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Testing of a Danish growth model for barley, turnip rape and timothy in Finnish conditions

ARI ILOLA[1], ESKO ELOMAA[2] and SEPPO PULLI[3]

[1] *Department of Crop Science, Agricultural Research Centre*
SF-31600 Jokioinen, Finland

[2] *Technical Department, Finnish Meteorological Institute*
P.O. Box 503
SF-00101 Helsinki, Finland

[3] *Department of Plant Breeding, Agricultural Research Centre*
SF-31600 Jokioinen, Finland

Abstract. The biological and meteorological data were collected at Jokioinen in 1982—87. Potential and actual (water limited) production of dry matter were simulated using a Danish WATCROS model for spring barley, spring turnip rape and timothy grass.

The most important data of the biological programme comprised weekly measurements of the crop surface (GAI), dry matter yield, root growth, soil water content and yield analyses of the harvest. All these measurements were performed for both irrigated and non-irrigated plots. The needed meteorological parameters for the daily simulation of the dry matter yield were global radiation, air temperature and precipitation.

The simulated dry matter production results with the WATCROS model were generally higher than those measured. In order to obtain a better fit into the Finnish climatic and soil conditions, the Finnish model should take soil water conditions and efficient use of photosynthetically active radiation into consideration.

Index words: Finland, crop growth, crop production, simulation, barley, turnip rape, timothy

Contents

Symbols

Symbols in the text marked with an asterisk denote capacities or potential values.

A	Gross CO_2 single leaf assimilation, photosynthesis
A_m	Gross CO_2 single leaf assimilation, photosynthesis, at light saturation
A_v	Albedo visible radiation (400—700 nm), light
c	Factor converting stored energy into structural plant dry matter
C	Crop area index
d_r	Maximum effective root depth
D	Slope of the saturation vapour pressure curve versus temperature
D_p	Precipitation deficit
e	Vapour pressure
e_s	Saturation water vapour pressure
e_{sa}	Saturation vapour pressure, at dry-air temperature
e_{sw}	Saturation vapour pressure, at wet-bulb temperature
E	Evapotranspiration
E_c	Evapotranspiration from the crop
$E_{c,g}$	Evapotranspiration from the crop, green active area
$E_{c,y}$	Evaporation from the crop, yellow inactive area
E_s	Evaporation from the soil
E_T	Transpiration from the crop
G	Crop area index, green active area
G_g	Ground heat flux
G_m	Maximum green area index
H	Harvest index
I	Irrigation
k	Extinction coefficient of PAR
K	Extinction coefficient of net radiation
L	Latent heat of the vaporization of water
m	Constant
p	Gross photosynthetic efficiency
P	Precipitation
P_g	Gross production
P_n	Net production
r_g	Growth respiration coefficient
r_m	Maintenance respiration coefficient
R_g	Growth respiration
R_m	Maintenance respiration
R_n	Net radiation above grass
S	Radiative flux density below the downward accumulated GAI (Green area index)
S_{abs}	Absorption of photosynthetic active radiation (PAR)
S_i	Global radiation
S_n	Radiative flux above the canopy
S_v	Visible radiation (400—700 nm) fraction of the global radiation (300—2500 nm)
S_t	Topsoil water capasity
S_r	Root zone water capacity
S_I	Storage, intercepted water
$S_{I,g}$	Storage, intercepted water, green active area
$S_{I,Y}$	Storage, intercepted water, yellow inactive area
t	time
t_a	Dry-air temperature, °C
t_w	Wet-bulb temperature, °C
t_s	Soil temperature, °C
v	Wind speed
W	Total dry matter in the field
W_h	Harvested dry matter yield
W_L	Non-harvested dry matter (stubble, root, etc. mass loss)
Y	Yellow area index
Y_p	Psychrometric constant

1. Introduction

The joint Nordic project on the effect of climatological factors on crop growth and production was started in 1982. The research programme was planned by a working group of the agricultural meteorology of Section I of the Association of the Agricultural Scientists of Scandinavia. It was carried out in Denmark in 1982—85, in Norway in 1982—86 and in Finland in 1982—87. It was funded by the national authorities (in Finland by the Academy of Finland).

Field experiments of climatic field (the experimental field) were carried out in 1982—87 at Jokioinen, in SW- Finland, to test Danish growing models for various crops. The main aim of the project was to calculate potential and water-limited crop growth and production. Danish models constructed by Aslyng and Hansen (1982), in modified forms, were used as the basis of calculations. The models are based on experimental results of the weekly dry matter and crop area index (CAI) measurements and daily measurements of the climatological and hydrological factors of the experimental field. The models are simple enough to be used for routine monitoring of changes during the growing season and of the production of various crops. Another aim of the project was to test the Danish models.

After six years of experimental work and one year of research work, results can be given for spring barley (barley), spring turnip rape (turnip rape) and timothy grass. Some details concerning the project have been published previously (Elomaa and Pulli 1985, Saarinen et al. 1986, Elomaa et al. 1986, Elomaa 1987).

2. The experimental field

2.1. Layout of the field

Three species, barley, turnip rape and perennial grass timothy, were tested in irrigated and non-irrigated plots (Fig. 3.1.). Detailed crop and soil observations were made for each of six plots from 1982 to 1987.

2.2. Soil properties

The topsoil (0—20 cm) was classified as heavy clay with 7—11 % organic matter. The subsoil was defined as heavy clay lacking C compounds and phosphorous, but rich in magnesium and calcium (Tables 2.1, 2.2). Chemical analyses of the plots were performed annually since 1983 (Table 2.3). Plots A and C were limed in spring 1986 and 1987.

In 1984, the water retention capacity of the soil profiles was studied, and the entire soil moisture retention curve was determined. The water capacity usable by plants was 15—20 percent of volume, depending on the plot and soil depth (Table 2.4).

The hydraulic conductivity of the soil was measured with the MSU (Michigan State University) method in 1987 (Saavalainen and Rintanen 1986). Normal reliable ($R > 0.95$) measurements were 0.15—0.38 (mean 0.22) cm water in one hour. The heterogeneity of the plots and the depth of the soil as well as pore holes caused some variation between the measurements (0.02—4.83 cm h^{-1}).

During the growth period, the soil moisture content of each plot was monitored weekly. In 1982 soil moisture was measured with gypsum blocks at five soil depths. Irrigated plots

Table 2.1. Chemical analysis and physical properties of soil layers in 1985.

Plot	Depth cm	pH	mg/l				per cent			Bulk Density g cm^{-3}
			Ca	K	Mg	P	C	Org.[1] matter	N[1]	
A1	00— 20	5.7	2175	265	542	7.0	3.6	7.9	0.20	1.25
	20— 40	5.8	2600	310	1250	1.9	1.8	3.8	0.04	1.31
	40— 70	6.7	2750	255	1775	0.6	0.4	2.5	—	1.37
	70—100	6.8	2600	305	1850	0.8	0.3	3.0	—	1.32
A2	00— 20	5.8	2375	225	585	5.4	3.3	7.2	0.23	1.34
	20— 40	5.9	2375	185	825	2.1	1.9	3.8	0.09	1.35
	40— 70	6.4	3325	245	1850	1.0	0.6	3.1	—	1.32
	70—100	6.9	3000	287	1775	1.4	0.3	2.8	—	1.32
B1	00— 20	5.6	2250	282	515	6.6	4.2	8.8	0.26	1.27
	20— 40	5.8	2250	277	877	3.8	3.0	7.2	0.04	1.29
	40— 70	6.2	2375	225	1500	1.0	1.3	3.5	—	1.32
	70—100	6.7	2550	267	1825	0.8	0.3	2.8	—	1.35
B2	00— 20	5.5	2275	350	475	8.1	4.6	10.4	0.23	1.33
	20— 40	5.6	1625	187	615	1.7	2.0	9.3	0.04	1.30
	40— 70	6.4	3000	240	1800	0.5	0.4	3.6	—	1.31
	70—100	6.6	2850	265	1750	0.6	0.3	2.7	—	1.35
C1	00— 20	5.7	2450	385	600	7.4	4.6	9.4	0.26	1.17
	20— 40	5.7	2275	340	1200	3.3	2.7	3.4	0.07	1.32
	40— 70	6.5	2775	245	2000	0.7	0.4	3.1	—	1.31
	70—100	7.0	2625	270	2025	0.9	0.3	2.8	—	1.32
C2	00— 20	5.7	2450	385	610	7.1	4.6	10.0	0.26	1.18
	20— 40	5.8	1875	245	790	2.2	2.7	4.9	0.07	1.27
	40— 70	6.2	2775	237	1925	1.1	0.6	3.3	—	1.27
	70—100	7.0	2925	275	2125	1.2	0.3	2.8	—	1.33

KEY: 1 = Year 1986; Plot 1 = irrigated, 2 = non-irrigated

were watered (plots 1, Fig. 3.1) if the soil moisture content available for plants was below 50 % (Table 2.5). Gypsum blocks were not reliable after winter, and soil moisture could not be measured in 1983. In 1984 soil water content was measured gravimetrically, taking soil samples from each plot, to a depth of 50 cm. Because 1984 was a rainy year, no irrigation was needed. In 1985 the soil water content was measured both gravimetrically and with the neutron scattering method, BASC depth moisture probe (Table 2.6).

3. Climate

3.1. General description of the meteorological measurements

Solar radiation and wind direction were measured at the top of a meteorological mast situated beside the experimental field. Profiles of wind speed and dry-air and wet-bulb temperatures were also measured at the mast. Short-wave solar radiation, air and soil temperature, air humidity and soil moisture were measured for each experimental plot (Fig. 3.1). In 1984 gypsum blocks were removed for soil moisture measurements; they were

Table 2.2. Mechanical analysis of the soil layers in the experimental field in 1987.

Depth cm	Weight %			
	Clay	Silt	Fine Sand	Coarse Sand
00— 20	63.0	13.8	20.0	3.2
20— 40	71.8	11.1	13.1	4.0
40— 70	75.0	10.1	13.8	1.1
70—100	87.2	3.1	8.6	1.1

Table 2.3. Chemical analysis of the tillage layer of the plots.

Plot	Year	pH	mg/l			
			Ca	K	Mg	P
A1	1983	6.3	2590	310	621	6.3
	1984	6.2	2330	325	625	6.0
	1985	5.7	2175	265	542	7.0
	1986	6.2	2279	262	615	5.0
	1987	6.2	2945	292	628	6.7
A2	1983	6.1	2660	300	631	5.4
	1984	6.1	2555	288	683	4.9
	1985	5.8	2375	225	585	5.4
	1986	5.8	2255	334	498	8.0
	1987	6.2	3304	333	752	9.2
B1	1983	5.9	2390	338	616	5.7
	1984	5.9	2165	345	572	6.2
	1985	5.6	2250	282	515	6.6
	1986	5.7	2190	294	478	8.8
	1987	6.1	2787	307	822	5.7
B2	1983	5.9	2320	326	515	6.0
	1984	6.0	2190	329	553	5.2
	1985	5.5	2275	350	475	8.1
	1986	5.7	2090	285	449	7.9
	1987	6.0	2846	296	892	5.6
C1	1983	6.1	2680	348	727	6.7
	1984	5.8	2135	338	683	4.5
	1985	5.7	2450	385	600	7.4
	1986	5.8	2303	296	714	7.5
	1987	6.0	3030	419	714	7.0
C2	1983	5.9	2480	331	595	6.9
	1984	5.9	2255	348	590	5.7
	1985	5.7	2450	370	610	7.1
	1986	6.2	2734	260	673	6.2
	1987	6.2	2962	345	691	7.2

Table 2.4. Soil capasity for available water mm in different soil layers for 1 cm, 25 cm and effective root depth.

Plot		Soil Depth (cm)			
		0—25	25—50	50—75	0—75
A	1 cm	1.6	1.6	1.5	
	25 cm	40	40	37	117
B	1 cm	1.7	1.7	1.6	
	25 cm	42	42	40	124
C	1 cm	2.0	1.8	1.6	
	25 cm	50	45	40	135

Table 2.5. Irrigation schedule in 1982—87.

