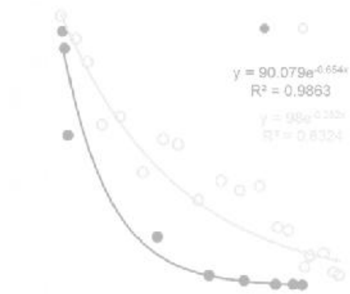
LECTURE 6:
RUE (Radiation Use Efficiency)



Success is a lousy teacher. It seduces smart people into thinking they can't lose. Bill Gates

LECTURE OUTCOMES

After the completion of this lecture and mastering the lecture materials, students should be able

1. to explain the growth rate of crops as a function of intercepted solar radiation
2. to explain and to quantify the quantity of extraterresrial radiation that is the solar radiation incident on the outer surface of earth's atmosphere.
3. to explain photosynthetically active radiation (PAR) used by plants to produce biomass
4. to quantify PAR interception and radiation use efficiency (RUE)

LECTURE FLOW

1. INTRODUCTION
   1. Initial Development
   2. RUE Model
2. SOLAR RADIATION
3. PAR INTERCEPTION
   1. PAR
   2. Interception
4. RUE ESTIMATION
   1. Experimental Evidence
   2. Estimation Procedure

1. INTRODUCTION

1. Crop Growth and Radiation

1. Monteith (1972, 1977) observed that net primary productivity (NPP) or crop growth rate is propor-tional to intercepted solar radiation, which represents the ultimate limit to productivity.

$$\mathbf{CGR} = \frac{\partial \mathbf{W}}{\partial \mathbf{t}} = \varepsilon \mathbf{Q}$$

where $\partial W/\partial t$ is the rate of biomass production per unit time (day, week etc.) (g m^{-2} t^{-1}; t, time), ε is the light (radiation) use efficiency (g.MJ^{-1}), and Q is the total intercepted radiation during the period under consideration (MJ m^{-2} t^{-1}).

2. Yoshida (1983) used a different approach to calculate CGR.

$$\mathbf{CGR} = \frac{\partial \mathbf{W}}{\partial \mathbf{t}} = \frac{\varepsilon.\mathbf{S}}{\mathbf{K}}$$

where ε = solar energy use efficiency (fraction or %), K = heat of biomass combustion ($cal.g^{-1}$), and S = total amount of incident solar energy during the time under consideration

3. Trials at 8 experimental stations in JIBP (Japanese International Biological Program), the highest recorded ε values ranged from 2.83% to 3.32% with a mean of 3.00% (Kanda, 1975)

Yoshida, S., 1983. Rice. In "Potential Productivity of Field Crops Under Different Environment. IRRI, Los Banos, Laguna, Philippines

4. Using the ε = 3.00% value and K = 3,750 $cal.g^{-1}$, the maximum growth rate of plants in Malang, with a mean solar radiation of about 400 $cal.cm^{-2}$ (400.10^4 $cal.m^{-2}$), is

$$\mathbf{CGR} = \frac{0.03 * 400}{3{,}750} 10^4$$

CGR = 32.0 $g.m^{-2}.day^{-1}$

2. RUE Definition

1. Using the Monteith's approach, biomass production can be modelled as a linear function of intercepted photosynthetically active radiation (PAR).

2. The slope of this relationship is the radiation use efficiency (RUE or ϵ), which is approximately constant for forests and natural ecosystems, and particularly for crops when growth is not limited by environmental conditions.
3. Radiation-use efficiency (RUE), light use efficiency (LUE), is defined as the ratio of dry matter produced per unit of radiant energy used in its production.
4. Because efficiency should be dimensionless, the term of “dry matter:radiation quotient” was suggested (Russell *et al*. (1989), however, RUE is used widely and considered a useful tool for simulating crop growth.

5. Linearity between biomass and accumulated intercepted radiation has been demonstrated for several many crops (e.g. beans, soybean, maize, lettuce) and for a few tree species (e.g., willow, mesquite and juniper).
6. Linder (1985) reported a mean RUE of 0.9 g (MJ shortwave)$^{-1}$ (approximately 1.8 g (MJ PAR)$^{-1}$) for a set of evergreen canopies.
7. Values of RUE for tree species are generally smaller than those for C3 herbaceous species (Kiniry *et al*. 1989), because of the high energy cost of woody biomass and the respiration of supporting organs.

