

QUANTIFYING THE EFFECT OF DIFFERENT IRRIGATION VOLUMES ON CUT-ROSE PRODUCTION

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for helping me when I felt helpless,
for carrying me when I felt I could not carry on
and for cheering me on when the race was almost run!!!

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What now, Prof?

Sorry Prof!?

I see, Prof!!

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SUMMARY

Quantifying the effect of different irrigation volumes on cut-rose production.

Rose plants in general, and especially rose plants of the Hybrid Tea cultivar, Grand Gala, are known for their demanding nature with respect to fertiliser, irradiance levels, night and day temperatures, carbon dioxide concentrations as well as irrigation water. The objective of the current experiment was to quantify the effect of different irrigation volumes on the production of cut-roses grown in a commercial greenhouse under South African conditions. Data was collected from late summer up to early winter (1 February – 16 June 1999) and consisted of, (1) yield data, (2) stem-quality data and (3) data of the photosynthesis parameters and environmental variables.

The rose plants were subjected to three different volumes of irrigation water (treatments 2X, X and $\frac{1}{2}X$). Treatment X served as the control treatment since the plants of this treatment received the same volume of water (late summer: $1.2 \text{ l plant}^{-1} \text{ day}^{-1}$; early winter: $1.0 \text{ l plant}^{-1} \text{ day}^{-1}$) as the rest of the plants in the greenhouse. The plants of treatment 2X received twice the volume of water than plants of treatment X, while the plants of treatment $\frac{1}{2}X$ received only half.

The number of stems yielded by each of the replicates of the different irrigation treatments, over the 20 week experimental period, was determined. The data collected for the stems of the replicas of each irrigation treatment was pooled into three major length classes viz. short (40 – 84.9 cm), medium (85 – 109.9 cm) and long (110 – 165 cm) and the number of stems per length class determined after it was divided into minor length classes ranging from 40 cm to 165 cm, in 5 cm intervals. The 2X, X and $\frac{1}{2}X$ treatments yielded 759, 699 and 654 short stems, 2927, 2776 and 2868 medium length stems, 1372, 1409 and 1737 long stems and a total number of stems of 5058, 4884 and 5258 per 556 plants respectively. The number of short stems harvested did not differ significantly. The number of medium stems yielded by the 2X treatment was significantly higher than that yielded by the other two treatments. The $\frac{1}{2}X$ treatment yielded a significantly higher number of long stems as well as the total number of stems than that yielded by treatment X and 2X. The Productivity Index (PI) was determined for the stems in the different major length classes of each treatment as well as for the total number of stems yielded by each treatment. PI was determined by dividing the fresh weight by the average length of the specific stems and then multiplying the answer with the total number of stems harvested per length class or per treatment. The PIs of the total number of stems harvested per treatment were 2388, 2285 and 2401 (g cm^{-1} total number of stems) for the 2X, X and $\frac{1}{2}X$ treatments respectively. As the PI is a function of the total number of stems, it concurs with the yield data, only emphasising the fact that the $\frac{1}{2}X$ treatment yielded a significantly higher number of stems than the 2X and X treatments.

The quality of the stems in the “long” length class was found to be of the highest, while the stems in the “short” length class were of the lowest quality and that of the stems in the “medium” length class to be of intermediate quality. The quality criteria measured were the leaf area, fresh weight, flower

bud length and the stem diameter. It was also observed that the quality of the leaf area, fresh weight and flower bud length increased as the winter period was closing in. The stem diameter of the short stems also increased as the experiment continued, while the stem diameter of the medium and long stems decreased slightly. When the stems within a certain length class were compared, no significant difference was found between the different irrigation treatments with respect to the four mentioned quality criteria; however, the stems in the “long” length class had the highest Quality Index (QI), while the short stems had the lowest. The QI was determined for the stems of the three irrigation treatments in each length class by dividing the average fresh weight by the average stem length of the stems of that specific length class. The general trend was a slight inclination in the QI over the 20-week period. No significant difference was found when the QI of the stems in a specific length class was compared, irrespective of the irrigation treatment.

