THE CLIMATOLOGY OF THE VINE (*VITIS VINIFERA* L.) THE COOL LIMITS OF CULTIVATION

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SUMMARY

An examination has been made of the temperature conditions at the polar limit of the cultivation of the grape vine *Vitis vinifera* L. in Europe. The principal limiting factors are the mean temperature of the warmest monthly period which must be in excess of 66° F. and of the coldest monthly period which must be in excess of 30° F. These are associated with periods of approximately six months during which the mean monthly temperature is in excess of 50° F.

Where mean winter temperatures fall below 30° F. special precautions must be taken to protect the vines.

The temperature characteristics have also been expressed in the harmonic form of annual mean, amplitude and phase and the use of temperature summations over the base level of 50° F. is discussed.

Experience in Australia and California has been examined with reference to the temperature limits established above.

In an appendix, the history of the use of temperature summations in agricultural climatology is briefly reviewed.

In an earlier communication (1947) it was demonstrated that the wave-form analysis of the annual temperature curve based on mean monthly temperatures could be applied to the search in Australia for the temperature homoclimes of species of pines native to the Mediterranean environment. Such a method is particularly successful when dealing with perennial species such as *Pinus radiata* and *Pinus canariensis* which have a geographically restricted native habitat. The march of temperature throughout the year takes care of adaptability to the summer heat and winter cold, leaving the question of moisture relations for studies of greater refinement.[2] In the case of a long established cultivated perennial such as the grape vine (*Vitis vinifera*), the question is complicated by the deciduous character of the plant and by the historical factors involved in the spread of its cultivation from its place of origin in the Armenian region, to all parts of the civilised world. In most cases at some time or other, the limits of cultivation have been advanced beyond a reasonable range both in the polar direction and equatorially, but the present polar limits in Europe at least have been stable for well over a century.

It is necessary, moreover, to take note of the introduction of species other than *V. vinifera* to meet special circumstances, such as the use of "direct producers" or hybrids of *V. vinifera* with various American species which bear commercially useful grapes and which are tolerant of cold conditions and which are resistant to phylloxera. Such vines are the basis of the wine industries in

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[2] See for example Johnston (1964).

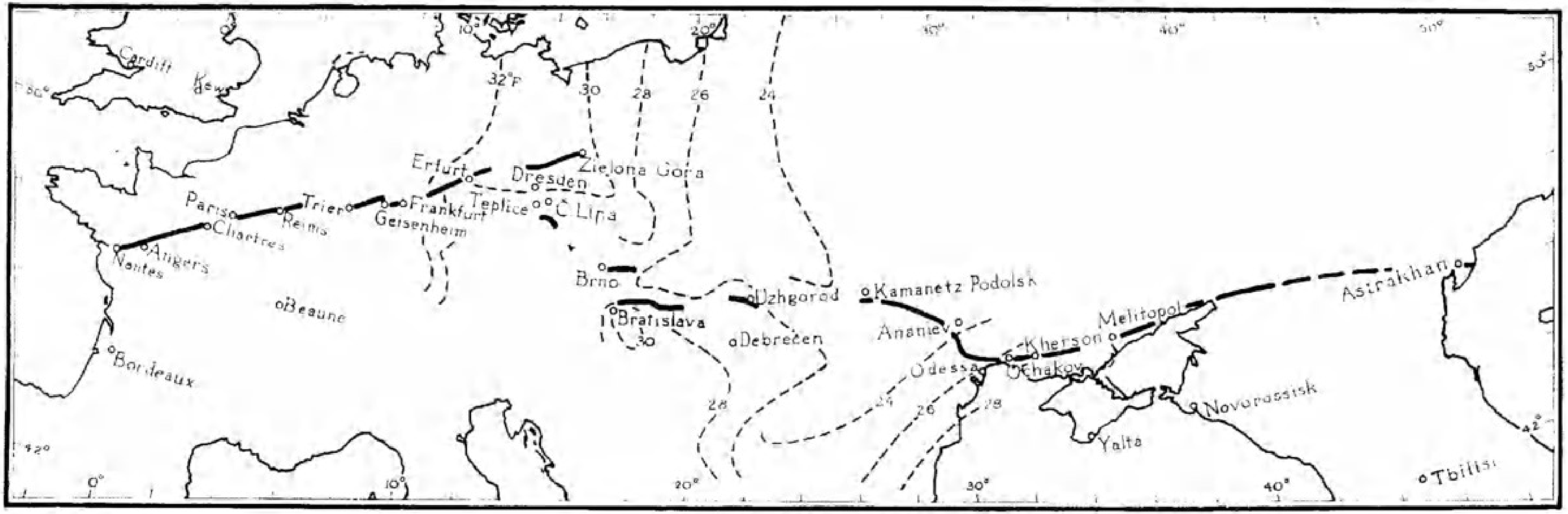

Fig. 1. Map illustrating the northern margin of the cultivation of the vine in Europe. Names and locations of stations with useful temperature records along this margin are indicated. South of this margin is given a selection of stations representing important viticultural areas. The broken lines represent isotherms for the mean temperature of the coldest monthly period.

the States of New York and Ohio in the United States and of the Province of Ontario in Canada. Such an hybrid, *Brandt*, of Canadian origin, has been used to extend the limit of cultivation to Britain, while the Asian species *V. lanata* is grown commercially in Egypt, particularly in the neighbourhood of the Mediterranean Sea.

The purpose of the present study is to examine the temperature conditions which appear to have determined the polar limits of the cultivation of the vine in Europe, to establish any generalisation which emerges and to test this generalisation against the newer experiences of Australia and California.

The present northern limits of the cultivation of the vine in Europe are the result of a process of trial and error extending back first to the Roman occupation and later to the spread of Christian establishments in northern Europe. In Britain at the time of the Norman conquest, the Domesday Book has 38 references to vineyards. An 18th century report from a physiocratic French source on the English counties mentions only Gloucestershire as having vineyards. These are recorded as having been recently abandoned in favour of apple orchards. Generally speaking, Gloucester, Somerset and Kent are regarded as the most favourable counties. In Germany during the middle ages the cultivation of the vine was extended to Lübeck, Stettin, Danzig, Königsberg and Tilsit. Most of these northern vineyards were destroyed, however, by the harsh winter of 1437. In 1592 there were 92 vineyards in Berlin, areas which subsequently reverted to orchards. In what is now Polish Silesia, the cultivation of the vine was introduced by Frankish and Flemish migrants and remained important until the period of the 30 years' war. The most famous wine district in the area is that based on Zielona Góra (Grünberg), including areas at Swiebodzin and Sulechów. The most prosperous period is said to have been between 1830 and 1890, when the area planted reached 1,400 hectares. In Saxony the most important area has been near Meissen and Hoflössnitz, advantage being taken of the favourable climate of the valley of the Elbe. In the late 16th century, 6,000 hectares are said to have been cultivated in this area, but this had decreased by the end of the 19th century to 526 hectares. Further up the valley of the Elbe vineyards were established in Bohemia and these are currently represented by areas at Mělník and Litomerice. The northern limits of cultivation in Czechoslovakia, Hungary and Rumania are much further south than in Germany and there is no doubt that this limit is determined by the colder winters.

