

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

ARTIFICIAL LIGHT SPECTRA AND

PLANT GROWTH.

A thesis presented in partial fulfilment
of the requirements for the degree of

Master of Horticultural Science

in

Plant Science

at

Massey University

Ian James Warrington

1972

ACKNOWLEDGEMENTS

I wish to thank my supervisor, Professor J.A. Veale for his support and guidance given during this work.

I extend special thanks to Dr. K.J. Mitchell, Director, Plant Physiology Division, D.S.I.R. for his encouragement and interest in the projects carried out in this thesis and for the use of equipment and resources of the Plant Physiology Division.

Thanks are extended also to the Department of Scientific and Industrial Research for leave granted on half-salary during part of this work and for full salary during the remainder. Specifically, I am indebted to Dr. K.J. Mitchell for a position on staff while this work was being done.

Further, I should like to thank all those who have helped me in a variety of ways, especially the Technical Systems Group of the Plant Physiology Division who competently set up and maintained the growth rooms and cabinets and carried out the electrical work required on each of the light rigs; the Nursery Management Group of the P.P.D. for their care of the plant material prior to its placement under treatment conditions; the electron microscope staff of the Applied Biochemistry Division for their supervision and instruction; and the professional and technical staff members of Massey University and the D.S.I.R. who have been associated with various aspects of this work. Thanks go especially to Dr. J.M. Wilson for his helpful criticism and advice in the writing of the manuscript.

Specifically I would like to thank my wife Gwendolyn, for her assistance in the drafting work involved and for her encouragement and understanding during this work.

Finally, I wish to thank Mrs. C. Le Cheminant for typing this thesis.

SUMMARY

This study was undertaken to investigate the suitability of various commercially available high-pressure discharge lamp systems for controlled environment use. Two main experiments were carried out. The Spectral Balance experiment consisted of three treatments each at a similar total visible irradiance (160 W m^{-2}) based on high-pressure discharge lamps (HPLR, HPI and "Metal-arc" types) supplemented with blue-fluorescent and tungsten lamps, and three subsequent treatments based on the "Metal-arc" lamp with varying supplementation and different irradiance levels (105, 200, 250 W m^{-2}). The Spectral Bias experiment consisted of blue-biased, balanced and red-biased spectral treatments obtained by varying the proportions of different artificial lamp types (viz. "Metal-arc", Blue HPI and Quartz Halogen). Each spectral bias treatment was studied at two irradiance levels (130 and 200 W m^{-2}). Four species (Sorghum bicolor L., Glycine max L., Lolium perenne L., Trifolium repens L.) were used as test plants at day and night regimes of $22.5/17.5^{\circ}\text{C}$ and 60/90% R.H. with a 12 h photoperiod for all treatments. The two experiments were carried out in Climate Rooms and Growth Cabinets of the Plant Physiology Division, D.S.I.R., Palmerston North.

Results from the Spectral Balance experiment showed that either of the three lamp types with adequate blue and red wavelength supplementation could be used for plant studies in controlled environments, but on an efficiency basis the order of selection was "Metal-arc", HPI, HPLR. Results from the Spectral Bias experiment showed marked changes in shoot dry-weight increases, leaf area formation, dry-weight per unit area of leaf, stem length, tiller number, main stem angle, root/shoot ratio, proportions of plant parts, relative growth rates, relative rates of leaf area expansion, net assimilation rates and leaf area ratios in response to the biased spectral treatments. Biochemical changes were also recorded which showed short-wave enhancement of total amino-acids, proteins, aspartic and glutamic and other amino acids, and a long-wave enhancement of soluble sugars, starch and total carbohydrates. A scheme is presented incorporating the observed responses with those recorded in the literature. Total leaf chlorophyll was

increased under short-wave conditions but chloroplast structure was found to be unaffected by the spectral treatments.

Calculations were made of the relationships between leaf area, the number of absorbed quanta and the total dry-matter accumulation for each Spectral Bias treatment and results indicated that the spectral influence on the distribution of the assimilated carbon within the plant (i.e. to leaf or to non-leaf tissue) primarily influenced the subsequent plant dry-weight increase.

The implications of the present studies are discussed in relation to providing a standardized artificial light spectrum for controlled environment work. This consideration includes a study of natural sunlight spectra under various environmental conditions and a discussion of the technical difficulties encountered when using these particular lamp systems.

