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ON WEATHER AND CROPS

by

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Syllabus of Lectures

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ON WEATHER AND CROPS

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1. Introduction

One of the aims of modern crop ecology is to estimate the yields obtained under conditions in which the weather is limited. In arid regions, where water is hard to come by, this is of course the amount of water available for transpiration and under these conditions the study centres around the relation between crop yield and transpiration. In other areas, or with irrigation the growth rate of crops and the amount of water necessary to maintain this growth rate is mainly limited by temperature and radiation.

A discussion on some of the work proceeding in this field is appropriate here, because some idea of potential yields may give the soil scientist a standard by which the result of his efforts may be measured (How could this be done?)

2. Evaporation and Transpiration

2.1 Radiation

Solar radiation, which is the primary source of energy for all processes on earth, falls at the earth's upper atmosphere at a rate of 2 cal $cm^{-2}min^{-1}$. Even with a perfectly clear sky some of this radiation is scattered and absorbed during its passage through the atmosphere, so that at most a radiant energy of 1.65 cal cm^{-2} min^{-1} reaches the earth's surface when the sun is overhead.

Due to the scattering about 15 percent of this radiation arrives in diffused form. With a decreasing inclination of the sun the rays traverse more air so that less light reaches the soil surface and the light intensity of a horizontal surface decreases also, because of the change in angle between the surface and the sun. (Try to scetch this). The resulting relation between the total radiant energy reaching the earth's surface and the inclination of the sun is shown by curve 1 in figure 1 and the direct and diffuse part of this radiation by the curves 2 and 3, respectively. These curves hold for perfectly clear days. Usually, there is so much dust and water vapour in the air that the total is about 15 percent lower on normal clear days. (Why is this reduction especially at the expense of the direct portion?)

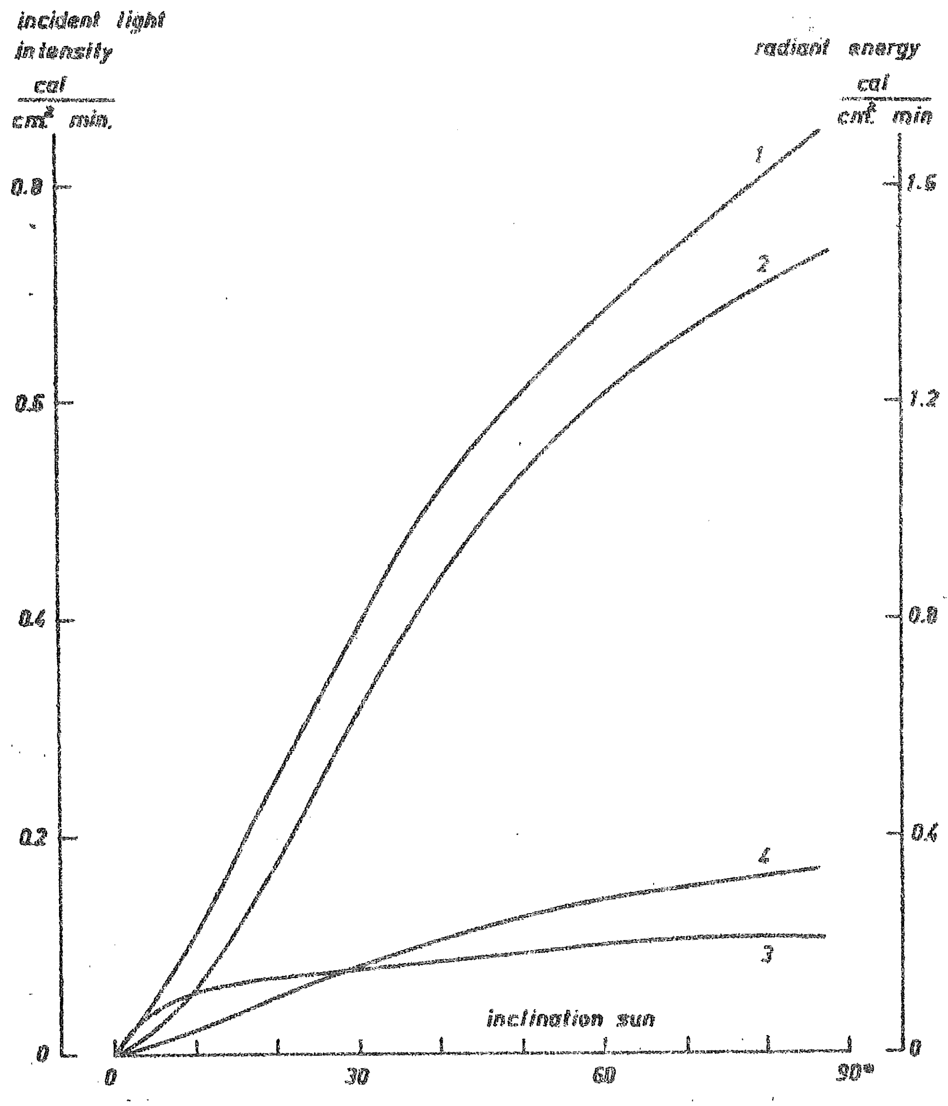

Fig. 1. Incident light intensity (left scale) and the total radiation (right scale) for various heights of the sun.
1. Total radiation with a very clear sky
2. Direct radiation with a very clear sky
3. Diffuse radiation with a very clear sky
4. Total and diffuse radiation with an overcast sky

Clouds absorb and reflect a great deal of the intercepted radiation and on days with overcast skies the radiation intensity may be as low as shown by curve 4 in figure 1. The radiation is not all of the same quality. About 50 percent is visible and the other 50 percent is in the infra-red region. A black surface is heated by both rays but only the radiation in the visible region, the light, supplies the kind of energy a plant needs to convert carbondioxyde into carbohydrates (section 3).

Any surface with a temperature above the absolute zero emits thermal radiation and the more so the higher the temperature. (Can you list examples?) Since the earth is warmer than space this leads to a net loss of heat. This heat loss occurs from the earth surface when the sky is bright and may amount to 0.2 cal cm^{-2} min^{-1}. With overcast skies this radiant heat is lost from the clouds, since these are not transparent and their temperature is about the same as that of the earth surface.

The net radiation is equal to the incoming visible and infra-red radiation minus the outgoing thermal radiation. The amount may be estimated at any time from the height of the sun, the cloudiness, and temperature and humidity of the air at screen height. The principle of instruments which enable the net radiation to be measured is a black surface of which the temperature can be determined. The radiation absorbed by this black surface is transformed into heat, leading to a temperature rise and this leads to a transfer of heat to the surroundings. A twice higher radiation leads to a twice higher temperature difference under otherwise similar conditions.

2.2 Heat and vapour transfer

The relation between sensible heat loss from a surface to the surroundings is expressed by the following equation

$$SHL = H\ (TS - TA) \qquad (1)$$

where H is the sensible heat transfer coefficient in cal cm^{-2} min^{-1} $^{o}C^{-1}$, S is the heat transfer rate in cal cm^{-2} min^{-1} and TS and TA the temperature in ^{o}C of the surface and the surrounding air, respectively.

The sensible heat transfer coefficient increases with increasing wind speed at the surface and has been experimentally determined. (How would you go about this?) For a small surface (leaf) it was found that

$$H = 0.0324\ U^{0.7} \qquad \text{cal cm}^{-2}\ \text{min}^{-1}\ {}^{o}C^{-1} \qquad (2a)$$

where U is the wind speed in meters sec^{-1} at the height of the leaf.

For a rather smooth land surface it was found that

$H = 0.0070\ (1 + 0.54\ U) \qquad cal\ cm^{-2}\ min^{-1}\ {}^{o}C^{-1}$ (2b)

It can be seen by plotting both relations (do this, please) that the value of H in the first equation is about 2-3 times higher than in the second one. The main reason is that in the latter case the wind speed and air temperature are not measured at the height of the surface but 2 meters above. It is clear from the figure you have just made that the equations are not suitable for wind speeds below 0.5 meters sec^{-1}.

(The temperature of a thin black surface which receives a net radiation of 1 cal $cm^{-2}\ min^{-1}$, exposed to an air stream with a temperature of 20°C and a wind speed of 1 m sec^{-1} is 35.5°C and not 51°C. Explain why).

The saturation vapour pressure of air (what is this?) increases with the temperature according to table 1.

Table 1. Saturation vapour pressure of water in millimeters mercury.

0	4	8	12	16	20	24	28	32	36	°C
4.58	6.10	8.04	10.5	13.6	17.5	22.4	28.3	35.7	44.6	

(The saturation vapour pressure of boiling water is .... mm Hg.)
A wet surface is a surface at which the vapour pressure of the water is equal to the saturation vapour pressure at the surface.

This surface of course loses vapourized water to the surrounding air if the vapour pressure of the water in this air is lower than the saturation vapour pressure at the surface and the more so the greater the difference. Since 560 cal are needed to evaporate 1 gram of water, this evaporation is associated to an evaporative heat loss which amounts to

EHL = K (ES - EA) (3)

in which the evaporative (latent) heat transfer coefficient K is expressed in cal $cm^{-2}\ min^{-1}\ (mm\ Hg)^{-1}$, the difference between the vapour pressure of the surface (ES) and the air (EA) in mm Hg and the evaporative heat loss EH in cal $cm^{-2}\ min^{-1}$. (How much is the correspondending vapour transfer coefficient in g water $cm^{-2}\ min^{-1}\ (mm\ Hg)^{-1}$?)

