2.3 A simple model of potential crop production

H. van Keulen

2.3.1 Introduction

In Section 2.1, potential crop production was defined as the total dry matter production of a green crop surface that, during its entire growth period, is optimally supplied with water and all essential nutrient elements, and grows without interference from weeds, pests and diseases. From this concept, a step may be made to the estimation of potential yield, i.e. the production of economically useful plant parts, by taking into account the phenological development of a particular crop species or cultivar, and the associated partitioning of dry matter over various organs of the plant, as outlined in Section 2.2. In this Section a scheme is presented to calculate both total dry matter production and economic yield for a number of crops, based on radiation and temperature regime, only.

The principle of the procedure is that repetitive calculations are performed, starting at some point in time at which the state of the crop can be described in quantitative terms, either determined from experimental data or estimated from other known relations. For most crops a suitable point in time is emergence, which is defined as the moment of transition from growth of the seedling from the reserves in the seeds to growth originating from carbohydrates formed in the process of assimilation. Transplanted rice is a special case, because the seedlings, growing on a nursery bed, are uprooted after some time and replanted on the site where they will eventually mature. The moment of transplanting is then a better starting point.

The state of the crop at the start of the calculations is characterized by measurable quantities, e.g. the weight of the aerial plant parts, the weight of the roots and the green leaf area, active in the assimilation process. From this state and the environmental conditions in the following period the rates of the relevant processes, such as assimilation and respiration, are calculated. These basic processes govern the rates of change of the various quantities that can thus be calculated. Realization of these rates over the relevant time interval and addition to the quantities present at the beginning of the period yield the magnitude of the quantities at the end of the period. Or, in mathematical notation:

$$Q_{t+\Delta t} = Q_t + R_q \cdot \Delta t \qquad (7)$$

where

$Q_{t+\Delta t}$ is quantity at time $t + \Delta t$
Q_t is quantity at time t
R_q is the rate of change of quantity Q during time interval Δt
Δt is time interval between the beginning of the period and the end of the period.

Exercise 10
If the unit of Q is kg ha^{-1}, and the unit of Δt is days, what is the unit of R_q?
Suppose $Q_t = 200$, $R_q = 15$ and $\Delta t = 10$, what will $Q_{t+\Delta t}$ be?

The calculations are then repeated for the next time interval, and so on, until the end of the growth period of the crop. In this way the growth curve, i.e. the cumulative dry matter production (Section 2.1) is obtained. By partitioning the dry matter produced during each time interval according to the coefficients given in Section 2.2, the weight of the various organs can be calculated. The partitioning coefficients are a function of the development stage of the vegetation and that 'quantity' must therefore also be calculated. This may be done in the way suggested in Section 2.2, by adding the average air temperatures in the course of the growing period and dividing the accumulated temperature sum at any moment by the sum required for the completion of a certain phenological phase. The ratio obtained is the required quantity, which is defined as the development stage.

The approach followed assumes that the rates of change calculated at the beginning of a time interval do not change during that interval. This assumption puts a restriction on the length of the time interval applied. In theory, infinitely small time intervals would have to be applied, because realization of a rate of change over even a small interval results in different values for the quantities and this would thus lead to a different rate of change for the next small time interval. That would, however, hardly be possible from a practical point of view. Moreover the deviations are often within reasonable limits, even if the time interval has a finite size. In our approach we have chosen a period of ten days which, on the one hand, permits calculations for an entire growth period of some hundreds of days to be performed in a reasonable time on a pocket calculator, and, on the other hand, yields acceptable results for the purpose pursued here.

The principles of the calculation procedure outlined sofar are those underlying the state variable approach in systems analysis and modelling. This approach will not be further elaborated upon in this volume; for descriptions of this approach see de Wit & Goudriaan (1978) and Penning de Vries & van Laar (1982).

Exercise 11
In the biological sciences, often the growth rate – i.e. the rate of increase of a quantity – is proportional to the quantity present, thus:

$$R_q = a \cdot Q_t$$

Calculate the time course of the quantity Q for a thirty day period when Q_0 = 5 kg ha^{-1} (Q_0 is the quantity at time zero) and the value of the proportionality factor a = 0.1 d^{-1}; use for Δt a value of 5 days.
Repeat the calculation for a value of Δt = 3 days. Compare the results. What do you notice? Explain the difference.

2.3.2 *An actual example*

This example concerns an experiment with the rice variety IR8, one of the so-called high yielding varieties (HYV) developed at the International Rice Research Institute. The experiment was carried out in Paramaribo, Suriname, South America (5°49' N, 55°09' W). The rice was transplanted on 10 November 1972 (Van Slobbe, 1973). The air temperatures used in the calculations were obtained from reported ten-day averages for the experimental period. Radiation was calculated from monthly averages of sunshine duration reported (Section 3.1). These data were used to calculate potential gross CO_2 assimilation (Section 2.1), which is given in Table 9.

Table 9. Potential daily gross assimilation expressed in CH_2O for Paramaribo, Suriname.

Date		F_{gs} (kg ha^{-1} d^{-1})
Jan.	15	332
Feb.	15	344
March	15	368
April	15	364
May	15	354
June	15	378
July	15	417
Aug.	15	454
Sept.	15	
Oct.	15	
Nov.	15	336
Dec.	15	283

Table 10. Calculation scheme for potential production.