TABLE OF CONTENTS

	Page
Acknowledgements	(ii)
Summary	(iii)
Table of Contents	(v)
List of Figures	(xi)
List of Tables	(xiii)
List of Plates	(xv)
List of Diagrams	(xv)
List of Schemes	(xvi)
I INTRODUCTION	1
II LITERATURE REVIEW	4
1. Influence of Light Spectra on Plant Growth and Development	4
1.1. General	4
1.2. Wavelength Dependence of Photo- morphogenesis	5
1.2.1. Leaf Responses	8
1.2.2. Stem Growth	9
1.2.3. Growth Analysis Components	12
1.3. Phytochrome and High Energy Systems	13
2. Effects of Light Quality on Photosynthesis in High Plants.	17
3. Wavelength Effects on Biochemical Metabolism	21
3.1. Influence of Specific Wavelengths on Metabolism	21
3.2. Mechanisms of Wavelength Action	23
3.3. Influence of Light Spectra on Chlorophyll Levels and Chloroplast Structure	28
3.4. Summary	31
4. Light	
4.1. Measurement Systems	31
4.1.1. The Measurement of Radiant Flux Density (Irradiance)	33
4.2. Illumination Engineering, Lamp Design and Choice, and Lamp Types	34
4.2.1. General	34

	Page
4.2.2. Lamp Types	36
4.2.2.1. (a) Incandescent or Filament Lamps	36
(b) The Quartz Halogen Lamp	36
4.2.2.2. Electric Discharge Lamps	37
(a) General	37
(b) High-Pressure Mercury-Vapour Discharge Lamps	38
(c) Type HPLR (MBFR) Lamps	38
(d) Recent Developments	39
4.2.2.3. Tubular Fluorescent Lamps	40
4.2.2.4. Xenon Lamps	40
4.3. Use of Artificial Light Sources	41
4.3.1. General	41
4.3.2. Early Studies	42
4.3.3. Fluorescent Tube Development and Use	44
4.3.4. High-Pressure Discharge Lamp Use	51
5. Current Studies	52
III MATERIALS AND METHODS	54
1. Controlled Environment Facilities	54
1.1. Spectral Bias Experiment	54
1.1.1. Climate Rooms	54
1.2. Spectral Balance Experiment	54
1.2.1. Growth Cabinets	54
2. Lighting Systems	55
2.1. Spectral Bias Experiment	55
2.2. Spectral Balance Experiment	57
2.3. Spectroradiometer Calibration	59
3. Environmental Conditions	59
3.1. Spectral Bias Experiment	59
3.1.1. Temperature and Humidity	59
3.1.2. Carbon Dioxide	60
3.1.3. Air Speed	60
3.1.4. Daylength	60
3.2. Spectral Balance Experiment	60
4. Plant Materials	60
4.1. Propagation	60
4.1.1. Spectral Bias Experiment	60
4.1.2. Spectral Balance Experiment	61
4.2. Experimental Conditions	61

	Page
4.2.1. Spectral Bias Experiment	62
4.2.2. Spectral Balance Experiment	62
5. Experimental Layout	62
5.1. Spectral Bias Experiment	62
5.2. Spectral Balance Experiment	63
6. Plant Measurements	64
6.1. Methods of Measurement	64
7. Data Analysis	65
7.1. Spectral Bias Experiment	65
7.2. Spectral Balance Experiment	67
8. Biochemical Analyses	68
8.1. Carbohydrate Determinations	68
8.1.1. Spectral Bias and Spectral Balance Experiments	68
8.2. Protein Nitrogen Determinations	68
8.2.1. Spectral Bias and Spectral Balance Experiments	68
8.3. Chlorophyll Determinations	69
8.3.1. Spectral Bias Experiment	69
8.4. Amino Acid Analysis	70
8.4.1. Spectral Bias Experiment	70
9. Electron Microscopy	71
9.1. Spectral Bias Experiment	71
IV RESULTS	73
1. Spectral Balance Experiment	73
1.1. General	73
1.2. Plant Weight	74
1.2.1. Shoot Dry Weight	74
1.2.2. Relative Growth Rate	74
1.2.3. Dry Matter Percentage	75
1.3. Stem Length	75
1.4. Leaf Area Per Plant	76
1.4.1. Dry Weight Per Unit Area	76
1.4.2. Leaf Shape	76
1.5. Tiller Number (Sorghum)	77
1.6. Proportions of Plant Parts	77
1.6.1. Shoot Components	77
1.6.2. Root:Shoot Ratio	78
1.7. Biochemical Results	78
1.7.1. Carbohydrate Content	78