Date, irrigation (mm)									
1982		1983		1985		1986		1987	
Barley									
27/7	45	18/7	35	11/6	25	18/6	35	1/6	10
3/8	10	1/8	30	28/6	30	2/7	50	21/7	25
				9/7	25				
Sum:	55		65		80		85		35
Turnip rape									
27/7	45	19/7	35	13/6	30	23/6	30	22/7	25
3/8	10	2/8	30	28/6	30	1/7	50		
				10/7	20				
Sum:	55		65		80		80		25
Timothy									
		20/7	35	12/6	25	16/6	50	20/7	25
		3/8	30	27/6	30	1/7	50		
				9/7	30	4/8	20		
Sum:	—		65		85		120		25

replaced by pyranometers to measure the reflected short-wave radiation of each plot.

A calculating data logger, an Autodata Ten/5 made by Acurex (USA), was used for data-logging. A one-minute scanning interval was used to measure the meteorological variables. Hourly mean values were stored in the C-cassettes of an MFE 2500 tape recorder. The C-cassettes were converted to magnetic tapes for further analysis.

The climatological measurement results for the experimental field were compared to the

Table 2.6. Measuring depths of soil moisture in 1982—87.

Year	Management	Depth (cm)
1982—1983	Gypsum Block	—10, —20, —30, —50, —100
1984—1987	Gravimetrically	—10, —20, —30, —50
1985—1987[1]	Neutron Scattering Method (BASC)	—10, —20, —30, —40, —50, —60, —80, —100

KEY: 1 = Year 1987: —15, —30, —45, —60, —75, —90

Fig. 3.1.

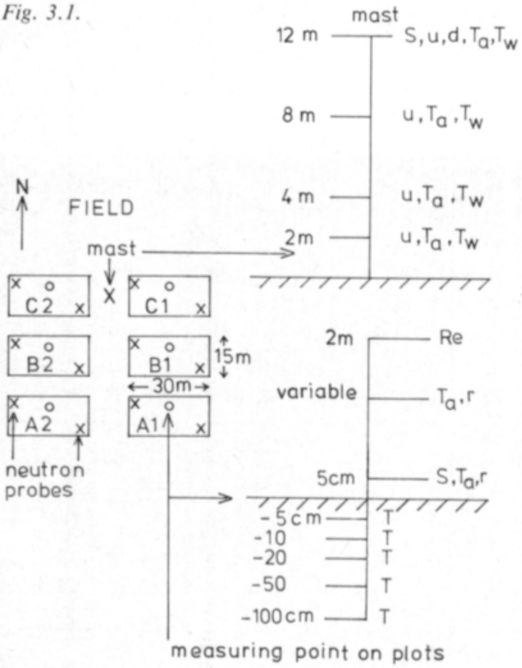

Fig. 3.2.

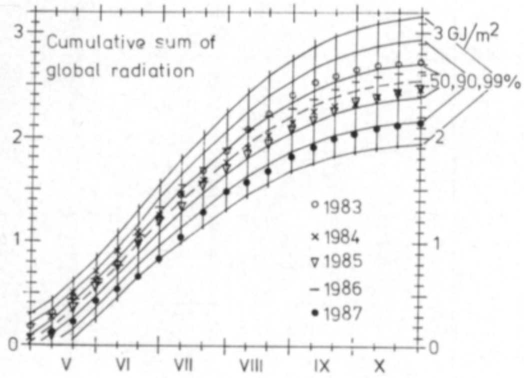

Fig. 3.3.

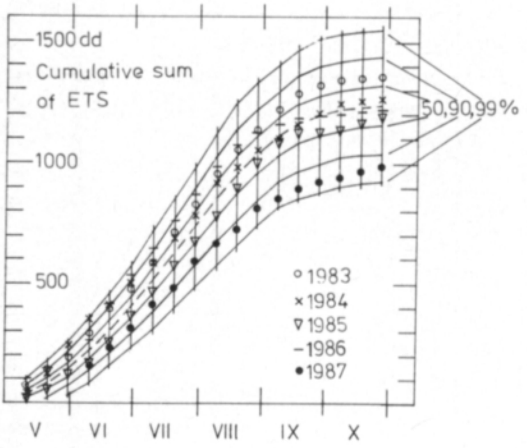

Fig. 3.4.

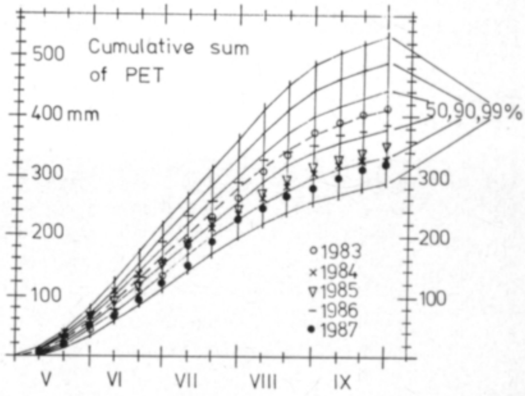

Fig. 3.5.

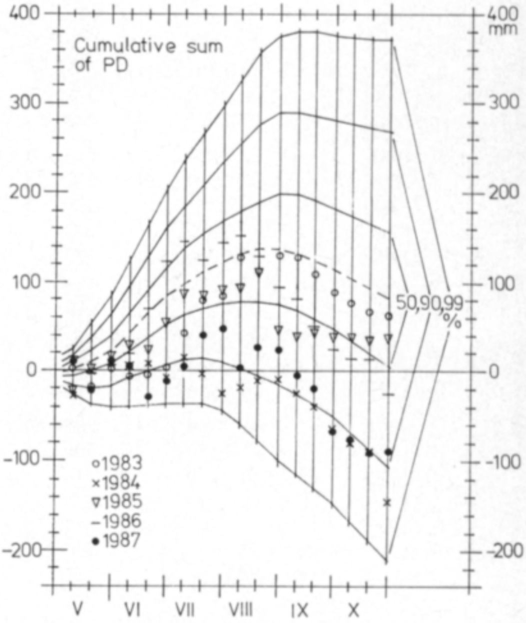

Fig. 3.1. Meteorological observations on the experimental field.

S = global radiation
u = wind speed
d = wind direction
T_a = dry-air temperature
T_w = wet-bulb temperature
R_e = reflected short-wave radiation
r = relative humidity
T = soil temperature

Fig. 3.2. Cumulative sum of global radiation at Jokioinen (medians and probability limits).

Fig. 3.3. Cumulative sum of effective growing temperature at Jokioinen (medians and probability limits).

Fig. 3.4. Cumulative sum of potential evapotranspiration at Jokioinen (medians and probability limits).

Fig. 3.5. Cumulative sum of precipitation deficit at Jokioinen (medians and probability limits).

Table 3.1. Monthly cumulative sums of global radiation (MJ/m^2) at Jokioinen Observatory in April—October.

	Mean 1957—1983	1983	1984	1985	1986	1987
April	391	309	412	419	343	464
May	578	453	601	585	544	436
June	639	581	592	585	680	416
July	573	638	535	556	578	642
August	441	537	455	391	377	356
September	242	240	180	264	247	217
October	105	93	95	123	109	108

Table 3.2. Mean air temperature (°C) at Jokioinen Observatory in April—October.

	Mean 1957—1984	1983	1984	1985	1986	1987
April	2.0	4.8	4.2	0.5	2.1	2.4
May	8.7	11.0	12.6	8.6	10.5	7.6
June	14.0	13.3	13.1	13.2	16.3	12.1
July	15.6	16.6	14.8	15.3	16.2	14.8
August	14.2	15.0	13.8	15.5	12.9	11.7
September	9.3	11.0	9.2	8.9	6.4	8.4
October	4.4	5.4	6.6	6.4	5.2	6.4

Table 3.3. Mean soil temperature (—10 cm, °C) at Jokioinen Observatory in May—September.

	Mean 1957—1983	1983	1984	1985	1986	1987
May	7.5	9.1	9.9	4.7	8.5	5.8
June	13.8	13.7	14.3	12.6	14.4	11.7
July	16.0	16.2	16.2	15.2	16.3	15.8
August	(15.1)	15.2	15.5	15.6	14.7	13.2
September	(10.8) (1957—1970)	11.8	10.6	10.3	8.5	9.8

measurements made by the Meteorological Observatory at Jokioinen, 1 km from the experimental field.

3.2. *Solar radiation*

Short-wave solar radiation was measured with Kipp & Zonen pyranometers, which were calibrated with the pyranometer used at the nearby Meteorological Observatory. Solar radiation was measured at the top of the mast (global radiation) and inside the stand, at a height of about 5 cm above ground level, with the same type of pyranometers used for estimating the extinction of solar radiation in the stand. In 1985—87, short-wave reflected radiation was also measured above each plot.

During the growing periods of 1982—86 the sum of global radiation was rather stable from year to year (Fig. 3.2). The highest values were registered in 1983, the lowest in 1987.

3.3. *Air and soil temperature*

Dry-air and wet-bulb temperatures were measured with Pt-100 sensors; the ventilation

Table 3.4. Mean wind speed ($m\ s^{-1}$) at Jokioinen Observatory in May—October.

	Mean 1957—1980	1983	1984	1985	1986	1987
May	3.9	3.2	3.4	3.6	4.3	4.4
June	3.8	3.4	3.4	3.4	3.9	4.1
July	3.4	3.5	2.9	3.4	3.5	3.4
August	3.3	3.4	2.7	3.9	3.8	3.7
September	3.8	4.5	3.6	3.8	3.9	3.4
October	4.0	4.4	3.8	4.3	4.5	4.7

Table 3.5. Potential evapotranspiration (PET, mm) at Jokioinen Observatory in May—October.

	Mean 1929—1986	1983	1984	1985	1986	1987
May	59 +/— 8	56	74	58	63	47
June	107 +/—18	94	94	92	139	73
July	113 +/—24	114	76	104	120	111
August	90 +/—23	108	80	80	70	62
September	41 +/— 7	43	27	45	36	30
October	20 +/— 5	22	18	32	21	25
May—October	430	437	369	411	449	348

Table 3.6. Monthly precipitation (mm) at Jokioinen Observatory in April—October.

	Mean 1957—1983	1983	1984	1985	1986	1987
April	32	22	18	32	38	5
May	40	44	66	43	52	38
June	48	84	113	41	11	81
July	77	41	91	55	65	68
August	79	58	69	119	110	83
September	66	86	77	51	102	120
October	68	62	99	36	74	43
May—October	378	375	515	345	414	438

of the psychrometers was centralized, and was some 3 $m\ s^{-1}$. Soil temperature was measured with Pt-500 sensors.

According to the effective temperature sum in degree days (ETS), with a threshold temperature of 5.0°C, the beginning of the growing seasons were warmer than average in 1983, 1984 and 1986, but in 1985 and 1987 they were cooler, and temperatures also remained cool throughout most of these two seasons. Fairly high ETS values were observed in 1984, in June and July 1986 and in July 1987 (Fig. 3.3). Soil temperatures in May 1985 and May 1987 were 2—3°C below average (Table 3.3).

3.4. Air humidity

Air humidity was measured psychrometrically at the mast by using dry-air temperatures. Water vapour pressure and relative humidity were calculated as follows. Saturation water vapour pressure (e_s, hPa) was calculated (Morton 1975):

$$(3.1) \quad e_s = 6.11 \times \exp(17.27 \times t_a/(t_a + 237.3))$$

where t_a = dry-air temperature (°C).

Water vapour pressure (e) was calculated:

$$(3.2) \quad e = e_{sw} - 0.67\,(t_a - t_w)$$

where e_{sw} = saturation water vapour pressure at wet-bulb temperature (t_w).

Values for relative humidity (r) were calculated using the following formula:

$$(3.3) \quad r = e/e_{sa}$$

where e_{sa} = saturation water vapour pressure at dry-air temperature t_a.

The air humidity in crops was measured using Humicap HM21 sensors constructed by Vaisala Oy.