In Russia, the limits have been set by experience gained in extending cultivation into the Ukraine beyond the existing limits in central Europe. With the occupation of the Crimea and its annexation in 1783, a winemaking school was established in that year at Sudak on the coast and this was moved in 1812 to the neighbourhood of Yalta, now one of the important centres in the Soviet Union. Vineyards were established in 1774 by the German settlers on the Volga between Saratov and Tsaritsin (Volgagrad, Stalingrad) but these do not appear to have survived, although mentioned by correspondents of Alph. de Candolle. An important surviving area extends along the banks of the Don. Vines have been grown in Kiev in gardens, but no wine can be made.

The present northern limits of the cultivation of the vine in Europe are shown on the map of Fig. 1. These limits are very similar to those shown on a map by Leunis (1883) except that the Russian limit is shown on this earlier map as extending to the northern margin of the Caspian Sea. This map also shows the polar limits of the cultivation of the olive as well as of a number of native tree species. He also plotted two sets of isotherms: *isotheres* or lines

TABLE 1.

Climatic Characteristics of Localities Along the Northern Limits of the Cultivation of the Vine in Europe.

Recording Station	Longitude °	Latitude °	Temperature Characteristics			Season above 50°F			Accumulated day-degrees above 50°F
			Mean °F	Amplitude °F	Phase Days	Beginning April	Ending October	Length months	
Nantes	W 1·6	47·2	52·2	13·0	30·4	9	26	6·55	1,880
Angers	W 0·6	47·4	52·3	13·8	29·1	6	26	6·65	2,000
Chartres	E 1·5	48·4	50·3	14·5	28·5	15	17	6·05	1,710
Paris	2·2	48·8	50·6	14·5	26·7	14	16	6·10	1,750
Reims	4·0	49·3	50·3	15·5	27·9	14	15	6·05	1,820
Trier	6·6	49·7	47·3	14·3	29·7	18	15	5·90	1,700
Geisenheim	8·0	50·0	49·2	16·3	26·4	16	14	5·90	1,790
Frankfurt	8·6	50·2	49·4	16·7	27·0	18	14	5·85	1,820
Erfurt[1]	11·0	51·0	46·8	17·0	29·4	30	6	5·20	1,430
Dresden[2]	13·7	51·1	48·4	16·7	30·4	26	12	5·55	1,660
Teplice[3]	13·8	50·6	48·1	17·8	26·3	21	5	5·45	1,770
Č. Lipa[3]	14·2	50·7	46·5	18·9	27·8	30	5	5·15	1,590
Zielona Góra[4]	15·5	51·9	47·3	17·9	29·9	26	8	5·40	1,630
Brno	16·6	49·2	47·2	19·7	28·1	22	11	5·60	1,780
Uzhgorod	22·3	48·6	49·1	20·4	30·2	17	18	6·00	2,170
Kamenetz-Podolsk	26·6	48·7	45·9	22·7	30·3	29	11	5·40	1,930
Ananiev	29·9	47·6	47·6	23·5	29·6	24	26	5·55	2,310
Odessa	30·7	46·4	49·3	23·5	32·9	24	18	5·80	2,580
Ochakov	31·5	46·6	49·8	24·3	33·4	21	20	5·95	2,730
Kherson	32·6	46·6	50·1	24·0	31·2	18	18	6·00	2,790
Melitopol	35·4	46·8	49·3	25·2	31·5	20	15	5·85	2,810
Astrakhan	48·2	46·4	49·0	29·4	30·3	18	15	5·90	3,160

1. Erfurt for the Saale-Unstrut valleys.
2. Dresden for Meissen and Grossenhain.
3. Teplice and Č. Lipa for the Bohemian areas of Melnik and Litomerice.
4. Zielona Góra (Grünberg) for Swiebodzin and Sulechow.

of equal summer temperatures and *isocheims* or lines of equal winter temperatures. Commenting on the interpretation of this map, Lennis remarks on the complications associated with the problems involved.

The map of Fig. 1 gives the locations of the temperature stations which provide the most useful available information associated with the limit of cultivation under discussion. In addition, the isotherms of the coldest month are plotted as these obviously play a part in determining the limit.

For each of the stations listed and for others in the vicinity the temperature characteristics of each station have been calculated by wave-form analysis, and in each case a smooth curve has been drawn from the values calculated from the first three harmonics. From these curves has been estimated the length of season over 50° F. and the accumulated "day-degrees" above this limit. These data have been brought together in Table 1.

It is now possible to summarise the data in the form of mean annual temperature and of temperature amplitude. This has been done in Fig. 2 where temperature characteristics have been plotted against longitude across Europe, as it is obvious that the degree of continentality of the temperature regime as determined by longitude is more important than latitude in determining the limit. The German climatologists have observed that a mean temperature of the warmest month of 20° C. (68° F.) is the probable requirement together with a mean temperature of the coldest month not below 0° C. (32° F.) with a mean annual temperature of at least 48° F.