8. RUE is influenced by plant development and many environmental factors. For example, RUE increases with increasing rate of leaf photosynthesis. RUE should decrease with increasing leaf age, respiration, and with the higher energy costs of some plant constituents.
9. The environmental conditions that may decrease the efficiency of metabolic and other processes determining RUE include water, nutrient shortage and adverse climatic conditions.
10. Using biomass to study RUE implies long-term experiments since, on a short time-scale (e.g. 1 d or less), biomass increases are difficult to measure.

SOLAR RADIATION

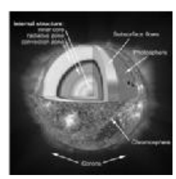
1. Crop yield is determined by biomass accumulation and its partitioning into the economical plant organ (Van der Werf, 1996).
2. Crop biomass production depends on the ability of the canopy to
   - (i) The quantity of the incoming photosynthetically active radiation (PAR)
   - (ii) The interception of PAR which is a function of leaf area index (LAI) and canopy architecture, and
   - (iii) The conversion of intercepted PAR into new biomass, i.e. radiation use efficiency (RUE) which is a function of genetic and environmental factors.

3. The quantity of the incoming photosynthetically active radiation (PAR) incident on the top of crop canopy is determined by many factors as shown by the following equation.

$$\mathbf{Ra} = \frac{24(60)}{\pi}\mathbf{S_0 d_r}\left[\omega_s \,\mathbf{sin}(\varphi)\mathbf{sin}(\delta) + \mathbf{cos}(\varphi)\mathbf{cos}(\delta)\mathbf{sin}(\omega_s)\right]$$

Where
R_a, extraterrestrial radiation [MJ m^{-2} day^{-1}],
S_0, solar constant = 0.0820 MJ m^{-2} min^{-1}, 1367 $J.m^{-2}.s^{-1}$
d_r, inverse relative distance Earth-Sun,
ω_s, sunset hour angle [rad],
φ, latitude [rad],
δ solar declination [rad]

4. Solar constant (S_0) is defined as the quantity of solar energy (W m^{-2}) at normal incidence outside the atmosphere (extraterrestrial) at the mean sun-earth that can be calculated as follows.



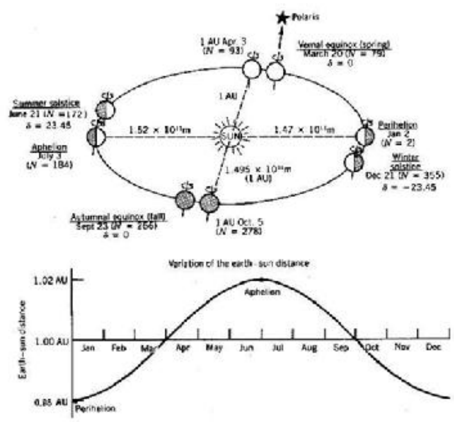
$$\mathbf{S_0} = \varepsilon.\sigma.\mathbf{T}^4\left(\frac{4\pi \mathbf{r}_s^2}{4\pi \mathbf{r}_D^2}\right)$$

where
ε = 1 for the sun is emissivity or the ability of an object to emit radiation compared to the black body ($0 \leq \varepsilon \leq 1$)
$\sigma = 5.67 \cdot 10^{-8}$ $W.m^{-2}.K^4$ is the Stefan-Boltzmann constant.
$r_s = 696.10^6$ m is the Sun radius
$r_D = 150.10^9$ m is the average distance between the Sun and the earth

5. The inverse relative distance Earth-Sun (d_r) varies with time and is calculated with the following equation.

$$d_r = 1 + 0.033\cos\left(\frac{2\pi J}{365}\right)$$

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December).



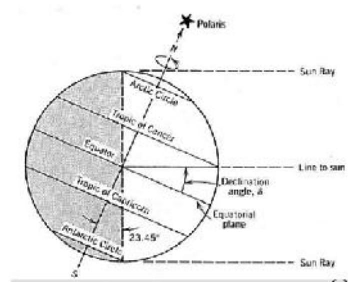
6. The sunset hour angle (ω_s) is calculated as follows.