3.5. Wind speed and wind direction

Wind speed was measured at four levels of the mast, using WAA15 sensors made by Vaisala. The top of the mast had a crossarm assembly to support an anemometer WAA15 and a wind vane WAV15.

3.6. Potential evapotranspiration

By using a modified version of Ivanov's equation (Ansalehto et al. 1985), a long series of potential evapotranspiration (PET) values at Jokioinen (1929—87) was calculated for comparison. Modification was made in order to obtain the best fit for comparisons with the PET values determined with the Penman equation (Penman 1956).

For the whole growing season, the cumulative sum of the daily PET values was lower than average in 1984—1987. The values for 1983 were on the average level. In 1984 and 1985 there were, however, periods when the PET sum was higher than average (Fig. 3.4).

Makkink (1957) proposed the following equation for estimating potential evapotranspiration (E*) from grass:

$$(3.4) \quad E^* = 0.61 \frac{D}{D + Y_p} \frac{S_i}{L} - 0.12 \text{ mm/day}$$

where D = the slope of the curve of the saturation vapour pressure vs the temperature, Y_p = the psychrometric constant (0.67 hPa/K), S_i = global radiation and L = the latent heat of vaporization of water.

Aslyng and Hansen (1982) used a simplified version for the calculation of E*:

$$(3.5) \quad E^* = 0.7 \frac{D}{D + Y_p} \frac{S_i}{L}$$

We have calculated D using the formula of Morton (1975) (equation 3.1) and L using that of Hankimo (1964):

$$(3.6) \quad L = 2494 - 2.29 \times t_a$$

where t_a = the dry-air temperature at a height of 2 m.

In the EVAPO submodel of WATCROS the following formula, which is the simple average of equations 3.1, 3.5 and 3.6, has been found to be satisfactory:

$$(3.7) \quad E^* = 0.606\,(0.399 + 0.0139\,t_a)\,S_i/2.47.$$

For the WATCROS model E* was calculated with the modified version of Penman (1956), too (Aslyng 1976)

$$(3.8) \quad E^* = \frac{D\,(R_n - G_g)}{L\,(D + Y_p)} + \frac{Y\,f(v)\,(e_s - e_a)}{D + Y_p}$$

where R_n = the net radiation above grass, G_g = ground heat flux and f (v) = the function of wind.

$$(3.9) \quad f(v) = 0.263\,(0.5 + 0.54\,v)$$

where v = the mean wind speed, m s^{-1}.

Daily net radiation values were given by the nearby Meteorological Observatory. The ground heat flux values were estimated in one-week intervals during the growth period in

1983—85, using measurements by KULMALA (1970):

$$(3.10)\ G_g = -5.5 - 7.959\ dt_s$$

where $dt_s = t_{s,2} - t_{s,1}$ and $t_{s,i}$ = the mean soil temperatures in soil layers $-10 \ldots -100$ cm.

In the last two study years, 1986—87, G_g was calculated as earlier, but the daily values were computed according to the distribution of net radiation.

3.7. Precipitation

Precipitation was measured both manually and automatically. Manually observations were made using a Finnish standard gauge, TRETYAKOV, at one point on the field. Precipitation was recorded automatically on both the non-irrigated and the irrigated plots, using a tipping bucket rain gauge with a resolution of 0.1 mm.

3.8. Precipitation deficit

Precipitation deficit (D_p) was calculated as follows:

$$(3.11)\ D_p = E^* - P$$

where E^* = the potential evapotranspiration (PET) and P = precipitation.

In 1983—1987 the precipitation deficit during the growing season was less than average; 1984 in particular was very wet. Only in 1986 was there a period, in June—August, when the precipitation deficit was greater than average (Fig. 3.5).

4. The biological programme

The Nordic research programme (1982—85) wanted to include plant species common to all participating countries. In Finland the Pomo cultivar was used for the barley tests, and Tarmo was the timothy variety used in 1982—87. The turnip rape cultivar used as the test plant was Span in 1982—86 and Kova in 1987. Of these plants only rape (Span) was cultivated in Denmark and Norway, too.

Plots of barley and turnip rape were established in the standard way each year. Timothy stands were clear seeded in 1982 and established with a cover crop barley in 1984. Because of the clear seeding and winter damages (Table 4.1), the growing seasons of 1982 and 1984 were discarded in timothy modelling. The barley plant stands were been quite dense in all years exept 1982. Turnip rape stands sprouted poorly throughout the study (Table 4.2).

Barley and turnip rape were fertilized with NPK (16-7-13) and timothy with NPK (20-4-8) fertilizers. The amounts of nutrients as kg per hectare for barley and turnip rape were 80—100 kg nitrogen (N), 35—40 kg phosphorous (P) and 40—65 kg potassium (K). For grass, the amounts after the year of establish-

Table 4.1. Wintering and Total available Carbohydrates (TAC) in root DM of timothy.

Year	Plot	TAC %		Stand Density %	
		Spring	Autumn	Spring	Autumn
1983	C1	10.3	26.8	89	79
	C2	9.8	26.8	98	75
1984	C1/B1	9.1	18.6	65	>90
	C2/B2	7.2	18.9	25	>90
1985	B1	7.3	17.1	85	85
	B2	7.6	18.2	81	80
1986	B1	6.8	6.8	72	68
	B2	3.5	7.8	73	76
1987	B1	6.1	8.2	63	75
	B2	4.1	10.0	70	75

Table 4.2. Shooting of barley and turnip rape in 1982—87 per m^{-2}.

Year	Barley	Turnip rape
1982	333	108
	334	179
1983	520	288
	427	256
1984	587	245
	501	269
1985	518	282
	500	320
1986	437	270
	507	287
1987	539	410
	512	389
Mean 1983—87	505	300

ment were: first cut 100—110 kg N, 20 kg P and 40—60 kg K; second cut 80 kg N, 20—35 kg P and 40—65 kg K; third cut 40—60 kg N, 20—30 kg P and 30—50 kg K. In 1982 and 1984 timothy was established by using 500 kg per hectare of NPK (16-7-13) fertilizer.

Plant protection was considered important for avoiding the influence of weeds, plant diseases and pests on yield and crop green area. The chemicals used and the timing of their sprayings are shown in Table 4.3. In 1984, turnip rape was sowed twice, but insect pests also caused some damage to the second plant stand despite protection.

During the growing season, the plants were monitored according to the programme of biological measurements. The central measurements were made weekly, except for some parameters which were monitored infrequently during the growth period or only at the time of harvest (Table 4.4).

5. Plant growth and development

5.1. Crop surface

Instead of the leaf area index (LAI), Aslyng and Hansen (1982) adopted the total crop area index (CAI), the green area index (GAI) and the yellow area index (YAI). These indices are the accumulated areas of leaves, stalks, stems and ears divided by the corresponding land surface. The total crop area influences the interception of radiation and precipitation, and the total green area corresponds to photosynthesis.

The growth period here is defined as the period from emerging to ripening for barley and turnip rape. In the case of timothy, growth is assumed to start at the beginning of the thermal growth period (≥ 5°C) and to end at the time of the last harvest.

The green and yellow crop area of studied plant species was measured with an automatic leaf area meter (HAYASHI DENKOD AAM-7). The yellow crop area was measured during the years of 1985—87). In the best years, timothy grass reached a GAI value over 15, barley near 10 and turnip rape only 8 (see chapter 8).

5.2. Root growth

In 1982—84 only the amount of main roots of the tillage layer (0—20 cm) was measured at the time of cutting in the autumn. From the year 1985 on, root growth was monitored more carefully in order to learn how fast the

Table 4.3. Plant protection schedule in the experimental field.

Year	Turnip rape	Barley	Timothy
1982	23/6 Decis		6/7 Dipro
	2/7 Decis		23/8 PCNB
	9/7 Sumicidin		28/12 Avicol
1983	13/6 Decis	9/6 Dipro	25/5 Actril S
	20/6 Decis		
1984	18/6 Decis		18/6 Actril S
	4/7 Decis		
1985	19/6 Butisan	19/6 Dipro	16/5 Actril S
	19/6 Decis	19/6 Roxion	
	24/6 Decis		
	27/6 Decis		
	4/7 Decis		
1986	13/6 Roxion		
	18/6 Roxion		
1987	26/6 Decis	23/6 Herbalon	
	3/7 Decis		

Table 4.4. Biological programme for the experimental field.

Management	Barley	Turnip rape	Timothy
Seeding rate (kg/ha):	180 (500/m²)	8 1987, 12	25
Seeding depth (cm):	3—5	3	1.5
Emergence date:	when 50 % sprouting		
CAI (starting at 10 cm height, whole crop):	6 × 30 cm at raw weekly		
Fresh weight (starting one week after CAI):	3 × 1.5 m² weekly		
Cutting height (cm):	5		
DM determinations:	2 × 200 g 100°C		
Height measurements:	5 points/1.5 m²		
Heading date:	at the time of 1st ear/m²		≥ 50 %
Maturity date:	determined		
Root sampling (at end harvest):	2—3 × 50 cm at raw (15 cm depth)		
Number of plants (at end harvest):	3—6 × 1 m at raw		
Number of ears/panicles (at end harvest):	3—6 × 1 m at raw		
Straw yield DM (cutting 5 cm):	4—6 × 20 m² (fall)		
Grain yield (barley 15 % and turnip rape 9 % moisture content):	4—6 × 20 m² (fall)		
1000 seed weight	3 × 100 seeds		

roots penetrate to the clay soil and the quantity with which they remain in the field. In 1985 root density in the soil (cm/cm³) was measured by NEWMAN's (1966) method for estimating the total length of root sampling (Table 5.1). According to MADSEN (1978), the effective root depth comprises at least 0.1 cm root per cm³ soil.

In 1986 and 1987, root depth growth was measured from emergence to the time when a root depth of 60 cm was attained. According to these results the average root penetration speed was 1.3 cm per day for barley, 1.2 cm per day for turnip rape and 0.7 cm per day for timothy. Root depth growth was not the same for the whole growth period (Table 5.2). According to JAKOBSEN's (1976) formula of root growth, with a threshold soil temperature of 4°C, the soil temperature of the root penetration zone did not restrict the root growth of barley or turnip rape during 1983—87. At the time of sowing the soil temperature of the tillage layer was uniformly + 10°C or more. According to this formula, soil temperature restricted the root growth of timothy about 1 to 2 weeks after the onset of the growth period.

The studies showed that the maximum effective root depth (d_r) remained ≤ 75 cm for all three plant species. SALONEN (1949), study-

Table 5.1. Root length, cm in cm³ soil in 1985.

Depth cm	Date		
	28/5	11/6	8/7
		Timothy	
00—10	9.0		
10—20	0.7		
20—30	0.3	0.4	1.8
30—40		0.2	0.9
40—50		0.0	0.5
50—60			0.2
		Barley	
00—10		1.7	
10—20		0.7	2.9
20—30			1.2
30—40			1.2
40—50			0.8
		Turnip rape	
10—20			1.6
20—30			0.9
30—40			0.5

Table 5.2. Root depth growth.

Year	Date	(Days)	Soil depth cm	Depth growth cm/day
		Barley		
1986	3/6—23/6	(21)	0—25	1.2
	24/6—14/7	(21)	25—60	1.7
Avg.	3/6—14/7	(42)	0—60	1.4
1987	5/6—29/6	(25)	0—25	1.0
	30/6—28/7	(29)	25—64	1.3
Avg.	5/6—28/7	(54)	0—64	1.2
		Turnip rape		
1986	3/6—23/6	(21)	0—10	0.5
	24/6—21/7	(28)	10—60	1.8
Avg.	3/6—21/7	(49)	0—60	1.2
1987	8/6—29/6	(22)	0—19	0.9
	30/6—28/7	(29)	19—60	1.4
Avg.	8/6—28/7	(51)	0—60	1.2
		Timothy		
1986	25/4—19/5	(24)	0—20	0.8
	20/5—16/6	(28)	20—35	0.5
	17/6—14/7	(29)	35—60	0.9
Avg.	25/4—14/7	(81)	0—60	0.7
1987	23/4—18/5	(25)	0— 6	0.2
	19/5—16/6	(29)	6—51	1.6
	17/6—20/7	(35)	51—61	0.3
Avg.	23/4—20/7	(89)	0—61	0.7

ing barley and timothy root growth in different soil types, showed a maximum root depth of 35—85 cm for barley and 40—70 cm for timothy in clay soils. In Denmark the average effective root depth in clay soil has been 100 cm containing 170 mm water as a root zone capacity.