The exchange of water vapour between the evaporating surface and the air is governed by the same physical processes (diffusion and convection) as the exchange of heat, so that the sensible and evaporative heat transfer coefficient are proportional. It was found that this ratio, referred to as Bowen's ratio, equals

H / K = 0.49 mm Hg / °C (= psychrometive constant) (4)

2.3 Evaporation

The equations 1 to 4 enable the evaporation and temperature to be evaluated of a wet surface if the environmental factors are known. This will be shown by calculating the temperature of a wet black paper receiving a net radiation of 1.20 cal cm^{-2} min^{-1}, exposed to an air stream with a speed of 1 m sec^{-1}, a temperature of 20°C, and the humidity of 10 mm Hg.

The sensible heat loss of the surface is absent if the temperature is the same as that of the surrounding air, but according to equations 2a, 4 and 3 and table 1 the evaporative heat loss is 0.13 (17.5 - 10) = 0.98 cal cm^{-2} min^{-1}. Obviously, the surface gains more heat by radiation so that the temperature rises. In a similar way it may be calculated that the loss of sensible plus evaporative heat is ...., ... and .... cal cm^{-2} min^{-1} at surface temperatures of 21, 22 and 23°C, respectively. By linear interpolation it is found that at an air temperature of ...., the loss of sensible plus evaporative heat equals the gain in heat due to the net radiation and that the amount of water lost by evaporation is .... g water cm^{-2} min^{-1} in this equilibrium situation (Do these calculations). This iterative process seems rather cumbersome, but it may be conveniently executed with a computer.

The evaporation of a water surface may be calculated in a similar way by using equation 2b instead of 2a, including a reflection coefficient of about 10 percent and a reasonable estimate of the heat storage in the water layer. (A much used and rather unreasonable assumption is that the water layer is thermally isolated from the soil and infinitely thin.) The incoming radiation varies under Dutch conditions from 50 in winter to 400 cal cm^{-2} day^{-1} in summer and the evaporation of a free water surface varies from little over zero in winter to 5 mm day^{-1} in summer. (Calculate the fraction of the incoming radiation used by evaporation.) The evaporation rates in arid regions may be as large as 10 mm/day.

The iterative process of calculating transpiration may be by-passed by using an approximate method which was first introduced by PENMAN. In the equilibrium situation (characterized by ....?) the absorbed short wave radiation minus the long wave radiation or the net radiation equals the sensible heat loss + the evaporative heat loss, or NRAD = SHL + EHL (5)

Substituting the equations (1), (3) and (4) gives

$$NRAD = H\ (TS - TA) + (H/.49)\ (ES - EA) \qquad (6)$$

There are two unknowns, the temperature (TS) and the vapour pressure at the surface (ES).

For a wet surface, ES equals the saturation vapour pressure which corresponds to TS, hence there is another equation and only one unknown.

To simplify the relation for further computations PENMAN introduced the approximate relation:

$$ES - EA = S(TS - TD) \qquad (7)$$

in which TD is the dewpoint (definition?) and S the avarage slope of the saturation vapour pressure curve (table 1) between TA and TD (Draw this curve and calculate S at 2, 6, 10, 14, 18, 22, 30 and 34 degrees).

Substituting (7) in (6) yields:

$$NRAD = H(TS - TA) + (H/.49)\ S\ (TS - TD)$$

in which TD is the only unknown and can be made explicite:

$$TS = TA + \frac{.49}{.49+S} \times \frac{NRAD}{H} - \frac{S}{S+.49} \times (TA - TD) \qquad (8)$$

Verify that the constant .49 and the variable S have the same dimension and that NRAD/H has the dimension of degrees. Find some conditions in which TS = TA, TS > TA or TS < TA.

By substituting (8) in (7) and substracting from NRAD it is found that

$$EHL = \frac{S}{S+.49}\ (NRAD + H(TA-TD)) \qquad (9)$$

Which expression for H has to be used to obtain the evaporative heat loss of a lake, and how is the evaporation in millimeter water calculated?

2.4 Potential transpiration

The leaf is protected against desiccation by the cuticula which is almost impermeable for water. This impermeable layer is covered with a large number of stomata so that carbondioxyde for photosynthesis may enter. These are open when the leaf is subjected to sufficient light and well supplied with water, and closed when there is a shortage of water and in the dark. Water is of course lost through the stomata, when these are open.

Compared to a wet surface, the water vapour in the leaf has to overcome an additional resistance and the evaporative heat exchange coefficient is therefore smaller than the one calculated with Bowen's ratio from the sensible heat exchange coefficient. (It was found that at a wind speed of 1 meter sec^{-1} the evaporative heat exchange coefficient of a barley leaf is about half that of a similar wet surface. Calculate the temperature and the transpiration of a barley leaf which absorbs a net radiation of 1.2 cal m^{-2} min^{-1} and is exposed to an air stream with a speed of 1 m sec^{-1}, a temperature of 20^{o} and a humidity of 10 mg Hg. Compare the outcome with the outcome of the calculations in section 2.3.)

With a closed crop surface this increased resistance is more or less off-set by the large number of leaves, and for this reason the transpiration rate of a green, closed crop surface well supplied with water (that is the potential transpiration rate) does not differ too much from the evaporation rate of a free water surface. More important reasons for differences are that the reflection coefficient of a green surface is about 20-25 percent and for water only 10 percent and that the sensible heat exchange coefficient of a rather rough crop surface is larger than that of a smooth surface.

These effects are often accounted for by introducing a multiplication factor of the free water evaporation to find the potential transpiration. This multiplication factor varies from about 0.8 for bowling greens to about 1.5 for alfalfa in its grand period of growth.

3. Photosynthesis of leaf canopies

3.1 Single leaves

It has already been mentioned that leaves are provided with stomata to enable carbondioxyde for photosynthesis to enter. This is the proces by which the carbondioxyde from the air is transferred to carbo-hydrates according to the following scheme $CO_2 + H_2O \rightarrow CH_2O + O_2$.

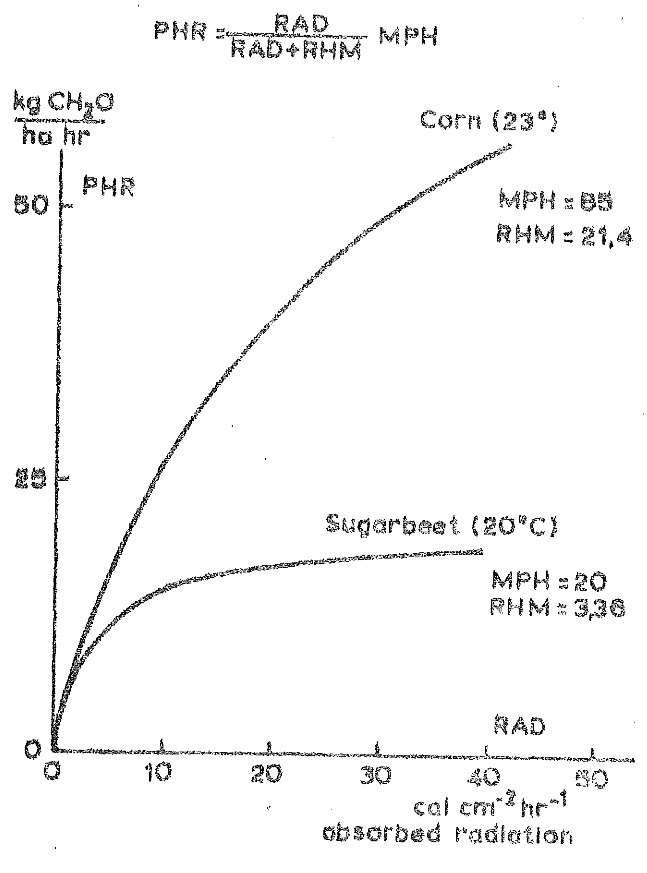

Figure 2a:

The photosynthesis function for leaves of sugarbeet and corn

$1 \text{ cal cm}^{-2} \text{ min}^{-1} = 60 \text{ cal cm}^{-2} \text{ hr}^{-1}$

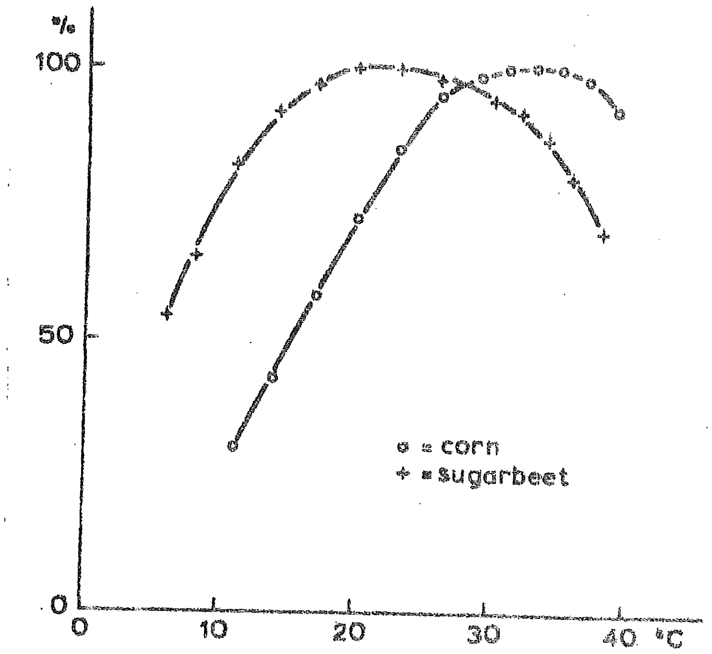

Figure 2b:

The influence of temperature on the photosynthesis of corn and sugarbeet.

