.2 (1.1)	9
Topt	30.8 (1.6)	8
Tmax	42.0 (3.3)	12

Table 1 Summary of mean (± SE) of: lethal minimum (TLmin) and lethal maximum (TLmax) temperatures; base (Tmin), optimum (Topt) and maximum (Tmax) temperatures for relevant processes and development phases in rice; n, number of literature sources

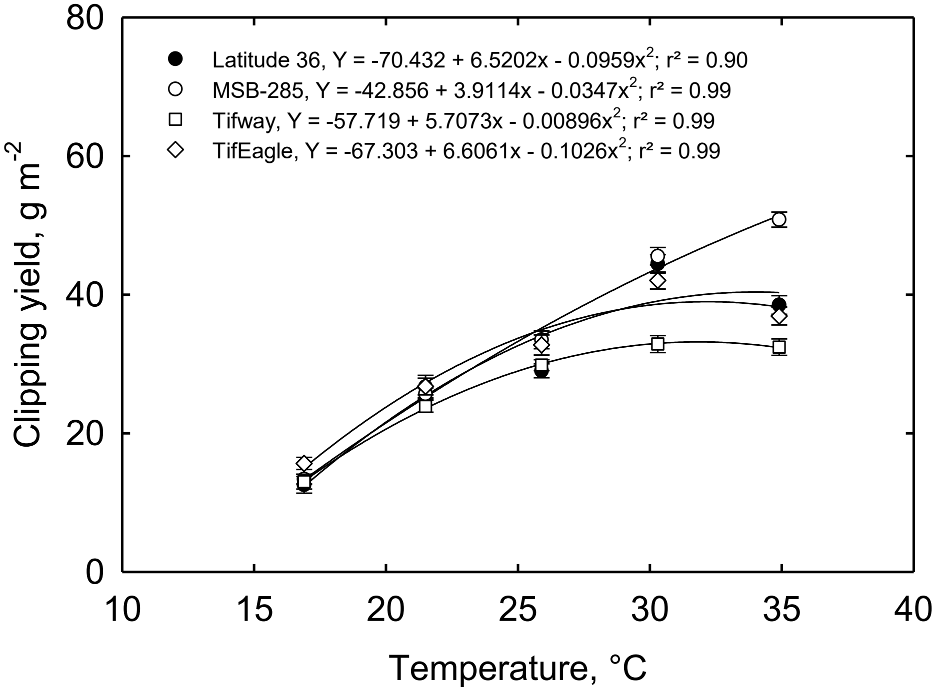
Processes	Mean temperature (± SE)(°C)					
	Specie Oryza Sativa	*N*	*Sub-specie Indica*	*n*	*Sub-specie Japonica*	*n*
Lethal Limits						
TLmin	4.7 (1.2)	8			2.2 (1.8)	2
TLmax	42.9 (0.7)	9			42.7 (1.5)	3
Leaf initiation						
Tmin	10.7 (0.6)	7	11.8 (0.2)	2	10.5 (0.5)	2
Topt	29.5 (0.8)	9	29.6 (1.2)	6	29.7 (1.2)	3
Tmax	42.5 (2.5)	2	40	1		
Shoot growth						
Tmin	13.7 (2.1)	4	14.5 (3.0)	2	11.5	1
Topt	28.5 (1.1)	5	27.5 (0.9)	4	27	1
Tmax	35.5 (0.5)	2	35.5 (0.5)	2		
Root growth						
Tmin	15.8 (0.8)	7	17.5	1	15.5 (3.5)	2
Topt	27.6 (0.0)	11	26.8 (0.8)	2	26	1
Tmax	35.9 (0.6)	7	35.5 (0.5)	2	32	1
Phenological phases						
Germination/Emergence						
Tmin	11.3 (1.1)	8	7	1	10 (1.7)	4
Topt	27.9 (2.8)	6	29.9 (4.9)	2	21.7 (2.7)	2
Tmax	40.1 (1.3)	5	41	1	35	1
Tillering						
Tmin	16.4 (0.8)	9	15	1	18.3 (2.1)	3
Topt	28.4 (1.2)	10	29.7 (2.4)	3	29 (3.1)	3
Tmax	35.3 (1.1)	6	37.5 (2.5)	2	32	1
Panicle initiation						
Tmin	15.8 (0.3)	6	11.4	1	14.9 (1.2)	4
Topt	26.7 (4.3)	2			26.7 (4.3)	2
Tmax	33.1 (1.7)	3	33.3	1	33.1 (1.7)	3
Anthesis						
Tmin	16.2 (1.5)	8	16.3 (5.8)	2	14 (2)	2
Topt	26.3 (1.3)	8	28.3 (1.2)	3	24.3 (1.4)	4
Tmax	37 (1.2)	9	37.7 (1.7)	5	36.9 (2.2)	3
Grain filling						
Tmin	20.7 (0.7)	17	21.2 (0.1)	4	17.9 (2.3)	4
Topt	24.2 (1.7)	7	30	1	21.2 (0.8)	3
Tmax	31.3 (0.7)	12			29.8	1
Whole plant	<13.5 (2.1)	7				
Tmin						
Topt	27.6 (2.0)	6			28	1
Tmax	>35.4 (2.0)	7			36	1

