REPRINTED FROM:
ADVANC. SCI. 23 (1966) 159-162

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C. T. DE WIT

Instituut voor Biologisch en Scheikundig Onderzoek van Landbouwgewassen, Wageningen
Mededeling 308

PHOTOSYNTHESIS OF CROP SURFACES*

Dr. C. T. de WIT *Institute for Biological and Chemical Research on Field Crops and Herbage, Wageningen, The Netherlands*

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 $1 \cdot 65$ cal cm^{-2} min^{-1} reaches the earth's surface when the sun is overhead.

Due to scattering about 15 per cent 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. 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 Fig. 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 per cent lower on normal clear days.

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 Fig. 1. The radiation is not all of the same quality. About 50 per cent is visible and the other 50 per cent 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 that is needed for photosynthesis.

This is the process by which the carbon dioxide from the air is transferred to carbohydrates according to: $CO_2 + H_2O \rightarrow CH_2O + O_2$.

* Text of the paper presented to Section M (Agriculture) on September 7, 1965, at the Cambridge Meeting of the British Association.

The curve in Fig. 2 presents how photosynthesis of single leaves in a vigorously-growing agricultural crop may depend on light intensity. The photosynthesis rate at low intensities is about proportional to the light intensity, but above $0 \cdot 3$ cal cm^{-2} min^{-1} the increase with increasing light intensities is small. The shape of the photosynthesis function

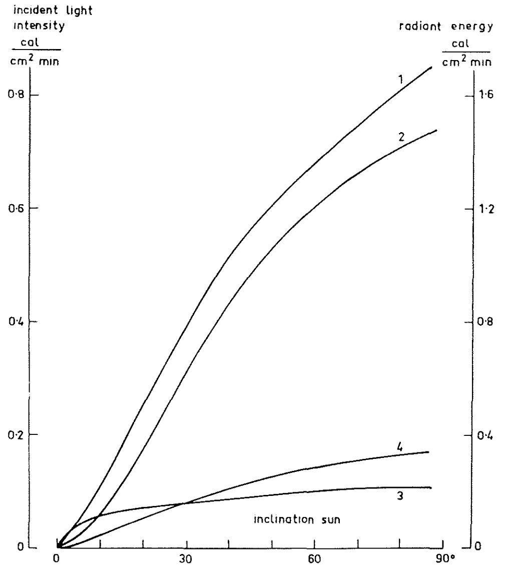

FIG. 1. Incident light intensity (left scale) and the total radiation (right scale) for various heights of the sun.
1. Total radiation with a very clear sky.
2. Direct radiation with a very clear sky.
3. Diffuse radiation with a very clear sky.
4. Total and diffuse radiation with an overcast sky.

varies with the plant species, temperature, nutrition status and water supply, but the curve as presented here is a good average for small grains, grass, beets and some other species at not too extreme temperatures and well supplied with water and nutrients.

A very simple crop surface consists of large, horizontal leaves. The first layer of leaves is subjected to a light intensity of about $0 \cdot 6$ cal cm^{-2} min^{-1} on a clear day with the sun at 45° (Fig. 1) and produces carbohydrates at a rate of about 18 kg CH_2O ha^{-1} hr^{-1} (Fig. 2). The second layer of leaves receives about 15 per cent 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.

However, a crop surface does not consist of large horizontal leaves but of small leaves, inclined at many angles. This is schematically presented in Fig. 3, for a crop surface with a Leaf Area Index (LAI) of 2 (this means that the leaf area is twice the soil area). The left side of the graph shows how the light from the vertical direction is distributed.

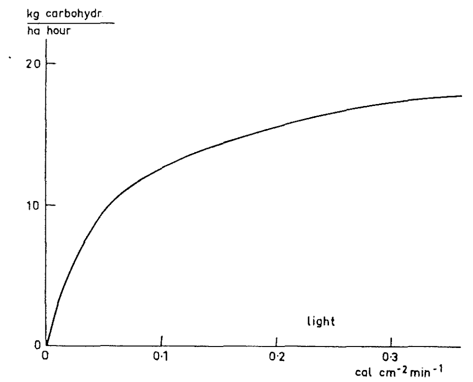

FIG. 2. A relation between the photosynthesis rate and the incident light absorbed by the leaf, which is supposed to hold for a number of common agricultural species.

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 per cent of the light arriving at a leaf is scattered, and the right hand side of Fig. 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, the height of the sun and the cloudiness. All these variables can be measured. Their mutual effect on light distribution and therefore on the photosynthesis rate of crop surfaces has been calculated by the aid of computers.*

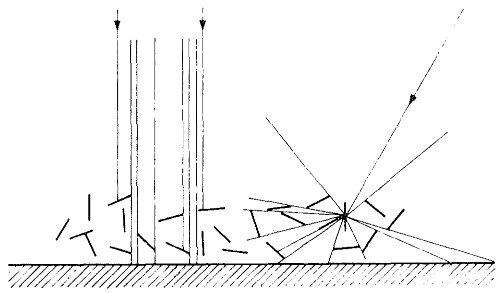

FIG. 3. Schematic representation of light interception by and scattering of light in a crop with a Leaf Area Index of 2.

For the present purpose it suffices to consider 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 per cent and with a photosynthesis function as shown in Fig. 2.

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

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 potentials are summarized in Fig. 5, together with the daily totals of light intensity. The potential photosyn-

* C. T. de Wit, 'Photosynthesis of leaf canopies', *Agric. Res. Report* 663 (1965), Wageningen.