Column no.	1	2	3	4	5	6	7	8	9	10	11	12
Period	T_a	TSUM	DVS	GASS	MRES	ASAG	DMI	FR	IWRT	WRT	FL	IWLV
										40		
1 Nov. 2	27.2	272	0.18	60.5	2.1	58.4	40.9	0.35	14.3	183	0.395	16.2
2 Nov. 3	26.3	535	0.36	127.2	8.2	119.0	83.3	0.165	13.7	320	0.445	37.1
3 Dec. 1	25.8	793	0.53	216.0	20.7	195.3	136.7	0.075	10.3	423	0.48	65.6
4 Dec. 2	26.4	1057	0.70	260.4	41.2	219.2	153.4	0.07	10.7	530	0.40	61.4
5 Dec. 3	26.3	1320	0.88	295.0	64.2	230.8	161.6	0.07	11.3	643	0.265	42.8
6a Jan. 1-7	26.0	1502	1.0	316.0	88.5	227.5	159.3	0.025	4.0	671	0.06	9.6
6b Jan. 8-10	26.0	1580	1.10	316.0	71.2	244.8	195.8	0	0	671	0	−48.0
7 Jan. 2	26.0	1840	1.43	332.0	75.7	256.3	205.0	0	0	671	0	−45.1
8 Jan. 3	26.0	2100	1.75	336.0	91.7	244.3	195.4	0	0	671	0	−36.1
9 Feb. 1-8	26.0	2308	2.0	319.6	107.6	212.0	169.6	0	0	671	0	−28.8

Table 10. (continued)

Column no. Period	13 WLV	14 FS	15 IWST	16 WST	17 FG	18 IWGR	19 WGR	20 LAI	21 TADW	22 TDW	23 TDWL	24 Line no.
1 Nov. 2	100			0				0.25	100	140	140	a
2 Nov. 3	262	0.255	10.4	104	0	0	0	0.65	366	549	549	b
3 Dec. 1	633	0.39	32.5	429	0	0	0	1.6	1062	1382	1382	c
4 Dec. 2	1289	0.445	60.8	1037	0	0	0	3.2	2326	2749	2749	d
5 Dec. 3	1903	0.53	81.3	1850	0	0	0	4.75	3753	4283	4283	e
6a Jan. 1-7	2331	0.665	107.6	2925	0	0	0	5.8	5256	5899	5899	f
6b Jan. 8-10	2398	0.225	35.8	3176	0.69	125.6	879	6.0	6453	7124	7124	g1
7 Jan. 2	2254	0	0	3176	1.0	195.8	1466	5.6	7040	7711	7567	g2
8 Jan. 3	1803	0	0	3176	1.0	205.0	3516	4.5	9090	9761	9166	h
9 Feb. 1-8	1442	0	0	3176	1.0	195.4	5470	3.6	11044	11715	10757	i
	1212	0	0	3176	1.0	169.6	6827	3.0	12402	13073	11886	j

The calculation procedure is illustrated in Table 10; the letters in the following text refer to the lines in Table 10, which are indicated in the last column (No. 24) of the table.

Line a specifies the situation at time zero. Because it concerns transplanted rice, the day of transplanting is chosen. Root dry matter after transplanting equals 40 kg ha^{-1} (Column 10); above ground 100 kg ha^{-1} is present, which consists entirely of leaf blades (Column 13). The green area, intercepting solar energy for the assimilation process, is calculated from the weight of the leaf blades, assuming a constant ratio between the area and the weight of leaf blades. This ratio is called the specific leaf area, expressed in square meters of green area per kg of dry matter of leaf blades. For rice, its value is 25, thus the area is 2500 m^2 ha^{-1}. From this, the leaf area index (LAI), i.e. the ratio of leaf area to soil surface area, is calculated. Since one hectare is 10 000 m^2, the leaf area index at transplanting time equals 0.25 (Column 20).

Line b describes the first full ten days of the growing period. The average daily air temperature during that period is 27.2 °C (Column 1), which when integrated over the period yields a temperature sum of 272 d °C (Column 2). As explained in Section 2.2, the accumulated temperature sum is a measure of the phenological development stage of the crop. For the variety IR8 the required temperature sum for anthesis is 1500 d °C, assuming a base temperature of 0 °C. The development stage (Column 3) is calculated as the ratio of the temperature sum accumulated and the value of 1500 d °C, hence 272/1500 = 0.18.

In Table 9, potential daily gross assimilation, F_{gs}, expressed in CH_2O is given for the middle of each month of the year in kg ha^{-1} d^{-1}. The value for any ten – day period is obtained by interpolation between the values given in Table 9. For the second ten – day period of November that value is found directly from the table: 336 kg $ha^{-1}d^{-1}$. This represents potential gross assimilation, i.e. that realized by a closed green canopy, which intercepts all incoming energy. For a leaf area index of 0.25, only part of the solar energy is

Table 11. Reduction factor for gross assimilation due to incomplete light interception.

LAI	Reduction factor
0.	0.
0.25	0.18
0.5	0.33
1.0	0.55
1.5	0.70
2.0	0.80
2.5	0.86
3.0	0.91
3.5	0.94
4.0	0.96
4.5	0.98
5.0	1.0

intercepted (Section 2.1), hence the potential as dictated by the environment is not realized. The reduction factor for various values of LAI is given in Table 11, calculated from Equation 5, in Section 2.1. For LAI = 0.25, the reduction factor equals 0.18. In Column 4, the rate of gross assimilation is introduced

$$GASS = 336 \times 0.18 = 60.5 \text{ kg ha}^{-1} \text{ d}^{-1}$$

As explained in Section 2.1, part of the energy fixed in the assimilatory process is respired by the crop to maintain the existing structures. For the vegetative material of a rice plant, the relative maintenance respiration rate is assumed to be 0.015 kg CH_2O per kg dry matter per day during the pre–anthesis phase when, especially in the potential production situation, the nitrogen content of the material is relatively high. Hence, the rate of maintenance respiration expressed in CH_2O is obtained by multiplying the total live dry matter present (Column 23) by the relative maintenance respiration rate, R_m:

$$MRES = 140 \times 0.015 = 2.1 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 5)}$$

The amount of assimilation products available for increase in dry weight of the crop equals the difference between gross assimilation and maintenance respiration. Thus:

$$ASAG = 60.5 - 2.1 = 58.4 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 6)}$$

The conversion of primary assimilation products into structural plant material again entails loss of energy. In the present approach, this growth respiration is represented by its complement, the conversion efficiency, E_g, (Section 2.1). This means that the dry weight increment is equal to the conversion efficiency times the available assimilation products. For vegetative material of average composition E_g equals 0.7. Thus:

$$DMI = 0.7 \times 58.4 = 40.9 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 7)}$$

The total increase in dry matter is utilized concurrently for the growth of various plant parts. In the early stages there is growth of roots, leaf blades and leaf sheaths and stems. The fraction of the increment partitioned to each of the organs is, under potential growth conditions, primarily determined by the phenological state of the crop (Section 2.2). In Table 12, the fractions allocated to each of the organs are given as a function of development stage.