Measurements of the photosynthesis parameters as well as the environmental variables were taken at 07h00, 12h00 and 15h30 daily. The photosynthesis parameters included the rate of photosynthesis (A), transpiration rate (E), stomatal conductance (G) and the internal CO₂ concentration (C_i), while the environmental variables included the irradiance level (I), ambient temperature (T_a) and external CO₂ concentration (C_a). The Water Use Efficiency (WUE) was determined by calculating the ratio between A and E. No significant differences were found between the respective photosynthesis parameters of the three irrigation treatments measured at 07h00, 12h00 and 15h30 respectively.

It can be concluded that the treatment receiving the lowest volume of water (treatment ½X) had the highest productivity, since it had the highest PI-value for the total number of stems harvested. Although no significant differences were found between the photosynthesis parameters of the different irrigation treatments, the average leaf surface area of the stems yielded by the ½X treatment as well as the Leaf Area Index (LAI) of the plants was the highest. This effectively means that the plants of the ½X treatment had the highest photosynthetic capacity, which explains the high productivity of the plants of this treatment.

Abbreviations:

Irrigation water volume; yield (number of stems, Productivity Index (PI)); stem quality (stem length, leaf surface area, fresh weight, flower bud length, stem diameter, Quality Index (QI)); photosynthesis parameters (photosynthesis rate(A), transpiration rate (E), stomatal conductance (G), internal CO₂ (C_i)); environmental variables (irradiance level (I), ambient temperature (T_a); external CO₂ (C_a)).

OPSOMMING

Kwantifisering van die effek van verskillende besproeiings volumes op sny-roos produksie

Roosplante oor die algemeen, en veral roosplante van die Hibriedteeroos-kultivar, Grand Gala, is bekend vir hul hoë vereistes, met betrekking tot kunsmis, vlak van bestraling, nag- en dag temperature, koolstofdiksied-konsentrasies sowel as besproeiingswater. Die doel van die huidige eksperiment was om die effek van verskillende besproeiingsvolumes op die produksie van sny-rose in 'n kommersiële kweekhuis onder Suid-Afrikaanse toestande, vas te stel. Data is ingesamel van laat somer tot vroeg winter (1 Februarie – 16 Junie 1999) en het bestaan uit, (1) opbrengsdata, (2) steelkwaliteitsdata en (3) data van die fotosintese parameters en die omgewings veranderlikes.

Die roosplante was blootgestel aan drie verskillende volumes besproeiingswater (behandelings 2X, X en $\frac{1}{2}X$). Behandeling X het gedien as die kontrolebehandeling aangesien die plante van die behandeling dieselfde volume water (laat Somer: $1.2 \text{ l plant}^{-1} \text{ dag}^{-1}$; vroeg Winter: $1.0 \text{ l plant}^{-1} \text{ dag}^{-1}$) ontvang het as die res van die plante in die kweekhuis. Die plante van behandeling 2X het twee keer die volume water ontvang as die plante van behandeling X, terwyl die plante van behandeling $\frac{1}{2}X$ net die helfte ontvang het.

Die aantal stele wat gelewer is deur elk van die herhalings van die verskillende besproeiings-behandelings oor die 20 week eksperimentele periode, is bepaal. Die data wat ingesamel is vir die stele van die herhalings van elke besproeiings-behandeling is saam gegroepeer in drie hoof lengteklasse, naamlik die kort- (40 – 84.9 cm), medium- (85 – 109.9 cm) en lang lengteklas (110 – 165 cm) en die aantal stele per lengteklas bepaal, nadat dit verdeel was in kleiner lengteklasse wat gestrek het vanaf 40 cm tot 165 cm, in 5 cm intervalle. Die 2X, X en $\frac{1}{2}X$ handelings het afsonderlik 759, 699 en 654 kort stele, 2927, 2776 en 2868 medium stele, 1372, 1409 en 1737 lang stele en 'n totale aantal stele van 5058, 4884 en 5258 per 556 plante gelewer. Die aantal kort stele wat gesny is het nie betekenisvol verskil nie. Die aantal medium stele wat gelewer is deur die 2X behandeling was betekenisvol hoër as dieselfde stele van die ander twee handelings. Die $\frac{1}{2}X$ behandeling het 'n betekenisvol hoër aantal lang stele as ook totale aantal stele gelewer in vergelyking met behandeling X en 2X. Die produktiwiteitsindeks (PI) is bepaal vir die stele in die verskillende hoof lengteklasse van elke behandeling as ook vir die totale aantal stele gelewer deur die verskillende handelings. Die PI is bereken deur die varsgewig te deel deur die gemiddelde lengte van die spesifieke stele en die antwoord dan te vermenigvuldig met die totale aantal stele wat gesny is per lengte-klas of per behandeling. Die PI van die totale aantal stele gelewer per behandeling was 2388, 2285 en 2401 (g cm^{-1} totale aantal stele) vir die 2X, X en $\frac{1}{2}X$ handelings afsonderlik. Aangesien die PI 'n funksie is van die totale aantal stele, stem dit ooreen met die opbrengsdata, en onderstreep dit die feit dat die $\frac{1}{2}X$ behandeling 'n betekenisvol hoër aantal stele gelewer het as die 2X of X behandeling.