	Page
1.7.2. Protein Content	79
2. Spectral Bias Experiment	80
2.1. General	80
2.2. Plant Appearance	80
2.3. Plant Weight	81
2.3.1. Shoot Dry Weight	81
2.3.2. Dry Matter Percentage	82
2.4. Leaf Area Per Plant	83
2.5. Growth Analysis Components	84
2.5.1. Relative Growth Rates	84
2.5.2. Leaf Area Ratio	85
2.5.3. Net Assimilation Rate	86
2.6. Proportions of Plant Parts	86
2.6.1. Root:Shoot Ratio	87
2.6.2. Leaf:Shoot Ratio	87
2.6.3. Petiole:Shoot Ratio	88
2.6.4. Stem:Shoot Ratio	88
2.7. Plant Leaf Characteristics	88
2.7.1. Dry Weight Per Unit Area of the Last Mature Leaf Blade	88
2.7.2. Leaf Shape (Last Mature Leaf Blade)	89
2.7.3. Leaf Number	90
2.7.4. Relative Rate of Leaf Area Expansion	91
2.8. Plant Height	91
2.8.1. Stem and Shoot Length	91
2.8.2. Sheath Extension (Sorghum)	92
2.9. Main Stem Angle (Sorghum)	92
2.10. Tiller Number (Sorghum)	93
2.11. Biochemical Results	94
2.11.1. Total Chlorophyll, Chlorophyll a and Chlorophyll b Levels	94
2.11.2. Carbohydrate Content	94
2.11.2.1. Leaf Carbohydrate Content	94
(a) Soluble Sugar	94
(b) Starch	95
(c) Total Carbohydrate	95
2.11.2.2. Petiole Carbohydrate Content	96
(a) Soluble Sugar	96
(b) Starch	96
(c) Total Carbohydrate	96

	Page
2.11.3. Protein Content	96
2.11.4. C:N Ratio	97
2.11.5. Amino Acid Content	98
2.12. Investigation of Treatment Effects on Chloroplast	98
2.12.1. Chloroplast Types, General	98
(a) Soybean	98
(b) White Clover	99
2.12.2. Chloroplast Types, Treatment Effects	99
V DISCUSSION	101
1. Plant Response to Various Spectra and Irradiance Levels	101
1.1. General	101
2. Morphological	103
2.1. Division of Assimilates	103
2.2. Leaf Area, Leaf Shape and Leaf Number	104
2.3. Stem Length	107
2.4. Sorghum Stem Length, Stem Angle and Tiller Number Interactions	108
2.5. Morphogenetic Response Control Mechanisms	110
2.6. Relationships to Other Environmental Studies	112
(a) Effects of Temperature	112
(b) Effects of Light Irradiance	114
3. Photosynthesis, Leaf Area and Dry Matter Yield	116
3.1. General	116
3.2. Interception of Photons	117
3.3. Absorption of Intercepted Photons	118
4. Biochemical Analyses	121
4.1. General	121
4.2. Glutamic and Aspartic Acids	121
4.3. Carbohydrates	122
4.4. Photorespiration Intermediates	123
4.5. Other Amino Acids	124
4.6. Summary	124
5. Chloroplast Form and Size and Chlorophyll Contents	125
6. Artificial Light Sources	127

	Page
6.1. Lamp Selection	127
6.2. Lamp Performance	131
VI CONCLUSION	134
1. General	134
2. Controlled Environment Requirements	134
3. Plant Systems' Responses	136
4. Concluding Remarks	140
VII APPENDICES	141
1. Procedure for Measuring Irradiance (Energy Flux Density)	141
2. Distribution Values of Light Irradiance over the Plant Area for Individual Light Types and Each Total Lamp Combination	142
A. Balanced Treatment	142
B. Red-Biased Treatment	143
C. Blue-Biased Treatment	144
D. All Spectral Treatments	145
3. Nutrient Solutions	146
A. Hoagland's 1.	146
B. N.C.S.U. Nutrient Solution	147
4. Absorbed Photon Flux Density Values for Each Spectral and Irradiance Treatment	150
5. Chloroplast Ultrastructure	152
6. Solar Radiation Characteristics	153
VIII BIBLIOGRAPHY	158