The instantaneous values of the partitioning factors for roots, leaf blades and stems plus leaf sheaths are read from this table through interpolation. The independent variable, i.e. the development stage, is taken as the value halfway between the beginning and the end of the ten–day period. For this period therefore, (0 + 0.18)/2 = 0.09.

Table 12. Partitioning factors for dry matter to various plant organs as a function of development stage

Development stage	f_r	f_l	f_s	f_g
0	0.6	0.375	0.025	0
0.1	0.325	0.40	0.275	0
0.2	0.225	0.425	0.35	0
0.3	0.14	0.46	0.4	0
0.4	0.075	0.485	0.44	0
0.5	0.075	0.475	0.45	0
0.6	0.07	0.42	0.51	0
0.7	0.07	0.32	0.61	0
0.8	0.055	0.21	0.735	0
0.9	0.04	0.1	0.36	0.5
1.0	0.	0.	0.	1.0
2.0	0.	0.	0.	1.0

In Column 8, the fraction allocated to the root is introduced, which is equal to 0.35. Thus the rate of increase in root dry weight is:

$$\mathrm{IWRT} = 0.35 \times 40.9 = 14.3 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 9)}$$

The weight of the root system at the end of the period is obtained by adding the rate of increase from Column 9 multiplied by the length of the time interval to the weight at the end of the preceding ten-day period (Line a, Column 10). Thus:

$$\mathrm{WRT} = 40 + 14.3 \times 10 = 183 \text{ kg ha}^{-1} \text{ (Column 10)}$$

The fraction of the dry weight increment allocated to the leaf blades is again obtained from Table 12 at development stage 0.09, which equals 0.395. The rate of increase in dry weight of the leaf blades is calculated as:

$$\mathrm{IWLV} = 0.395 \times 40.9 = 16.2 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 12)}$$

The weight of the leaf blades at the end of the ten-day period is obtained by adding the rate of increase times Δt to the value at the beginning of the ten-day period (Line a, Column 13). Hence,

$$\mathrm{WLV} = 100 + 16.2 \times 10 = 262 \text{ kg ha}^{-1} \text{ (Column 13)}$$

The remainder of the above ground vegetative material is designated 'stems' in the present approach. It consists not only of the true stems, but contains also the leaf sheaths and the ear structures other than the seed. For the present ten – day period the fraction of the increment allocated to the stem is obtained from Table 12 at development stage 0.09, which equals 0.255. The rate of increase in stem dry weight is equal to that fraction multiplied by the rate of total dry matter increase:

$$IWST = 0.255 \times 40.9 = 10.4 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 15)}$$

The weight of the stem at the end of the ten – day period follows from the addition of the rate of increase times the length of the time interval to the weight at the end of the preceding ten – day period (Line a, Column 16):

$$WST = 0 + 10.4 \times 10 = 104 \text{ kg ha}^{-1} \text{ (Column 16)}$$

During this ten – day period, the crop is still in its vegetative phase, hence the fraction allocated to the grain is zero (Column 17). Therefore the values in Columns 18 and 19 also remain zero.

The leaf area index at the end of the ten – day period is obtained from the dry weight of the leaf blades (Column 13) by multiplying with the specific leaf area of 25 and taking into account the surface area:

$$LAI = 262 \times 25 \times 10^{-4} = 0.65 \text{ m}^2 \text{ m}^{-2} \text{ (Column 20)}$$

At the end of all calculations for the ten – day period, three auxiliary variables are calculated that are helpful for comparison with measured data. In Column 21, total above ground dry weight is introduced, which is the sum of the weight of leaf blades (Column 13), stems (Column 16) and grains (Column 19). Thus:

$$TADW = 262 + 104 + 0 = 366 \text{ kg ha}^{-1}$$

The total dry weight of the vegetation (Column 22) is equal to the above – ground dry weight, plus the weight of the root system (Column 10):

$$TDW = 262 + 104 + 0 + 183 = 549 \text{ kg ha}^{-1}$$

The total dry weight of live material (TDWL, Column 23) that is subject to maintenance respiration is equal to the total dry weight, because no dead material is present as yet. With this calculation, the treatment of the first ten – day period is finalized and the calculations can be repeated for the next ten – day period.

The conditions are not basically different for that period (Line c) from those in the previous one, therefore the line will be described in less detail.

Line c refers to the last ten – day period of November. The average air temperature then is 26.3 °C (Column 1). The accumulated temperature sum for the crop at the end of the period is obtained by adding the 263 d °C for this ten – day period to the value accumulated up till the beginning of the period (Column 2, Line b). Therefore the value in Column 2, Line c, equals:

$$TSUM = 272 + 263 = 535 \text{ d °C}$$

The corresponding value of the development stage is found by dividing the value in Column 2 by 1500 d °C, the required temperature sum for anthesis of this variety:

$$DVS = 535/1500 = 0.36 \text{ (Column 3)}$$

The value of potential gross assimilation for the last ten – day period of November is obtained by interpolation in Table 9:

$$GRA = 336 + 1/3 \times (283 - 336) = 318 \text{ kg ha}^{-1} \text{ d}^{-1}$$

The first and second value within the brackets are for the middle of December and the middle of November, respectively. To account for the influence of incomplete light interception, due to the low leaf area index, potential assimilation must be multiplied by the reduction factor from Table 11 for an LAI of 0.65:

$$0.33 + (0.15/0.5) \times (0.55 - 0.33) = 0.40$$

In Column 4, therefore, the rate of gross assimilation is introduced as:

$$GASS = 318 \times 0.40 = 127.2 \text{ kg ha}^{-1} \text{ d}^{-1}$$

Maintenance respiration for the period is calculated from the total live plant dry weight at the beginning (Column 23) and the relative maintenance respiration rate, 0.015 kg CH_2O per kg dry weight per day:

$$MRES = 549 \times 0.015 = 8.2 \text{ kg ha}^{-1} \text{ d}^{-1} \text{(Column 5)}$$

Carbohydrates available for increase in structural dry weight of the vegetation are equal to:

$$ASAG = 127.2 - 8.2 = 119.0 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 6)}$$

From this, the total rate of increase in dry weight is calculated, taking into account the conversion efficiency:

$$DMI = 119.0 \times 0.7 = 83.3 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 7)}$$