In 1983—1985 the amount of main roots was only 400—500 kg for barley and 250—400 kg of dry matter (DM) per hectare for turnip rape. Careful washing of soil samples to a depth of 60 cm in 1986 introduced root DM yields of barley 1000—1500 kg and 500—550 kg per hectare for turnip rape. Timothy had a 2—4 ton root DM mass per hectare, but that sum also contained old, dead roots (Table 5.3).

5.3. *Dry matter production*

Crop growth was measured weekly throughout the study period. Cuttings were measured weekly from a plant height of about 20 cm, the measurements continuing until the end harvest. Daily above ground (> 5 cm) dry matter production per hectare for barley after emergence was 50—90 kg of DM per day

Table 5.3. Total amount of roots (kg DM/ha) in 1986.

Plot	Soil Depth (cm)						
	00—10	10—20	20—30	30—40	40—50	50—60	00—60
				Barley			
C1	991	265	158	44	20	43	1521
C2	632	139	110	71	63	18	1033
Avg.	812	202	134	58	42	30	1277
				Turnip rape			
A1	280	102	95	56	22	—	555
A2	305	54	82	56	28	—	525
Avg.	292	78	88	56	25	—	540
				Timothy			
B1	2478	170	110	37	22	—	2817
B2	3377	195	120	32	24	9	3757
Avg.	2928	182	115	34	23	4	3287

and increased during the next four to six weeks to a maximum value of 200—300 kg of DM per day. At the very early phase of the development, turnip rape growth was very slow, but the pace of growth increased quickly after the sprouting period to a level of 100—150 kg of DM per day. The maximum values were 150—250 kg of DM per day. The DM growth of timothy varied enourmously from one year to another and also between cuts. During spring, daily grass growth was 50—100 kg of DM, and later reached the maximum value of 200—250 kg of DM per day. Summer grass growth varied between 30 and 180 kg of DM per day. The autumn growth of timothy ranged from 10 to 100 kg of DM per day. (see chapter 8.)

6. Results of the end harvestings

6.1. *Barley and turnip rape*

Table 6.1 shows the results of dry matter production at harvests, divided into grain DM yield and total production above ground level (>5 cm). End harvests were done with an experimental harvester on four to six subplots, each 20 m² in size. Straw and grain were separated, but it was impossible to keep the cutting height constant at a stubble height level of 5 cm. When results of end harvests were compared to those of the last periodic cuttings, the existing error was estimated to be about 10—15 % of the actual total dry matter yield.

Plant height and harvest analyses are presented in Tables 6.2 and 6.3. Harvest index values of barley and turnip rape were calculated as the dry matter yield of grain (seed) at the end harvest per the maximum measured (> 5 cm) crop dry matter yield of the growth period. The shoot height growth of barley ended at the time when the maximum GAI values were reached. In the case of turnip rape, height development was related to the time of blooming.

The best growing conditions for DM production of the studied crops occurred in 1983, which was warm and dry. In 1985 and 1986, irrigation had a positive effect on plant height development, but the yields were greater only in 1986. 1987 was a cloudy, cold and rainy year and was the least favourable year for plant production since 1962.

6.2. *Timothy*

Timothy plots were established in the spring of 1982 and of 1984. These years were not included in crop growth simulation (Table 6.4).

Table 6.1. Growth period, dry matter production above ground level (>5 cm) and grain yield of barley and turnip rape at end harvest (kg DM/ha).

Year	Plot	Dates of				Non-irrigated		Irrigated	
		Sowing	Emerging	Ripening	Harvest	Grain	Total	Grain	Total
					Barley				
1982	B	27/5	5/6	23/8	7/9	4023	6525	3224	5896
1983	A	10/5	20/5	8/8	11/8	4408	8580	4167	8276
1984	B	15/5	21/5	10/8	15/8	3483	7031	3591	7571
1985	A	24/5	2/6	23/8	26/8	3891	6617	3283	6824
1986	C	27/5	3/6	23/8	28/8	3630	6122	4604	7920
1987	A	26/5	5/6	8/9	17/9	2994	6294	3012	6208
					Turnip rape				
1982	A	27/5	7/6	13/9	16/9	1702	3832	1815	4326
1983	B	10/5	20/5	18/8	25/8	1482	5388	1647	5636
1984	A	31/5	4/6	3/9	10/9	650	1735	877	2748
1985	C	24/5	3/6	9/9	12/9	1726	4833	1560	4603
1986	A	27/5	3/6	13/9	19/9	1323	3835	1566	5188
1987	C	26/5	6/6	23/9	2/10	1450	5330	1259	5403

Table 6.2. Harvest analyses of Pomo barley in 1983—87.

Year/Plot		Weight		Plant height cm	Harvest index H
		1000 seed g	Hecto-litre kg		
1983	A1	39.2	66.5	98	0.52
	A2	38.8	67.2	99	0.53
1984	B1	33.4	62.1	101	0.39
	B2	33.3	60.4	102	0.39
1985	A1	29.7	59.1	108	0.41
	A2	37.3	62.9	95	0.53
1986	C1	38.2	60.3	89	0.55
	C2	41.3	62.7	71	0.50
1987	A1	38.3	61.9	79	0.42
	A2	39.0	63.3	76	0.38
Mean 1983—87		36.8	62.7	92	0.46

Table 6.3. Harvest analyses of Span turnip rape (Kova 1987) in 1983—87.

Year/Plot		Weight 1000 seed g	Plant height cm	Harvest index H
1983	B1	2.44	111	0.25
	B2	2.31	110	0.20
1984	A1	2.61	85	0.26
	A2	2.46	90	0.18
1985	C1	2.83	127	0.25
	C2	2.40	105	0.28
1986	A1	2.73	100	0.25
	A2	2.60	78	0.28
1987	C1	2.88	88	0.22
	C2	2.82	88	0.24
Mean 1983—87		2.61	98	0.24

The best growing season for grass production occurred in 1983, when the total DM yield above ground was about 11 tons of DM per hectare (Table 6.5). For timothy, the growth of plant height was equal to the development of GAI.

The spring of 1985 was cold, and the yields of the first end cut were the lowest of any of the studied years. In 1985 and 1986, irrigation after the first end harvest hastened the development of crop growth. In 1987 grass development was slow and only two end cuttings were taken, but the DM yield was still about 9 tons per hectare.

7. The model

7.1. Simulation of the crop area

Aslyng and Hansen (1982) used the long-term average CAI and GAI values of the studied crops when developing their simulation model. For the crops surface development of used model, it is necessary to know the date of emergence (JDAY1), the date when the GAI values reach 5 (JDAY2), the date of the developmental point when the GAI decreases below 5 (JDAY3) and the date of full maturity, when the GAI = 0 (JDAY4). In cereals the CAI is 0 before emergence; it then rises exponentially to 5:

$$\text{CAI} = G_m\,(\exp(2.4\,(t - \text{JDAY1})/(\text{JDAY2} - \text{JDAY1})) - 1)/10 \tag{7.1}$$

where t = time, JDAYs = Julian days from the beginning of the year and G_m = the maximum value of GAI.

In the model of maximum value of GAI (G_m) is stated as 5 to the onset of ripening. GAI values over 5 had a minor influence on the amount of energy absorbed by the crop (Aslyng and Hansen 1982). After the onset

Table 6.4. Dry matter production (kg DM/ha) and plant height of timothy in the years of establishment.

Year/Plot		Dates of			DM yield		Plant height	
		Sowing	Emerging	Harvest	1	2	1	2
1982	C	27/5	7/6	6/9	1417	1898	59	45
1984	B	14/5	24/5	5/9	1731	2591	45	40

KEY: Plot 1 = irrigated, 2 = non-irrigated

Table 6.5. Dry matter production (kg DM/ha) and plant height (cm) of timothy in grass years.

Year/Plot	Dates of		Plant height			DM yield	
	Onset	Harvest	1	2		1	2
1983 C	20/4	16/6	103	105		6654	6893
		2/8	59	62		2817	2777
		9/9	26	36		1548	778
					Sum	11019	10448
1985 B	8/5	24/6	66	67		2231	2958
		12/8	83	95		4058	2750
		26/9	33	25		983	1240
					Sum	7272	6948
1986 B	25/4	13/6	76	74		5118	4995
		4/8	79	43		3211	1172
		8/9	26	35		558	911
					Sum	8887	7078
1987 B	30/4	25/6	76	75		4269	4340
		10/9	96	86		4593	5067
					Sum	8862	9407

KEY: Plot: 1 = irrigated, 2 = non-irrigated

of ripening, the GAI and CAI values decrease linearly to full ripening (GAI = 0), and in cereals the CAI at harvest equals 2 (YAI = 2):

(7.2) $GAI = G_m - G_m (t - JDAY3)/(JDAY4 - JDAY3)$

(7.3) $CAI = G_m - (G_m - Y)(t - JDAY3)/(JDAY4 - JDAY3)$

where Y = the yellow area index (YAI).

The same type of crop area model was applied for turnip rape as for barley, fit to the development of rape. The turnip rape stand did not always reach a GAI value of 5. In 1984 the maximum value of 2.5 was used for rape, because leaf area development was poor.

The simulation model of GAI for grass was developed for Italian ryegrass cut five times during the growing season (Aslyng and Hansen 1982). We used the same type of GAI model for timothy in a three cut system. Development of GAI to the value of 5 was the same as for barley; a GAI unit of 0.5 was added to describe the plant stand after cuttings:

(7.4) $CAI = G_m (\exp 2.4 (t - JDAY1)/(JDAY2 - JDAY1)) - 1)/10 + (0.5)$

For the timothy simulation model of GAI, the G_m-value of 5 remains stable until harvest.

Aslyng and Hansen (1982) used the common development of GAI, which depends on the temperature sum. Our data of GAI in all plant species showed that GAI development varied yearly and was not entirely dependent on the effective temperature sum (ETS, > 5°C). In our study it was more reliable to simulate the real yearly development of GAI for all three species studied (Fig. 7.1—7.3).