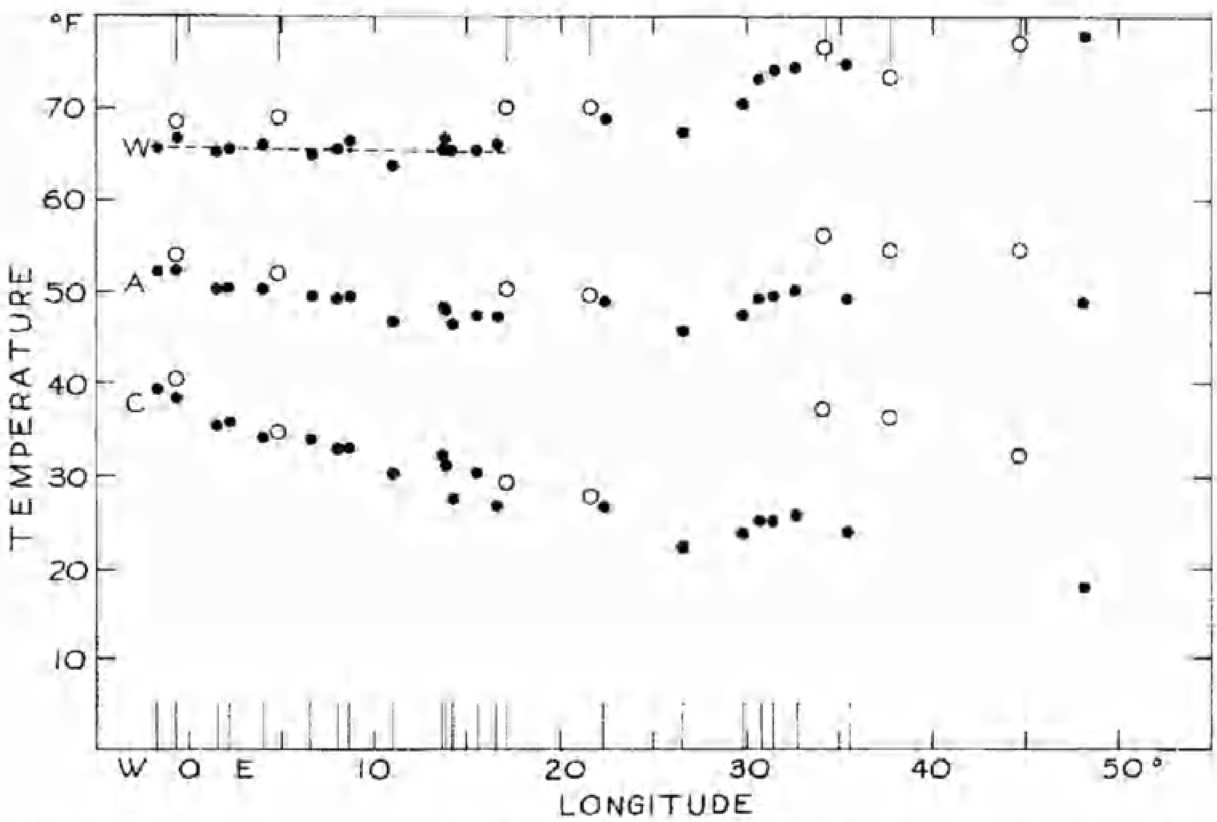

Fig. 2. Illustrating the relationship between temperature and longitude along the northern margin of the cultivation of the vine in Europe. W. Temperature of the warmest monthly period. The broken line is the calculated regression of temperature on longitude over the range 2°W to 16°E. A. Mean annual temperature. C. Temperature of the coldest monthly period. Open circles are for well-established stations well within the northern limits.

In Fig. 2, the calculated line of regression of temperature on longitude has been plotted for the warmest month over the range of longitude 2°W. to 16°E. There is no significant departure over this range from a mean temperature of 65·6° F. On the other hand, the mean temperature of the coldest month falls over this range of longitude from 39° F. to about 30° F. At the lowest temperatures and generally speaking further east at the Ukrainian winter temperatures of about 25° F., it is recognised that protection of the vine in winter is very necessary. French observers regard an absolute minimum of −15° C. to −18° C. (say, 0° F. to 5° F.) as the ultimate limit of danger in winter.

This northern limit of cultivation is reasonably continuous from the coast of the Atlantic to the valley of the Rhine, but east of the Rhine the cultivation is less continuous, edaphic factors of soil and slope being sought as in the Rheingau, the valleys of the Saale and Unstrut and of the Elbe, on dune sands in Silesia and on south-facing slopes at Tokaj in Hungary. The continuity is also interrupted by the mountain ranges such as the Erzgebirge, the Riesengebirge and the Carpathians. It will be noted that the eastern limit of this continuous cultivation is determined by a mean temperature of the coldest month of 32° F.

Another temperature factor which has been considered to be of importance is that controlling the period of vegetative growth. The nineteenth century botanists agreed that for most woody species, bud burst in Spring began when the mean monthly temperature reached 10° C. (50° F.) and this temperature limit has been extensively used in many climatic studies on the vine. From Table 1 it will be noted that over practically the whole range of longitude from Chartres to Astrakhan, the period during which the temperature limit of 50° F. is exceeded varies from approximately 5·5 to 6·0 months. In every case the beginning of this season is in April and the end in October, mean dates being 21 April and 14 October, a period of 5·8 months.

In order to provide some perspective the records of a number of well-established areas south of the northern limit have been examined and these are brought together in Table 2 as well as being plotted in Fig. 2. The length of season over 50° F. is in general between six and seven months and summer temperatures about 3° to 4° F. higher than on the northern limit.

This northern limit of the cultivation of the vine is only valid for early varieties. An historical experience in this connection is that of Boussingault (1837b), who recounts the establishment of a vineyard on the family estate in Alsace in 1818. The varieties first planted were those from the region of Perpignan, presumably *Grenache*, *Carignan* and similar varieties. These thrived, but the grapes did not ripen and the vineyard was replanted in 1828 with early varieties including *Pinot*, *Sauvignon blanc*, *Tokay*, *Riesling* and *Traminer*. It is of interest that the vintage was followed over a period of years and recorded quantitatively from 1833 to 1836. Boussingault records his opinion that the temperature of the warmest month should be 4 or 5 degrees higher than the recorded probable mean of 64° F., for the season to be favourable in Alsace.

It has been pointed out above that a temperature factor which has been considered to be of great importance is that controlling the period of vegetative growth. This temperature limit was established for a number of species by Alph. de Candolle (1855) and for the vine the limit was established at 10° C. (50° F.), and was used extensively by him and adopted by the American workers Amerine and Winkler (1944, 1963) for determining the climatic regions for the cultivation of wine grapes in California.

TABLE 2.

Climatic Characteristics of Important Wine Districts of Europe Immediately South of the Northern Limits of Cultivation of the Vine.

Recording Station	Longitude °	Latitude °	Temperature Characteristics: Mean °F	Amplitude °F	Phase Days	Season above 50°F: Beginning April	Ending October	Length months	Accumulated day-degrees above 50°F
Bordeaux	W 0·6	44·9	54·2	13·9	31·5	1	31	7·05	2,390
Beaune	E 4·9	47·1	52·0	16·5	28·7	6	20	6·45	2,300
Bratislava	17·1	48·1	50·4	20·2	28·6	14	20	6·20	2,420
Debrečen[1]	21·2	47·5	49·7	20·8	27·5	12	15	6·10	2,350
							November		
Yalta	34·2	44·5	56·1	18·7	40·6	11	17	7·20	3,300
Novo-rossisk	37·8	44·7	54·6	18·5	39·3	15	9	6·80	2,990
Tbilisi	44·7	41·7	54·7	21·4	33·3	3	2	7·00	3,370

[1] Debrečen for Tokaj

Three examples have been selected from the range of stations in Table 1 so that a comparison may be made between the original use of this temperature limit by de Candolle and the current use by the Californian workers.*

These examples are illustrated and explained in Fig. 3. De Candolle's rule (1855 loc. cit. p. 365) with respect to the limits of cultivation of the vine may be quoted in full:

"The cultivation of the vine, for the manufacture of wine, can be undertaken in Europe, on slopes with a favourable exposure, up to those localities which provide a sum of 2,900 day-degrees (Centigrade) from the day when the mean temperature first reaches 10° C. until the day when the temperature falls below 10° C. in the shade, provided that at the approach of maturity, the number of days with rain does not exceed a dozen per month."

De Candolle's choice of 10° C. was made only after he had satisfied himself that it was better than 8° C. or 9° C. He was, moreover, well aware that this temperature sum could be modified by other factors, the chief of which he regarded as the amount of solar radiation, but as he had no method of estimating this, he noted the effect of latitude in influencing the length of day in summer

* For a fuller account of the history of the development of this concept, see appendix page 20.

