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Scheduling irrigation to meet crop demands

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WHY PLANTS USE WATER

Plants require amazingly large amounts of water. Every day a leafy, actively growing plant uses five to ten times as much water as it can hold at one time. A good crop of wheat extracts enough water during the growing season to cover the ground 45 cm deep. In other words, about 1000 kg of water is needed to produce 1 kg of wheat. But only a fraction of this water is retained by the plants.

Why do plants remove so much water from the soil and expel nearly all of it into the air? Water is used to transport nutrients from the soil to green plant tissue where they are used in photosynthesis. Carbohydrates, the products of photosynthesis, are conveyed in water solution to storage organs such as seeds, roots, or tubers. Having transported the various materials to their destinations in the plant, the water simply evaporates through the stomata, tiny pores in the leaves. This evaporation process, called transpiration, absorbs heat, cools the plant, and prevents the buildup of injuriously high temperatures.

Plant cells are like little water bags. Without internal pressure, called turgor, they lose their shape. Turgor pressure results because the concentration of salts and sugars in solution within the plant cells differs from that outside the cells. When plants are amply supplied with soil moisture, the solution outside the cells is less concentrated than the solution within the cells. Water tends to move through the cell membranes into the cells to equalize the concentration of both solutions. Thus, turgor pressure is high, and the plants maintain their shape. When plants have insufficient water, the solution outside the cells becomes more concentrated than the solution within the cells, water moves out of the cells to equalize the concentration, turgor pressure drops, and the plants wilt. Consequently, herbaceous plants require ample water to maintain their rigidity and shape.

Plants automatically reduce transpiration when their water intake cannot equal the rate of water loss. They simply close their stomata when the water content of the leaf tissue declines. But this closure also prevents carbon dioxide from entering the leaf tissue and restricts photosynthesis and plant growth. Therefore, transpiration cannot be reduced without reducing crop yield. When soil moisture is restricted or chemicals that close stomata artificially are applied, crop yields are usually lowered.

During hot weather, low-volume sprinkling to cool the crop reduces transpiration. But the water saved by reducing transpiration is offset by increased evaporation losses. No overall saving of water is realized. When this procedure was tested under the climatic conditions of southern Alberta, neither yield nor quality of beans or potatoes was notably increased, provided that an adequate level of soil moisture was maintained.

The apparently extravagant use of water by plants can be reduced, but not eliminated. For example, the soil need not be wetted deeply when the crop is young and rooting is shallow. Nor is full soil moisture required when seeds have nearly ripened. But these water-saving measures only prevent loss of soil moisture through drainage or direct evaporation from the soil surface. Transpiration continues at a natural rate.

Water is used most efficiently when high-yielding crops and varieties are grown with optimum soil fertility, good cultural practices, and correct amount and timing of irrigation. These procedures ensure the greatest crop yield for each unit of water used. The method of irrigating does not significantly influence crop response.

THE SOIL–PLANT SYSTEM

The soil occupied by plant roots is the immediate and most important storage reservoir of water for the crop. But part of this water is held too tightly in the soil to be removed by plants. When soil moisture is reduced to this level, plants wilt; hence, the soil moisture is said to be at the wilting point.

Often, soil cannot hold all the water that comes as precipitation or irrigation, and the excess drains uselessly away. Field capacity is the upper limit of water that the soil can hold without appreciable drainage. The available water in the soil represents the field capacity minus the water held by the soil at the wilting point.

As the available water is used by the crop, increasing suction is required to extract it. At field capacity, the suction required to extract the soil moisture is about 0.3 bar, which is the force required to lift the water about 3.4 m. At the wilting point, the suction required to extract the soil moisture is about 15 bars, the force required to lift water about 155 m (if that were possible). This figure represents the practical limit at which plants can extract moisture. In fact, only about half the water held between field capacity and wilting point is said to be readily available. The remaining half becomes increasingly difficult for the plants to remove as extraction proceeds.

Plants function somewhat like water pumps, using differences in suction between the soil, plant, and air to take water from the soil and deliver it to the atmosphere. Heat from the sun warming the air, directly or by radiation from the soil surface, creates a difference in vapor pressure between the air and the leaves. When the suction exerted by the warm air exceeds that holding the water in the plant, water is transpired. Suction forces of adhesion, cohesion, and osmosis in the soil in contact with the roots tend to prevent the flow of water and plant nutrients into the plant. Within the plant, there are suction forces similar to those in the soil plus the additional effect of elevation. If the soil moisture suction is less than the suction that tends to move water into the roots, through the plant, and into the atmosphere, the crop can remove moisture from the soil. When soil moisture suction is greater than the moisture suction in the plant, the plant stops removing water from the soil and growth ceases.

EVAPOTRANSPIRATION

The evapotranspiration value, ET, is the amount of water the crop removes from the soil and transpires plus the amount of water evaporated directly from the soil. It is usually expressed in millimetres. Measured or estimated ET values can be used to indicate the amount of irrigation needed to replenish soil moisture and the point at which irrigation becomes necessary. The technique is explained in the section on budgeting soil moisture and scheduling irrigation.

Potential evapotranspiration, ET_p, is the water required by a vigorously growing crop that completely shades the ground and is adequately supplied with soil moisture. ET_p is about the same for all common field crops and depends almost entirely upon the amount of heat energy available. From mid-July to early August, it averages about 7 mm/day; but on excessively warm days, it may reach 13 mm. If soil moisture is below the readily available range, or if the crop is either not fully developed or nearly ripe, actual ET will be less than ET_p.

Total ET for the growing season is greater for perennial crops than for annuals because perennials are already established in the spring and continue vegetative growth later in the fall. Row crops such as sugar beets or corn have lower ET values in the spring than close-seeded crops because they do not establish ground cover as quickly. Short-season crops like green peas or beans have lower seasonal ET values than longer-season crops like sugar beets.

When soil moisture is kept readily available, plants take most of their water from the top 50 cm of the root zone. As the water in the upper portion of the root zone is used and soil moisture suction increases, more water is drawn from greater depths. Depths of rooting differ among crops and vary with stage of growth, physical characteristics of the soil, and content and distribution of soil moisture. For practical purposes, rooting depths are as follows: alfalfa 120–180 cm; grass, cereals, flax, rape, and sugar beets 90–120 cm; corn 75–120 cm; potatoes 60–90 cm; and peas 75–90 cm. Unless they are extreme, differences in rooting depth do not cause differences in rate of water use. But rooting depth does determine the amount of water available to the crop. The deeper the root zone, the greater its capacity for storing available water. The root zone of most mature annual crops is about 120 cm deep.