7.2. *Actual evapotranspiration*

Daily evapotranspiration was calculated according to the EVAPO simulation model (Aslyng and Hansen 1982). The input parameters of this submodel are precipitation (P), irrigation (I) and potential evapotranspiration (E*). The daily values of maximum effective root depth (d_r) and crop area index (CAI) are also needed. The soil water capacity is divided into two parts. The topsoil reservoir (S_t^*) is considered to occupy the upper 10 cm layer of the soil, and is stated contain-

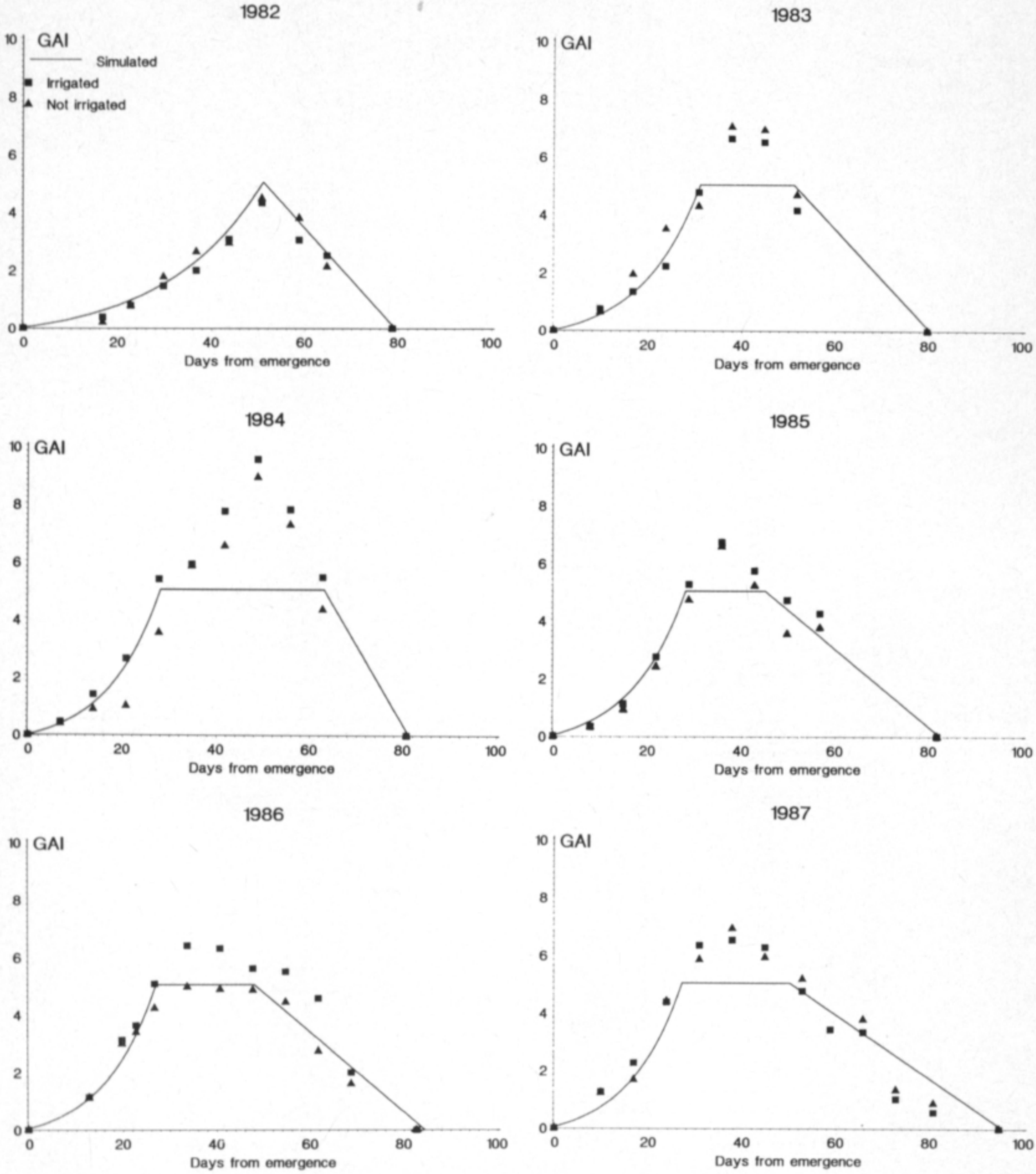

Fig. 7.1. Simulated and measured green area index (GAI) of barley in 1982—87.

ing 10 mm water. Heinonen (1985) proposed that this reservoir is a ''microrelief of the surface'', which delays the beginning of the flow of the surface water. S_t^* is not independent of the root zone reservoir, which is considered to be a function of soil type and the effective root depth. S_t^* can be readily evaporated from the soil surface, and root zone reservoir is available to the plants in the root zone.

The priori assumption is that the actual evapotranspiration (E) can reach, but cannot exceed, the potential evapotranspiration. In the EVAPO model a break point ($E/E^* = 1.0$) is adopted, when 50 % of the water is used by the plants. The pressure head at which soil water begins to limit plant growth seems to range between a pF-value 2.6 and 3 (Feddes et al. 1978). Denmead and Shaw (1962)

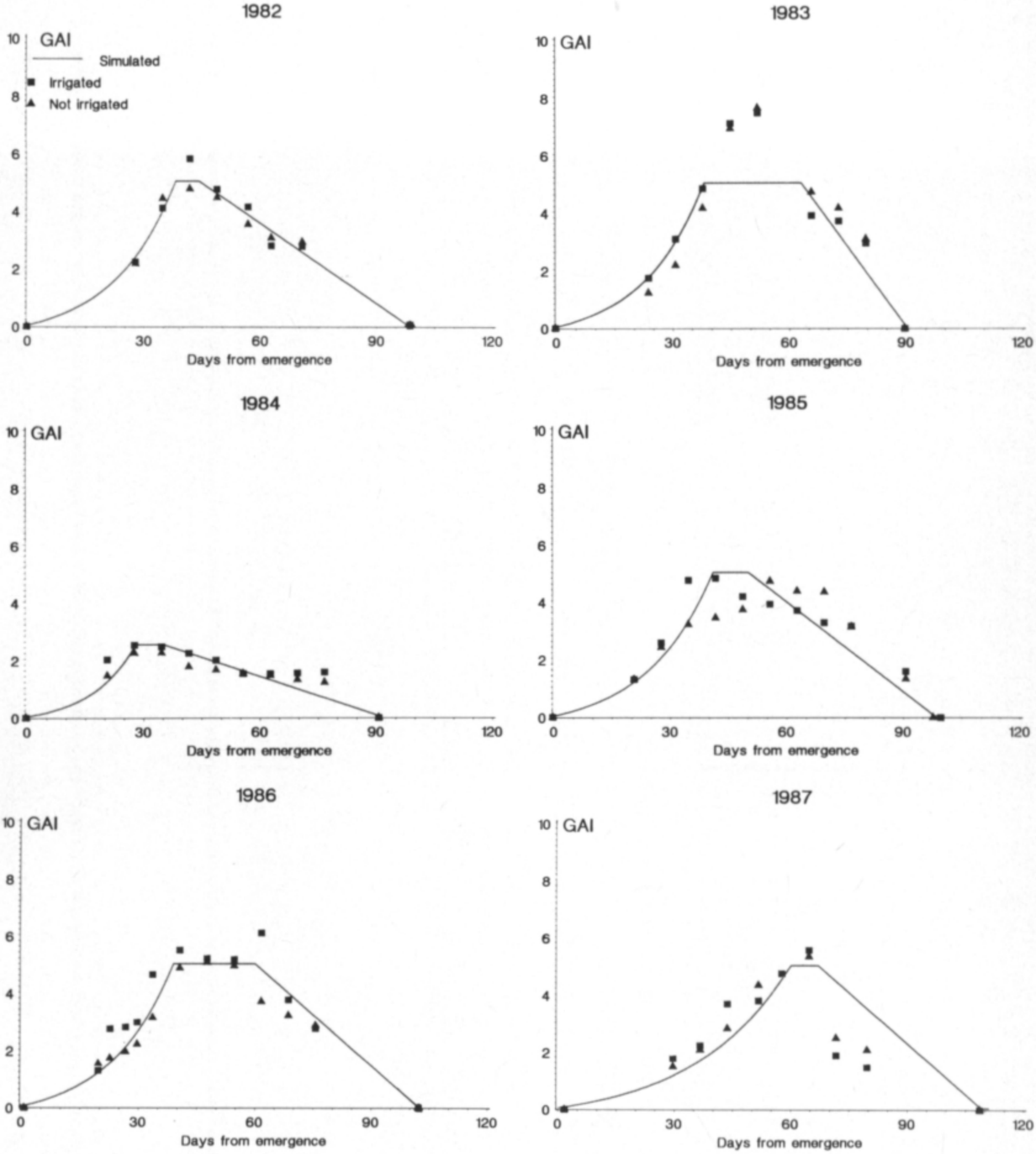

Fig. 7.2. Simulated and measured green area index (GAI) of turnip rape in 1982—87.

reported the influence of particular meteorological conditions on the relationship between actual and potential transpiration. They determined the point of soil moisture at which the wilting of the plants increased at the same rate as the increase in potential transpiration. LONG and FRENCH (1967) showed that loss of soil moisture by evaporation occurred mainly from the upper 30 cm of soil, in conditions when the soil contained less water than it does at field capacity. Drying below this depth is caused by the extraction of water by the roots.

In the WATCROS model, the break point of the soil moisture function value of 0.5 (50 %) was used from May to August, and a value of 0.6 (60 %) was used for april and September for all plants. In the potential case of the simulation, irrigation was applied,

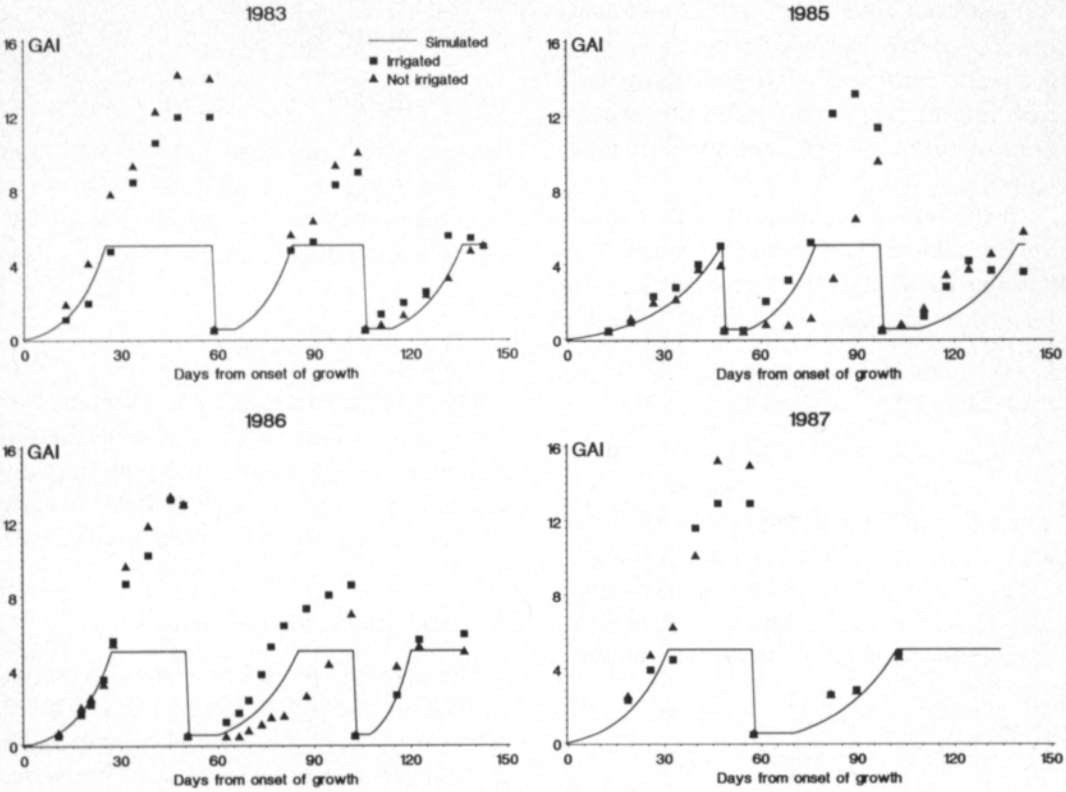

Fig. 7.3. Simulated and measured green area index (GAI) of timothy in 1983, 1985—87.

when the 40 % fraction of the root zone capasity was utilized. The upper limit of water applied in an irrigation was 50 mm.

According to SAUGIER (1970), evaporation behaves in the same way as does the net radiation. When the evaporative demand is distributed between the soil (E_s^*) and the crop (E_c^*) and using BEER's law (see equation 7.18.), the following equations can be drawn:

(7.5) $E_s^* = E_e^{*-KG}$

(7.6) $E_c^* = E^* (1 - e^{-KC})$

(7.7) $E_{c,\,g}^* = E^* (1 - e^{-KG})$

(7.8) $E_{c,\,y}^* = E_c^* - E_{c,\,g}^*$

where K = the extinction coefficient (equal to a net radiation of 0.6), G = the green area index (GAI), C = the crop area index (CAI), $E_{c,\,g}^*$ = the evaporative demand of the green active crop area and $E_{c,\,y}^*$ = the evaporative demand of the yellow, inactive, crop area.