The curve for sugarbeets in figure 2a presents how the photosynthesis of single leaves of a well developing agricultural crop may depend on radiation intensity. The photosynthesis rate at low intensities is about proportional to the light intensity, but at radiation intensities above 20 cal cm^{-2} hr^{-1} the increase with increasing radiation is small. The shape of the photosynthesis function for this species is not very temperature dependent within the normal temperature range (figure 2b). Other species, like corn, have a much higher saturation value of photosynthesis, whereas at the same time the temperature dependence is also much higher.

3.2 Crop surfaces

A very simple crop surface consists of large, horizontal leaves. The first layer of leaves is subjected to a light intensity of about 0.6 cal cm^{-2} min^{-1} on a clear day with the sun at 45° (figure 1) and produces carbohydrates at a rate of about 18 kg CH_2O ha^{-1} $hour^{-1}$ (figure 2, sugarbeet). The second layer of leaves receives about 15 percent of that on the first layer and its production rate is about 11 kg CH_2O $ha^{-1}hr^{-1}$. The next layer receives a negligible amount of light, so that the total production of such a crop surface is about 30 kg CH_2O $ha^{-1}hr^{-1}$ under these conditions. (Check these estimates, taking care of units and of the difference between radiation and light-intensity).

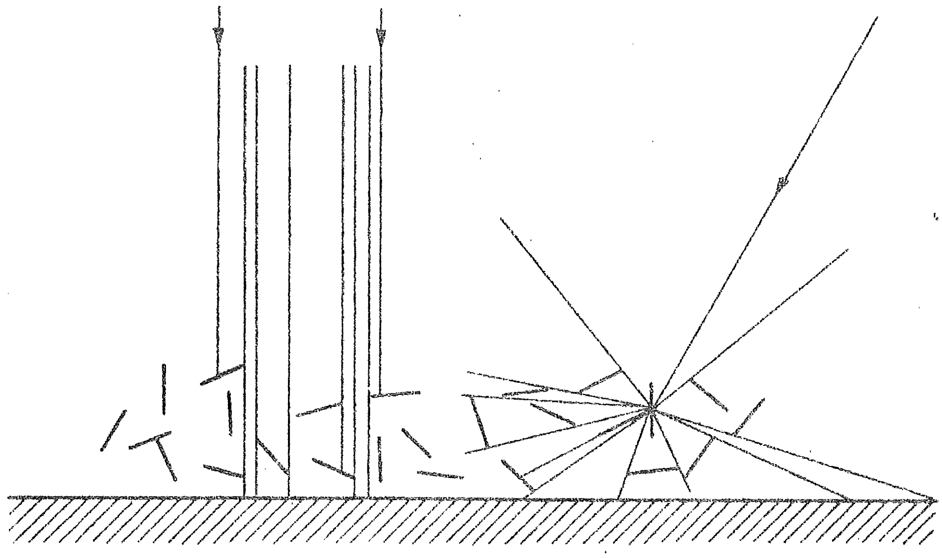

Figure 3: Schematic representation of light interception by and scattering of light in a crop with a leaf area index of 2.

However, a crop surface does not consist of big, horizontal leaves but of small leaves, inclined to many angles. This is schematically presented in figure 3, for a crop surface with a leaf area index of 2 (this means that the leaf area is two times the soil area). The left side of the graph shows how the light from vertical direction is distributed. Obviously many more leaves than one LAI are necessary to intercept all the light, so that this light is distributed over a much larger leaf area than with horizontal leaves. Moreover, about 30 percent of the light arriving at a leaf is scattered and the right hand side of figure 3 shows that this also results in a more even distribution of the light.

This better distribution of light over a large number of leaves causes a higher photosynthesis per unit crop area because the photosynthesis of single leaves is not proportional to the light intensity. The distribution of light in a crop surface depends on many factors, such as amount of leaves, reflection and transmission (scattering), position of the leaves with respect to the soil and each other and the height of the sun and the cloudiness. All these variables can be measured and their mutual effect on light distribution and therefore on the photosynthesis rate of crop surfaces can be calculated with computers.

3.3 Potential photosynthesis

For the present purpose only the potential photosynthesis is defined here as the photosynthesis of a crop surface with a LAI of 5, the structure of young grass or small grains, consisting of leaves with a reflection and transmission of 15 percent and with a photosynthesis function as shown in figure 2, for sugarbeet.

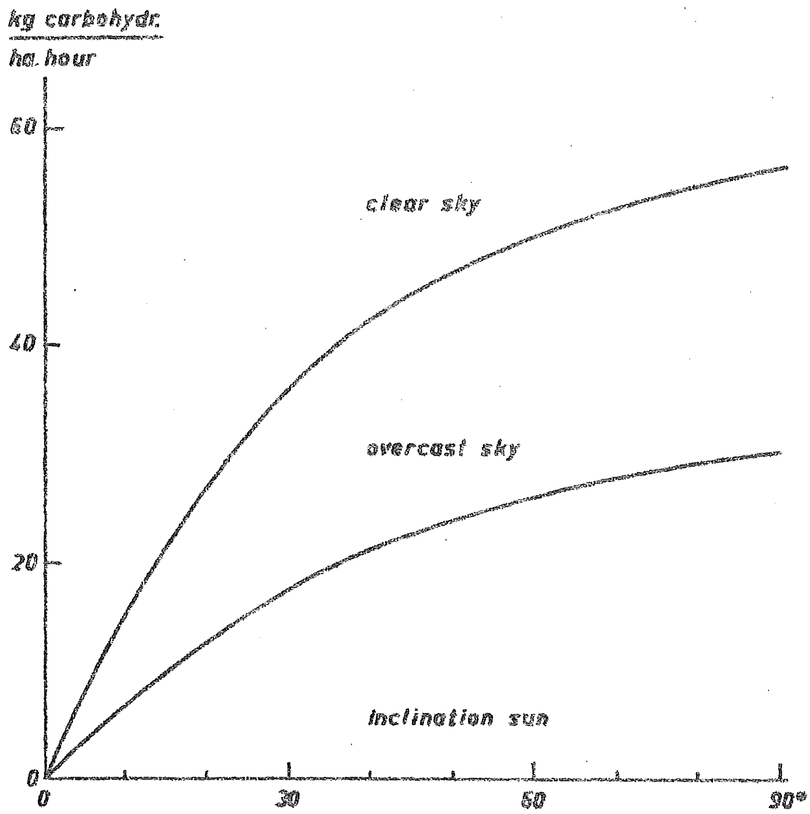

Figure 4: Potential photosynthesis in relation to the height of the sun with clear and overcast skies.

The dependence of this potential photosynthesis on the height of the sun with clear and overcast skies is shown in figure 4. The maximum rate appears to be about 60 kg CH_2O ha^{-1} hr^{-1} which is considerable higher than that of a crop surface with horizontal leaves. The light intensities with overcast skies is about 20 percent of the light intensity of clear skies (figure 1), but the photosynthesis rate is about 50 percent. This relatively high rate with overcast skies is due to a better distribution of light under these conditions.