The partitioning factors for the various plant organs are obtained from Table 12, at the appropriate value of the development stage:

$$DVS = 0.18 + 0.5 \times (0.36 - 0.18) = 0.27$$

Thus:

FR = 0.165	(Column 8)
FL = 0.445	(Column 11)
FS = 0.39	(Column 14)
FG = 0.	(Column 17)

The rate of increase in root dry weight is calculated by multiplying the increase in total dry weight by the partitioning factor:

$$IWRT = 0.165 \times 83.3 = 13.7 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 9)}$$

and the total root weight at the end of the ten – day period equals:

$$WRT = 183 + 13.7 \times 10 = 320 \text{ kg ha}^{-1} \text{ (Column 10)}$$

The rate of increase in leaf dry weight is obtained by multiplying FL and DMI, hence:

$$IWLV = 0.445 \times 83.3 = 37.1 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 12)}$$

and the dry weight at the end of the period follows from addition of the increment to that present already:

$$WLV = 262 + 37.1 \times 10 = 633 \text{ kg ha}^{-1} \text{ (Column 13)}$$

The rate of increase in stem dry weight is calculated from total increase in dry weight and the fraction partitioned to the stem:

$$IWST = 0.39 \times 83.3 = 32.5 \text{ kg ha}^{-1} \text{ d}^{-1} \text{ (Column 15)}$$

Total stem weight at the end of the ten – day period equals:

$$WST = 104 + 32.5 \times 10 = 429 \text{ kg ha}^{-1} \text{ (Column 16)}$$

The leaf area index at the end of the ten – day period follows from the dry weight of the leaf blades:

$$LAI = 633 \times 25 \times 10^{-4} = 1.6 \text{ m}^2 \text{ m}^{-2} \text{ (Column 20)}$$

Total above – ground dry weight at the end of this ten – day period equals:

$$TADW = 633 + 429 + 0 = 1062 \text{ kg ha}^{-1} \text{ (Column 21)}$$

The total dry weight of the vegetation is:

$$TDW = 633 + 429 + 0 + 320 = 1382 \text{ kg ha}^{-1} \text{ (Column 22)}$$

which is all live material, hence:

$$TDWL = 1382 \text{ kg ha}^{-1} \text{ (Column 23)}$$

The calculations for the *Lines d, e* and *f* follow exactly the same pattern as the preceding ones; they are therefore not treated here.
Line g refers to the first ten – day period of January.

Column 1: average air temperature during the period is 26.0 °C
Column 2: accumulated temperature sum at the end of the period equals
$1320 + 260 = 1589$ d °C!

That is a point beyond anthesis. The temperature relations with respect to development are different for the period before anthesis and after anthesis, therefore these ten days cannot be treated in one line, but are split into two parts. The first part covers the period until the anthesis date, the length of that part is determined by the remainder of the required temperature sum, i.e.:
$$(1500 - 1320)/26.0 = 7 \text{ days}$$
The sixth ten – day period can thus be depicted as:

Line g1, which refers to the first seven days of the period.
Column 1: average air temperature during the period is 26.0 °C
Column 2: accumulated temperature sum at the end of the period equals:
$1320 + 7 \times 26.0\ °C = 1502$ d °C
Column 3: corresponding development stage is calculated as:
$1502/1500 = 1.0$ (i.e. anthesis)

Column 4: potential gross assimilation during the period follows from Table 9:
$283 + 2/3 \times (332 - 283) = 316 \text{ kg ha}^{-1} \text{d}^{-1}$;
The light interception factor equals 1 (Table 11), thus the gross assimilation rate equals:
$316 \text{ kg ha}^{-1} \text{d}^{-1}$
Column 5: maintenance respiration is calculated from total canopy dry weight:

$5899 \times 0.015 = 88.5$ kg ha^{-1} d^{-1}

Column 6: assimilate availability for increase in structural material equals:
$316.0 - 88.5 = 227.5$ kg ha^{-1} d^{-1}

Column 7: the rate of increase in dry weight of structural material equals:
$227.5 \times 0.7 = 159.3$ kg ha^{-1} d^{-1}

Column 8: the fraction of dry weight allocated to the roots is obtained from Table 12 at development stage 0.94 and equals 0.025

Column 9: the rate of increase in root dry weight equals:
$0.025 \times 159.3 = 4$ kg ha^{-1} d^{-1}

Column 10: total dry weight of the roots at the end of the period equals:
$643 + 4 \times 7 = 671$ kg ha^{-1}

Column 11: the fraction allocated to the leaf blades equals: 0.06

Column 12: the rate of increase in dry weight of the leaf blades equals:
$0.06 \times 159.3 = 9.6$ kg ha^{-1} d^{-1}

Column 13: total dry weight of the leaf blades at the end of the period is:
$2331 + 9.6 \times 7 = 2398$ kg ha^{-1}

Column 14: the fraction of dry weight allocated to the stems equals: 0.225

Column 15: the rate of increase in dry weight of the stems equals:
$0.225 \times 159.3 = 35.8$ kg ha^{-1} d^{-1}

Column 16: total dry weight of the stems at the end of the period equals:
$2925 + 35.8 \times 7 = 3176$ kg ha^{-1}

Column 17: the fraction of dry weight allocated to the grains, derived from Table 12 equals 0.69. This period is before anthesis. However, a substantial part of the assimilates produced in this period is temporarily stored in the stems, and later translocated to the growing grain (Yoshida, 1980). In the present approach, these assimilates are directly added, therefore, to grain dry weight

Column 18: the rate of increase in grain dry weight equals:
$159.3 \times 0.69 \times 0.8/0.7 = 125.6$ kg ha^{-1} d^{-1}
The ratio 0.8/0.7 is introduced to account for the fact that the efficiency of conversion of primary photosynthates into grain structural dry matter is higher than in vegetative dry matter.