The model operates on a daily basis; at the beginning of each step the amounts of precipitation and irrigation, called the potential interception storage (S_l^*), are supplied to the reservoir. JENSEN (1979) proposed that the plant can, at most, hold water equal to 0.5 mm H_2O on the crop surface (C) and on the crop green area (G). The interception storage can further be distributed as follows:

(7.9) $S_l^* = 0.5\ C$

(7.10) $S_{l,\,g}^* = 0.5\ G$

(7.11) $S_{l,\,y}^* = S_l^* - S_{l,\,g}^*$

where $S_{l,\,g}^*$ = the potential interception storage of the green crop area and $S_{l,\,y}^*$ = the interception storage of the yellow crop area.

The rest of P and I are supplied to the topsoil and root zone reservoir. Extra water is transferred to a through-flow reservoir, where it remains for three days if not evapotranspirated during that period. After this, water is drained out of the root zone as a deep percolation.

At the beginning, water is extracted from the topsoil at a potential rate as long as there is water in the reservoir; next it is extracted from the root zone, at a rate equal to 0.15 E_s^*.

$$(7.12)\quad \begin{aligned} E_s &= E_s^* &&; S_t \geq E_s^* \\ E_s &= 0.15\ E_s^*; &&S_t < E_s^* \end{aligned}$$

where E_s = the actual evaporation of the soil and S_t = the actual topsoil water storage.

$E_{c,g}^*$ extract water from the green crop area and $E_{c,y}^*$ from the yellow crop area in the potential rate equal to the actual values:

$$(7.13)\quad \begin{aligned} E_{c,y} &= S_{I,y} &&; S_{I,y} \leq E_{c,y}^* \\ E_{c,y} &= E_{c,y}^* &&; S_{I,y} > E_{c,y}^* \end{aligned}$$

$$(7.14)\quad \begin{aligned} E_{c,g} &= E_{c,g}^* &&; S_{I,g} \geq E_{c,g}^* \\ E_{c,g} &= S_{I,g} + E_T; &&S_{I,g} < E_{c,g}^* \end{aligned}$$

where $E_{c,y}$ = the actual evapotranspiration of the yellow crop area, $E_{c,g}$ = the actual evapotranspiration of the green crop area, $S_{I,y}$ = the actual interception storage of the yellow inactive crop area, $S_{I,g}$ = the actual interception storage of the green crop area and E_T = the actual transpiration.

If the actual and potential evapotranspiration of the green crop area are the same, then $E_T = 0$; but if they are not the same there is a transpiration demand:

$$(7.15)\quad E_T^* = E_{c,g}^* - S_{I,g}$$

where E_T^* = potential transpiration.

At first water is used of the through-flow reservoir and then it is extracted from the root zone. Transpiration decreases if there is less than 50 % available water in the soil.

$$\begin{aligned} E_T &= E_T^* &&; S_r \geq 0.5\ S_r^* \\ (7.16)\quad E_T &= E_T^* \frac{S_r}{0.5\ S_r^*}; &&0 < S_r < 0.5\ S_r^* \\ E_T &= 0 &&; S_r \leq 0 \end{aligned}$$

where S_r = the root zone water content and S_r^* = the whole root zone water capacity.

S_r^* depends on the root depth growth. The actual evapotranspiration can now be calculated:

$$(7.17)\quad E = E_s + E_{c,g} + E_{c,y}$$

The model operates as a book-keeping system on a daily basis. The initial conditions in spring are as follows: the interception reservoir is empty, the soil stays at field capacity and the through-flow reservoir is empty.

7.3. Potential gross production

The potential production rate of a crop is defined as "the growth rate of a closed, green crop surface, optimally supplied with water and nutrients, in a disease-free and weed-free environment under the prevailing weather conditions" (GOUDRIAAN 1982). Plant production can be divided into four levels after PENNING de VRIES (1980). The first level is the potential plant production, when there are no limiting factors in prevailing global radiation and air temperature conditions. The WATCROS model reaches only the second level, when lack of water can decrease the DM production. The next production levels, levels three and four, include also the effect of the main nutrients (N, P, K) on plant growth.

The interception of photosynthetic active radiation (400—700 nm) in the crop is described by BEER's law:

$$(7.18)\quad S = S_n\, e^{-kG}$$

where S = the radiative flux density below the downward accumulated GAI (G), s_n = the radiative flux above the canopy and k = the extinction coefficient of PAR.

k depends on the crop structure, the optical properties of leaves, solar altitude, the fraction of diffuse radiation etc. in general

BEER's law is reliable only when the canopy stand is homogeneous and dense (k is relative high). ASLYNG and HANSEN (1982) adopted a k value of 0.8 for photosynthetic active radiation (PAR), whereas KVIFTE (1987) used $k = 0.65$. This study used a value of 0.8 for barley and timothy and 0.65 for turnip rape. The absorption of PAR is as follows:

(7.19) $S_{abs} = S_v \times S_i (1 - A_v)(1 - e^{-kG})$

where S_v = the fraction of the photosynthetic active (or visible) radiation (PAR), S_i = global radiation (300—2500 nm) and A_v = hereof reflectivity of the crop (albedo).

In Denmark, the calculation basis for S_v has been 48 % of S_i, the albedo of dense short grass stand being 0.06 (PAR) (HANSEN et al. 1981).

The potential gross CO_2 assimilation of a single leaf is used as the basis for calculations of the whole crop assimilation. The photosynthetic rate (A) can be described as follows:

(7.20) $A = A_m (1 - e^{-S_v/m})$

where A_m = the rate of leaf photosynthesis at light saturation and m = constant.

In the WATCROS model the adopted value of A_m equals 0.83 mg $CO_2 m^{-2} s^{-1}$, which is a typical value for C_3 plants. ASLYNG and HANSEN (1982) calculated the gross CO_2 assimilation and the absorbed PAR, and computed a mean daily photosynthetic efficiency:

(7.21) $p = \dfrac{\text{stored energy}}{\text{absorbed PAR}}$

The potential gross production is then calculated:

(7.22) $P_g = c \times p \times S_v (1 - A_v)(1 - e^{-kG}) S_i$

where c = the conversion factor converting stored energy into structural plant dry matter.

ASLYNG and HANSEN (1982) used selected values for mean photosynthetic efficiency (p) for different crops. We used the value of 8 % for p, as did Kvifte in Norway. The conversion factor (c) converts 70 g DM MJ^{-1}, which is 14.3 kJ g^{-1} DM. In Great Britain GALLAGHER (1976) reported a c value equal to 16.7 kJ g^{-1} and $p = 5.7$ % for barley carbohydrates.

7.4. *Respiration and net plant production*

Crops have many types of respiration, some of which is rather difficult to take into consideration. The WATCROS model uses only maintenance and growth respirations. Total respiration is understood to be the sum of these two respirations.

Maintenance respiration (R_m) is a function of the dry weight of the plant, and with the rate of respiration depending upon temperature according to a temperature coefficient ($Q_{10)}$ relation of the form:

(7.23) $R_2 = R_1 \times Q_{10}^{(t_{a,2} - t_{a,1})/10}$

where R = respiration and t_a = temperature.

The Q_{10} factor is stated equal to value 2 at 20°C (BISCOE and GALLAGHER 1977, ROBSON 1981). In the literature, the respiration coefficient (r_m) values have normally been equal to 1—4 % DM day^{-1} for various species. In the WATCROS model, r_m-values for grass 4.0 % day^{-1} and for spring barley and turnip rape 1.5 % day^{-1} of the daily estimated quantity of plant dry matter were used throughout the growth period.

Besides maintenance respiration, plants also have growth respiration (R_g), which is described as the factor of efficiency in converting carbohydrates into structural plant material. In the literature, growth respiration is reported to be 20—30 % of the gross assimilation, and is independent of temperature and plant species. In the WATCROS model a value of growth respiration equal to 30 % is used; this is understood as a converting factor (0.7) also covering transport respiration.

Net dry matter production (P_n) can now be calculated by subtracting growth and maintenance respiration from the potential gross production:

$$(7.24)\quad P_n = P_g - R_g - R_m$$

where P_g = gross production (eq. 7.22), R_m = maintenance respiration and R_g = growth respiration.

Maintenance respiration is calculated from the stored dry weight (W_{i-1}) and from the average daily dry matter production ($0.5 \times P_{n,i}$):

$$(7.25)\quad R_m = r_m\,(0.5 \times P_{n,i}) + W_{i-1})$$

where r_m = the maintenance respiration coefficient.

Growth respiration occurs only if there is net production:

$$(7.26)\quad R_g = r_g\,(P_g - R_m);\ P_g > R_m$$

$$(7.27)\quad R_g = 0 \qquad ;\ P_g \leq R_m$$

where r_g = the growth respiration coefficient.

When the given formulas are combined, the amount of recently assimilated carbohydrates ($P_{n,i}$) not yet converted into structural plant dry matter can be calculated:

$$(7.28)\quad P_{n,i} = \frac{0.7\,(P_{g,i} - r_m \times W_{i-1})}{1 + (0.5 \times 0.7 \times r_m)};\ P_g > R_m$$

$$(7.29)\quad P_{n,i} = \frac{P_{g,i} - r_m \times W_{i-1}}{1 + (0.5 \times r_m)};\ P_g\ R_m$$

the total amount of accumulated plant dry matter cannot be harvested; some of it remains in the field. As the basis of their calculations, Aslyng and Hansen (1982) used 3 ton DM losses in the field; the same value was used in Norway (Kvifte 1987). This study also used 3 ton losses for our plant species, because of difficulties in determinations of the actual root yields in the heavy clay soil.

Simulation of the daily non-harvested DM yield from the total DM production should take into consideration the formula of plant dry matter partitioning between roots and shoots (Heemst 1986, Keulen and Seligman 1987). The daily stubble, root etc. mass loss ($W_{L,i}$) is calculated by using the simulated daily potential DM production ($P_{n,i}$) until the maximum root depth (d_r) or the full 3 ton DM loss is reached:

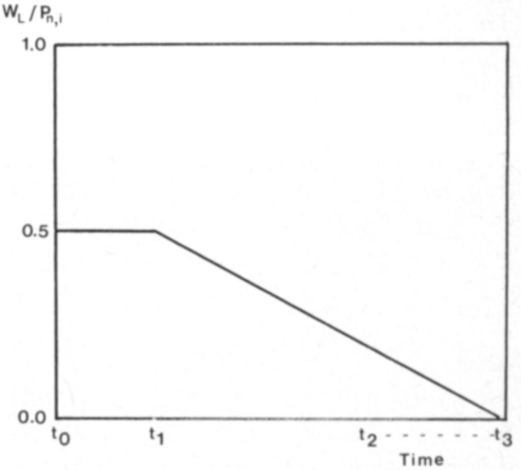

Fig. 7.4. Estimation of daily non-harvested dry matter (stubble, root, etc. mass loss) for barley and turnip rape (explanation see text).

(7.30)
$$W_{L,i} = 0.5\ P_{n,i} \qquad (t_0 < t \leq t_1)$$

(7.31)
$$W_{L,i} = 0.659 - 0.01\ P_{n,i}\ \text{(barley)}$$

$$(t_1 < t \leq t_3)$$

(7.32)
$$W_{L,i} = 0.644 - 0.01\ P_{n,i}\ \text{(t. rape)}$$

(7.33)
$$W_{L,i} = 3.0 \qquad (t > t_3)$$

where $P_{n,i}$ = the daily potential net production, including the loss, t_0 = the beginning of simulated potential DM production, t_1 = 2 weeks from t_0, t_2 = the time, when 3 ton DM loss is reached and t_3 = the time of maximum root depth (Fig. 7.4).

After calculations of these formulas (7.30—7.33), the total loss of 3 tons per hectare was reached, on average, 47 days from sowing for barley and 61 days for turnip rape. In Great Britain the maximum root yield of cereals were obtained at about 50 days from sowing (Welbank et al. (1973).

In the Danish and in the our version, DM loss of timothy was calculated using a linear function from the onset of growth to the maximum root depth:

$$(7.34)\quad W_{L,i} = \frac{3.0}{d_r} \text{ (timothy).}$$

Where d_r = the maximum effective root depth (75 cm).