Fig. 3. Three selected examples of temperature curves of localities on the northern limit of the cultivation of the vine in Europe. The curves are drawn from the calculated values based on the wave-form analysis of the original mean monthly temperatures following the equation:

$$u = a_0 + a_1 \cos x + a_2 \cos 2x + a_3 \cos 3x + b_1 \sin x + b_2 \sin 2x + b_3 \sin 3x$$

For the three localities the constants of the equation are:
with mid-January as 0°, mid-February 30° etc.

	a_0	a_1	a_2	a_3	b_1	b_2	b_3
Nantes	52·20	−12·92	+0·40	+0·12	−0·77	−0·98	+0·03
Geisenheim	49·25	−16·30	0·00	+0·33	+0·17	−0·42	+0·17
Astrakhan	48·97	−29·35	−0·55	−0·10	−1·67	−1·65	−0·82

For the first harmonic these correspond to the values:

	Annual mean temperature °F	Amplitude °F	Phase lag behind the sun days
Nantes	52·2	13·0	30·4
Geisenheim	49·2	16·3	26·4
Astrakhan	49·0	29·4	30·3

The shaded areas correspond to temperature summations, the whole area represents the original summation recommended by de Candolle (Centigrade) and the upper area (Fahrenheit) that currently (1965) adopted by Californian workers. These values are:

	day-degrees	
	California	De Candolle
Nantes	1877	3034
Geisenheim	1786	2886
Astrakhan	3162	3551

in northern latitudes and he also made note as in the rule quoted above of the number of days without rain. Black (1960) has recently calculated values for solar radiation for northern Europe. The southern limit of Black's values coincides approximately with the northern limit of the cultivation of the vine so that a re-appraisal may become possible in these terms.

It will be noted from Fig. 3 that de Candolle, although confining his summations to periods with mean temperatures in excess of 10° C., added the actual temperatures in degrees centigrade so that a new base line of 0° C. was established. For regions, such as Madeira, where the mean temperature of all months of the year exceeds 10° C., he refused to commit himself.

The Californian workers using the Fahrenheit scale have measured temperatures above the base line of 50° F. and where this temperature is exceeded throughout the year an arbitrary selection of the time period has been made, say, April to October, although it is recognised that crop periods such as bud-burst to ripeness, or flowering to ripeness for each specific variety would be more satisfactory.

Phenological observations are not sufficiently numerous to give more than a general confirmation of the soundness of the concepts employed.

In the German regions of the Palatinate, Bavaria and Franconia, the variety *Riesling* begins its vegetative growth about 25 April, begins flowering about 11 June, and the berry begins to ripen about 2 September. The time from bud-

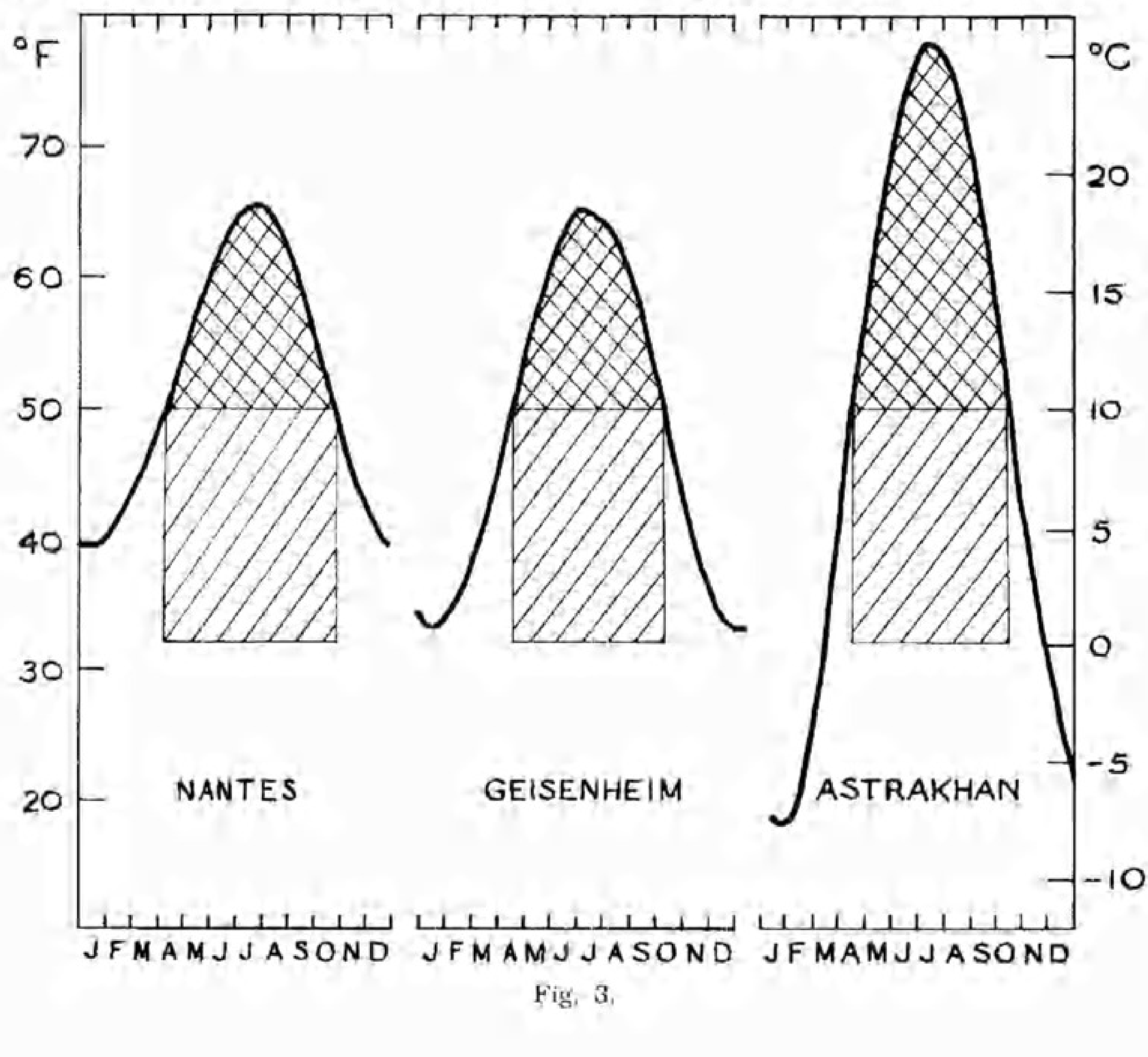

Fig. 3.

burst to the beginning of ripening has a mean value of 126 days. In the Nahe region over a recent period of ten years, the mean date of the beginning of ripening for this variety was 22 August and of the completion of ripening 3 October (Hillebrand, 1963). In these observations the degree of ripeness was based on the specific gravity of the grape juice.

In northern France varieties such as *Gamay* begin vegetative growth from 7-18 April, begin flowering on 9 June and ripen from 17-28 September.

In the commune of Beaune, Burgundy, the proclamation of vintage (*Ban de vendange*), over the years 1909 to 1933, ranged from 15 September to 16 October with a mean date of 28 September. This is to be compared with 20 October, the date ending the mean period above 50° F. at Beaune.