Column 19: grain dry weight at the end of the period equals:
$125.6 \times 7 = 879$ kg ha^{-1}

Column 20: the leaf area index at the end of the period is calculated from leaf dry weight:
$2398 \times 25 \times 10^{-4} = 6.0$ m^2 m^{-2}

Column 21: total above ground dry weight of the vegetation equals:
$2398 + 3176 + 879 = 6453$ kg ha^{-1}

Column 22: total dry weight of the vegetation equals:
$2398 + 3176 + 879 + 671 = 7124$ kg ha^{-1}

Column 23: there is still no dead material present, hence, DWLV equals 7124 kg ha^{-1}

Line g2 refers to the remainder of the first ten–day period of January, a period of three days.

Column 1: average temperature during the period is 26.0 °C

Column 2: the temperature sum till the end of the period equals:

$$1502 + 3 \times 26.0 = 1580$$

Column 3: for the post–anthesis phase, the development scale runs from the value 1 at anthesis to the value 2 at maturity. During the post–anthesis phase a required temperature sum of 800 d °C for this (and most other) varieties has been established. The development stage is calculated as the total temperature sum above 1500 d °C divided by 800, added to the value of 1 at anthesis. Thus:

$$(1580 - 1500)/800 + 1 = 1.10$$

Column 4: potential gross assimilation rate is equal to that in the previous period at 316 kg ha^{-1} d^{-1}

Column 5: maintenance respiration is calculated from the total dry weight. However, the relative maintenance respiration rate is changed after anthesis from 0.015 to 0.01 kg CH_2O per kg dry matter per day. This change is mainly related to the fact that the nitrogen content of the vegetative material decreases after anthesis, even when the nitrogen supply to the vegetation is abundant (Section 4.1). Thus:

$$7124 \times 0.01 = 71.2 \text{ kg ha}^{-1} \text{ d}^{-1}$$

Column 6: assimilate availability for increase in dry weight is equal to:

$$316 - 71.2 = 244.8 \text{ kg ha}^{-1} \text{ d}^{-1}$$

Column 7: the rate of dry weight increase during the period, taking into account conversion efficiency equals:

$$244.8 \times 0.8 = 195.8 \text{ kg ha}^{-1} \text{ d}^{-1}$$

Columns 8, 9 and 10: after anthesis the sink strength of the above–ground organs and notably that of the growing grains is such that no more assimilates are diverted to the root system.

Column 11: leaf growth also ceases after anthesis, hence FL = 0

Column 12: leaves have a limited life span, thus after a certain time period, they senesce and stop functioning. This process is accelerated after anthesis, when translocation of essential substances to the developing grains takes place; therefore the weight of active leaf blades declines after anthesis; it is assumed that the relative rate of decline is constant, i.e. each day a constant fraction of the leaves senesces. The value of this constant equals 0.02 kg leaf blades per kg leaf blades per day. The rate of decline in dry weight of the leaf blades equals WLV x 0.02, thus:

$$2398 \times 0.02 = 48 \text{ kg ha}^{-1} \text{ d}^{-1}$$

Column 13: the dry weight of the living leaf blades at the end of the period equals:

$2398 - 48 \times 3 = 2254$ kg ha^{-1}

Columns 14 and 15: after anthesis there is no increase in stem dry weight, hence both values are zero.

Column 16: stem dry weight remains constant at 3176 kg ha^{-1}

Column 17: after anthesis all available assimilates are monopolized by the growing grain, thus that fraction equals 1

Column 18: the rate of increase in grain dry weight over the period equals:

$1 \times 195.8 = 195.8$ kg ha^{-1} d^{-1}

Column 19: grain dry weight at the end of the period equals:

$879 + 195.8 \times 3 = 1466$ kg ha^{-1}

Column 20: leaf area index follows from leaf dry weight:

$2254 \times 25 \times 10^{-4} = 5.6$ m^2 m^{-2}

Column 21: total above ground dry weight equals:

$2254 + 3176 + 1466 + 144 = 7040$ kg ha^{-1}

Column 22: total canopy dry weight equals:

$7040 + 671 = 7711$ kg ha^{-1}

Column 23: live tissue, subject to maintenance respiration equals:

$7711 - 144 = 7567$ kg ha^{-1}

Line h refers to the second ten – day period of January.

Column 1: average air temperature during the period is 26.0 °C

Column 2: the temperature sum at the end of the period equals:

$1580 + 260 = 1840$ d °C

Column 3: the corresponding development stage equals:

$(1840 - 1500)/800 + 1 = 1.43$

Column 4: potential gross assimilation rate equals 332 (Table 9) and the leaf area index permits full light interception, therefore gross assimilation equals:

$332 \times 1 = 332$ kg ha^{-1} d^{-1}

Column 5: maintenance respiration is calculated from the live tissue weight:

$7567 \times 0.01 = 75.7$ kg ha^{-1} d^{-1}

Column 6: assimilate availability for growth equals:

$332 - 75.7 = 256.3$ kg ha^{-1} d^{-1}

Column 7: rate of increase in structural dry weight, taking into account conversion efficiency, is:

$256.3 \times 0.8 = 205.0$ kg ha^{-1} d^{-1}

Columns 8 and 9: values remain zero

Column 10: weight of the root system remains constant: 671 kg ha^{-1}

Column 11: fraction to the leaves is zero

Column 12: the rate of decrease in weight of live leaves is approximated by:
$2254 \times 0.02 = 45.1$ kg ha^{-1} d^{-1}

Column 13: live leaf blade dry matter at the end of the period equals:
$2254 - 45.1 \times 10 = 1803$ kg ha^{-1}

Columns 14 and 15: values are zero.

Column 16: weight of stems is constant at 3176 kg ha^{-1}

Column 17: fraction allocated to the grain is 1.0

Column 18: the rate of increase in dry weight of the grain equals that in total dry weight: 205.0 kg ha^{-1} d^{-1}

Column 19: total grain dry weight at the end of the period is:
$1466 + 205.0 \times 10 = 3516$ kg ha^{-1}

Column 20: leaf area index at the end of the period equals:
$1803 \times 25 \times 10^{-4} = 4.5$ m^2 m^{-2}

Column 21: total above ground dry weight of the vegetation equals:
$1803 + 3176 + 3516 + 595 = 9090$ kg ha^{-1}

Column 22: total dry weight of the vegetation equals:
$9090 + 671 = 9761$ kg ha^{-1}

Column 23: total live dry weight equals 9166 kg ha^{-1}

The calculations for *line (i)* follow exactly the pattern of the previous line and they are not treated here.