The model continues to operate with W_h until the total lost dry matter yield (3 tons) is reduced:

$$(7.35)\quad W_h = P_n - W_L$$

where W_h = the harvested dry matter yield.

Grain (barley) and seed (turnip rape) yields (W_g) were calculated as follows:

$$(7.36)\quad W_g = H \times W_h$$

where H = the harvest index.

The harvest index values applied were H = 0.45 for barley and H = 0.25 for turnip rape. Timothy yield is considered to have a harvest index of H = 1.0.

7.5. Water limited crop production

Aslyng and Hansen (1982) used a linear relation between transpiration and potential crop production in calculating the water limited (actual) plant gross production (P_g):

$$(7.37)\quad P_g = \frac{E_{c,g}}{E^*_{c,g}} P^*_g$$

where $E_{c,g}$ = transpiration plus the evaporation of water intercepted on the green active crop surface, $E^*_{c,g}$ = the same in the potential case and P^*_g = the potential gross production.

The WATCROS model does not consider the effect of water stress on the crop green area. Aslyng and Hansen (1982) prefer gross production to net production because of difficulties and errors in estimating respiration.

Determination of actual production differs from that of potential production in only one essential aspect. Potential crop production is obtained through optimal irrigation treatment, but the actual crop production is entirely dependent on water, in the soil, available to the plant and on root depth growth. Aslyng and Hansen (1982) and Kvifte (1987) used the same maximum efficient root depth of 100 cm. According to root measurements made in 1986 and 1987, the maximum root depth in the Finnish studies was assumed to be 75 cm.

8. Results and discussion

8.1. Barley and turnip rape

In 1983—87 the time of the GAI development of barley was 29 (27—31) days for the increasing phase. It was 23 (17—34) days at GAI ≥ 5, and 33 (19—45) days in the decreasing phase. The simulation for the increasing phase of GAI, using an exponential function, succeeded well. The simulated DM production for barley was 30—45 % in the increasing phase of GAI, 35—55 % at GAI ≥ 5 and 15—30 % in the decreasing phase of GAI.

In the prevailing weather conditions the simulated actual (water limited) DM production of barley in the experimental field was the highest in 1983 and 1984, whereas the actual DM production of turnip rape reached the maximum level in 1982 and 1983. Simulated total potential DM yields containing root, stubble etc. mass loss were 13.2—15.5 tons per hectare for barley and 12.1—15.3 tons per hectare for turnip rape exept in 1984, when it was only 7.0 tons DM per hectare.

The simulated development of actual dry matter production for barley was somewhat greater than the values measured (Fig. 8.1). The difference was even greater for turnip rape than for barley (Fig. 8.2). Such behaviour is explained by the fact that the WATCROS model takes into consideration only the limits in water use, but not the excess of water in the soil. In Finnish climatic and soil conditions, root development seems to be more restricted than in the Danish conditions. Soil

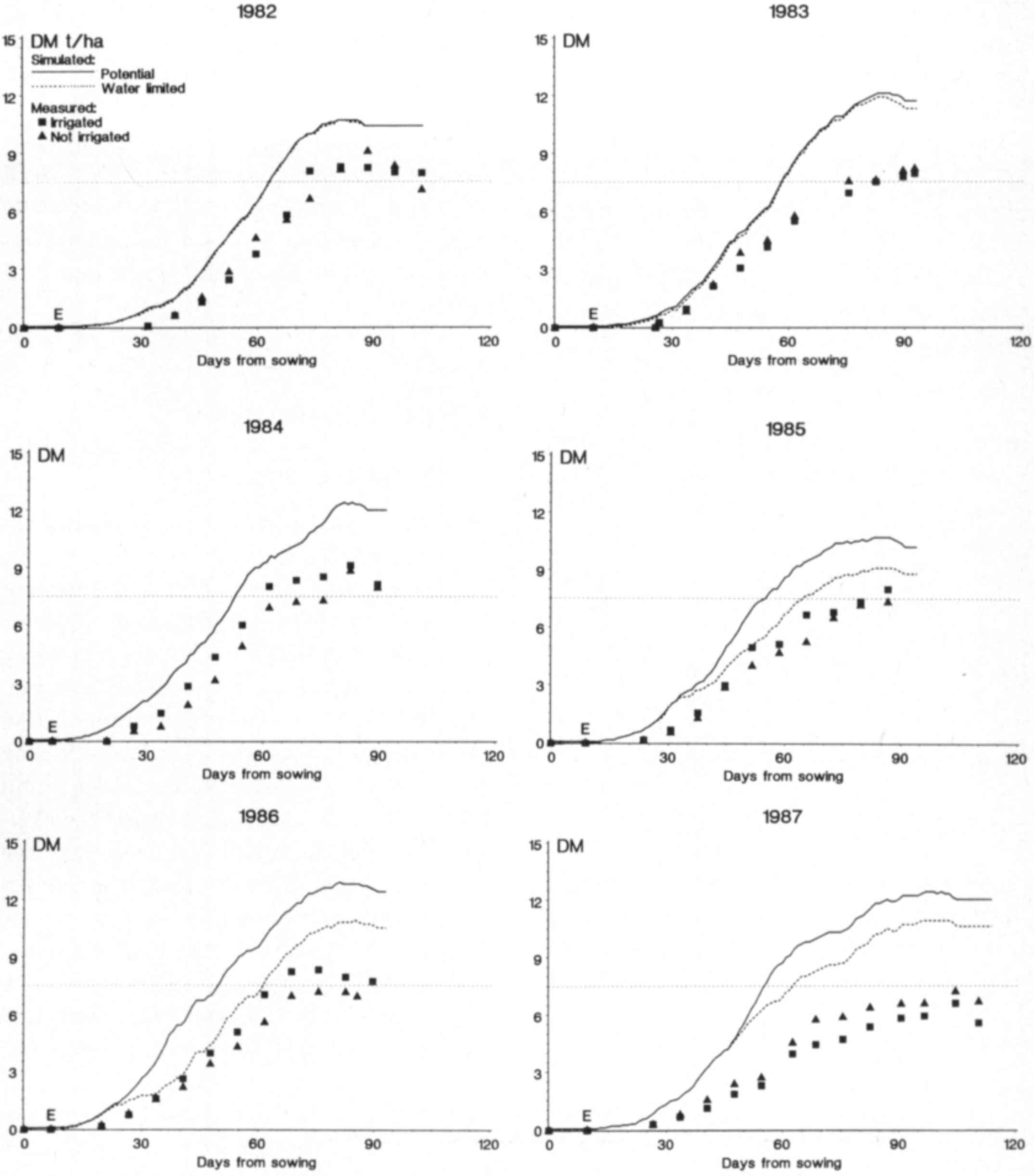

Fig. 8.1. Above ground dry matter (DM) production of barley in 1982—87. E = emergence day.

conditions and root development seem to lead the plant to a lower PAR use of stand in Finland than in Denmark.

In some years the grain yields at Jokioinen district were higher than the simulated potential grain yields in the experimental field (Tables 8.1 and 8.2). In such cases harvested yields that were greater than simulated potential ones may be the result of differences in sowing time, the development of GAI in relation to incoming radiation and the values of the harvest index. For example, in the first study year (1982), the crop surface development of barley was poor, which decreased the simulated yield. In 1987, though generally a rainy and cool year, the development of GAI

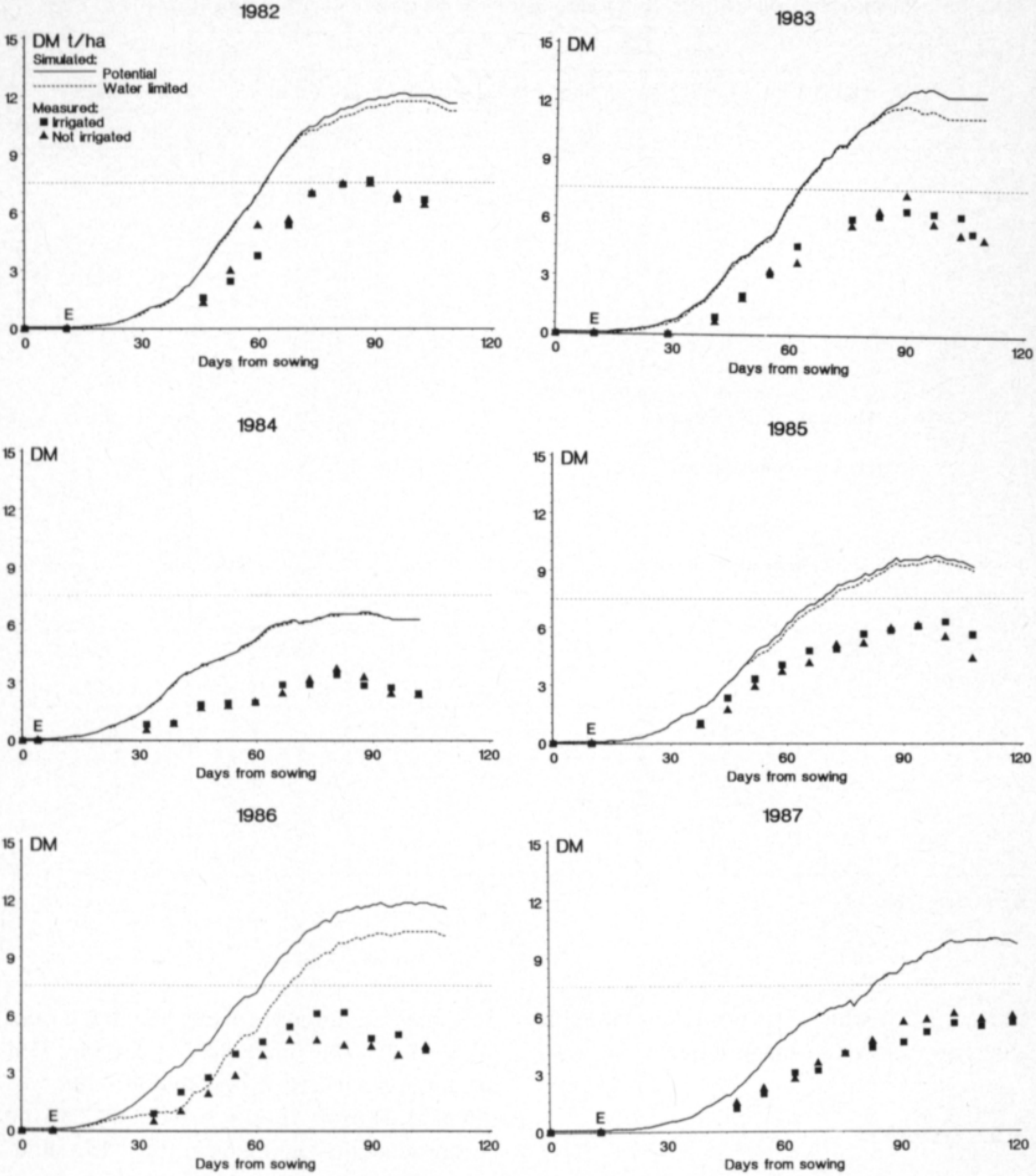

Fig. 8.2. Above ground dry matter (DM) production of turnip rape in 1982—87. E = emergence day.

was great due to the high incoming radiation in July, and the simulation of potential DM production of barley was also high, 15.0 tons per hectare. The measured DM production remained low due to the excess of water and low temperature during the filling period of grain.

According to the results of the simulated potential yield, irrigation was meaningful during the last three tests years (1985—87) for barley but only in 1983 and 1986 for turnip rape. The simulated model introduced requirements for irrigation; these varied from 30 to 165 mm in the growing season for barley and 15—170 mm for turnip rape. In the rainy seasons of 1984 and 1987, occasionally there was too much water in the field for crop produc-

Table 8.1. Production results of Pomo barley including 15 % moisture at Jokioinen (grain tons/ha).