De Candolle quotes a group of observations on the beginning of vegetative growth of the vine at Brussels. Over a period of ten years this is given 25 April.

These dates correspond well with the choice of 50° F. as the basal temperature.

EXTENSION OF EUROPEAN EXPERIENCE TO OTHER COUNTRIES

From the observations made in Europe, it can be assumed that the polar limits of cultivation of the vine are determined climatically by the temperature limit of not less than 66° F. for the mean of the warmest month combined with a mean temperature for the coldest month of not less than 30° F. Below this mean for the coldest month provision has to be made for the protection of dormant vines in winter. The rainfall limit may be taken as an annual mean of 30 inches as a maximum with 20 inches as a possible minimum below which irrigation is likely to be needed. Important areas, such as the Bordeaux region, do, in fact, have areas with an annual rainfall as high as 40 inches, but in such regions fungoid diseases will become increasingly important. A further requirement will be that the length of the season above 50° F. must be in the region of six months and the temperature summation over 50° F. within the period must be of the order of 1,600 to 1,800 day-degrees, corresponding approximately to Alph. de Candolle's original requirements of 2,900 day-degrees on the Centigrade scale. With a seasonal length of six months 1,800 day-degrees corresponds to a de Candolle value of 2,830.

An alternate approach would be the use of appropriate combinations of the harmonic characteristics of the temperature curve for the year. This would mean seeking such appropriate combinations of the annual mean temperature and amplitude as would correspond to the limits set above for the warmest and coldest months. Appropriate combinations would be mean annual values of 52° F. to 48° F. with amplitudes of 14° to 18° and phase values of 26 to 30 days of lag behind solar radiation. Such combinations would be required to reproduce more precisely the temperature conditions along the main northern boundary of cultivation in Europe.

The relevant areas of widest experience with *V. vinifera* outside Europe are likely to be found in South America (Argentina and Chile), in South Africa, in Australia and in California. It is proposed to examine the conditions in Australia and California and to discuss briefly the conditions in England.

Vine Growing in England

It has already been pointed out that English experience goes back for many centuries and that for sentimental and other reasons attempts are always being made to produce wine from grapes grown in England. Generally speaking the enthusiastic wine-maker is satisfied if he can produce wine, say, once in three or five years. Frequently the vines are grown on walls with a southern aspect as is also the case in Silesia. The varieties grown must be very early and according to Ordish (1953) include the Canadian hybrid: *Brandt, Golden Chasselas, Gamay Hatif* and *Meslier Précoce*. Commercial wine production in England, however, is based on concentrated grape juice imported principally from Cyprus and Greece.

For an assessment of temperature conditions, Cardiff, Oxford and Kew have been selected as affording probable northern limits for Britain. Appropriate climatic information is given in the following table:

Station	Temperature Characteristics			Temperature of warmest monthly period °F	Length of season over 50°F months	Accumulated day-degrees above 50°F
	Mean F	Amplitude °F	Phase Days			
Cardiff	49·8	10·7	36·0	61·0	5·6	1,230
Oxford	49·2	11·9	32·9	62·1	5·3	1,110
Kew	49·8	11·9	33·2	62·9	5·5	1,340

Using the accumulated day-degrees above 50° F. as the simplest criterion, none of the values approaches the lower limit set at 1,600 for European continental conditions. Similarly, the mean temperature of the warmest monthly period is significantly below the established limit of 66° F.

California

The grape vine *V. vinifera* is the species commercially established in the western United States, almost entirely in California, although small areas have been noted in the States of Oregon and Washington. There is, of course, a long experience going back to the days of Spanish settlement, and the cultivation of the vine has been adjusted through experience to the geographical limits imposed by climatic conditions. Amerine and Winkler (1944, 1963) have, on the basis of this experience, grouped the California areas into five regions based on accumulated temperatures over 50° F. Here the difficulty arises that was encountered by de Candolle with respect to Madeira in that either all months have mean temperatures above 50° F. or a substantial number of months are so placed. In their first paper they used as a criterion the period from full bloom to ripeness as indicated by a given specific gravity of the grape juice. This is of particular value in the comparison of varieties in different localities and seasons. They obtain as values for their coolest region (No. 1) 1,800 to 2,000 day-degrees. In their second paper they chose the period April to October inclusive which gives a value of less than 2,300 day-degrees for the coolest region.

On the map of California (Fig. 4) have been plotted the criteria mentioned earlier, namely, 66° F., for the warmest month, 30° F. for the coolest month and 30 inches of annual rain. The areas considered climatically suitable for the cultivation of the vine within these limits have been margined. The counties included by Amerine and Winkler in Region No. 1 are indicated by hatching. Below an annual rainfall of 20 inches, irrigation is likely to be needed, above 30 inches special conditions are likely to be encountered. The map has been constructed essentially from the data provided in "Climate and Man" (1941) supplemented by data in the official reports of the U.S. Weather Bureau.

It will be noted that the isotherm of 66° F. for the warmest month is determined in the first place by proximity to the Pacific Ocean and is parallel to the coast, and in the second place by the altitude in the mountains to the east of the central valley.

As an example, Napa (lat. 38·3°N., long. 122·3°W.) has been taken as a recording station in an established wine-growing district.