The increase in crop growth associated with improved crop management is usually greater than the relative increase in water use. For example, fertilizers, where required, increase the rate of water use by promoting earlier and faster crop development; but the increased crop growth more than compensates for the increased water consumption.

Crops that are appreciably taller than the surrounding vegetation or crops on small, irrigated fields surrounded by dry land or summer fallow may capture heat from outside the cropped area. This movement of extra heat into the cropped area is known as advection and can cause ET to exceed ET_p slightly.

EVAPOTRANSPIRATION FOR DIFFERENT CROPS

The solid lines in Figs. 1–11 show the average daily values of ET as the season progresses from seeding to harvest for some of the important irrigated field crops in southern Alberta. The areas enclosed by the dotted lines on either side of the solid lines indicate two-thirds of the range of fluctuation that arises from daily variations or changes from year to year. Consequently, two-thirds of the time the curves are expected to lie between these dotted lines. The curves for alfalfa and grass are constructed as if the crop were not harvested in mid-season. In practice, daily ET is substantially reduced after each mid-season harvest of hay or forage.

The data for each curve were obtained over a minimum of 3 and usually 5 or 6 years of study at the Irrigation Research Substation, Vauxhall, Alta. The soil is a medium-textured loam, typical of much of the irrigated land of southern Alberta. Yields of the crops in these studies were consistently higher than the commercial averages. Soil moisture was maintained in the readily available range to allow for full expression of the yield potential. Estimated deep drainage amounted to only about 5% of ET, and low salinity was maintained in the root zone. Average dates for stages of crop development and percentage of ground cover are shown with the curves for the annual crops (Figs. 3–11). ET is best expressed as a function of growth stage rather than time of year because growth stages do not always occur on the same date each year.

DETERMINING POTENTIAL EVAPOTRANSPIRATION AND EVAPOTRANSPIRATION

ET_p and ET cannot be measured conveniently on farm fields but can be estimated from evaporation, E, measured with any of several evaporimeters. The class A evaporation pan (Fig. 12) is the device that measures E to an accepted world standard. The close correlation of evaporation from a class A pan (E_A) with ET is well documented. But the large size and large water requirement of the A pan limit its convenience as a field instrument.

Small evaporimeters that use a black porous carborundum disc continuously supplied with water are more convenient than the class A pan and are widely used in Alberta. These are the alundum disc (Fig. 13) and the Gen evaporimeters (Fig. 14). They perform alike, relate closely to A pan evaporation, and can be used to estimate *ET* from previously established *ET/E* relationships (Figs. 1–11). To convert E_A, expressed in millimetres, to equivalent evaporation from the alundum disc (E_d) or the Gen evaporimeters (E_G), expressed in millilitres, use the following formula:

$$E_d \text{ or } E_G = E_A \times 9.5$$

With this conversion, E_A as well as E_d or E_G can be used to calculate *ET* using the coefficients given in Figs. 1–11.

In extremely hot, windy weather, water conduction through the plants may be insufficient to meet the evaporational demand. Then, *ET* becomes less responsive than *E* from an evaporimeter, and the relationship between *ET* and *E* no longer remains the same as at lower rates of *E*. Consequently, when E_G or E_d is converted to *ET*, an upper limit on *E*, tentatively suggested to be 110 ml/day, should be set.

APPLICATION OF EVAPOTRANSPIRATION CURVES IN IRRIGATION SCHEDULING

Average daily E_G for 16 years is shown as a broken line in Figs. 1–11. Since E_G and *ET* are related, the inclusion of E_G as a climatic index provides a common reference for all the *ET* curves and a means of integrating broad climatic differences and day-to-day weather fluctuation into the scheduling procedure. Relationships of *ET* with *E* from other evaporimeters may also be used.

Mean values of *ET* and E_G depicted in Figs. 1–11 do not illustrate the wide daily fluctuations that occur. But if weather is characterized daily with an evaporimeter, actual *ET* can be determined from mean *ET* in the same proportion that actual E_G bears to mean E_G. Relationships of *ET* with *E* from other evaporimeters or with that calculated from meteorological indexes may also be used to estimate the daily evapotranspirational demand of the environment.

ET values are much lower than *E* or ET_p values in spring, increase to nearly identical values in summer, and decline in fall. Therefore, *E* measurements cannot be used as a direct measurement of *ET*. The coefficients used to estimate *ET* from E_G are shown in each figure. These coefficients are for various stages of crop growth. It may be convenient to ignore slight differences and group together crops whose coefficients are similar at similar growth stages. Combining groups of crops such as cereals or row crops is particularly useful.

The coefficients do not change abruptly at each new stage of growth; rather, they vary continuously through the season, depending on changes in the characteristics of the particular crop. The season can be divided into any number of parts, each with a different coefficient. Accuracy of the *ET* estimate is improved as the number of increments is increased. The breakdown given in the figures is satisfactory for field application, but the curves are provided so that any appropriate interval can be selected. Eventually, daily coefficients based on a continuously changing relationship of *ET* to *E* will be derived mathematically.

BUDGETING SOIL MOISTURE AND SCHEDULING IRRIGATION

To schedule irrigation according to need, a daily soil moisture budget must be kept. Water is applied when the account shows that the level of soil moisture is low. For most crops, irrigation is needed when half the available soil moisture is used. Exceptions include potatoes, which require that soil moisture be kept in the upper third of the available range, and alfalfa, which can safely use two-thirds of the available soil moisture before irrigation becomes necessary. If irrigation is started when these lower limits of available soil moisture are indicated by the budget, the entire field can usually be covered before soil moisture stress becomes serious. To be safe, however, daily deductions of *ET* from the account should be resumed the day after irrigation is started rather than after the field is completely covered.

On a medium-textured soil with fairly heavy crops, irrigating according to the above guidelines results in about 5% downward leaching. This leaching is sufficient to prevent the accumulation of salts in the root zone on most soils and with most irrigation waters.