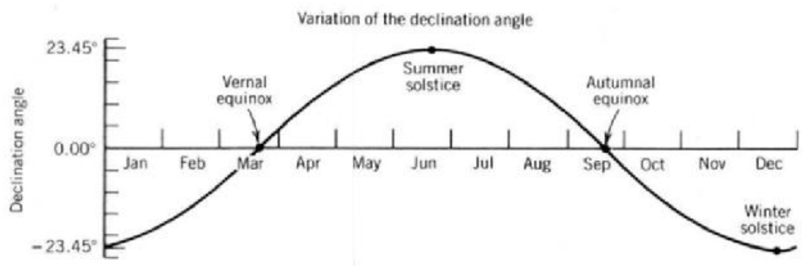
$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)]$$

7. The solar declination (δ) is calculated with the following equation.

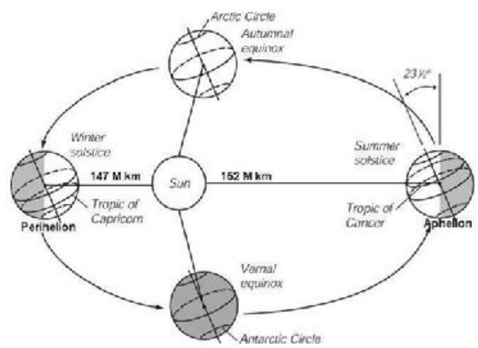
$$\delta = 0.409\sin\left(\frac{2\pi J}{365} - 1.39\right)$$

Declination is the angle made between the plane of the equator and the line joining the two centers of the earth and the sun



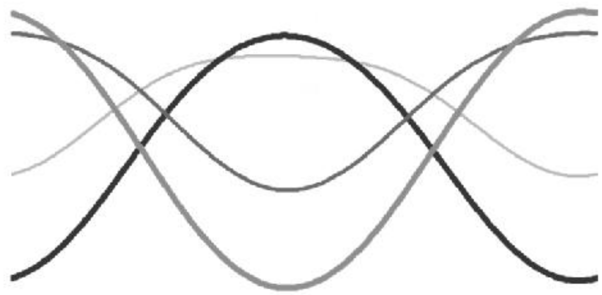


Distance of Earth from the sun, and solar declination that vary with time



0.0820 MJ m^{-2} min^{-1}

Determine the extraterrestrial radiation (R_a) for 3 September at 20°S.			
S_0	$S_0 = \varepsilon\sigma T4((4\pi r_s^2)/(4\pi r_D^2))$	0.0820	MJ m^{-2} min^{-1}
Lati-tude	20°S or j = (p /180) (-20) = (the value is negative (-) for the southern hemisphere)	-0.35	rad
Days	The number of day in the year, J =	246	days
d_r	$d_r = 1 + 0.033 \cos(2\pi\ 246/365)$ =	0.985	rad
¢	$\delta = 0.409 \sin(2\pi 246/365 - 1.39)$ =	0.120	rad
μ_s	$\omega_s = \arccos[-\tan(-0.35)\tan(0.120)]$ =	1.527	rad
	$\sin(\varphi)\sin(\delta)$ =	-0.041	-
	$\cos(\varphi)\cos(\delta)$ =	0.933	-
Ra	$R_a = 24(60)/\pi\ (0.0820)(0.985)[1.527(-0.041) + 0.933 \sin(1.527)]$ =	32.2	MJ m^{-2} d^{-1}
The extraterrestrial radiation is 32.2 MJ m^{-2} day^{-1}.			

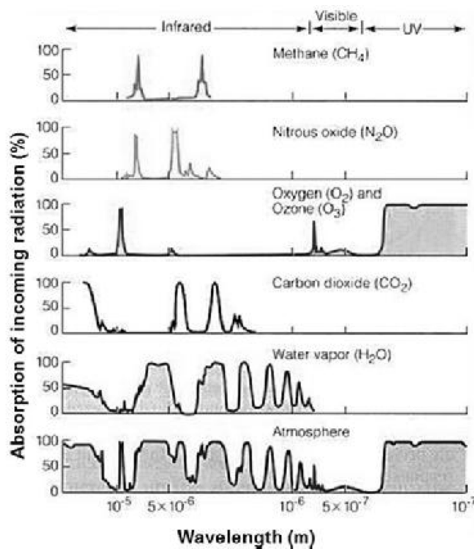


PAR INTERCEPTION

1. PAR

1. The 400–700 nm waveband is usually designated ‘photosynthetically active radiation’ (PAR) (McCree, 1981).
2. The intercepted PAR was the main factor determining crop growth. However, only c. 39% of extraterrestrial solar energy is in the 400–700 nm waveband (Gueymard, 2004).
3. The fraction of PAR increases as solar radiation approaches Earth’s surface because the atmosphere more strongly absorbs and reflects radiation outside this waveband.