Sanchez et al. (2014), Global Change Biology, 20:408-417

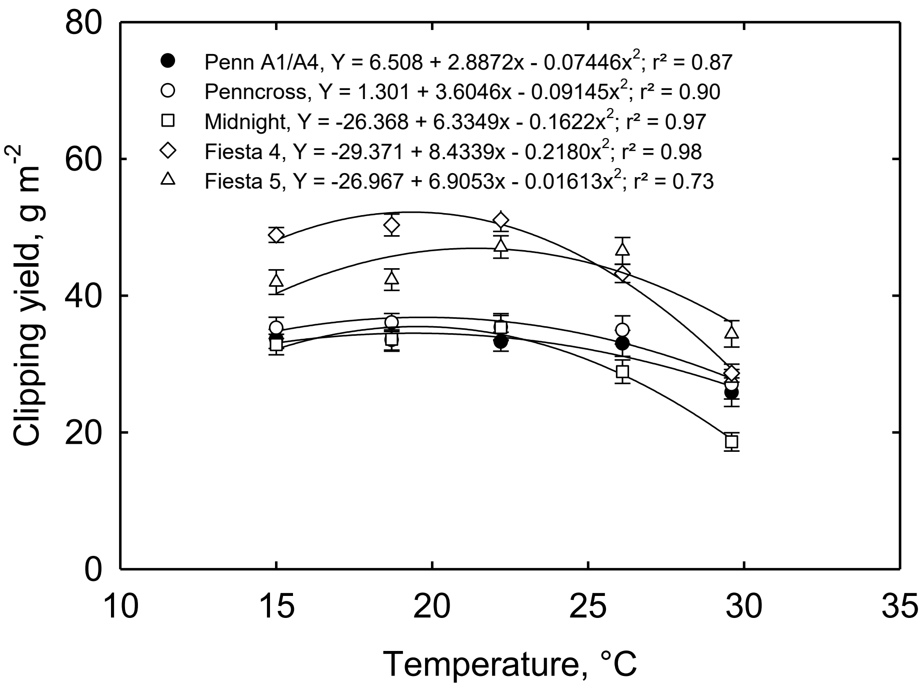
Phenology and Growth - Species Variability