Line j refers to the first ten – day period of February.

Column 1: average air temperature during the period is 26.0 °C

Column 2: accumulated temperature sum till the end of the period equals:
$2100 + 260 = 2360$

Column 3: corresponding development stage is:
$(2360 - 1500)/800 + 1 = 2.075$
development stage 2 corresponds to maturity, therefore the duration of this period is only:
$(800 - (2100 - 1500))/26.0 = 8$
Hence, eight days till maturity.

Column 2: accumulated temperature sum till the end of the period equals:
$2100 + 8 \times 26.0 = 2308$

Column 3: corresponding development stage at the end of the period is:
$1 + (2308 - 1500)/800 = 2.0$

Column 4: gross assimilation rate for the first ten – day period of February equals:
$332 + 2/3 \times (344 - 332) = 340$ kg ha^{-1} d^{-1}
The reduction factor for light interception equals 0.94, gross assimilation rate for the period thus equals:
$340 \times 0.94 = 319.6$ kg ha^{-1} d^{-1}

Column 5: maintenance respiration is calculated from total live dry weight:
$10757 \times 0.01 = 107.6$ kg ha^{-1} d^{-1}

Column 6: assimilate availability for increase in dry weight equals:
$319.6 - 107.6 = 212.0$ kg ha^{-1} d^{-1}

Column 7: rate of increase in total dry weight taking into account conversion efficiency equals:
$212.0 \times 0.8 = 169.6$ kg ha^{-1} d^{-1}

Column 8 and 9: fraction to roots and root growth is zero.

Column 10: root dry weight remains at 671 kg ha^{-1}

Column 11: fraction to leaf blades is zero.

Column 12: rate of decrease in leaf dry weight is
$1442 \times 0.02 = 28.8$ kg ha^{-1} d^{-1}

Column 13: live leaf dry weight at maturity equals:
$1442 - 28.8 \times 8 = 1212$ kg ha^{-1}

Columns 14 and 15: fraction to the stem and increase in stem dry weight is zero.

Column 16: stem dry weight is constant at 3176 kg ha^{-1}

Column 17: fraction allocated to the grain equals one.

Column 18: rate of increase in grain dry weight equals:
69.6 kg ha^{-1} d^{-1}

Column 19: total grain dry weight at maturity equals:
$5470 + 169.6 \times 8 = 6827$ kg ha^{-1}

Column 20: green leaf area index at maturity is calculated from leaf blade dry weight:
$1212 \times 25 \times 10^{-4} = 3.0$

Column 21: total above ground dry matter equals:
$1212 + 3176 + 6827 + 1187 = 12402$ kg ha^{-1}

Column 22: total plant dry weight at harvest equals:
$12402 + 671 = 13073$ kg ha^{-1}

Column 23: total live weight at harvest equals:
11886 kg ha^{-1}

2.3.3 Comparison with measurements

In Figure 19, the calculated time course of dry matter production is compared to the measured data and a very satisfactory agreement between both is evident. The measured grain yield (at 12% moisture content) was 7.5 t ha^{-1}, which again is close enough to the calculated value of 7.7 t ha^{-1} (6827 x 1.12).

The calculation procedure, outlined in the preceding Subsection was also applied to a set of data from IRRI, Los Baños. In a maximum annual production trial, rice was grown year — round, three different cultivars being used (Yoshida et al., 1972). The first one was IR8, for which parameters identical