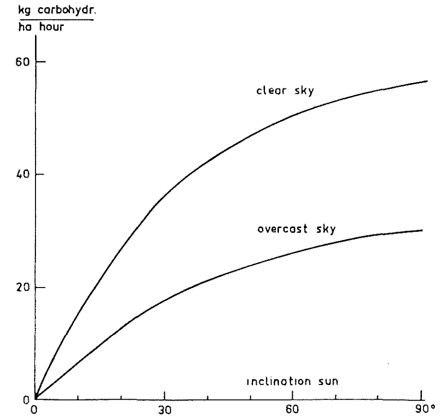

FIG. 4. Potential photosynthesis in relation to the height of the sun with clear and overcast skies.

thesis varies from about 375 kg CH_2O ha^{-1} day^{-1} in June to 40 kg CH_2O ha^{-1} day^{-1} in December.

The potential photosynthesis with clear and overcast skies has been calculated for different latitudes and places. The results are given in Table 1, together with the daily light total on clear days. The potential photosynthesis for other sky conditions can be estimated by means of linear interpolation when radiation or cloudiness data are available.

The plant uses its photosynthesis products in growth, but for 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 considerably temperature dependent, as shown for grass in its vegetative stage in Fig. 6. This is mainly why the net

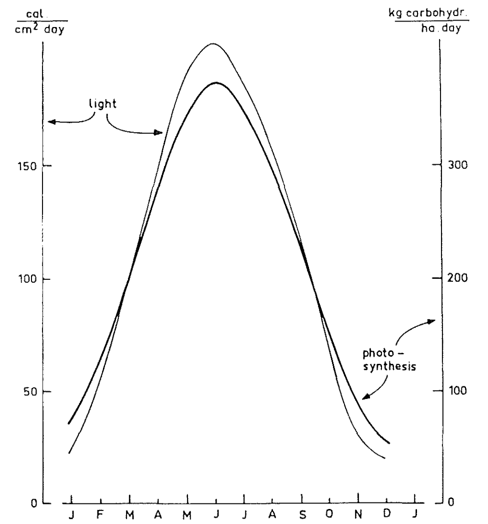

FIG. 5. Daily total of potential photosynthesis and light throughout the year in the Netherlands.

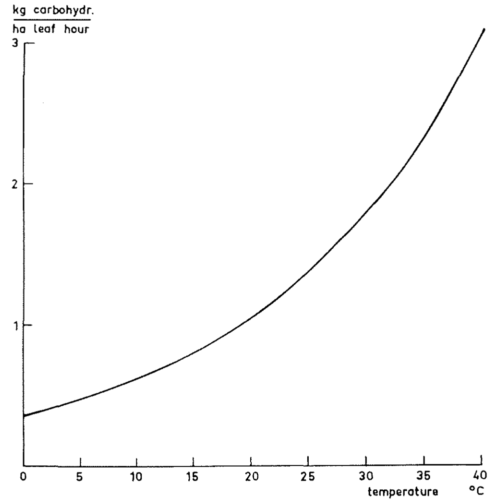

FIG. 6. The respiration of a grass sward in dependence of temperature.

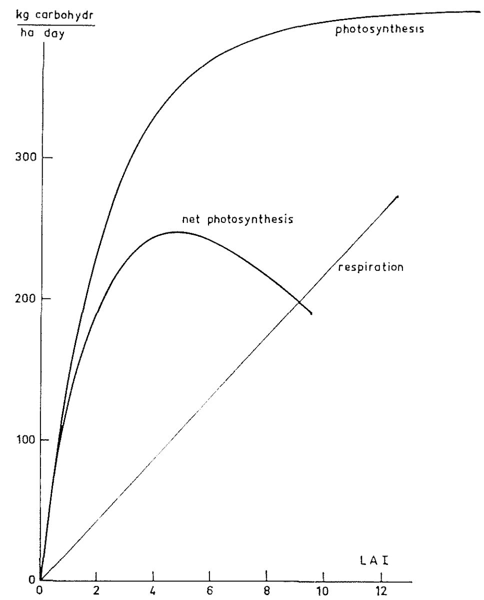

FIG. 7. The relation between the Leaf Area Index and the photosynthesis, the net photosynthesis and the respiration for a grass-like green crop surface in the Netherlands on June 21.

photosynthesis of many crop surfaces is temperature dependent.

The respiration increases more or less linearly with the leaf area index, but the photosynthesis rate approaches a maximum value because of mutual shading of leaves. The composite effect of all this is illustrated in Fig. 7, where potential photosynthesis, respiration and net photosynthesis occurring in the Netherlands on June 21, are shown for increasing values of LAI. 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 per cent of the photosynthesis is lost by respiration.

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 70 per cent of the potential photosynthesis given in Table 1, taking into account the cloudiness. In the Netherlands, the maximum dry matter production of spring cereals is so estimated at about 60 days × 200 kg ha^{-1} day^{-1} or 12·000 kg ha^{-1} and of sugar beets at 7000 kg in July plus 6000 kg in August plus 5000 kg in September plus some 2000 kg in October, a total 20·000 kg ha^{-1}. These are not unreasonable estimates for the total dry-matter yield. Methods are being developed which would enable the length of the grand period of growth to be estimated in relation to the density of planting, the temperature of air and soil etc., but the discussion of these is outside the scope of this paper.

TABLE 1. THE DAILY TOTALS OF LIGHT AND POTENTIAL PHOTOSYNTHESIS FOR A CANOPY WITH A LAI OF 5

North Lat.		15 *Jan.*	15 *Feb.*	15 *March*	15 *Apr.*	15 *May*	15 *June*	15 *July*	15 *Aug.*	15 *Sept.*	15 *Oct.*	15 *Nov.*	15 *Dec.*
0[2]	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	439	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

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}.

(1 kg ha^{-1} day^{-1} = ·891 lbs a day^{-1}).