4. Substantial amounts of infrared energy (between about 850 and 1300 nm) are absorbed by CO_2, ozone and especially by water vapour, while ozone is principally responsible for a cut-off in ultraviolet radiation below about 300 nm.



5. The fraction at Earth's surface varies with location, season, solar elevation and sky condition.
6. Based on summer data in a comprehensive study at 36.6N latitude (Texas, USA), 48% is taken as a representative fraction of total solar energy that is in the 400–700 nm waveband (Britton & Dodd, 1976).
7. On clear days, PAR represents about half (50%) of the total shortwave (solar) radiation or radiant energy flux (expressed as J m^{-2} s^{-1}) incident on a canopy, and is totally responsible for photosynthesis.

2. Interception

1. The proportion of incident solar radiation that is absorbed by a crop canopy is also a function of the spectral distribution of the irradiance.
2. Green leaves absorb most irradiance in the PAR region of the solar spectrum and reflect and transmit most of the irradiance in the near IR region.
3. Consequently, interception of solar irradiance by a crop canopy results in both quantitative and qualitative changes in the photon flux, which may have impact on intra and interspecific competition.

4. The arrangement and orientation of the leaves within the canopy influences the proportion of PAR that is absorbed by the canopy and the amount of PAR per unit sunlit leaf area.
5. Monsi and Saeki (1953) developed a mathematical model of light attenuation within a crop canopy based on Beer–Lambert Law. The rate of decrease in PAR or radiation (R) with an increase in leaf area (L) within the canopy from the top to the bottom is dependent upon the incoming PAR as shown below.

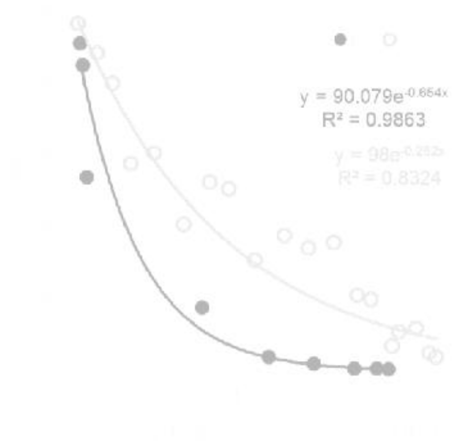
$$\frac{-\partial \mathbf{R}}{\partial \mathbf{L}} = \mathbf{kR}$$

where *k* is the extinction or foliar absorption coefficient.

6. The integration of above equation results in the following equation.

$$\mathbf{R} = \mathbf{R}_0\mathbf{e}^{-\mathbf{kL}}$$

Where R is PAR incident at any layer within the canopy and at the ground surface below the canopy (R_Z) and R_0 is PAR at the top of the canopy.



Clovery sward –N and +N (Stern & Donald 1962)

7. Therefore, the quantity of PAR intercepted by the canopy after a particular canopy layer is as follows

$$\mathbf{R_I} = \mathbf{R}_0\left(1 - \mathbf{e}^{-\mathbf{kL}}\right)$$

8. When the reflection of PAR by leaves (canopy) is taken into account, then

$$\mathbf{R_I} = \mathbf{R}_0\left(1 - \rho_{\mathbf{c}}\right)\left(1 - \mathbf{e}^{-\mathbf{kL}}\right)$$

Where ρ_C is the canopy reflection coefficient

9. The canopy reflection coefficient (ρ_C) is lower than the reflectance of individual leaves due to interception of reflected flux by other leaves in the canopy; ρ_C is about 5% for a maize canopy with a LAI $\geq$ 4.

10. The (light) extinction coefficient k (unitless) is a function of the mean leaf angle of the crop canopy and the fraction of PAR that is reflected and transmitted by individual leaves.
    - A high extinction coefficient ($0.8<k<1.0$) is associated with a crop canopy of leaves that are oriented parallel to a horizontal plane.
    - A low extinction coefficient ($k<0.6$) is associated with a crop canopy of leaves that are erect (i.e., a relatively high angle between the leaves and a horizontal plane).
11. The extinction coefficient (k) also declines with an increase of the reflectance and transmittance of individual leaves in the canopy.