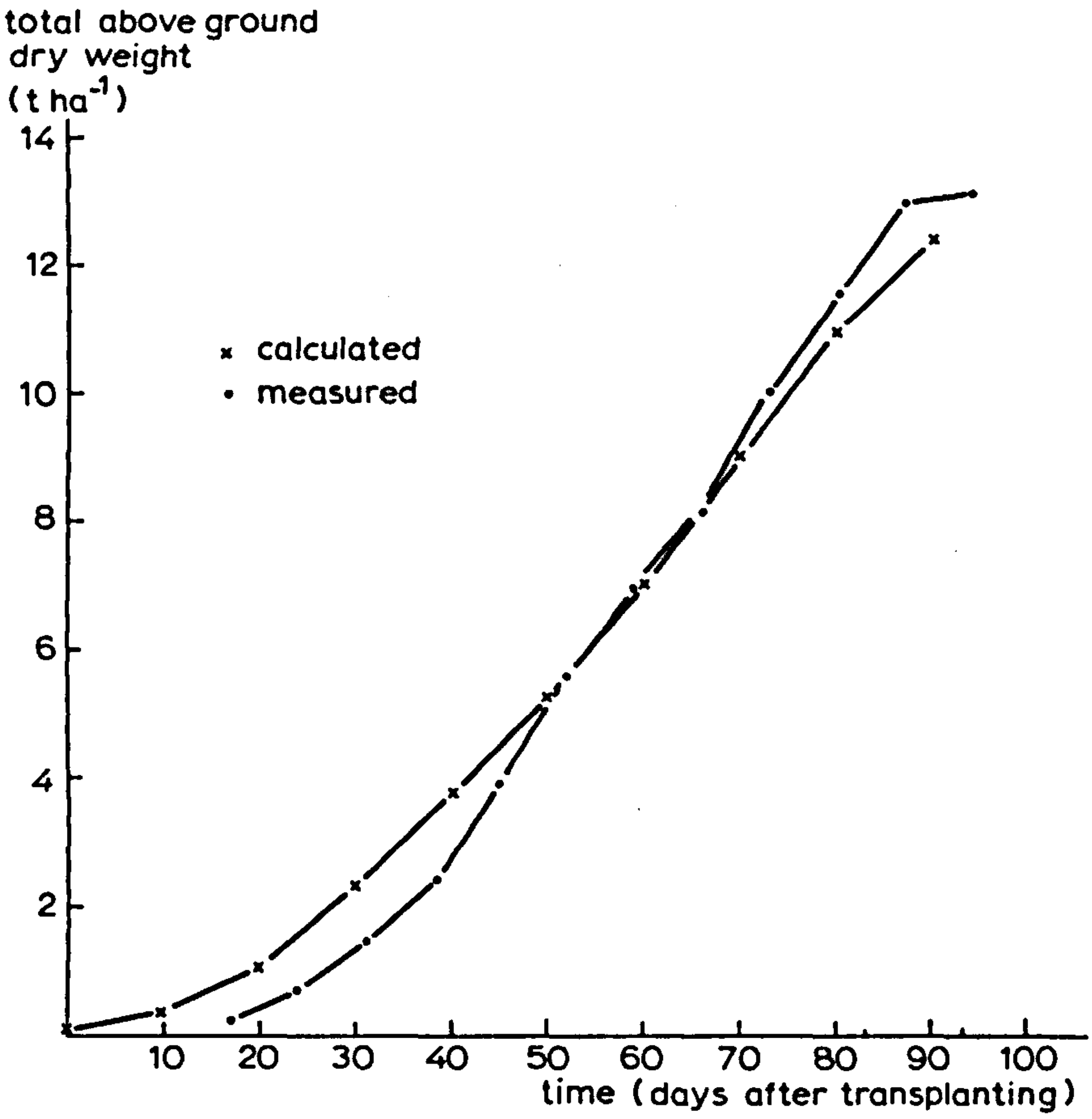

Figure 19. Comparison of measured and calculated above-ground dry-matter accumulation for bunded rice grown in Paramaribo, Suriname.

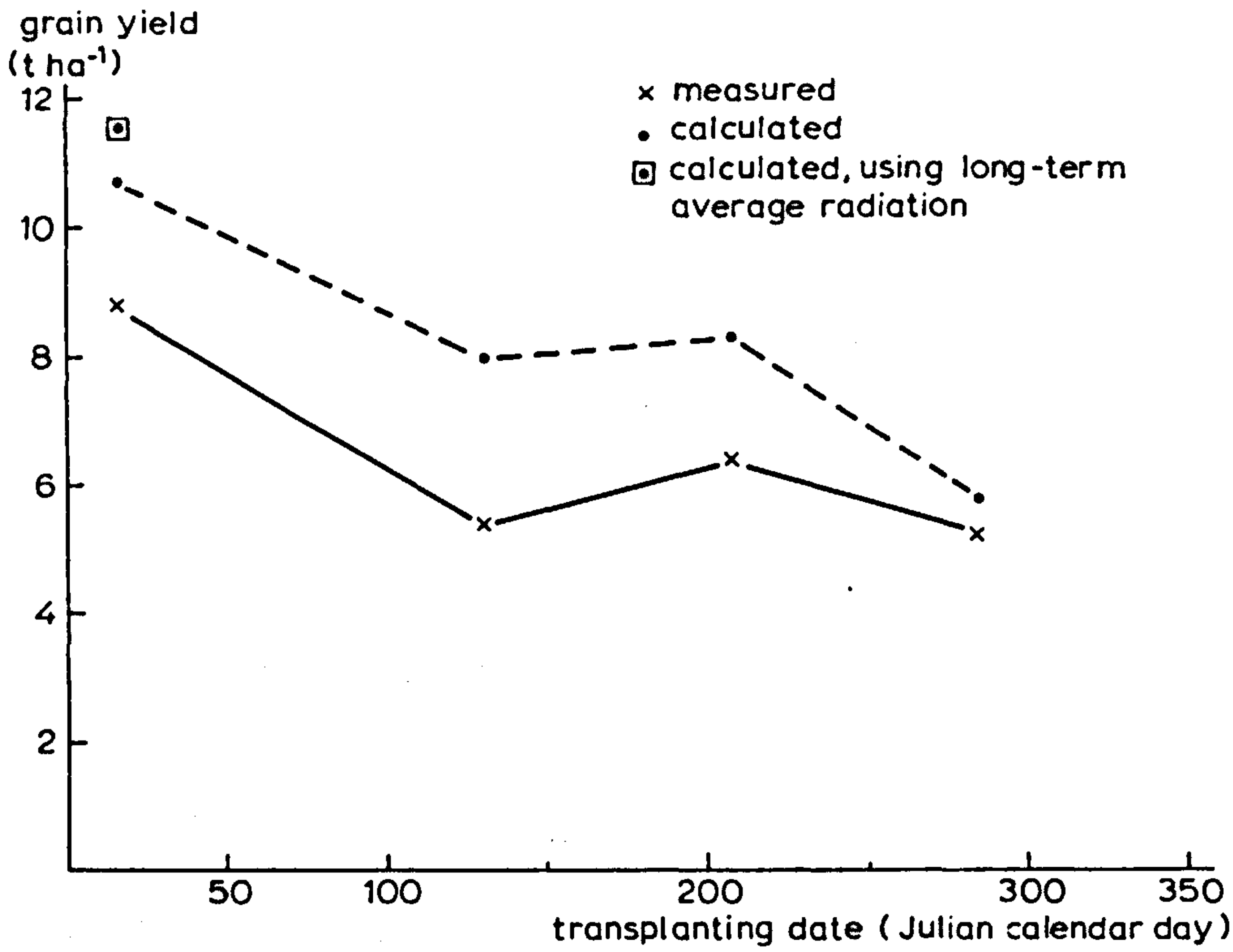

Figure 20. Measured and calculated grain yields for bunded rice transplanted on different dates at IRRI, Los Banos, the Philippines.

to those of the preceding section were used. The other two were the early naturing cultivars, IR—747—B2 and IR—667—98, respectively. For these varieties, the required temperature sum from transplanting to anthesis was set at 1100 d °C, i.e. a development rate of 0.0182 d^{-1} at a temperature of 20 °C.

The results of the calculations are presented in Fugure 20, along with the measured data. The figure shows that the pattern of grain yield with time of transplanting is identical for the measured and the calculated data, but that the calculations are consistently of a higher level. It would seem, therefore, that in the experiments the potential, dictated by weather conditions was not fully reached. Reasons for the discrepancy can only be speculated upon, but nitrogen application of 125 — 150 kg N ha^{-1}, more than two — thirds of which applied as a basal dressing seems hardly sufficient for yields of over 6000 kg ha^{-1} (Section 4.1). It would seem, therefore, that the conclusion reached by the authors that a maximum annual yield of over 28000 kg ha^{-1} is possible, is valid. The more so, if it is considered that the year 1971 was unfavourable in terms of radiation as is shown in Figure 20 by the result calculated with long — term average radiation data.