Because the water-holding capability of soil varies with texture, soil type influences the amount of readily available moisture. The root zones of most annual crops at maturity (120 cm) can hold about 100 mm of available water in loamy sand, 140 mm in fine sandy loam, 190 mm in silt loam, 200 mm in silty clay loam, and 220 mm in clay loam. Soil moisture can safely be depleted by half these amounts. When soil moisture is reduced, for example, to 50 mm below field capacity on sandy loam or 110 mm on clay loam, sufficient irrigation is required to bring the moisture content back to field capacity.

The *ET* curves were determined from crops for which optimum soil moisture was provided and good agronomic practices were used. When crop growth is below optimum, conversion factors that are lower than those given in the figures may be more realistic. When growth is restricted by inadequate soil moisture, *ET* values are substantially lower than those shown. When other factors, such as low soil fertility, limit growth but soil moisture is adequate, *ET* values are lowered only slightly. Conversion ratios during the latter part of the growing season may be reduced for some crops, such as cereals, by allowing full depletion of stored soil moisture as harvest time approaches.

The soil moisture at the start of the budget is preferably determined by oven-drying soil samples. Alternatively, the budget could be started about 2 days after a heavy rain or an irrigation when the root zone is known to be near field capacity. For a medium-textured soil, moisture content is near field capacity when a ball of soil definitely resists crumbling after being firmly squeezed in the hand.

LIMITATIONS AND SPECIAL CONSIDERATIONS

There are some limitations to these simple budget procedures. The actual depth of rooting of annual crops does not begin at maximum depth in the spring and remain constant, but increases from seeding depth at planting time to a maximum depth around mid-season. When the crop is young, the soil moisture recorded by a simple budget may be unavailable because it is held below and out of reach of the roots. Therefore, the depth at which the soil is moist in the spring in relation to the rooting depth of the crop should be determined. Fields should be irrigated in the fall if soil moisture at harvest is in the lower half of the available range. This precaution ensures readily available moisture in the lower part of the root zone, and only a small amount of precipitation in winter or spring is needed to moisten the upper part of the root zone adequately.

When crops are young, the need for irrigation is best determined by actually examining the soil in the shallow root zone.

Environmental indexes other than *E* can be used to estimate *ET*. These include air temperature, humidity, wind, and solar radiation; but *ET* appears to be almost as well correlated with *E* as it is with individual, or combinations of, meteorological variables.

The budget method of scheduling irrigation described here is intended primarily as a tool with which a central agency can provide scheduling advice to farmers in a district. The moisture-holding characteristics of the soil and actual soil moisture levels must be determined on individual fields, but *E* can be measured and *ET* calculated at a central location.

Refinements to the simple soil moisture budget to account for daily changes in rooting depth and continuous changes in crop coefficient, soil moisture content, and soil surface wetness and to permit estimation of *ET* from combinations of weather data require complicated calculation best performed by computers. These refined procedures are being studied at the Research Station, Lethbridge.

SAMPLE SOIL MOISTURE BUDGET

Table 1 shows a soil moisture budget for wheat grown near Vauxhall, Alta., during June 1975. Rainfall and *E* were recorded at the Irrigation Substation. The soil is sandy loam with a field capacity of 300 mm of water to the maximum rooting depth, 120 cm. Of this water, 90 mm is readily available and can safely be used before irrigation is necessary.

The rooting depths, corresponding field capacities and minimum allowable soil moisture, and the ET/E_G coefficients that were used in calculating the budget are given in Table 2.

On June 1, the moisture content of the root zone, which extended to 60 cm, was 135 mm, as determined by soil sampling. On June 2, 92 ml of water evaporated from the Gen evaporimeter. The coefficient required to convert *E* to *ET* at this time is 0.030. Therefore, *ET* for June 2 amounted to 3 mm. This loss reduced moisture in the root zone to 132 mm. Similarly, *ET* for each day was subtracted from the calculated soil moisture content of the previous day. Rain was added as it occurred. When the rooting depth was changed on June 11 to 90 cm and on June 25 to 120 cm, the 50 mm of soil moisture that was contained in the additional 30 cm of rooting depth was added to the moisture balance. Timely rains in mid-month resulted in a net gain in soil moisture. On June 26, 27, and 28, *E* exceeded 110 ml and so the maximum rule was applied. On June 29, the soil moisture content fell to 204 mm. Because the moisture level was below the minimum allowable level of 210 mm, 96 mm of irrigation was applied to restore root zone soil moisture to field capacity.

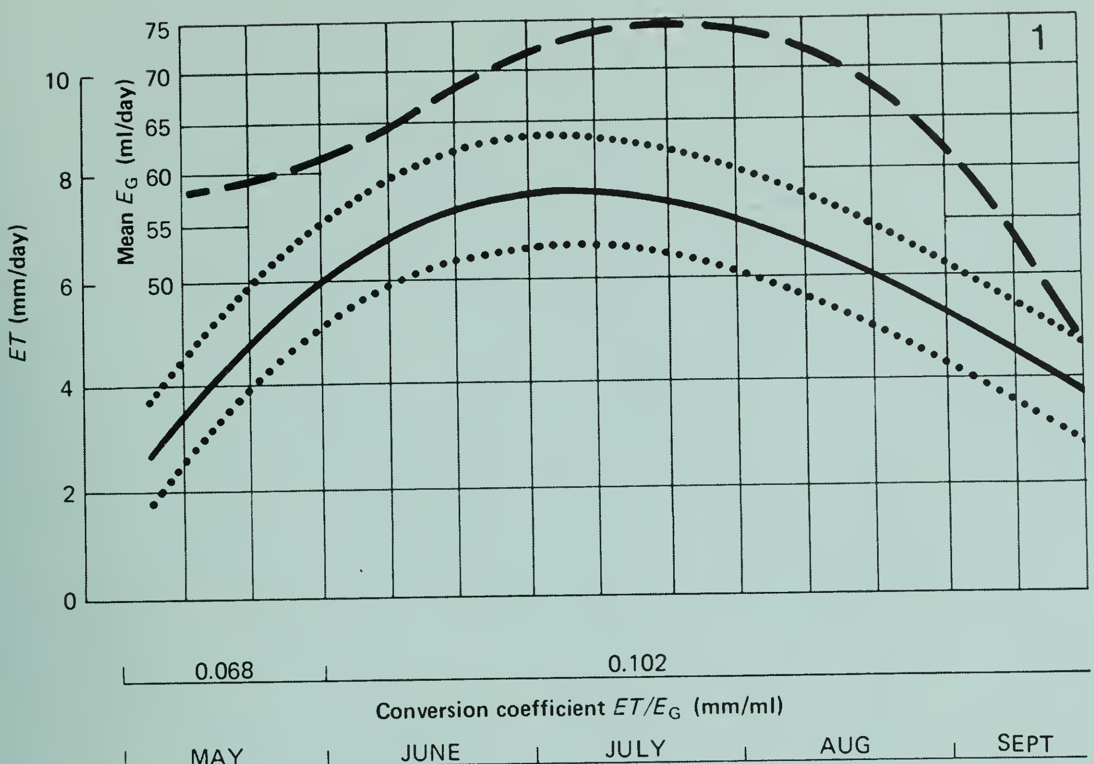
Table 1. SOIL MOISTURE BUDGET FOR WHEAT, JUNE 1975