Dit is bevind dat die kwaliteit van die stele in die “lang” lengteklas die hoogste was, terwyl die stele in die “kort” lengteklas van die laagste kwaliteit was. Die kwaliteit van die stele in die “medium”

lengteklas was middelmatig. Die kwaliteitkriteria wat gemeet is, was die blaaroppervlak, vars gewig, blomknoplengte en die steeldeursnee. Daar is opgemerk dat die kwaliteit van die blaaroppervlakte, varsgewig en blomknoplengte toeneem soos die winter periode nader gekom het. Die steeldeursnee van die kort stele het ook toegeneem soos met die verloop van die eksperiment, terwyl die steeldeursnee van die medium- en lang stele effens afgeneem het. In die geval waar die stele binne 'n sekere lengteklas met mekaar vergelyk is, is geen betekenisvolle verskille gevind tussen die verskillende besproeiings-behandelings met betrekking tot die vier kwaliteitkriteria nie, alhoewel die stele in die "lang" lengteklas die hoogste Kwaliteitsindeks (KI) gehad het en die kort stele die laagste. Die KI is bereken vir die stele van die drie besproeiings-behandelings in elke lengteklas deur die gemiddelde varsgewig te deel deur die gemiddelde steellengte van die stele van die betrokke lengteklas. Die KI het 'n effense styging getoon oor die 20 week periode. Geen betekenisvolle verskille is gevind tussen die KI van die stele in 'n sekere lengteklas nie, ongeag die besproeiings-behandeling.

Lesings van die fotosintese parameters sowel as die omgewings veranderlikes is daaglik geneem om 07h00, 12h00 en 15h30. Die fotosintese parameters sluit die tempo van fotosintese (A), transpirasietempo (E), stomatêre geleiding (G) en die interne CO₂-konsentrasie (C_i) in, terwyl die omgewingsveranderlikes die graad van bestraling (I), omringende temperatuur (T_a) en die eksterne CO₂-konsentrasie insluit. Die Waterverbruikseffektiwiteit (WVE) is bepaal deur die verhouding te bereken tussen A en E. Geen betekenisvolle verskille is gevind tussen die lesings van die onderskeie fotosintese parameters van die drie besproeiings behandelings wat onderskeidelik geneem is om 07h00, 12h00 en 15h30.

Daar is tot die gevolgtrekking gekom dat die plante van die behandeling wat die minste water ontvang het (½X behandeling) die hoogste produktiwiteit toon, aangesien dit die hoogste PI waarde vir die totale aantal gesnyde stele gehad het. Alhoewel geen betekenisvolle verskille gevind is tussen die fotosintese parameters van die verskillende besproeiings-behandelings nie, was die gemiddelde blaaroppervlakte van die stele wat deur die ½X behandeling gelewer is, sowel as die Blaaroppervlakindeks (BOI) van die plante, die hoogste. Dit beteken dat die plante van die ½X behandeling die hoogste fotosintese kapasiteit gehad het, wat die hoë produktiwiteit van die plante van die behandeling verduidelik.

Afkortings:

Besproeiingswatervolume; opbrengs (aantal stele, Produktiwiteitindeks (PI)); steelkwaliteit (steekkebgte, blaaroppervlakte, vars gewig, blomknoplengte, Kwaliteitindeks (KI)); fotosintese parameters (fotosintese tempo (A), transpirasietempo (E), stomatêre geleiding (G), interne CO₂ (C_i)); omgewingsveranderlikes (graad van bestraling (I), omringende temperatuur (T_a), eksterne CO₂ (C_a)).