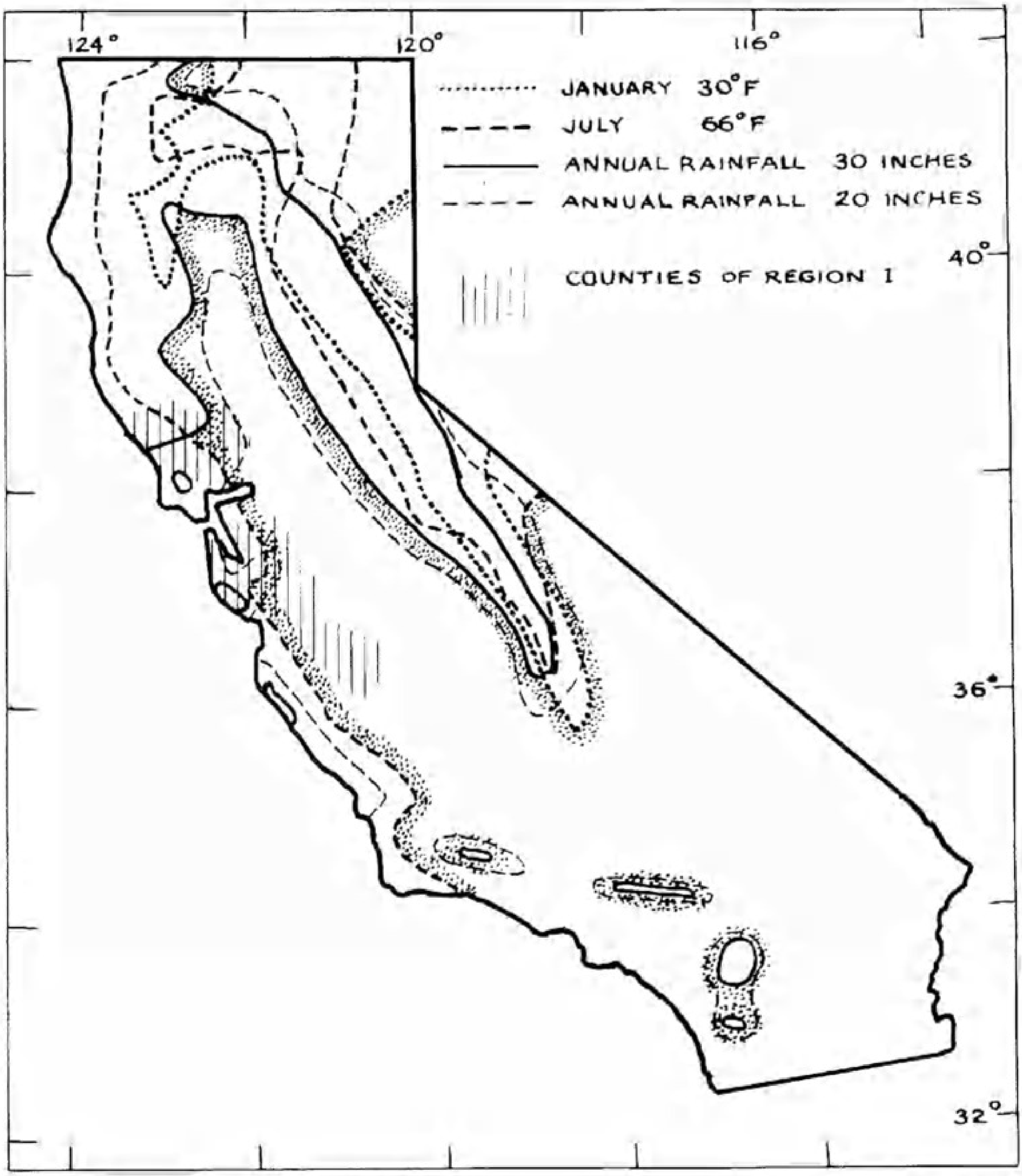

Fig. 4. Map of California on which have been projected temperature limits for the cultivation of the vine established at the northern margin in Europe. The area within which favourable conditions can be expected is margined. Counties included by Amerine and Winkler in their coolest Region I are shaded.

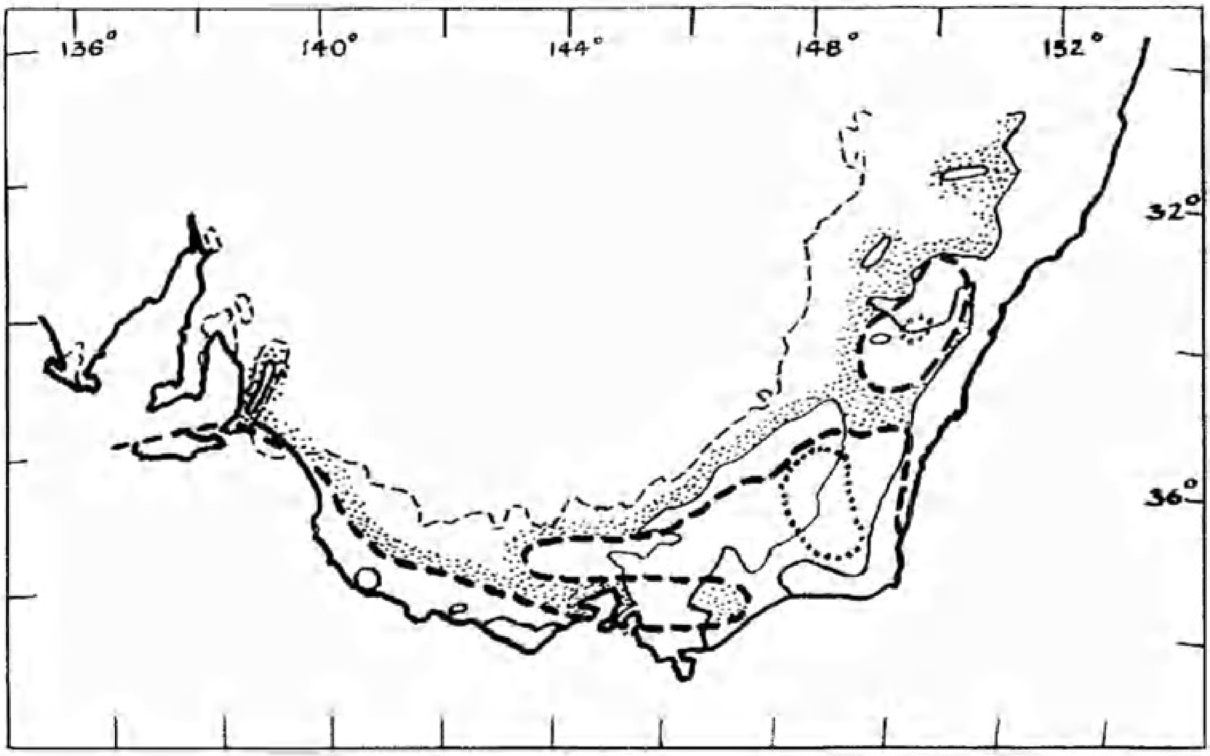

Fig. 5. Map of south-eastern Australia on which have been projected temperature limits for the cultivation of the vine established at the northern margin of cultivation in Europe. The area within which favourable canditions can be expected is margined.

The temperature characteristics are given below:

Station	Temperature Characteristics			Temperature of warmest monthly period °F	Length of season over 50°F months	Accumulated day-degrees above 50°F
	Mean °F	Amplitude °F	Phase Days			
Napa	57·5	10·0	36·2	66·7	9·4	2,890

These temperature characteristics are obviously quite different from those of the European limits, due principally to the length of the season. If the criterion of seven months, April to October, be taken the temperature accumulation is 2,680 day-degrees corresponding to Region II of Amerine and Winkler, the region regarded by them as most important for table wines. For the established viticultural area of California, criteria independent of northern European experience must therefore be established if the summation of temperatures is to be used.

TABLE 3.

Localities in California with Temperature Characteristics Approaching those of the Northern Limit of the Cultivation of Vines in Europe.

Station	Latitude °N	Longitude °W	Altitude feet	Temperature characteristics: Mean °F	Amplitude °F	Phase days	Season over 50°F months	Annual rainfall inches
Alturas	41·5	120·5	4,346	47	18	32	5·1	13
Cedarville	41·5	120·2	4,675	48	19	33	5·1	12
Mt. Shasta City	41·3	122·3	3,543	49	17	34	5·6	34
Fall River Mills	41·0	121·5	3,340	50	17	31	7·0	17
Susanville	40·4	120·6	4,152	49	18	31	5·4	18
Mineral	40·3	121·6	4,850	46	16	39	4·7	45
Bowman Dam	39·5	120·7	5,347	50	16	43	5·5	70
Nevada City	39·3	121·0	2,600	54	15	39	6·7	49
Dudley's	37·8	120·1	3,000	53	14	36	6·5	37
Yosemite	37·7	119·6	3,985	51	18	31	5·2	34
Giant Forest	36·6	118·8	6,360	48	14	41	4·9	24

The map reveals, however, a number of intersections between the isotherms of 30° F. and 66° F. for the coolest and warmest months respectively. These are inland areas and at some altitude. Recording stations near such intersections are given above (Table 3), together with temperature characteristics.