In Figure 21, the measured and calculated growth curves are shown for a

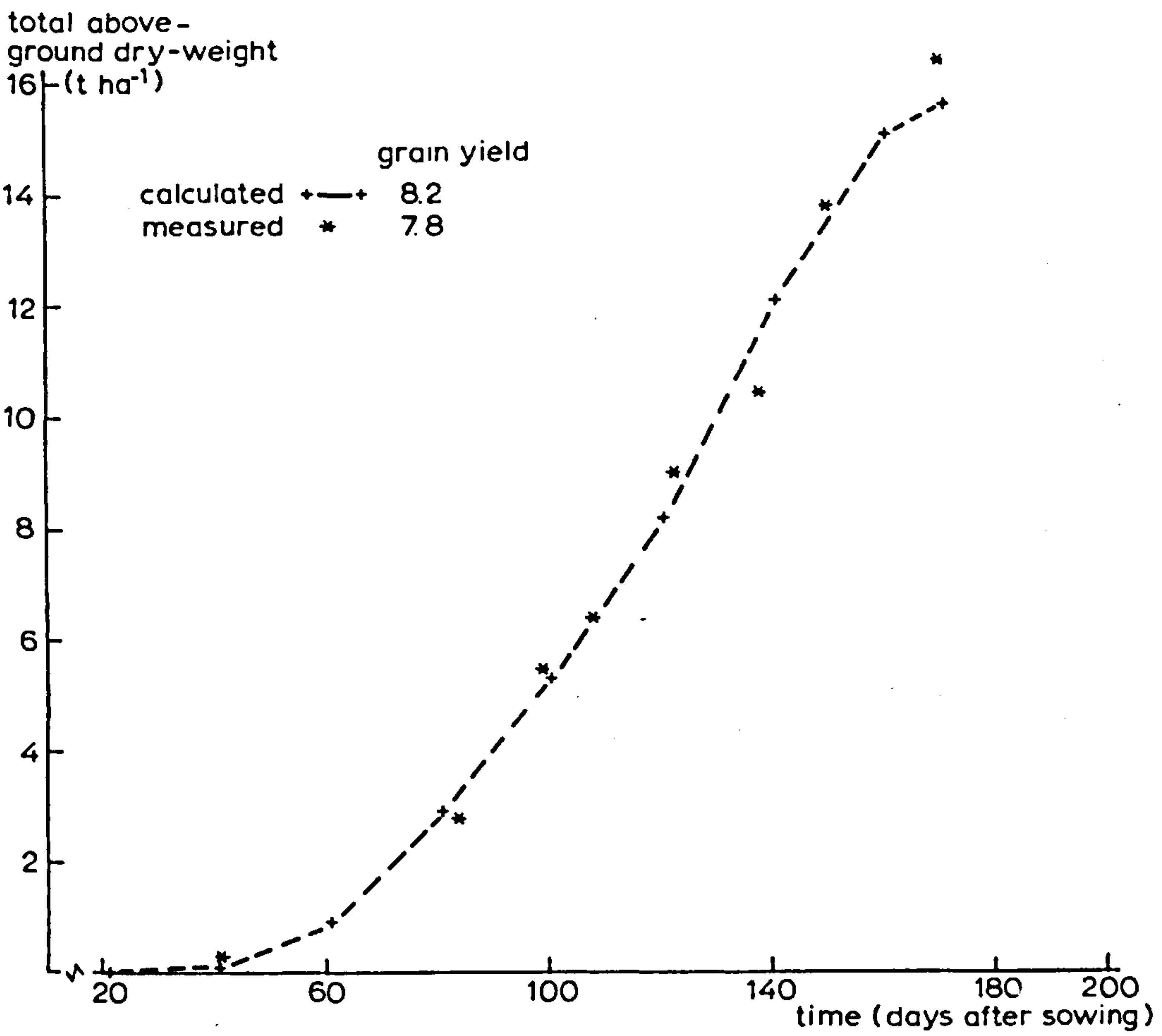

Figure 21. Measured and calculated above-ground dry-matter accumulation for spring wheat, grown in Israel.

spring wheat crop grown in the Central Negev Desert in Israel under irrigation (Hochman, 1982). The variety Lachish used in this experiment requires a temperature sum of 1500 d °C from emergence to anthesis and 850 d °C from anthesis to maturity, both at a base temperature of 0 °C. The partitioning functions used in the model are given in Section 3.4, where the same experiment is used to illustrate the effect of water shortage on production.

These examples show that potential yield and production may be estimated with reasonable accuracy on the basis of crop characteristics and weather conditions.

Exercise 12

Calculate the grain yield for the rice variety IR8, transplanted in Los Baños on January 20. Use the basic data given in Table 13. Assume for each month three ten – day periods as in Table 10. The values for F_{gs} are averages for the month and are not, as in Table 9, applicable to the middle of the month.

Table 13. Basic data for Exercise 12, F_{cl} and F_{ov} expressed in CO_2, F_{gs} expressed in CH_2O, Los Banos, Philippines, 14° N.

Month	H_a ($MJ\ m^{-2}d^{-1}$)	T_a (°C)	H_g ($MJ\ m^{-2}d^{-1}$)	f_o –	F_{cl} ($kg\ ha^{-1}d^{-1}$)	F_{ov} ($kg\ ha^{-1}d^{-1}$)	F_{gs} ($kg\ ha^{-1}d^{-1}$)
J	14.07	23.4	22.60	0.47	616	252	303
F	18.31	24.5	25.11	0.34	674	281	368
M	20.03	24.8	28.55	0.37	734	311	393
A	23.81	25.3	30.82	0.28	781	334	447
M	21.00	27.0	31.55	0.42	800	342	414
J	18.48	26.0	31.58	0.52	804	342	385
J	16.80	26.0	31.60	0.59	803	343	363
A	15.70	25.3	31.28	0.62	791	339	348
S	15.96	25.9	29.69	0.58	757	323	344
O	15.16	25.9	26.73	0.54	698	293	327
N	13.31	25.3	23.46	0.54	633	261	295
D	12.31	24.2	21.78	0.54	600	244	278