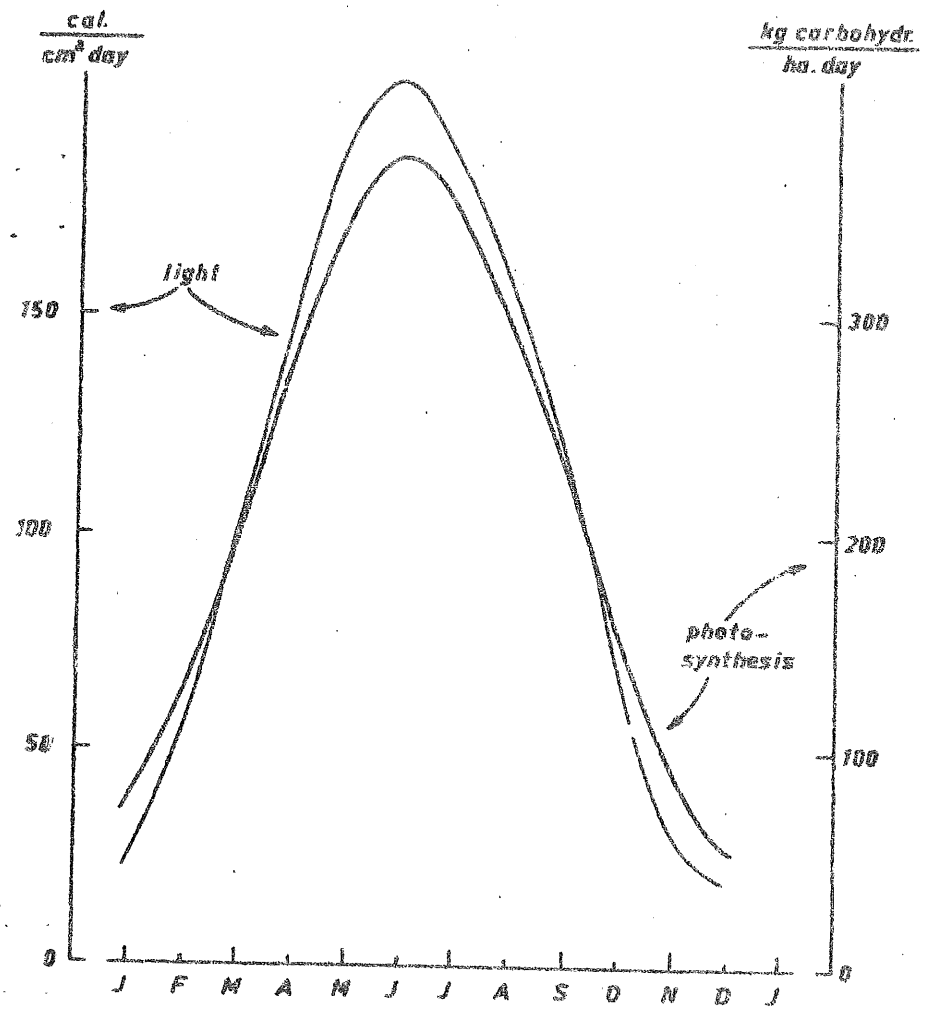

Figure 5: Daily total of potential photosynthesis and light throughout the year in the Netherlands

The height of the sun for any place and hour of the day may be calculated and the cloudiness can be measured. It is therefore possible to calculate the daily total of potential photosynthesis for any date and place. Under Dutch conditions these potential photosynthesis are summarized in figure 5, together with the daily totals of light intensity. The potential photosynthesis is about 375 kg CH_2O ha^{-1} day^{-1} in June which is equivalent to 375 x 4 x 1000 kilocal ha^{-1} day^{-1}, (what does the 4 stand for?) the daily light total amounts to 20.5×10^6 kilocal ha^{-1} day^{-1}, and therefore the efficiency of photosynthesis is $(1.5 \times 10^6/20.5 \times 10^6)100 = 7.3$ percent. (Why is the efficiency of photosynthesis higher (11 percent) in winter?)

Table 2. The daily totals of light and potential photosynthesis for a canopy with a LAI of 5. HC is the light on very clear days and is expressed in cal cm^{-2} day^{-1}. The light intensity on overcast days is 0.2 times HC. PC and PO are the daily totals of photosynthesis on very clear and overcast days, respectively, and are expressed in kg CH_2O ha^{-1} day^{-1}.

North Lat.		15 Jan.	15 Febr.	15 March	15 Apr.	15 May	15 June	15 July	15 Aug.	15 Sept.	15 Oct.	15 Nov.	15 Dec.
0°	HC	343	360	369	364	349	337	342	357	368	365	349	337
	PC	413	424	429	426	417	410	413	422	429	427	418	410
	PO	219	226	230	228	221	216	218	225	230	228	222	216
10°	HC	299	332	359	375	377	374	375	377	369	345	311	291
	PC	376	401	422	437	440	440	440	439	431	411	385	370
	PO	197	212	225	234	236	235	236	235	230	218	203	193
20°	HC	249	293	337	375	394	400	399	386	357	313	264	238
	PC	334	371	407	439	460	468	465	451	425	387	348	325
	PO	170	193	215	235	246	250	249	242	226	203	178	164
30°	HC	191	245	303	363	400	417	411	384	333	270	210	179
	PC	281	333	385	437	471	489	483	456	412	356	299	269
	PO	137	168	200	232	251	261	258	243	216	182	148	130
40°	HC	131	190	260	339	396	422	413	369	298	220	151	118
	PC	218	283	353	427	480	506	497	455	390	314	241	204
	PO	99	137	178	223	253	268	263	239	200	155	112	91
50°	HC	73	131	207	304	380	418	405	344	254	163	92	61
	PC	147	223	310	409	484	522	509	448	358	260	173	130
	PO	60	100	150	207	251	273	265	230	178	121	73	51
60°	HC	22	72	149	260	356	408	389	309	201	103	37	41
	PC	66	151	254	383	487	544	523	436	316	195	94	49
	PO	19	60	114	187	245	276	265	216	148	82	31	11
70°	HC	0	20	89	209	331	408	380	269	142	45	2	0
	PC	0	65	185	350	506	612	575	427	262	114	7	0
	PO	0	16	74	158	241	291	273	200	112	38	1	0
80°	HC	0	0	28	162	334	424	393	248	81	3	0	0
	PC	0	0	94	333	571	663	632	474	195	11	0	0
	PO	0	0	24	133	257	318	297	196	69	2	0	0
90°	HC	0	0	0	154	339	428	397	252	40	0	0	0
	PC	0	0	0	371	588	677	646	497	167	0	0	0
	PO	0	0	0	131	269	319	302	215	35	0	0	0

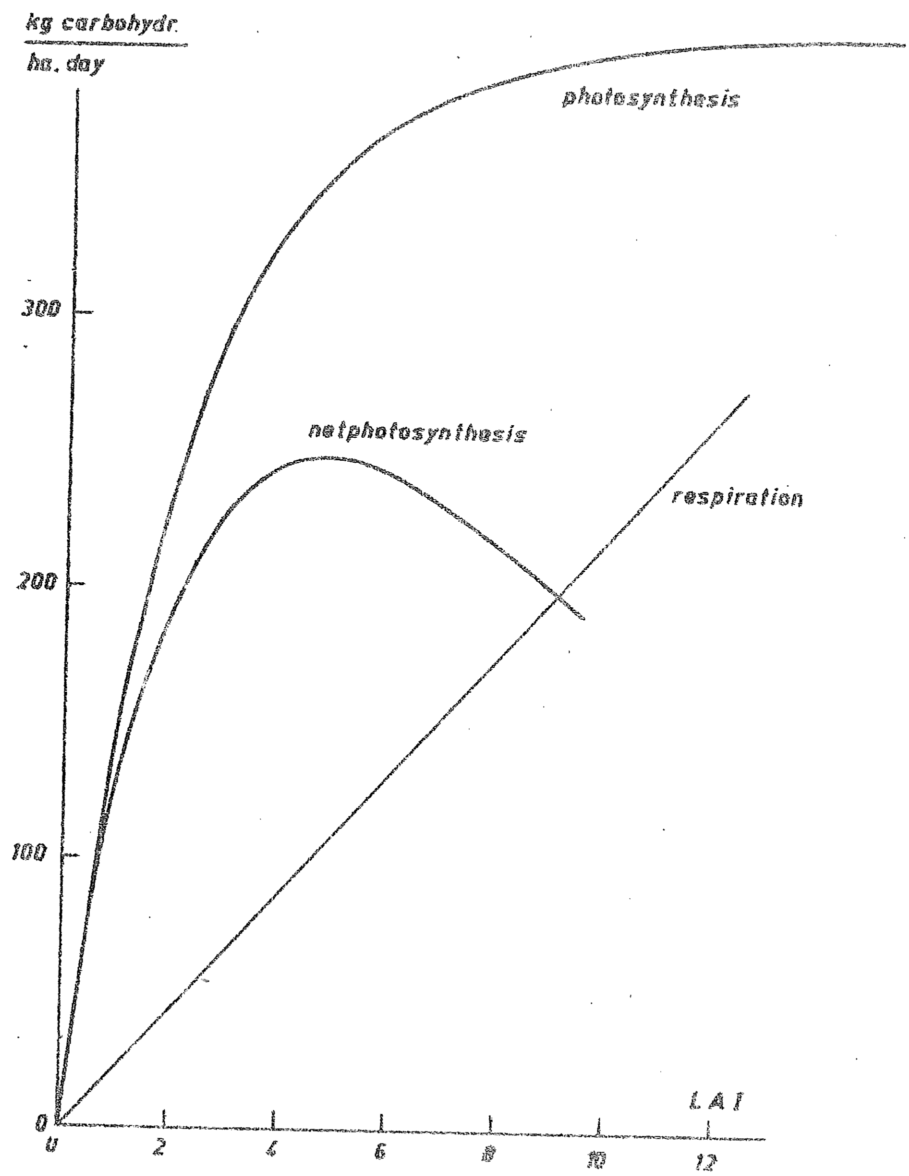

Figure 6:

The relation between the leaf area index and the photosynthesis, the net photosynthesis and the respiration for a grass like green crop surface in the Netherlands on the 21st of June.