12. An erectophile canopy (i.e., a canopy with erect leaves) will absorb less PPFD than a planophile canopy (i.e., a canopy with horizontal leaves) when the LAI is relatively low.
13. A canopy with more erect leaves will distribute the absorbed PAR across a larger sunlit leaf area, resulting in lager leaf area active in photosynthesis.
14. Therefore, canopy photosynthesis will be greater in erectophile than in planophile canopies when PAR absorption is similar for the two kinds of canopies, because photosynthetic efficiency (i.e., photosynthesis per unit absorbed PAR) is greater at low than at high PAR.

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RUE ESTIMATION

1. Experimental Evidence

1. Radiation use efficiency (RUE) is regarded as a crop specific parameter. Extensive experimentation has shown that biomass formed per unit intercepted PAR (g dry matter MJ^{-1}) is **constant**.
2. Factors affecting RUE include atmospheric CO_2, light quality (i.e. direct and diffuse light), nutrients, temperature and crop development.
3. The efficiency of conversion of absorbed light into carbon varies with time, light intensity, temperature and water availability.

2. Estimation Procedure

1. The estimation of RUE requires at least an experiment to obtain data of dry matter and light interception.
2. An experiment was carried out on peanut with plant samples harvested on day 32, 45, 53 and 71 after sowing.

Days	Total Dry Weight (g m^{-2}) of Replicate		
	I	II	III
32	108.9	147.1	153.8
45	266.7	284.9	148.0
53	248.4	294.7	527.1
71	1097.3	866.7	1368.0

3. On day 27, 32, 45, 53, 71, and 83 after sowing, light at the top of the canopy and at the ground surface below of the canopy for each replicate were observed

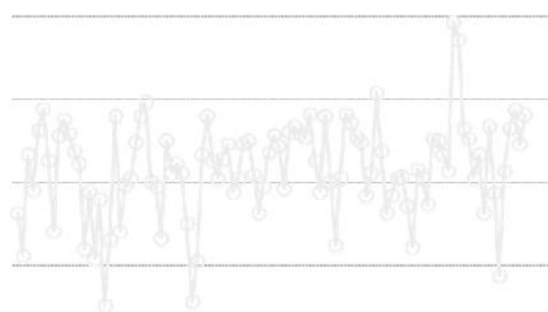
Day	Light (lux) of replicate					
	I		II		III	
	R_0	R_Z	R_0	R_Z	R_0	R_Z
27	996	797	974	836	1040	764
32	1022	764	1029	754	992	892
45	899	143	918	191	946	303
53	1054	35	1024	16	1033	58
71	979	9	1055	20	1085	12
83	1117	17	1254	19	1220	16

R_0 and R_Z is the light at the top of the canopy and at the ground surface below the conopy

4. The fraction of light intercepted (FIR) is simply calculated as FIR = $(R_0-R_Z)/R_0$.
5. The relationship between FIR and time is analyzed to obtain estimated FIR on daily basis.
6. The trend of observed FIR with time follows a pattern close to a logistic model. The use of the logistic model to analyze the data results in

$$\mathbf{FIR} = \frac{1}{1+2500\mathbf{e}^{-0.2t}}; \mathbf{R}^2 = 0.9929$$

7. Data of total solar radiation (R_0) on daily basis were obtained from a climate station close to the location of experiment, and PAR = $0.5*R_0$



PAR ($MJ.m^{-2}.d^{-1}$)									
Day	PAR	Day	PAR	Day	PAR	Day	PAR	Day	PAR
1	7.895	21	7.255	41	8.962	61	9.303	81	10.226
2	6.657	22	7.895	42	7.682	62	9.048	82	9.529
3	9.004	23	8.706	43	8.236	63	8.109	83	8.485
4	8.236	24	9.133	44	10.157	64	8.663	84	8.181
5	8.450	25	8.877	45	8.749	65	7.255	85	8.703
6	8.237	26	7.853	46	7.255	66	9.355	86	6.788
7	6.999	27	9.218	47	7.682	67	7.745	87	9.138
8	5.121	28	9.346	48	8.109	68	5.744	88	10.835
9	6.103	29	9.176	49	8.150	69	8.268	89	9.268
10	8.663	30	9.090	50	7.427	70	9.312	90	9.573
11	9.602	31	9.645	51	6.443	71	9.747	91	9.965
12	8.535	32	8.535	52	8.322	72	8.920	92	6.527
13	8.109	33	7.767	53	8.109	73	9.617	93	9.791
14	8.578	34	9.602	54	7.468	74	6.440	94	7.049
15	8.919	35	8.023	55	9.048	75	7.745	95	8.181
16	7.767	36	6.485	56	9.004	76	8.050	96	7.658
17	8.109	37	8.109	57	8.663	77	10.356	97	6.828
18	8.919	38	9.644	58	8.280	78	9.704	98	7.127
19	9.005	39	9.431	59	11.864	79	9.704	99	6.273
20	8.194	40	9.090	60	11.437	80	9.355	100	5.932