Year	Measured:				Simulated:			
	KVO	KJO	Climatic field		Potential		Actual	
			1	2	MAK	PEN	MAK	PEN
1982	7.5	7.3	3.8	4.7	5.5	5.5	5.5	5.4
1983	4.6	7.3	4.9	5.2	6.2	6.2	6.0	6.1
1984	3.3	4.2	4.2	4.1	6.3	6.3	6.3	6.3
1985	5.6	6.4	3.9	4.6	5.4	5.4	4.6	5.3
1986	4.0	5.8	5.4	4.3	6.6	6.6	5.6	5.8
1987	4.2	4.6	3.2	3.2	6.4	6.4	5.6	6.2

KEY: Department of Agricultural Centre:
KVO = Crop Science, KJO = Plant Breeding
Formula of Potential evapotranspiration (PET):
MAK = Makkink, PEN = Penman
Plot:
1 = Irrigated, 2 = Non-irrigated

Table 8.2. Production results of Span turnip rape (Kova 1987) including 9 % moisture at Jokioinen (seed tons/ha)

Year	Measured:				Simulated:			
	KVO	KJO	Climatic field		Potential		Actual	
			1	2	MAK	PEN	MAK	PEN
1982	2.7	1.9	2.1	1.9	3.2	3.2	3.1	3.0
1983	2.8	2.6	1.8	1.6	3.4	3.4	3.1	3.3
1984	1.9	0.7	1.0	0.7	1.6	1.5	1.6	1.6
1985	2.0	—	1.7	1.9	2.5	2.5	2.4	2.5
1986	1.8	—	1.7	1.5	3.2	3.2	2.7	2.9
1987	2.0	2.4	1.4	1.6	2.6	2.6	2.6	2.6

KEY: (see Table 8.1)

tion, a factor which was not taken into consideration in this growing model.

8.2. Timothy

For timothy, the real annual development of crop surface was simulated separately for each of the cuts. Aslyng and Hansen (1982) used the long term mean development of GAI for Italian ryegrass. The maximum values measured for GAI were often much greater than the value, $G_m = 5$, used in the simulation model. In Norway Kvifte (1987) used the value of $G_m = 7$ for the first cut and $G_m = 5$ for the second cut in the simulation of GAI of timothy.

The total DM yields measured for timothy were only about 60 % of the simulated ones (Table 8.3). The simulation of timothy DM production succeeded best in 1987, but was still unsatisfactory (Fig. 8.3). Timothy had the best production conditions in 1983. The simulation model introduced the need for irrigation for the whole growth period; it varied from 55 to 150 mm per year. In the field, irrigated plots had better yields than the non-irrigated plots only in 1985 and 1986, which were relatively dry years.

The total annual simulated poatential DM yields of timothy were 15.4—20.2 tons per ha. One reason for the differences between the simulated grass dry matter yields and the actual measured DM yields may have been the effect of soil temperature, which was a

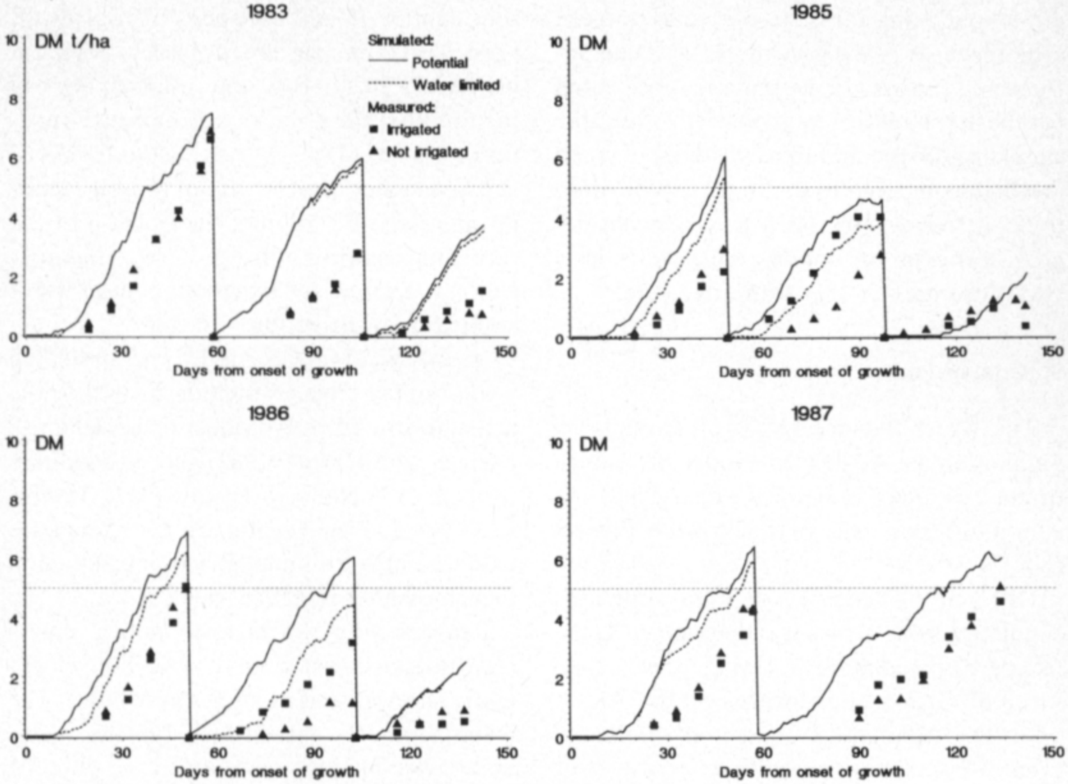

Fig. 8.3. Above ground dry matter (DM) production of timothy in 1983, 1985—87.

Table 8.3. Production results of Timothy grass at Jokioinen (tons DM/ha).

Year	End cut	Measured:			Simulated:			
		KVO	Climatic field		Potential		Actual	
			1	2	MAK	PEN	MAK	PEN
1983	I	5.8	6.6	6.9	7.5	7.5	7.5	7.5
	II	5.2	2.8	2.8	6.0	6.0	5.9	5.9
	III	1.4	1.5	0.8	3.7	3.7	3.5	3.6
	Sum	12.4	11.0	10.4	17.2	17.2	16.9	16.9
1985	I	3.9	2.2	3.0	6.1	6.1	5.4	5.4
	II	3.7	4.1	2.8	4.6	4.6	3.9	4.0
	III	—	1.0	1.2	2.1	2.1	2.1	2.1
	Sum	7.6	7.3	6.9	12.8	12.8	11.4	11.5
1986	I	4.7	5.1	5.0	7.0	7.0	6.3	6.4
	II	2.3	3.2	1.2	6.1	6.1	4.5	4.7
	III	—	0.6	0.9	2.5	2.5	2.5	2.5
	Sum	7.0	8.9	7.1	15.6	15.7	13.3	13.6
1987	I	3.5	4.3	4.3	6.4	6.4	5.9	6.3
	II	4.4	4.6	5.1	6.0	6.0	6.0	6.0
	Sum	7.9	8.9	9.4	12.4	12.4	11.9	12.3

KEY: (see Table 8.1)

growth-reducing factor in one to two weeks after the onset of the growth period. Other influencing factors are the same as those noted for barley and turnip rape. However, the simulated second and third yields were much too high compared to the first yield of timothy. The reason for this may be the natural growth rhythm of timothy, which includes a very slow start of regrowth after cuts.

9. Conclusions

The Water Balance and Crop Production Simulation (WATCROS) model of Danish origin was tested in Finnish climatic and soil conditions as a part of the Nordic Project (NKJ-47).

Different from the WATCROS model, the simulated crop surface was determined as the real development of GAI, owing to the importance of GAI in the absorbance of PAR.

In the simulation model of potential evapotranspiration, modified versions of MAKKINK (1957) and PENMAN (1956) were tested. As a result, the calculated values of potential evapotranspiration by MAKKINK or PENMAN led to the same result of the simulated actual DM yields of the three studied plant species. The MAKKINK was used as the basis of calculations.

The constants used in the WATCROS model are as follows: gross CO_2 single leaf assimilation = 0.83 mg m^{-2} s^{-1}; albedo = 6 % of PAR; the factor converting stored energy to plant structural DM = 70 g DM MJ^{-1}; the max. GAI = 5; the harvest index, = 0.45 for barley, = 0.25 for turnip rape and = 1.0 for timothy; the extinction coefficient = 0.8 for timothy and barley and = 0.65 for turnip rape; the extinction coefficient for net radiation = 0.6; the growth respiration coefficient = 30 %; the maintenance respiration coefficient = 1.5 % for barley and turnip rape and = 4.0 % for timothy; the maintenance respiration Q_{10} = 2; PAR = 48 % of global radiation; gross photosynthetic efficiency = 8 %; the stubble, root etc. mass loss in harvest = 3 ton DM per hectare; the maximum effective root depth = 75 cm; the speed of root depth growth = 1.3 cm per day for barley, = 1.2 cm per day for turnip rape and = 0.7 cm per day for timothy; the point of soil moisture function = 0.5 for May—August, = 0.6 for April and September; the capasity of topsoil evaporation reservoir = 10 mm; the fraction of the root zone capasity utilized = 0.40, when irrigation is applied; the largest amount of water applied in an irrigation = 50 mm.

In the WATCROS model the simulated water limited crop production fit well to the actual measured crop production in Denmark (ASLYNG and HANSEN 1982) and, in modified form, also in Norway (KVIFTE 1987). In Finland the Danish version of the model introduced higher simulated actual production than measured in actual yields.

Reasons why the Danish model, unless modified, does not seem to fit to Finnish climatic and soil conditions are as follows: The Danish model consentrates on the water limited production conditions, excluding the excess of water in the soil and in the plant. The maximum efficient root depth growth in Finland (75 cm) is more limited than in Denmark (100 cm). Also the daily depth growth of the roots in Finland was lower (from 0.7 to 1.3 cm) than in Denmark (1.5—2.0 cm per day). The gross photosynthetic efficiency 8 % from PAR, used in Danish model seems to be an overestimate in the Finnish conditions, owing to soil type and excess of water in the soil and in the plant, but also to the temperature conditions in shoot growth, and especially, in root growth.

The Finnish studies on simulation models occurred during growing seasons characterized by heavy amounts of precipitation. The WATCROS model did not include possible losses of nitrogen in the calculations. Water, PAR efficiency and possibly nitrogen should be taken into consideration when constructing a production model for Finnish climatic and soil conditions.

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SELOSTUS

Tanskalaisen kasvumallin testaaminen ohralla, rypsillä ja timoteilla Suomen olosuhteissa

A. Ilola,[1] E. Elomaa[2] and S. Pulli[3]

[1] *Kasvinviljelyosasto, Maatalouden tutkimuskeskus 31600 Jokioinen*

[2] *Havaintotekninen toimisto, Ilmatieteen laitos PL 503 00101 Helsinki*

[3] *Kasvinjalostusosasto, Maatalouden tutkimuskeskus 31600 Jokioinen*

Biologis-meteorologinen aineisto kerättiin Jokioisissa vuosina 1982—87. Ohran, rypsin ja timotein potentiaalinen ja vesirajoitteinen kuiva-ainesato simuloitiin tanskalaisen WATCROS-mallin mukaan.

Tärkeimpiä biologisia mittauksia olivat kasvustoalan (GAI), kuiva-ainesadon, juurten kasvun ja maan kosteuden viikoittainen seuranta sekä puintiajankohdan satoanalyysit sekä sadetetuilta että sadettamattomilta lohkoilta. Simuloinnissa tarvitut ja myös kentältä mitatut meteorologiset parametrit olivat puolestaan päivittäinen auringon kokonaissäteily, ilman lämpötila ja sadanta.

WATCROS-mallilla simuloidut kuiva-ainesadot olivat yleensä suurempia kuin koekentältä saadut sadot. Jatkotutkimuksissa tulisikin selvittää fotosynteettisesti aktiivisen auringon säteilyn tehokkuus Suomen kasvuoloissa, sekä maan liiallisen märkyyden ja kasveille käyttökelpoisen typen huuhtoutumisen vaikutus kasvien kasvuun ja tuotantoon.