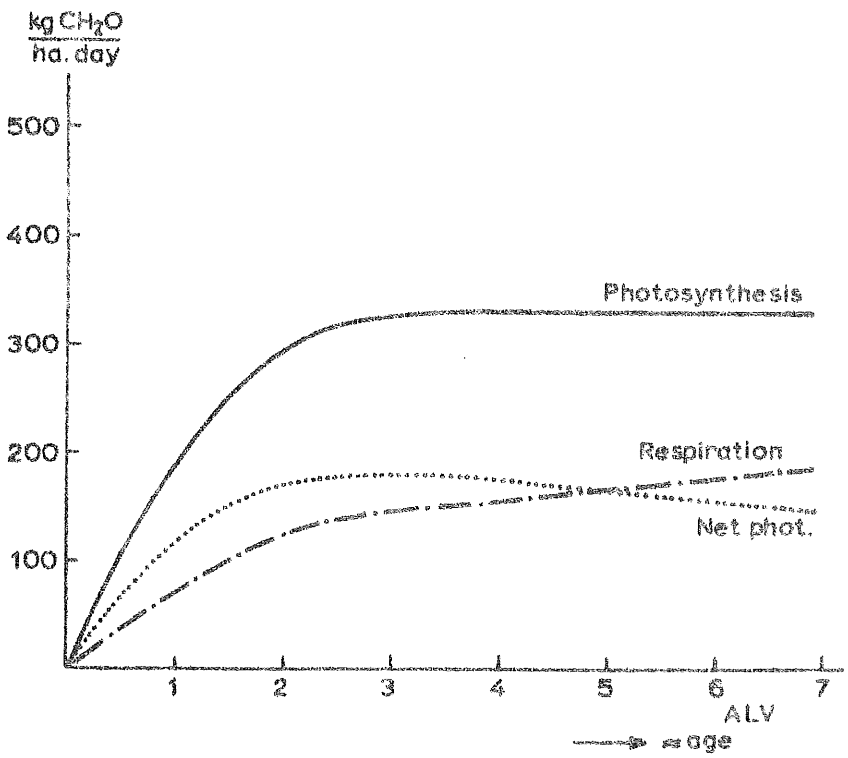

Figure 7:

Photosynthesis and respiration of subterranean clover in dependence of leaf area index under controlled conditions (after McGree).

The potential photosynthesis with clear and overcast skies has been calculated for different latitudes and places. These results are given in table 2 together with the daily light total on clear days. The daily light total and potential photosynthesis in less extreme weather conditions can be estimated from the relative duration of sunshine (N in a scale of 0 to 1) with the following equations:

Daily total light = 0.8(0.25 + 0.75 x N)HC cal cm^{-2} day^{-1} and

Potential photosynthesis = PO + 0.9 N(PC - PO) kg CH_2O ha^{-1} day^{-1}

(Try to understand these equations. The factors 0.8 and 0.9 are used to reduce the value for perfectly clear skies to normal clear skies.)
(Calculate also the daily light total and potential photosynthesis with a relative duration of sunshine (N) of 0.7 and for the 15th of August in a North latitude of 30^o, 24^o and -30^o and for the 23rd of August in a North Latitude of 24^o. Use linear interpolation whereever necessary.)

3.4 Respiration and net photosynthesis

The plant uses its photosynthesis products in growth but in this process, and for the maintainance of the structure, energy is needed which is derived from respiration of carbohydrates. This process $CH_2O + O_2 \rightarrow CO_2 + H_2O$ is like growth considerably temperature dependent.

It is often assumed that the respiration increases more or less linearly with the amount of plant material on the field or the leaf area index, whereas the photosynthesis rate approaches a maximum value because of mutual shading of leaves. The composite effect of all this is illustrated in figure 6, where photosynthesis, respiration as estimated from laboratory experiments with single plants and net photosynthesis are presented in dependence of the LAI in de Netherlands on the 15th of June. The photosynthesis increases to a maximum of about 395 kg CH_2O ha^{-1} day^{-1}, but the optimum photosynthesis is reached at an LAI of about 4.5 and amounts to 250 kg CH_2O ha^{-1} day^{-1}. It appears that at optimum LAI about 30 percent of the photosynthesis is lost by respiration. A ceiling leaf area index (net photosynthesis zero) has been observed* after placing plants, grown apart, close together.

However measurements on growing crops do not corroborate the assumption of linearity as shown by some results in figure 7, obtained with subterranean clover and for the time being it seems better to assume that respiration is a fraction of photosynthesis in the order of magnitude of 30-50 percent, more or less independent of the amount of plant material on the field.

* for short periods

3.5 Maximum dry matter yields

Farmers know fairly well for each crop how long a green closed crop surface can be maintained under favourable conditions in their region. The maximum dry matter production of such a crop can be estimated in a first approximation by multiplying this period in days with 60 percent of the potential photosynthesis given in table 2. In the Netherlands, the maximum dry matter production of summer grains is estimated about 60 days x 200 kg ha^{-1} day^{-1} or 12.000 kg ha^{-1} and of sugarbeets at 7000 kg in July plus 6000 kg in August plus 5000 kg in September plus some 2000 kg in October or in total 20.000 kg ha^{-1}. These are not unreasonable estimates for the total dry matter yields as is shown in figure 8. (Make in the same fashion some estimates of total production in your own country and check whether these are reasonable).

GROWTH OF CLOSED GREEN CROP SURFACES IN THE NETHERLANDS

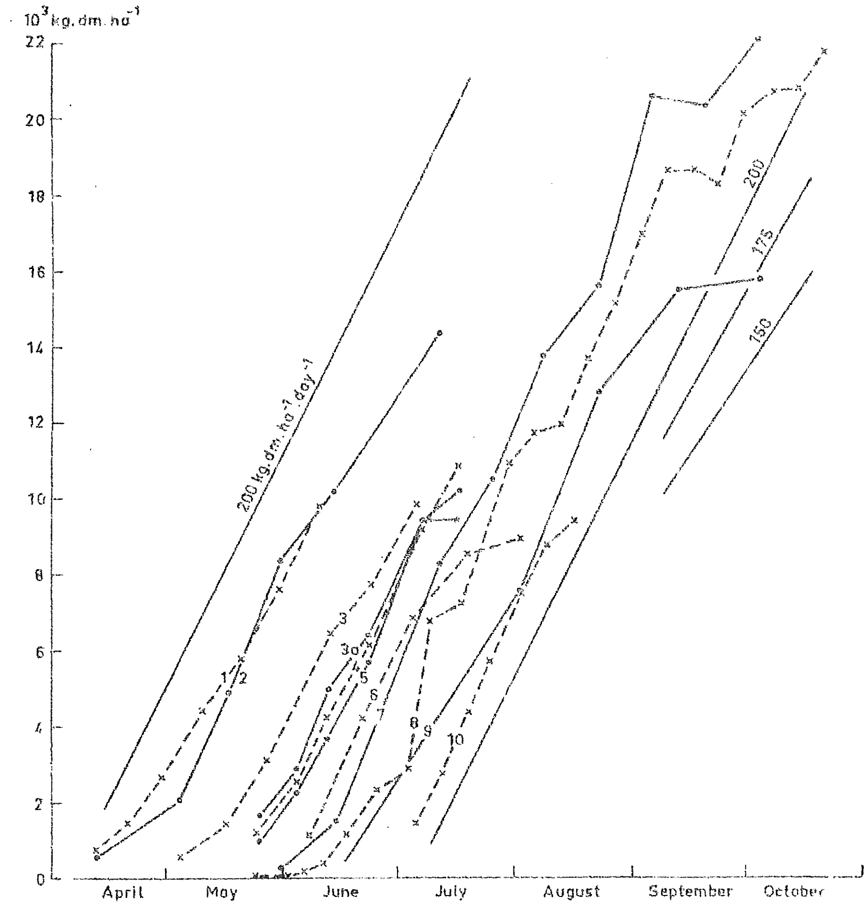

Figure 8:

Comparison of growth rates of agricultural crops and algae with the curves corresponding to 200, 175 and 150 kg ha^{-1} day^{-1}

(after Sibma)

1. Grass	1960 Alberda	6. Barley	1966 de Wit
2. Wheat	1965 de Vos	7. Potatoes	1965 Bodlaender
3. Oats + Barley	1960 de Wit	8. Sugarbeets	1965 Bakermans
3a. Oats + Peas	1964 de Wit	9. Maize	1937 Meyers
4. Oats	1964 de Wit	10. Algae	1954 van Oorschot
5. Peas	1964 de Wit		

Methods are being developed enabling the length of the grand period of growth to be estimated in dependence of the density and date of planting, the temperature of air and soil etc., but these are too complicated to discuss here.

It was found in section 2.3 and 2.4 that the transpiration rate of a closed, green crop surface is about 5 mm day^{-1} of 50.000 kg ha^{-1} day^{-1} during the summer months in the Netherlands. This means that with an optimum photosynthesis of 200 kg CH_2O ha^{-1} day^{-1} about 250 kg of water is used during the production of 1 kg dry matter, or that the transpiration ratio is 250 under these conditions.

4. Transpiration and crop yields under arid conditions

4.1 Transpiration and production of single plants

The ratio between the transpired amount of water (W) and the dry matter production (P) of plants grown in containers, i.e. the transpiration ratio (W/P) has been determined under a wide range of conditions in course of time. It was found, at least under arid conditions, that this transpiration ratio is more or less proportional to the evaporation rate of a free water surface (E), averaged over the grand period of growth. But the remaining scattering of the observations, attributed to different growing conditions, appeared to be so uncomfortably large that the usefulness of this approach has been and is often doubted.