Temperatures Response Functions - Major Crops

Warm-season Turf Grasses



Cool-season Turf Grasses



Phenology – Species Variability

Horticultural Crops

Phenology – Species Variability

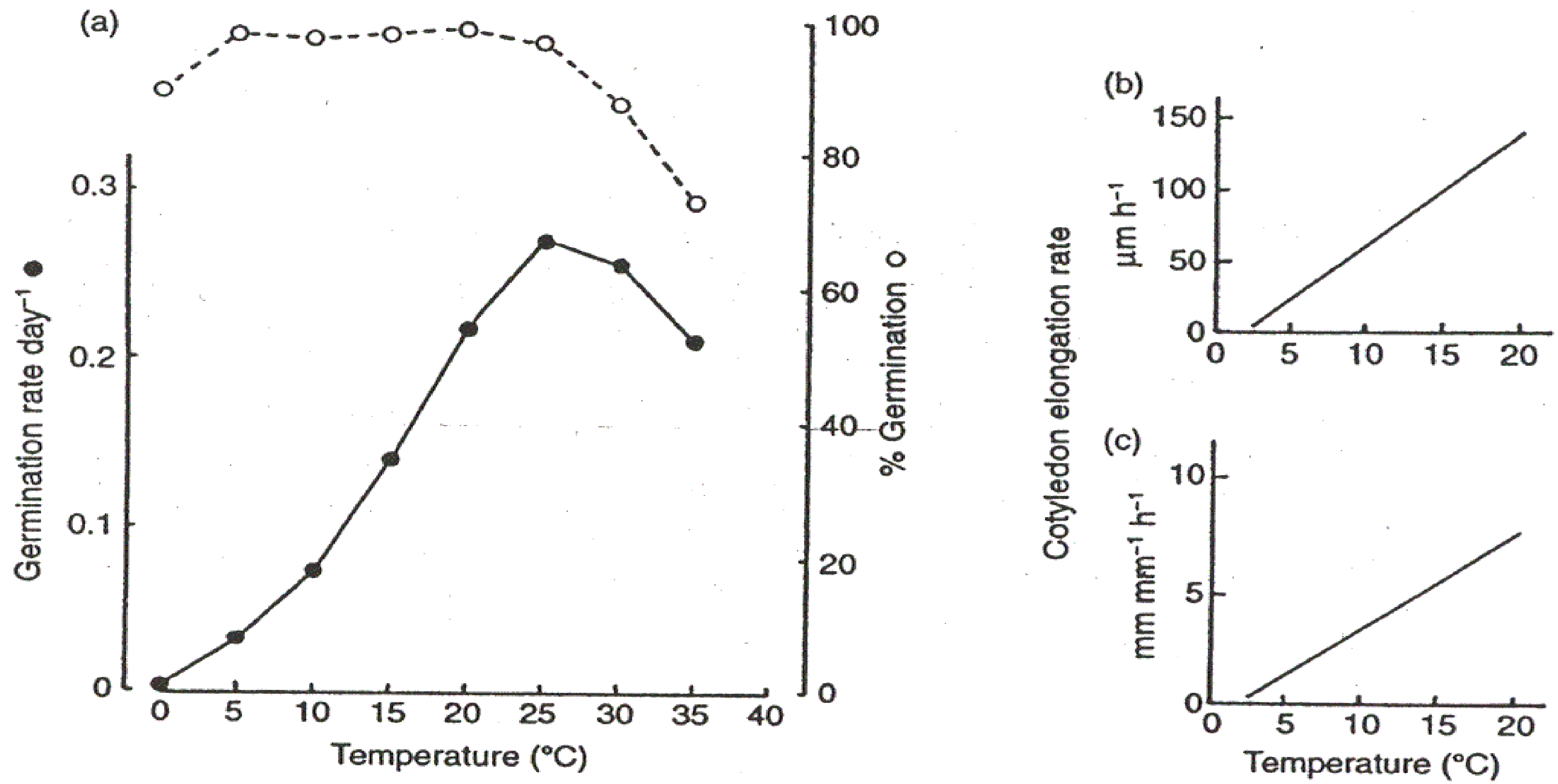


Fig. 10.3. (a) Relationship between temperature and the rate and percentage of germination of onion seeds on moist paper. Rates are reciprocals of the number of days for 50% of viable seeds to germinate (data of Harrington, 1962). (b) Relationship between temperature and rate of cotyledon elongation before hook formation for newly germinated onion seedlings cv. White Lisbon (Wheeler and Ellis, 1991). (c) Relationship between temperature and relative rate of cotyledon elongation after hook formation for the same seedlings as in (b) (Brewster, 1997).