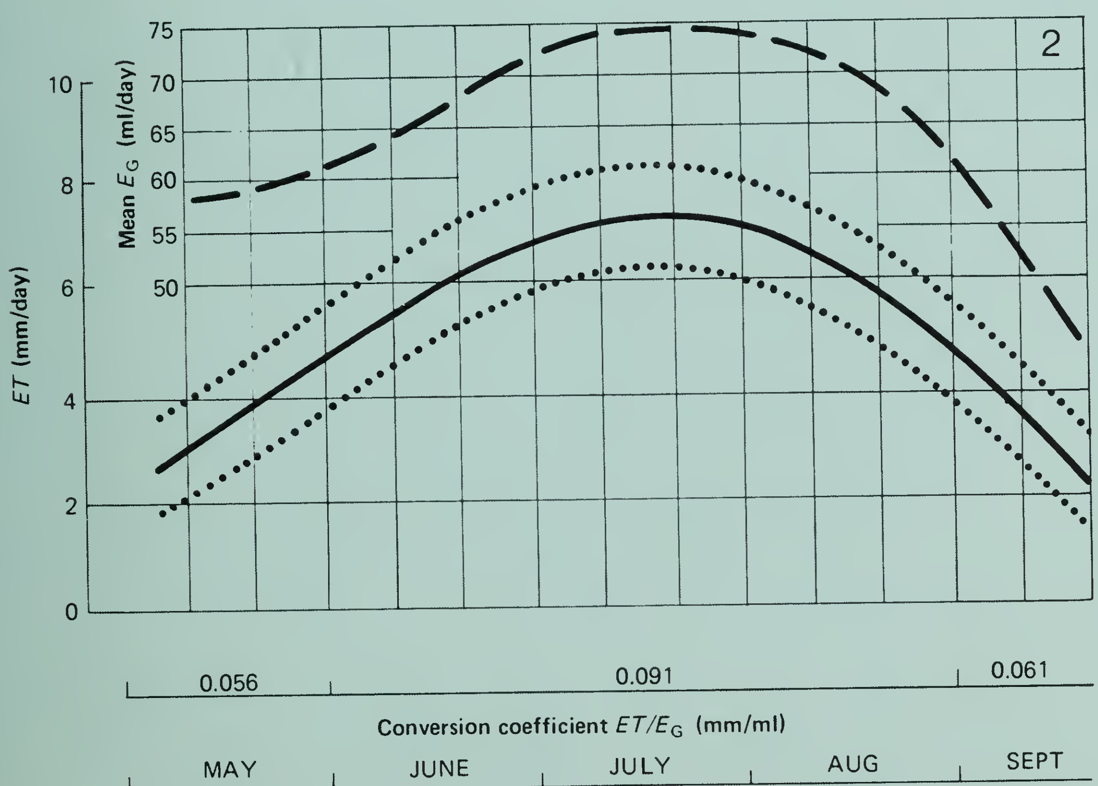
Date	*E* (ml)	*ET* (mm)	Rain (mm)	Irrigation (mm)	Soil moisture content (mm)
1	58	2			135
2	92	3			132
3	86	3			129
4	106	3			126
5	81	2			124
6	82	2	3		125
7	26	1			124
8	32	1			123
9	74	2			121
10	70	2			119
11	73	6			163*
12	49	4			159
13	0	0	6		165
14	38	3			162
15	14	1	4		165
16	16	1	5		169
17	42	3	1		167
18	39	3	2		166
19	0	0	43		209
20	17	1			208
21	96	7			201
22	90	7			194
23	71	5			189
24	59	4	17		202
25	106	8			244*
26	112	11			233
27	149	11			222
28	116	11			211
29	70	7			204
30	76	7		96	293

*50 mm of soil water added to the account with the added rooting depth.

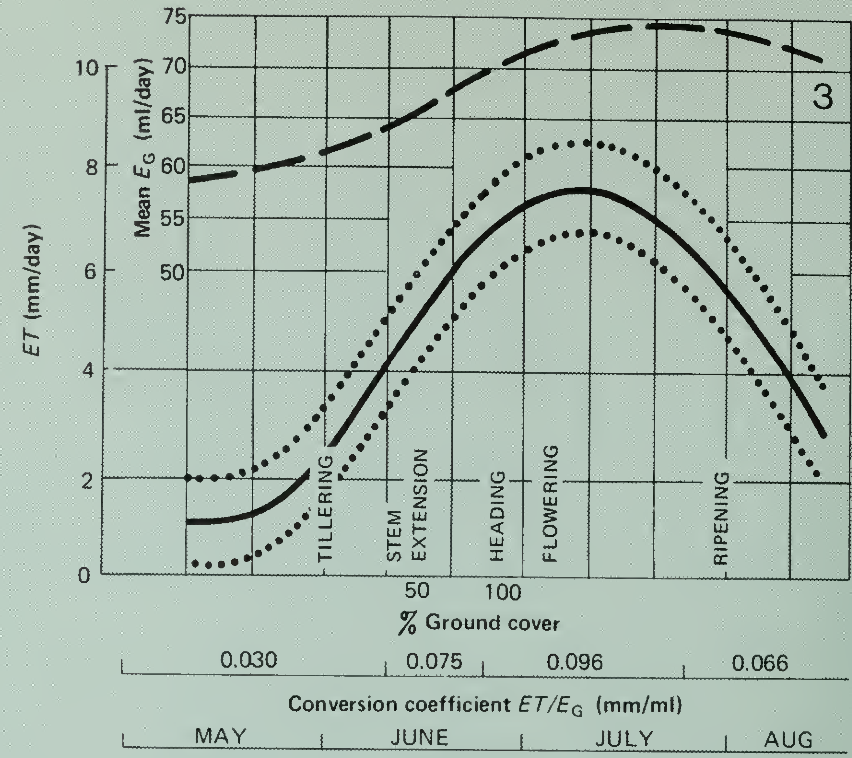
Table 2. DEPTHS OF ROOTING, FIELD CAPACITY (*FC*), MINIMUM ALLOWABLE SOIL MOISTURE (M_{min}), AND ET/E_G COEFFICIENTS USED IN CALCULATING A SOIL MOISTURE BUDGET FOR WHEAT IN JUNE 1975