8. The quantity of PAR intercepted on daily basis is obtained from PAR*FIR. This is summed up for the duration of growth under consideration.

Days	**Total intercepted PAR (MJ m^{-2})**		
	I	II	III
32	12.5	12.7	10.8
45	70.9	71.6	65.6
53	132.0	133.4	126.3
71	284.7	287.6	280.2

9. Total dry weight (g m^{-2}) is then divided by the total intercepted PAR **(MJ m^{-2})** to obtain RUE for each stage of observation and replicate.

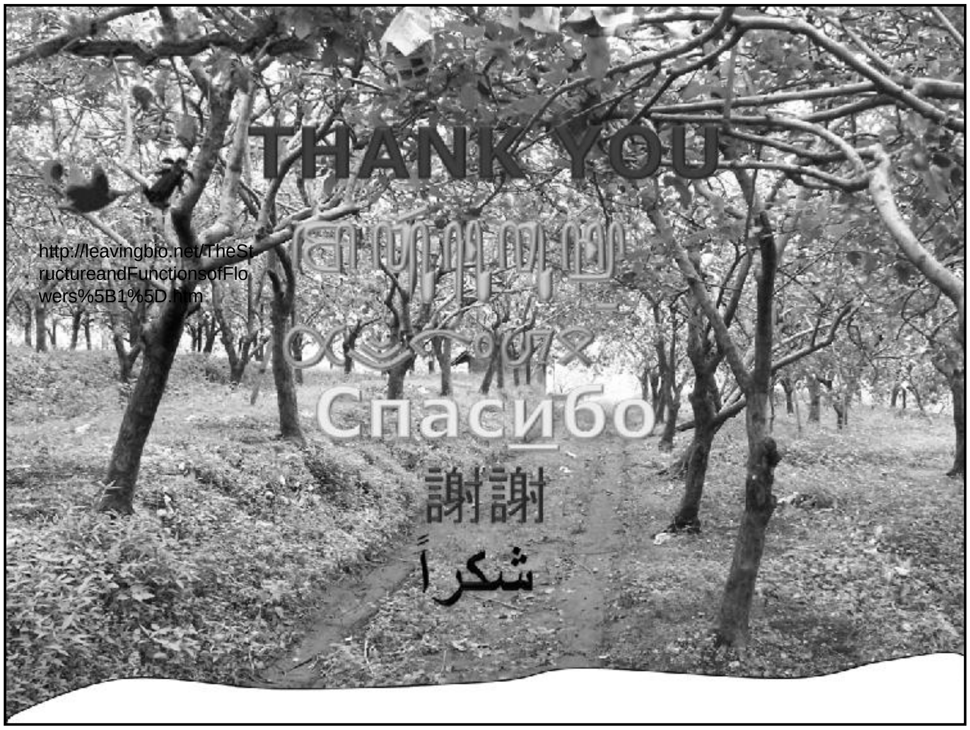
Day	**RUE (g MJ^{-1})**		
	I	II	III
32	8.7	11.6	14.2
45	3.8	4.0	2.3
53	1.9	2.2	4.2
71	3.9	3.0	4.9

6. The results of analysis shows RUE to vary with the stage of growth and replicate. There is a tendency of RUE high at the initial stage of growth and declining with time.
7. Other approach often used is the data of total dry matter are plotted against the data of intercepted PAR.

MESSAGES

You have to

1. learn (study) what you want to know
2. understand what you have learnt
   - (read the lecture notes and other sources, and listen carefully to the explanation in the lectures)
3. be able to explain what you have understood
4. be able to apply what you have been able to explain
5. be able to make further development (improvement) what you have been able to apply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Спасибо
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