However,it has been shown that this conclusion is based on an incorrect statistical evaluation of the information and that not the ratio W/P should be compared to the value of E, but the dry matter production P should be compared to the quotient W/E. The results of many pot experiments with sorghum, wheat and alfalfa throughout the Great Plains of the U.S.A. in the years 1910 - 1927 are presented in figure 9. It appears that the observations are around a straight line through the origin, so that the relation between the dry-matter production and the quotient W/E can be expressed by the simple equation $P = m\ (W/E)$ (5)

in which the constant m depends on the plant species and appeared to be 20.7, 11.5 and 5.5 for sorghum, wheat and alfalfa when P is expressed in grams, W in kg and E in mm/day. The value of m for corn was found to be equal to 17, and the value of wheat holds also for other small grains. Obviously, sorghum and corn are much more efficient in their water use than alfalfa.

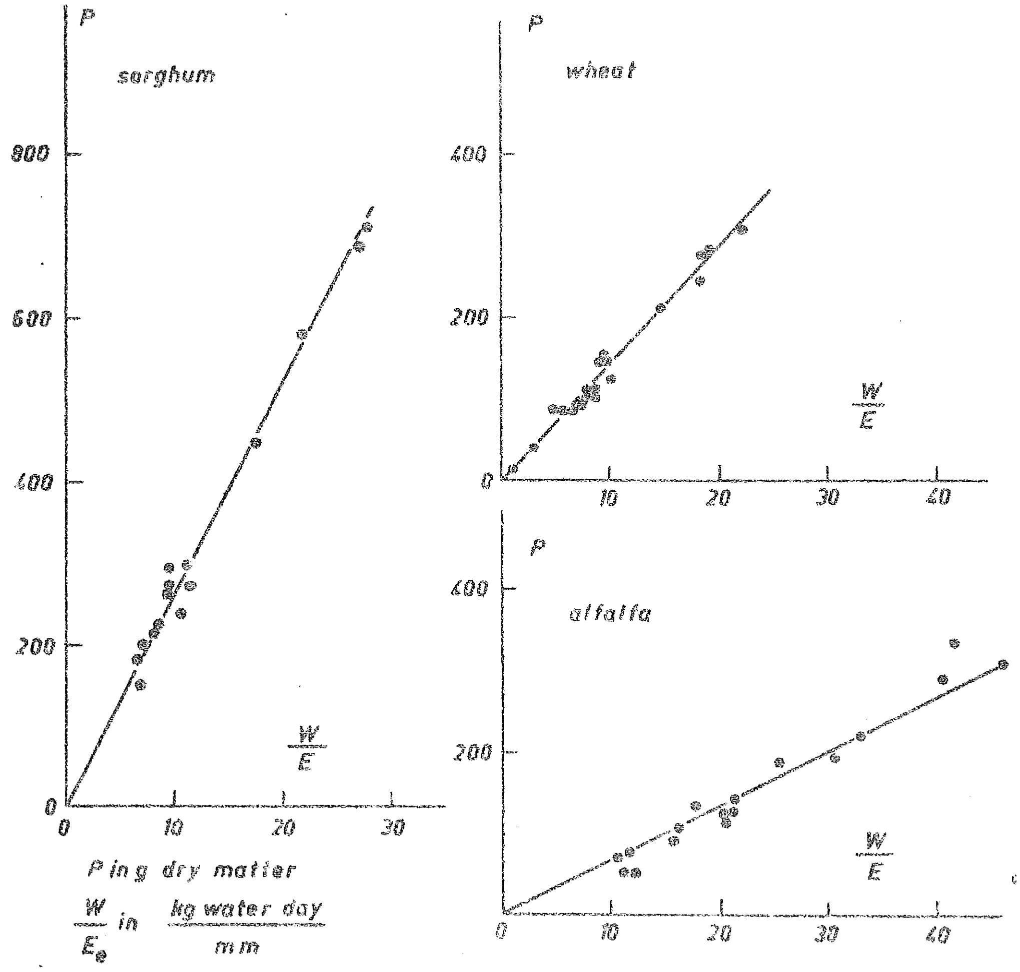

Figure 9: The relation between dry matter production P and the ratio W/E of the transpired amount of water W and the free water evaporation E for sorghum, wheat and alfalfa plants grown in containers in the arid region of the U.S.A. Data from Briggs, Shants and Piemiesel.

The relation of equation 5 excists only when transpiration and evaporation vary for other reasons than variations in radiation (mention a few) or when the light intensity is so high during a considerable part of the day that the photosynthesis of well exposed leaves is near its maximum, and therefore should be used with caution.

(A small experiment in a climate room gave the following results:

Corn	Oats	Barley	
5.03	2.56	2.14	P in grams dry matter
553	768	620	W in g water
14.2	45.8	37.8	Transpiration rate in g water $(g\ shoot)^{-1}$ day^{-1}

Calculate the transpiration ratio and estimate the net photosynthesis per unit shoot weight. Are differences in m between the plant species due to differences in transpiration rate or to differences in net photosynthesis rates per unit shoot?)

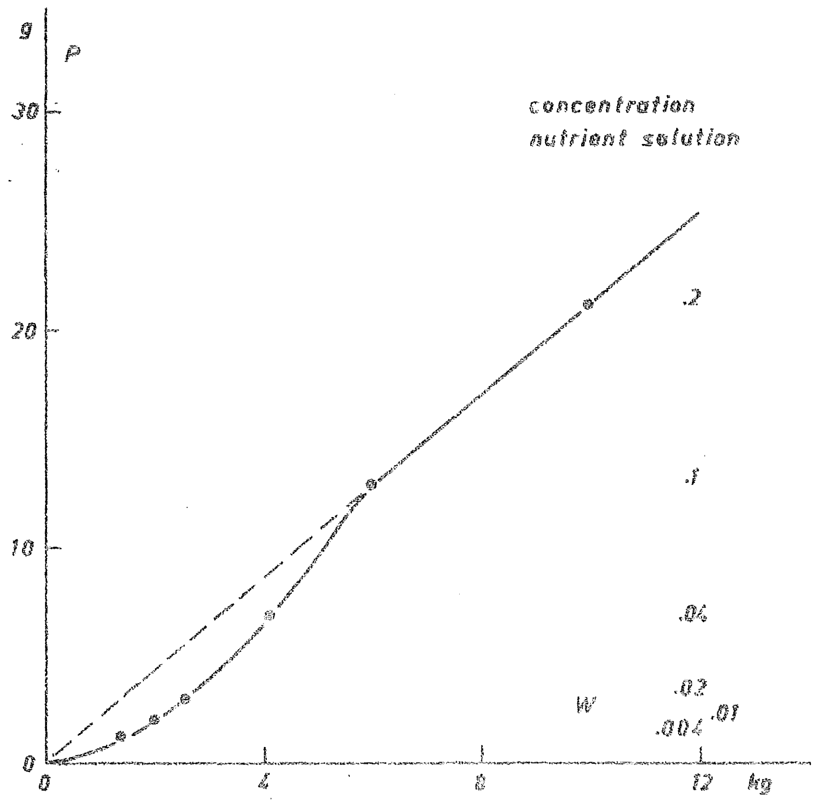

Figure 10: The influence of nutrition on the relation between transpiration (W) and production (P) of wheat plants. Data from Thom and Holtz.

Influenced by differences in nutrition, plants form more or less leaf surface or surface that can transpire water and assimilate carbondioxyde. Only with more severe nutrient shortages, plants form leaves with a smaller photosynthetic capacity. This is illustrated in figure 10, in which the transpiration and yield of wheat plants grown at different nutrition levels are given. (Explain how it is possible that plants with the same photosynthesis per unit leaf area grow at different rates.)

Plants suffering from water shortage first reduce their size, but under more severe stress the photosynthetic rate and the transpiration rate per unit leaf area are also reduced. Fortunately, it appears that the effect on both is about the same, at least in normal light intensities, so that the relation between transpiration and production of plants under water stress is about the same as that of plants with a normal water supply. This is illustrated in figure 11 for corn. (Try to explain why with excess water in the soil, the observations deviate from the line).