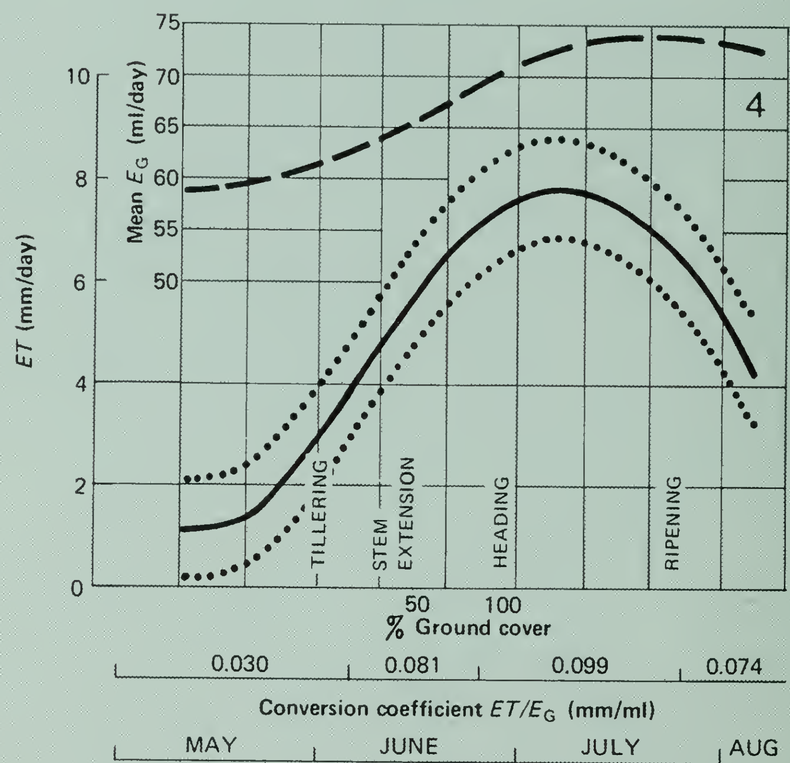
Date		Root depth (cm)	Soil moisture		Conversion coefficient, ET/E_G (mm/ml)
From	To		*FC* (mm)	*M*min (mm)	
June 1	June 10	60	150	105	0.030
June 11	June 25	90	225	157	0.075
June 26	June 30	120	300	210	0.096



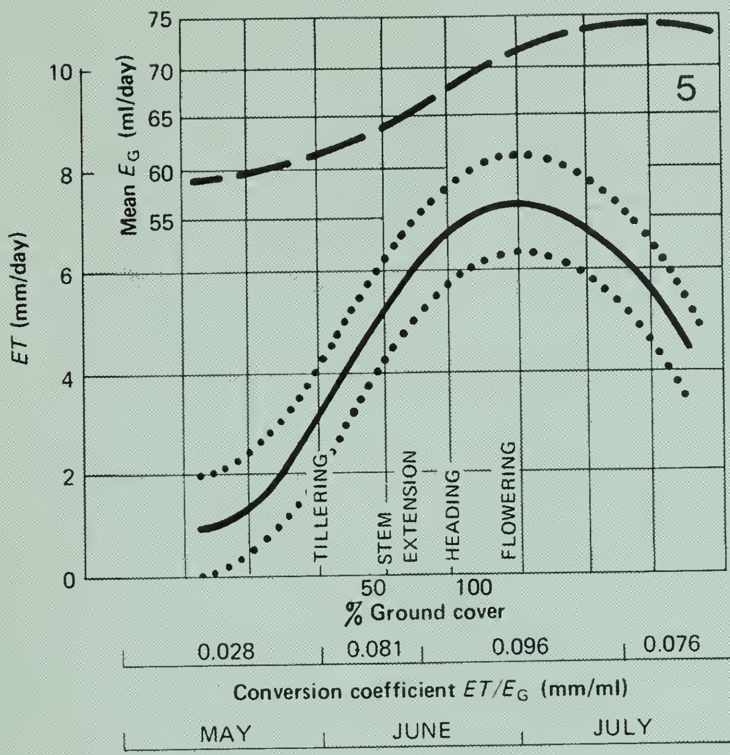


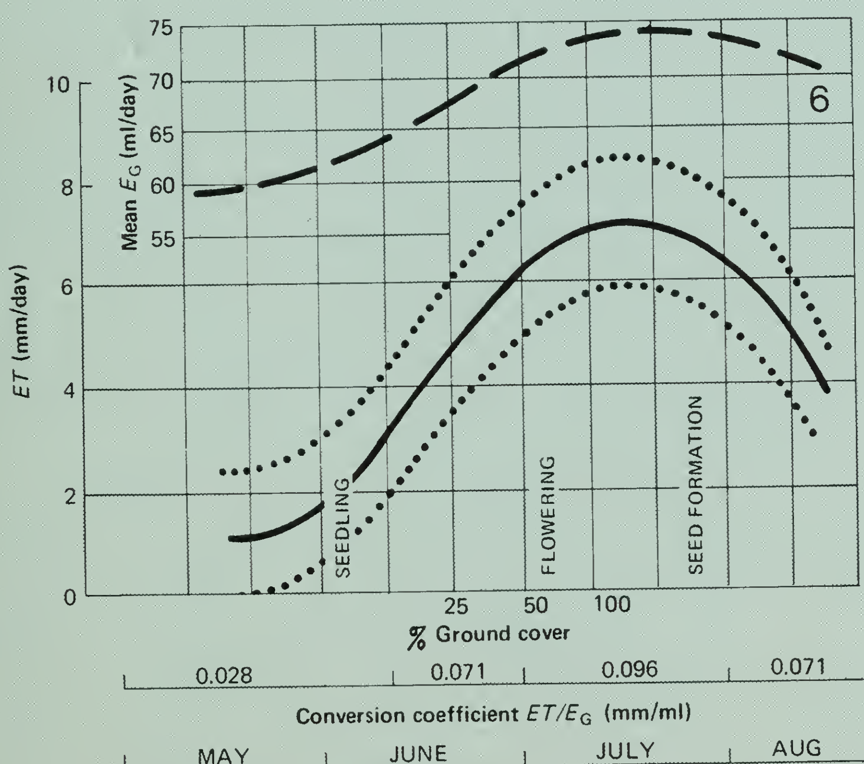
Figs. 1 and 2. Evapotranspiration from (1) **alfalfa** and (2) **grass** during the growing season, and the corresponding evaporation from a Gen evaporimeter. Solid lines are the *ET* curves that best fit the data; dotted lines indicate the standard error. Dashed lines show the mean daily loss of water, E_G, from the evaporimeter.