This Californian experience may be extended to the State of Washington where approximately 8,000 acres of vines are grown, nearly all of which are under irrigation, in the south central portion of the State.[1] Approximately 85 per cent of this acreage is planted to the American variety Concord (*V. labrusca*) and most of the vinifera varieties have to be covered to survive the severest winters. The mean temperature of the warmest month at the Irrigation Experiment Station at Prosser is 71° F. and of the coldest month 29° F. The length of the season over 50° F. is 6·4 months.

Australia

The appropriate temperature and rainfall limits have been plotted on the map of Fig. 5 for south-eastern Australia. Tasmania is well outside the limit of 66° F. for the warmest month, and all of the rest of Australia west of Kangaroo Island comes within the limit. As with California, there is a temperature control imposed by proximity to the oceans and away from these a further control imposed by altitude.

The most interesting locality near the limit is that of Coonawarra (37·3°S., 140·3°E.) in South Australia which in recent years has become an area noted for red table wines. The temperature characteristics of Coonawarra, based on interpolations from long-established recording centres in the general region are given below:

Station	Temperature characteristics			Temperature of warmest monthly period °F	Length of season over 50 F months
	Mean °F	Amplitude F	Phase Days		
Coonawarra	57·5	8·4	31·2	66·4	9·4

These conditions are very similar to those at Napa in California recorded in the preceding section, but the conditions in winter are much milder than those in Europe. In no locality in Australia does the isotherm of 30° F. for the coolest month intersect that of 66° F. for the warmest month.

Mean Summer temperatures of 66° F. are reached at altitudes of approximately 3,800 feet in the northern tablelands of New South Wales, at 3,000 feet in the central tablelands, at 2,500 feet in the southern tablelands and at 1,700 feet in Victoria. The Canberra region comes just within the limit.

In general, the conditions in Australia will need a separate study allowing for wider comparisons with the warmer regions of Europe, western Asia and California.

[1] Personally communicated by W. J. Clore, May, 1965.

APPENDIX

THE SUMMATION OF TEMPERATURES IN AGRICULTURAL CLIMATOLOGY

Soon after his invention of the alcohol thermometer in 1730, Reaumur organised a series of temperature observations in Paris and overseas. He noted (Reaumur, 1735) that the agricultural season of 1735 was much later than in recent years and that the wheat and grape harvests had been delayed by at least a month. He noted that this was associated with lower temperatures in spring and early summer and proceeded to compare the conditions in the months of April, May and June in 1734 and 1735 on the basis of the "sum of the degrees of heat". For each day he determined the mean temperature by taking half the sum of the maximum and minimum and proceeded to add them day by day for each of the three months.

Sums of temperature above freezing point °R at Paris

	April	May	June
for 1734	343	405	512
for 1735	270	328	417

He suggested that by this means different countries and years could be compared.

In view of the fact that the same grain crops can be harvested in countries with very different temperatures, one should be able to compare the sums of degrees of heat for the months during which the cereals made the greatest part of their growth and came to maturity in warm countries such as Spain and Africa, in temperate countries as in France, and in cold countries as in those of the north.

This idea of treating temperature readings as measuring the quantity of heat appears to have been projected forward into the nineteenth century in spite of the discovery and naming of "quantity of heat" and "latent heat" by Joseph Black in 1760. The idea of "absolute temperature" was not to come until after 1850.

The first notable application of this suggestion of Reaumur was made by Boussingault (1837), who compared the temperatures under which wheat, barley, maize and potatoes were grown both in Europe and in the Americas. He was able to make observations on his own farm at Bechelbronn in Alsace. He expressed the requirement in the quantitative form:

"The number of days between the beginning of the growth of an annual plant and its maturation is inversely proportional to the mean temperature during this period of growth, so that the product of the number of days by the temperature is constant."

Of seven examples which he gives for maize, two may be quoted:

Locality	Mean annual temperature °C	Mean temperature during crop °C	Number of days	Product
Bechelbronn (Alsace)	9·8	20·0	122	2,440
Valley of the Magdalena	17·0	27·0	92	2,484

The principal contribution of the botanists who followed Boussingault was to recognise that plant activities ceased below certain temperatures and this information was critically examined by Alph. de Candolle (1855) and applied to a large number of wild species – annual, perennial and woody – in Europe. He then proceeded to extend the concept to cultivated species and established useful minimum temperatures for a number of crops.

De Candolle's table for cultivated species is worth quoting in view of the continued application of the concept to the present day.

Alphonse de Candolle's table of temperature summation:

Crop	Extreme limit in Europe		Minimum useful Temperature		Summation of temperatures above useful minimum day-degrees
	Country	Latitude °N	°C	°F	C
Barley	Norway	70	5	41	1,250
Vine (for wine)	Germany	52·2	10	50	2,900
Maize	Germany	51	13	55	2,500
Date palm (for fruit)	Spain	39·5	18	64	5,100

De Candolle always insisted that mean daily temperatures below the freezing point of water (0° C.) were not to be taken into account, thus establishing a secondary base level below the effective minimum.

De Candolle advocated the regular publication by official meteorological departments of mean temperatures and summation in excess of specified minima and this was, in fact, taken up by the London meteorological office and noted by de Candolle (1884). At this period the London office was already publishing weekly a summation to temperatures above 42° F. These were recorded as "day-degrees", a term invented by the Meteorological Office in London.

De Candolle (1886) attended the 69th Session of the Swiss Society for Natural Sciences in August of that year, at which J. H. Gilbert (1886) of Rothamsted gave an account of the relationship which exists between sums of temperatures and agricultural production. This paper is reported in full. Gilbert reported that in 1881, the London meteorological office on the suggestion of Lawes and himself began to publish weekly sums of temperature above a fixed base, together with hours of sunshine and rain, for the information of agriculturists, the base temperature chosen being 42° F. as stated above.

Gilbert tabulated the sum of temperatures from certain fixed dates until the time of harvest of wheat at Rothamsted for the years 1852 to 1885. For the years 1878 to 1885 these are based on the weekly publications of the meteorological office. Gilbert recorded for winter wheat, over the full period, sums of temperatures of the order of 1,100 to 1,200 day-degrees.[1] The London Meteorological Office is still (1965) interested in accumulated temperatures, above and below 42°F., and these are entered in the monthly returns from all crop-weather stations in Britain. The continued use of accumulated temperatures is, however, currently under discussion.[2]

Modern applications in terms of this concept of temperature summation come mainly from North America. The bridge between the European work of the nineteenth century and the American work of the twentieth is provided

[1] The responsible people at the Meteorological Office in London were R. H. Scott and General Strachey.