Phenology – Species Variability – Crops and weeds

Species	**Tmin or Tbase, °C**	**GDD per leaf tip**
Maize	**8**	**39**
Sorghum	8	48
Pearl millet	**12**	**26**
Wheat	0	99
Barley	**1**	**75**
Rice	5	90
Soybean	**7**	**54**
Sunflower	9	29
Cowpeas	**16**	**30**
Sugar beet	2	30
Velvet leaf	**8**	**24**
Pigweed	10	12
Banana	**8**	**196**

Phenology – Species Variability

Phenology and Seed Germination:

- The minimum or the base temperature, heat sum (s) or the growing degree days (GDD) from that base temperature for a number of horticultural crops.

Table 10.2. Minimum germination temperature (T_{min}) and heat sum (S) in degree-days for seedling emergence, and the applicable temperature (T) range for germination of various vegetables. Crops are ranked within groups by heat sum (S) in degree-days. (From Taylor, 1997.)

Group	Crop	Genus and species	T_{min} (°C)	S (degree days)	T (°C)
Leaf vegetables and brassica crops	Purslane	*Portulaca oleracea*	11.0	48	15–25
	Cress	*Lepidium sativum*	1.0	64	3–17
	Lettuce	*Lactuca sativa*	3.5	71	6–21
	Witloof, Chicory	*Cichorium sativa*	5.3	85	9–25
	Endive	*Cichorium endiva*	2.2	93	3–17
	Savoy cabbage	*B. oleracea* var. *sabauda*	1.9	95	3–17
	Turnip	*B. campestris* var. *rapa*	1.4	97	3–17
	Borecole, kale	*B. oleracea* var. *acephala*	1.2	103	3–17
	Red cabbage	*B. oleracea* var. *purpurea*	1.3	104	3–17
	White cabbage	*B. oleracea* var. *capitata*	1.0	106	3–17
	Brussels sprouts	*B. oleracea* var. *gemmifera*	1.1	108	3–17
	Spinach	*Spinacea oleracea*	0.1	111	3–17
	Cauliflower	*B. oleracea* var. *botrytis*	1.3	112	3–17
	Corn salad	*Valerianella olitoria*	0.0	161	3–17
	Leek	*Allium porrum*	1.7	222	3–17
	Celery	*Apium graveolens*	4.6	237	9–17
	Parsley	*Petroselinum crispum*	0.0	268	3–17
Fruit vegetables	Tomato	*Lycopersicon esculentum*	8.7	88	13–25
	Aubergine	*Solanum melongena*	12.1	93	15–25
	Gherkin	*Cucumis sativus*	12.1	108	15–25
	Melon	*Cucumis melo*	12.2	108	15–25
	Sweet pepper	*Capsicum annuum*	10.9	182	15–25
Leguminous crops	Garden pea	*Pisum sativum*	3.2	86	3–17
	French sugar pea	*P. sativum* var. *sacharatum*	1.6	96	3–17
	Bean (French)	*Phaseolus vulgaris*	7.7	130	13–25
	Broad bean	*Vicia faba*	0.4	148	3–17
Root crops	Radish	*Raphanus sativus*	1.2	75	3–17
	Scorzonera	*Scorzonera hispanica*	2.0	90	3–17
	Beet	*Beta vulgaris*	2.1	119	3–17
	Carrot	*Daucus carota*	1.3	170	3–17
	Onion	*Allium cepa*	1.4	219	3–17

EPI Concept and Plant Growth and Development

One way to quantify the effects of environmental factors on plant growth and development is to use the EPI concept similar to the one that we used in cotton as model crop.

EPI-phenology = Temperature (potential) * Nutrient Index (C, N, P, K) * Water index * PPF Index * PGR Index etc.,

EPI-growth = Temperature (potential) * Nutrient Index (C, N, P, K)* Water index * PPF Index * PGR Index etc.,

Once the potential is defined and quantified, then we can use EPI concept to decrease that potential to account for the effects of multiple environmental factors on given process such growth or development of any plant/crop species as in cotton crop.

EPI Concept and Plant Growth and Development

- Environmental productivity index concept, if applied, works across species and locations.
- EPI also allows one to interpret and to understand stresses in the field situations.
- If we know the factor that is limiting most at any point of time during the growing season, then, we can make appropriate management decisions to correct that limitation.
- EPI concept is the way to quantify the effects of multiple environmental factors on plant growth and development (photosynthesis, phenology, and growth) and thus productivity of any species or crop.