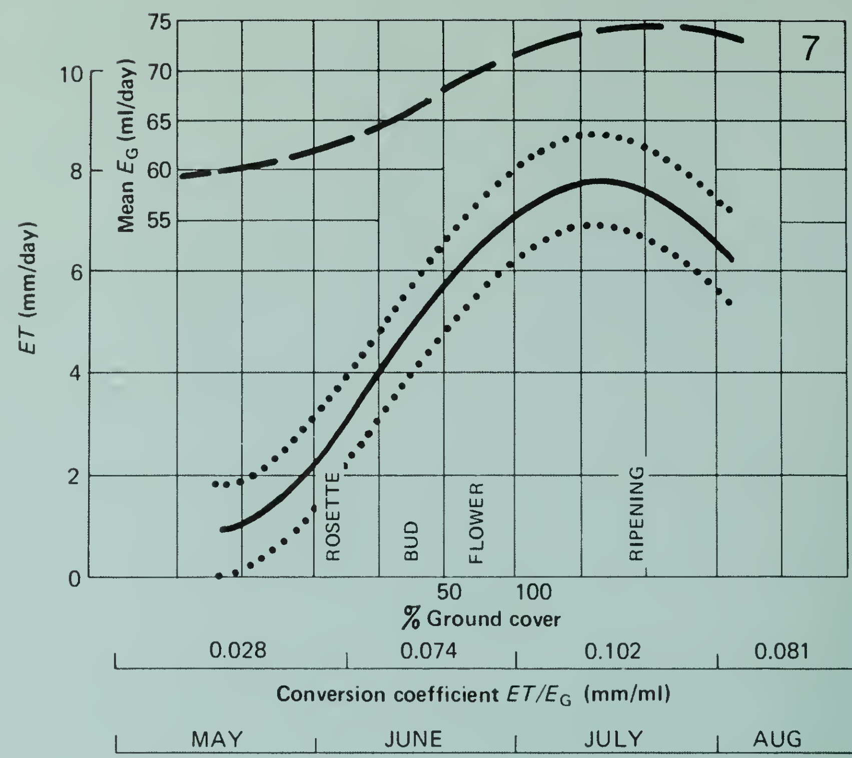


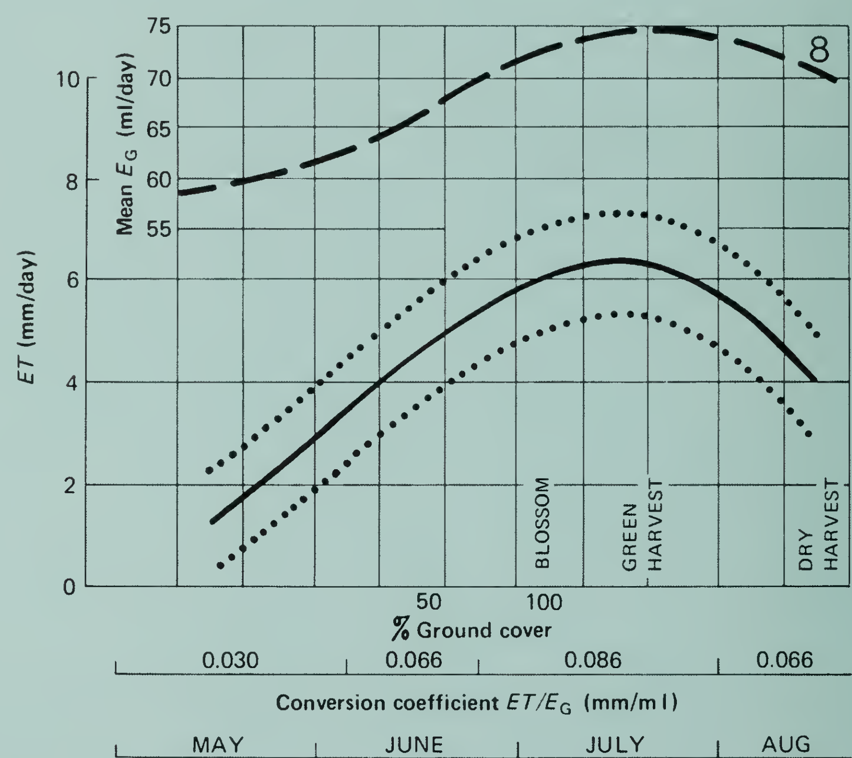
Figs. 3 and 4. Evapotranspiration from (3) **wheat** and (4) **oats** during the growing season, and the corresponding evaporation from a Gen evaporimeter. Solid lines are the *ET* curves that best fit the data; dotted lines indicate the standard error. Dashed lines show the mean daily loss of water, E_G, from the evaporimeter.