[2] Personally communicated by H. L. Penman.

by Abbe (1905). Livingston (1916) compared the summation of direct temperatures with the summations of temperature efficiences based on the physico-chemical concepts of Arrhenius and Van't Hoff and with those of physiological efficiencies based on experimental studies. He was a strong advocate of the provision of experimental facilities to enable studies of plant growth to be made in controlled environments.

Of more recent years, Nuttonson (1955, 1957, 1958) of the American Institute of Crop Ecology has applied the summation of temperatures above a fixed base line to the study of the climatic requirements of wheat, barley and rye, and found that a base temperature of 40° F. gave the most satisfactory values. This temperature was selected after testing 32°, 36°, 40° and 45° F. Following Livingston, he refers to the method as the *remainder-index* system.

Amerine and Winkler (1944, 1963) have applied the method to the study of the climatology of the grape-vine in California, and Amerine (1963) also gives references to work in the Soviet Union. They classify the vine areas of California into five regions from the coolest to the warmest on this basis. In the earlier publication the physiological period, blooming to harvest, was used; in the later publication a fixed calendar period, April to October inclusive, is employed.

Clore and Drummund (1963, 1964) also have applied the method to the interpretation of seasonal conditions for grape growing in the State of Washington. In view of the increasing use of the concept in horticultural practice in the United States, involving shorter periods and more accurate assessments of temperature summations, Arnold (1960) has proposed a convenient method for estimating degree-days from daily temperatures when the minimum temperature is below the base temperature.

It is evident from the long history of the use of temperature summations in crop physiology, that it will find its most useful applications when restricted to crop periods, such as the emergence of an annual crop to its harvest period, or in the case of a deciduous perennial from bud-burst to leaf-fall or to ripeness of the fruit. In this connection both de Candolle and Gilbert were aware of the need to bring in solar radiation and Gilbert even noted the lag between the time of greatest sunshine and the time of warmest temperature.

As soon as the method is used over a fixed calendar period there is no advantage to be gained over quoting the mean temperature during the period. The use of harmonic characteristics, moreover, can be used to express much of the relevant information and can be used, if required, to calculate the summation of temperatures over any specified period and more particularly the temperatures at the warmest and coolest periods.

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SOURCES OF INFORMATION

BRIQUET, J. (1940). Biographies des botanistes à Genève de 1500 a 1931. Bull. Soc. Bot. Suisse., vol. 50a.

KENDREW, W. G. The Climates of the Continents, fourth edition, Oxford, 1953.

LEUNIS, J. (1883). Synopsis der drei Naturreiche, Part 2, Vol. 1. Synopsis der Pflanzenkunde Allgemeiner Theil. 3rd edition by A. B. Franz, Hanover.

UNITED STATES DEPARTMENT OF AGRICULTURE YEARBOOK, 1941. Climate and Man. Washington D.C., 1941.

WEINBAU-LEXIKON für Winzer, Weinhändler, Küfer und Gastwirte. Berlin, 1930.

REFERENCES

ABBE, C, 1905. First Report on the Relations between Climates and Crops. U.S. Dept. Agr. Weather Bureau, Bull. 36.

AMERINE, M. A., 1963. Viticulture and Enology in the Soviet Union. The Wine Districts of the Soviet Union. Notes on Wines Tested in the Soviet Union. Wine and Vines. Oct., 29-36. Nov., 57-64. Dec., 25-29.

AMERINE, M. A., and WINKLER, A. J., 1944. Composition and Quality of Musts and Wines of California Grapes. Hilgardia, 15, No. 6, pp. 493-673.

AMERINE, M. A., and WINKLER, A. J., 1963. California Wine Grapes. Cal. Agr. Expt. Sta. Bull. 794.

ARNOLD, C. Y., 1960. Maximum-minimum Temperatures as a Basis for Computing Heat Units. Proc. Amer. Soc. Hort. Sci., 76, pp. 682-692.

BLACK, J. N., 1960. A Contribution to the Radiation Climatology of Northern Europe. Arch. Met. Geophys. Bioklim. B., 10, pp. 182-192.

BOUSSINGAULT, J. B., 1837a. Examen comparatif des circonstances météorologiques sous lesquelles végètent les céréales, le maïs et les pommes de terre à l'équateur et sous zone tempéré. C.R., 4, pp. 178-179.

BOUSSINGAULT, J. B., 1837b. Des influences météorologiques sur la culture de la vigne. C.R., 4, pp. 371-378.

CANDOLLE, ALPH. L. P. P. DE, 1855. Geographie botanique raisonée. Paris, Geneva, 2 vol., 1365 pp., particularly Chap. 4, Sec. 5, pp. 393-405.

CANDOLLE, ALPH. L. P. P. DE, 1884. Indexed as: Notation des températures au point de vue de l'agriculture et des faits de végétation. Arch. Sci. Phys. Nat. Ser., 3, 11, p. 320.

CANDOLLE, ALPH. L. P. P. DE, 1886. Indexed as: Sur la valeur des sommes des températures en géographie, botanique et en agriculture. Arch. Sci. Phys. Nat. Ser. 3, 16, pp. 325-326.

CLORE, W. J., and BRUMMUND, V. P., 1963. Some Aspects of Washington State's Remarkable 1963 Grape Crop. Wash. State Hort. Assoc. Proc., 59, pp. 165-169.

CLORE, W. J., and BRUMMUND, V. P., 1964. 1964—a Quality Year for Grapes. Wash. State Hort. Assoc. Proc., 60, pp. 135-139.

GILBERT, J. H., 1886. Remarques sur la relation qui existe entre les sommes de température et la production agricole. Arch. Sci. Phys. Nat. Ser. 3, 16, pp. 421-436.

HILLEBRAND, W., 1963. Deutsche Wein Zeitung, 99, p. 879.

JOHNSTON, R. D., 1964. Water Relations of *Pinus radiata* under Plantation Conditions. Aust. J. Bot., 12, pp. 111-124.

LIVINGSTON, B. E., 1916. Physiological Temperature Indices for the Study of Plant Growth in Relation to Climatic Conditions. Phys. Res., 1, 8, pp. 399-420.

NUTTONSON, M. Y. Amer. Inst. Crop Ecology (Washington):
Wheat-Climate Relationships (1955), 388 pp.
Barley-Climate Relationships (1957), 280 pp.
Rye-Climate Relationships (1958), 219 pp.

ORDISH, G., 1953. Wine Growing in England. London.

PRESCOTT, J. A., and LANE-POOLE, C. E., 1947. The Climatology of the Introduction of Pines of the Mediterranean Environment to Australia. Trans. Roy. Soc. S. Aust., 71, pp. 67-90.

REAUMUR, R. A. F. DE, 1735. Observations du thermometre, faits à Paris pendant l'année 1735. Comparées avec celles qui ont été faites sous la ligne, à l'Isle de France, à Alger, et en quelques-unes des nos Isles de l'Amerique. Mem. Acad. Roy. Sci., pp. 545-576, particularly p. 559.