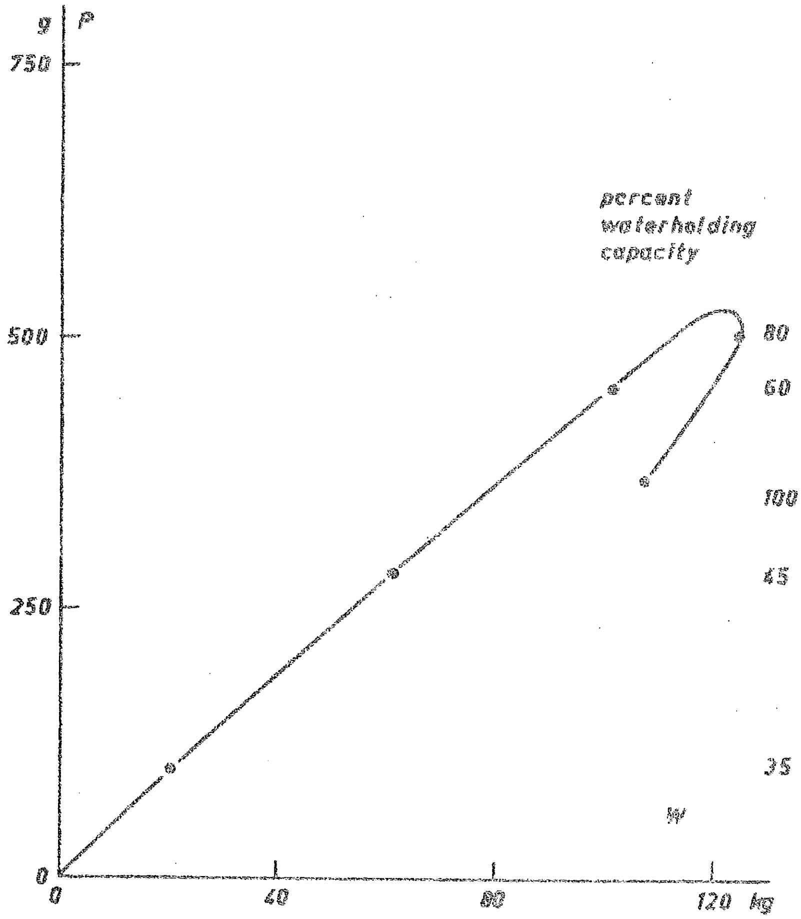

Figure 11: The influence of the availability of water on the relation between transpiration (W) and production (P) of corn. Data from Kieselbach. (What is the waterholding capacity of a soil?)

4.2 Transpiration and production in the field.

The transpiration ratio of a closed crop surface is in the order of 250 kg water per kg dry matter (section 3.5) whereas the same value for single plants of alfalfa amounts to about 1000. Hence, the efficiency of water use should increase with increasing density of planting, except for sorghum. (Why this exception?)
However, under arid conditions the growth of plants is checked by water shortage, so that closed crop surfaces do not develop. Because, moreover, the transpiration ratio is independent of the availability of water, the same relation between transpiration and production may be found in the field under arid conditions as in containers well supplied with water.

Under field conditions, the value of W in the equation P=m(W/E) is given in mm, and since E is expressed in mm/day the ratio W/E is given in days. It represents the number of days that transpiration at a rate equal to the evaporation of a free water surface is possible. The yield

P is expressed in kg/ha (or similar units), so that the most convenient unit for m is kg.ha^{-1} day^{-1} (or lbs acre^{-1} day^{-1}. tons acre^{-1} day^{-1}, etc.). From the data given in section 4.1, the value of m expressed in kg ha^{-1} day^{-1} can be calculated to equal 207, 170, 115 and 55 for sorghum, corn, wheat and alfalfa, respectively.

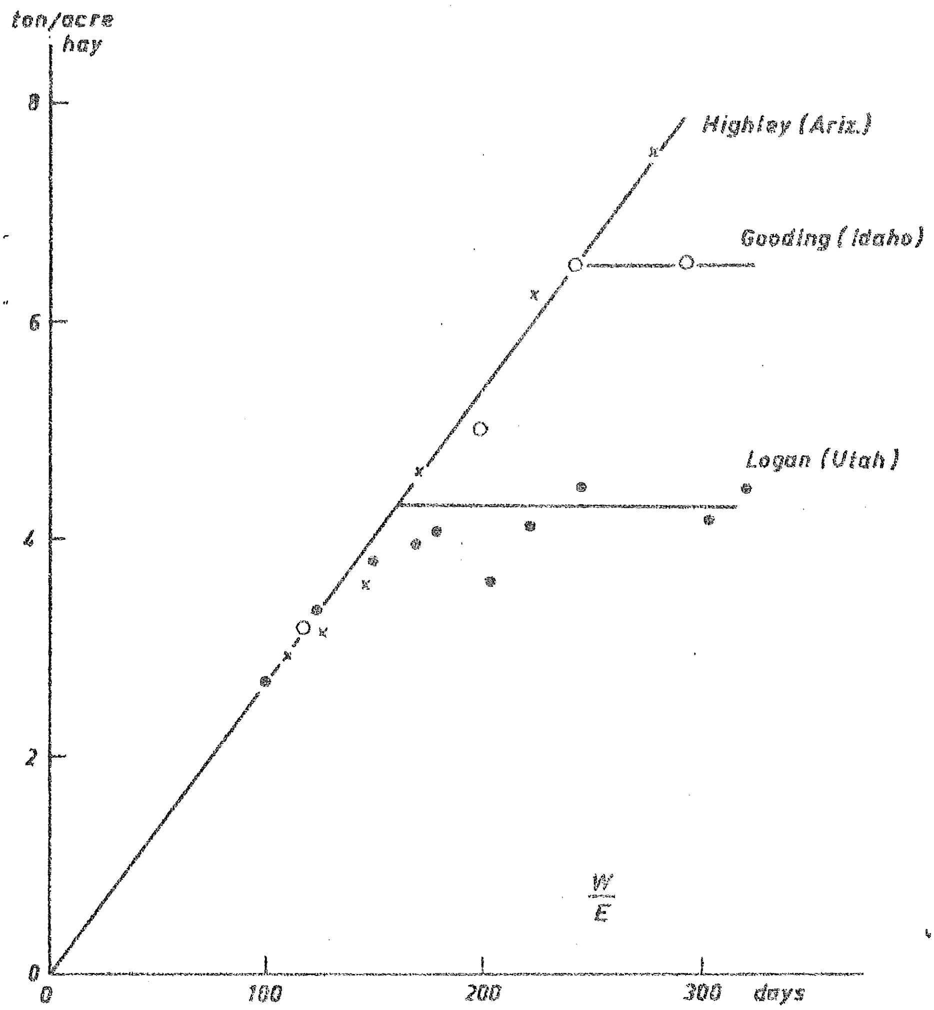

Figure 12: The relation between the yield of alfalfa hay and the amount of water available for transpiration in days at three experimental fields in the U.S.A. Data from Harris and Pittman, Fortier, Marr.

	Highly	Gooding	Logan	
Evaporation	6	4	4.5	mm/day
Growing season	260	150	160	days

Figure 12 shows that this indeed holds if the amount of water available for transpiration (rain water plus irrigation water minus an estimate of losses) expressed in days (i.e. W/E) is plotted against the alfalfa yield in tons/acre. The full drawn line is calculated from the pot experiments (figure 9) and the observations are the results of irrigation experiments in Logan (Utah), Gooding(Idaho) and Highly(Arizona). The observation points coincide with the line from pot experiments as long as water is the limiting factor. Beyond that region the yield is limited by other factors and the amount of water available for transpiration is probably not completely used. It is seen that the closed crop condition where the transpiration ratio is in the order of 250 instead of 1000 is not at all achieved with these yields.

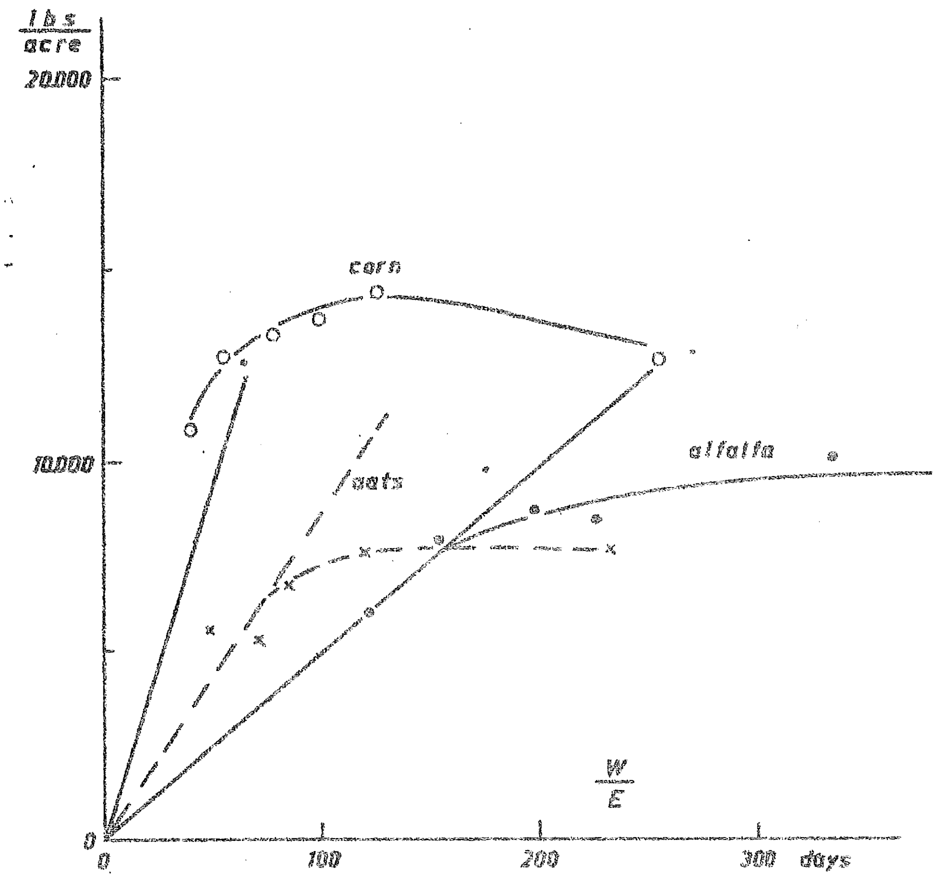

Figure 13: The relation between the amount of water available for transpiration and dry matter yield of oats, corn and alfalfa on irrigated fields in Logan (Utah). Data from Widstoe.