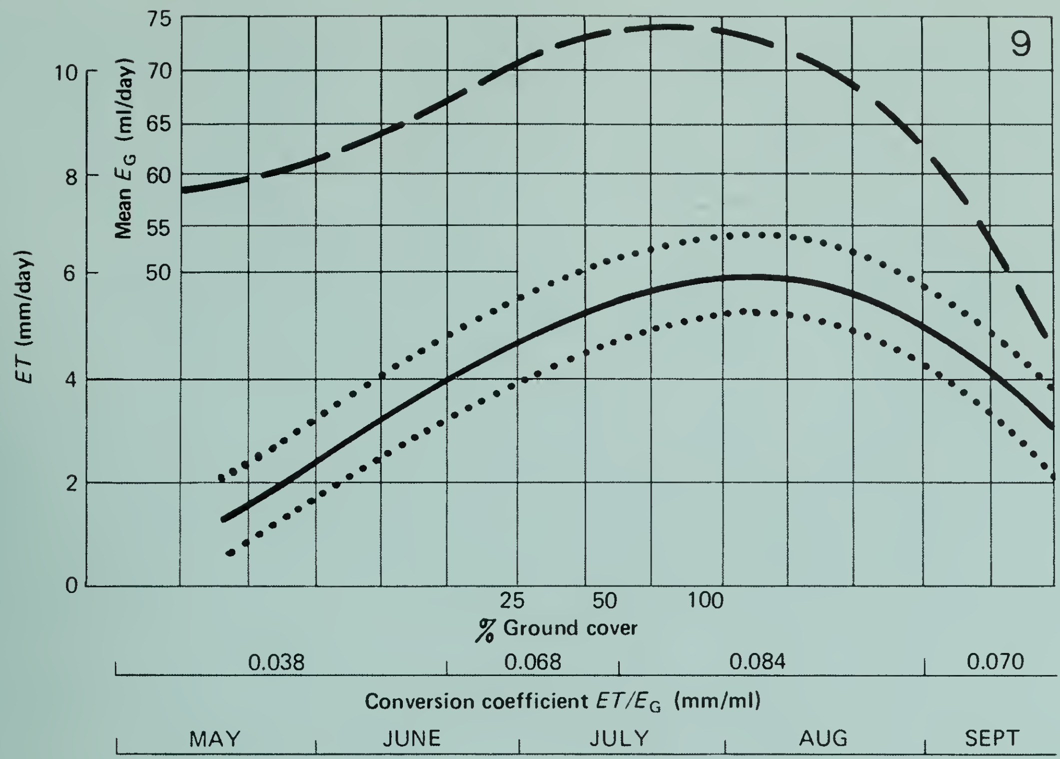


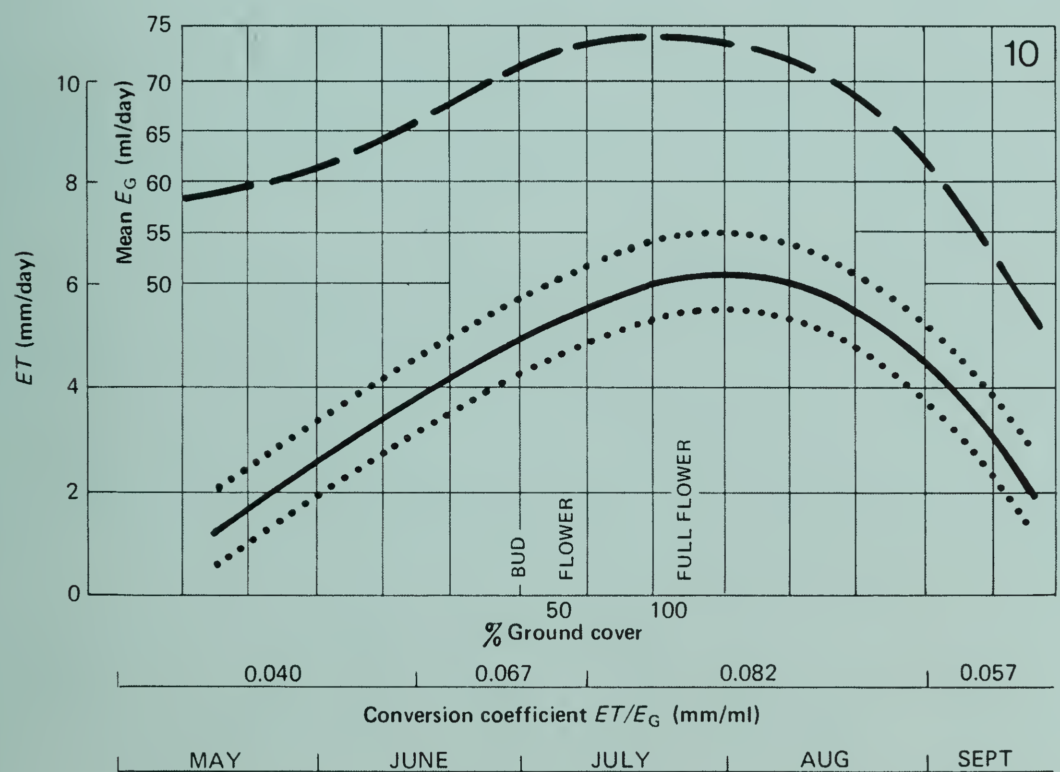
Figs. 5 and 6. Evapotranspiration from (5) **barley** and (6) **flax** during the growing season, and the corresponding evaporation from a Gen evaporimeter. Solid lines are the *ET* curves that best fit the data; dotted lines indicate the standard error. Dashed lines show the mean daily loss of water, E_G, from the evaporimeter.





Figs. 7 and 8. Evapotranspiration from (7) **rape** and (8) **peas** during the growing season, and the corresponding evaporation from a Gen evaporimeter. Solid lines are the *ET* curves that best fit the data; dotted lines indicate the standard error. Dashed lines show the mean daily loss of water, E_G, from the evaporimeter.





Figs. 9 and 10. Evapotranspiration from (9) **sugar beets** and (10) **potatoes** during the growing season, and the corresponding evaporation from a Gen evaporimeter. Solid lines are the *ET* curves that best fit the data; dotted lines indicate the standard error. Dashed lines show the mean daily loss of water, E_G, from the evaporimeter.