FIGURES

Fig. No.	Title	After Page
1.	Spectral Bias experiment. Spectral Irradiance Distribution Curves. (High irradiance treatment)	56
	A. Blue Biased treatment	
	B. Balanced treatment	
	C. Red Biased treatment	
2.	Spectral Balance experiment. Spectral Irradiance Distribution Curves.	58
	A. Rig I	
	B. Rig II	
	C. Rig III	
 IV Results		
1	Spectral Balance experiment	
3.	Shoot dry-weight increase	74
4.	Shoot dry-matter percentage	75
5.	Stem (shoot) length	76
6.	Leaf area per plant	76
7.	Dry-weight per unit area of leaf	76
8.	Last mature leaf length	77
9.	Sorghum tiller number	77
10.	Leaf soluble sugar content	78
11.	Leaf starch content	78
12.	Leaf total carbohydrate content	78
13.	Leaf protein content	79
2	Spectral Bias experiment	
14.	Shoot dry-weight increase	81
15.	Shoot dry-matter percentage	82
16.	Leaf area per plant	83
17.	Relative growth rate	84
18.	Root:shoot ratio	86
19.	Plant part ratios	86
20.	Dry-weight per unit area of leaf	88
21.	Last-mature leaf length	89
22.	Last-mature leaf width	89
23.	Stem (shoot) length	91
24.	Sorghum tiller number	93
25.	Sorghum main stem angle	93

Fig. No.	Title	After Page
26.	Total leaf chlorophyll, chlorophyll a and chlorophyll b content	94
27.	Leaf chlorophyll a:b ratio	94
28.	Leaf soluble sugar content	94
29.	Leaf starch content	94
30.	Leaf total carbohydrate content	94
31.	Leaf protein content	96
32.	Leaf C:N ratio	97
V Discussion		
33.	Combined response results to the Spectral Bias experiment treatments	101
34.	Sorghum tiller number vs. stem length	108
35.	Sorghum stem angle vs. tiller number	108
36.	Sorghum tiller number vs. stem length	108
37.	Relative growth rate vs. irradiance level	114

Table No.	Heading	After Page
19.	Relative rate of leaf area expansion (RLAGR)	91
20.	Amino acid content	98
V	Discussion	
21.	Relative growth rate (RGR)	114
22.	Relative relationships of leaf area, photon flux absorption and dry-matter accumulation	117
		Page
VII	Appendices	
23.	Distribution values of light irradiance over the plant area for individual light types and each total lamp combination	142
	A. Balanced Treatment	142
	B. Red-Biased Treatment	143
	C. Blue-Biased Treatment	144
	D. All Spectral Treatments	145
24.	Distribution of standard solar radiation curve	154
25.	Spectral distribution of solar energy	155
26.	Proportional distribution of spectral energy for various air masses and equivalent sun angles on basis of amount in 400-700 nm range = 100	156
27.	Relative solar irradiance, luminous efficiency, and colour temperature at sea level for various air-mass values	157
28.	Absorbed photon flux density for 25 nm wavebands	150

PLATES

Plate No.	Headings	After Page
1.	Light rig in servicing position	54
2.	Light rig in operating position	54
3.	Lamp types	58
4.	Sorghum, Spectral Bias treatments	80
5.	Soybean, Spectral Bias treatments	80
6.	Perennial Ryegrass, Spectral Bias treatments	80
7.	White Clover, Spectral Bias treatments	80
8.	Sorghum, side view, main stem angle	92
9.	Sorghum, face view, glasshouse post-treatment	109
10.	Sorghum, side view, glasshouse post-treatment	109

Fig. E.M. 1.	Soybean	152
	a. Lower Palisade Mesophyll	
	b. Spongy Mesophyll	
2.	Soybean	152
	a. Upper Palisade Mesophyll	
	b. Spongy Mesophyll	
3.	Soybean High Light	152
	Upper Palisade Mesophyll	
4.	Soybean High Light	152
	Lower Palisade Mesophyll	
8.	Soybean Low Light	152
	Spongy Mesophyll	
9.	White Clover	152
	a. Palisade Mesophyll	
	b. Spongy Mesophyll	
10.	White Clover High Light	152
	Palisade Mesophyll	
13.	White Clover Low Light	152
	Spongy Mesophyll	

DIAGRAMS

1.	Climate Room, side view	54
2.	Growth Cabinet, front view	55
3.	Contribution of lamp types to combined spectral irradiance distribution	56

SCHEME

No.	Heading	After Page
1.	Wavelength effects on metabolic pathways	121

"If at any time I speak of Light and Rays as coloured or endued with colours, I would be understood to speak not philosophically and properly, but grossly, and according to such Conceptions as vulgar People in seeing all these experiments would be apt to frame. For the Rays to speak properly are not coloured. In them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour".

"OPTICKS"

NEWTON.