The result of a similar experiment in Logan (Utah) with corn, oats and lucerne is given in figure 13. The lower yields coincide again with the lines calculated from the pot experiments. (Give a possible reason why the observations of corn are rather far from the line).

The relation between the amount of rainfall plus the amount of water in the soil, divided by the average free water evaporation and the yield of wheat grown in different years and places throughout the Great Plains of the United States is shown in figure 14. The line through the observations is again obtained from pot experiments and the intersection with the horizontal axis suggests that in these regions about 15 days of water is lost in other ways than by transpiration, which is not an unreasonable result. The scattering of observations of this type is of course large, but the average points in the graph show that here again the results of field and pot experiments agree.

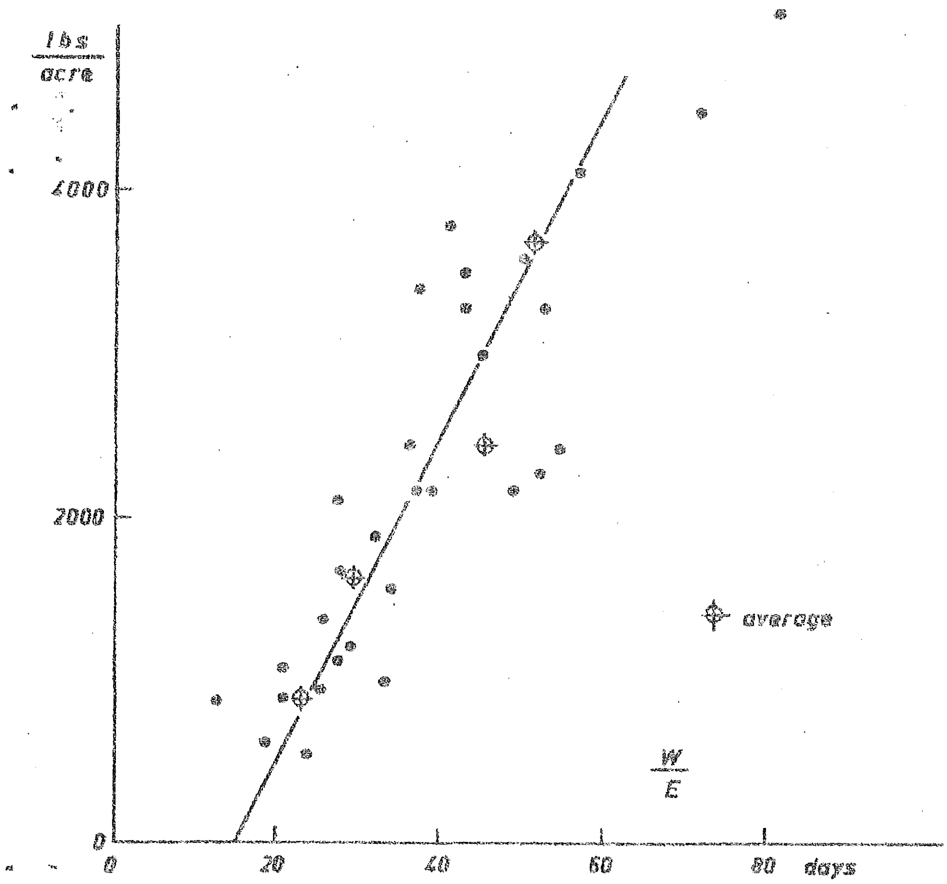

Figure 14: The relation between transpiration in days and dry matter yield of durum wheat in different years and at different places of the dry region of the U.S.A. Data from Cole and Mathews.

The full drawn line in figure 15 presents the relation between seed yield and seed plus straw yield as calculated from pot experiments; the points represent field observations in the Great Plains. Obviously it is more difficult to reach a favourable ratio when the yield (in casu the amount of available water) is small. If the crop is managed in such a way that a large portion of the available water is transpired during the first part of the growing season, a large straw yield is obtained, but seed yields are low. In dry regions, where late rains may fail it is a good practice to save water for later stages of growth. The best way to do this is to avoid luxurious growth during the first part of

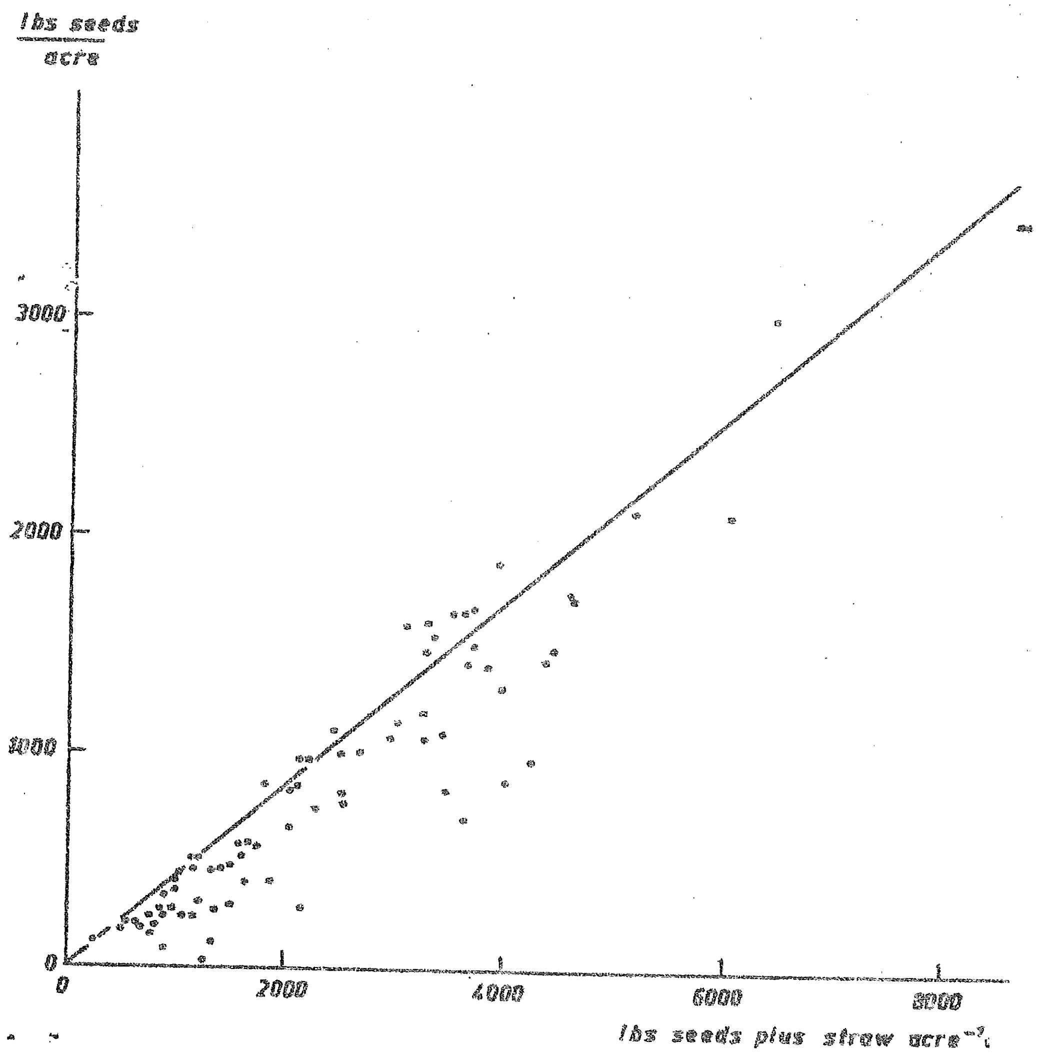

Figure 15: The relation between seed and seed plus straw yield (total yield) in several places of the great plains of U.S.A. in several years. The straight line through the origin presents the same ratio as in containers, but corrected for the stubble. Data from Cole and Mathews.

the growing period by planting in wide rows, being carefull with (nitrogen) fertilizer application and good soil management. Of course early growth may be so slow that the plants do not consume all the water in later stages and this also leads to a drop in yield. In avoiding all these pitfalls nothing is more helpful than a good farmer.

Further reading on the subject:

REITEMA, P.E.: Aan analyses of actual evapotranspiration.
Versl. Landb. Onderz. (Agr. Res. Reports) 659 (1967).

WIT, C.T. de : Transpiration and crop yields.
Versl. Landb. Onderz. (Agr. Res. Reports) 64.6 (1958).

WIT, C.T. de : Photosynthesis of leaf canopies.
Versl. Landb. Onderz. (Agr. Res. Reports) 663 (1965)

JEN-HU CHANG : Climate and agriculture.
Aldine, Chicago, 1968

PIETRO, A.S., F.A. Greer, T.A. Army, : Harvesting the sun.
Ac. Press, 1967