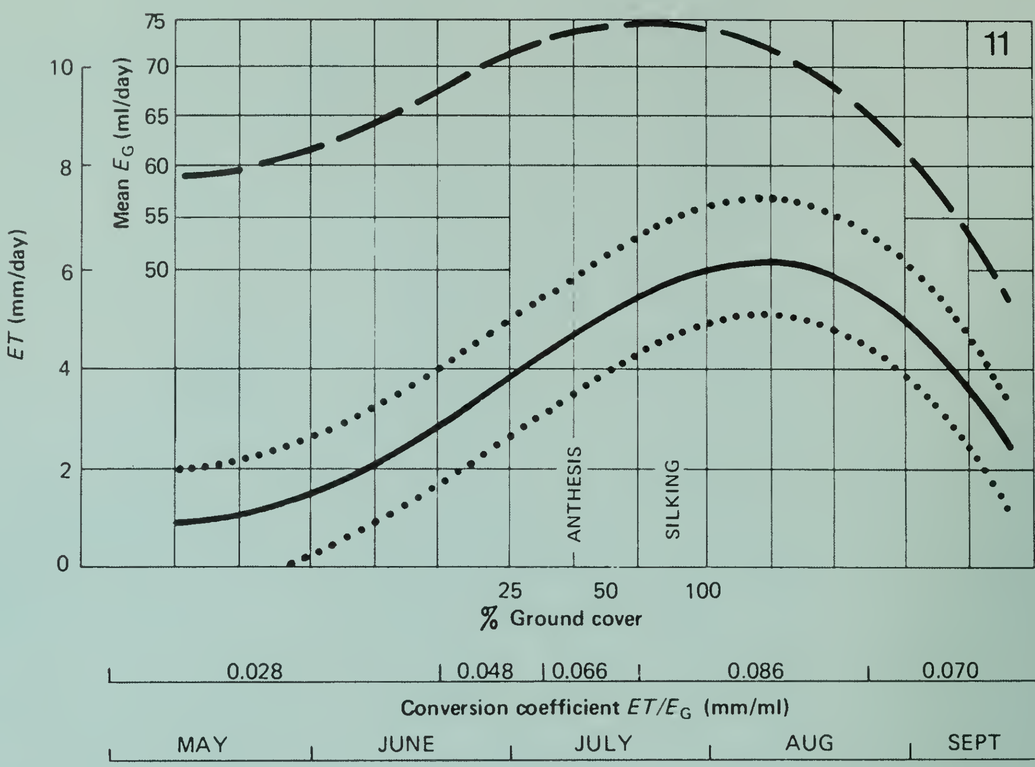


Fig. 11. Evapotranspiration from **corn** during the growing season, and the corresponding evaporation from a Gen evaporimeter. Solid line is the *ET* curve that best fits the data; dotted lines indicate the standard error. Dashed line shows the mean daily loss of water, E_G, from the evaporimeter.

Fig. 12. Class A evaporation pan.

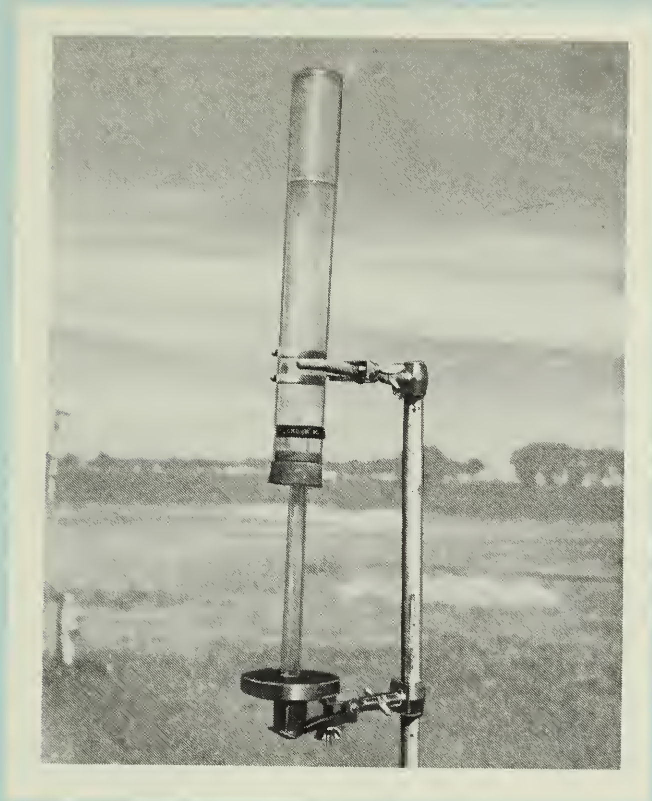


Fig. 13. Alundum disc evaporimeter.

Fig. 14. Gen evaporimeter.

CONVERSION FACTORS FOR METRIC SYSTEM

Imperial units	Approximate conversion factor	Results in:	
LINEAR			
inch	x 25	millimetre	(mm)
foot	x 30	centimetre	(cm)
yard	x 0.9	metre	(m)
mile	x 1.6	kilometre	(km)
AREA			
square inch	x 6.5	square centimetre	(cm^2)
square foot	x 0.09	square metre	(m^2)
acre	x 0.40	hectare	(ha)
VOLUME			
cubic inch	x 16	cubic centimetre	(cm^3)
cubic foot	x 28	cubic decimetre	(dm^3)
cubic yard	x 0.8	cubic metre	(m^3)
fluid ounce	x 28	millilitre	(mL)
pint	x 0.57	litre	(L)
quart	x 1.1	litre	(L)
gallon	x 4.5	litre	(L)
WEIGHT			
ounce	x 28	gram	(g)
pound	x 0.45	kilogram	(kg)
short ton (2000 lb)	x 0.9	tonne	(t)
TEMPERATURE			
degrees Fahrenheit	(°F-32) x 0.56 or (°F-32) x 5/9	degrees Celsius	(°C)
PRESSURE			
pounds per square inch	x 6.9	kilopascal	(kPa)
POWER			
horsepower	x 746	watt	(W)
	x 0.75	kilowatt	(kW)
SPEED			
feet per second	x 0.30	metres per second	(m/s)
miles per hour	x 1.6	kilometres per hour	(km/h)
AGRICULTURE			
gallons per acre	x 11.23	litres per hectare	(L/ha)
quarts per acre	x 2.8	litres per hectare	(L/ha)
pints per acre	x 1.4	litres per hectare	(L/ha)
fluid ounces per acre	x 70	millilitres per hectare	(mL/ha)
tons per acre	x 2.24	tonnes per hectare	(t/ha)
pounds per acre	x 1.12	kilograms per hectare	(kg/ha)
ounces per acre	x 70	grams per hectare	(g/ha)
plants per acre	x 2.47	plants per hectare	(plants/ha)