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List of Abbreviations

General Abbreviations (units in parenthesis)	
A = Net CO₂ assimilation rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$) Rate of photosynthesis ($\mu\text{mol m}^{-2} \text{s}^{-1}$) A_{avg} = Average photosynthesis rate A_{max} = Maximum rates of photosynthesis Avg. = Average Br = Branch Cham = Chamber C₃ = plant in which the first stable product of carbon fixation is a three-carbon compound C_a = Ambient air CO₂ concentration ($\mu\text{mol mol}^{-1}$) Atmospheric CO₂ concentration ($\mu\text{mol mol}^{-1}$) External CO₂ concentration ($\mu\text{mol mol}^{-1}$) C_{cp} = CO₂ compensation point ($\mu\text{mol mol}^{-1}$) C_i = Internal CO₂ concentration ($\mu\text{mol mol}^{-1}$) CO₂ = Carbon dioxide [CO₂] = Carbon dioxide concentration ($\mu\text{mol mol}^{-1}$) C_{opt} = optimum [CO₂] ($\mu\text{mol mol}^{-1}$) C_{sp} = CO₂ saturation point ($\mu\text{mol mol}^{-1}$) C_{ue} = CO₂ utilisation efficiency ($\text{mol m}^{-2} \text{s}^{-1}$) C gain = Carbon gain ($\text{g m}^{-2} \text{day}^{-1} / \text{mol m}^{-2} \text{day}^{-1}$) Cut = Cutting position Dif = Different DT_a = Day air temperature (°C) DW = Dry weight (g) E = transpiration rate ($\text{mmol m}^{-2} \text{s}^{-1}$) EC = Electrical conductivity (mS cm^{-1}) EvapC = Evaporative cooling FC = Flowering cycle FR = Far red light ($\mu\text{mol m}^{-2} \text{s}^{-1}$) FT = Flowering time (days) FW = Fresh weight (g) G = Stomatal conductance of water ($\text{mol m}^{-2} \text{s}^{-1}$) Gibb In = Gibberellic acid inhibition H₂O = Water (l) HL = High light conditions I = Irradiance ($\mu\text{mol m}^{-2} \text{s}^{-1}$; $\text{mol m}^{-2} \text{day}$) Irradiance level ($\mu\text{mol m}^{-2} \text{s}^{-1}$; $\text{mol m}^{-2} \text{day}$) I_{cp} = Irradiance compensation point ($\mu\text{mol m}^{-2} \text{s}^{-1}$) I_{dur} = Irradiance duration (hours) Int = Interval IRGA = Infrared gas analyser Irr = Irrigation ($\text{l plant}^{-1} \text{day}^{-1}$) Irr_{dur} = Irrigation duration (hours) I_{sp} = Irradiance saturation point ($\mu\text{mol m}^{-2} \text{s}^{-1}$) I_{ue} = Irradiance utilisation efficiency (mol mol^{-1}) LAI = Leaf area index LD = Long day treatment	LL = Low Light Conditions Max = Maximum Min = Minimum NB = Night Break No. = Number NT_a = Night air temperatures (°C) Or = Own Rootstock P = Atmospheric pressure (kPa) PAR = Photosynthetic active radiation ($\text{J m}^{-2} \text{s}^{-1}$) PAR = Daily photosynthetic active radiation ($\text{MJ m}^{-2} \text{day}^{-1}$) PCA = Principal component analysis Pl = Plants PPF = Photosynthetic photon flux ($\mu\text{mol m}^{-2} \text{s}^{-1}$) PPF = Daily photosynthetic photon flux ($\text{mol m}^{-2} \text{day}^{-1}$) PT = Pulsing temperature (°C) R = Respiration rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$) R² = Squared correlation coefficient R_d = Dark respiration rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$) RH = Relative humidity (%) RH_{opt} = Optimum relative humidity (%) Red = Red light ($\mu\text{mol m}^{-2} \text{s}^{-1}$) RuBP = Ribulose-1,5-bisphosphate RZT = Root zone temperature (°C) RZW = Root zone warming (°C) s.d. = Standard deviation [Salt] = Salt concentration (g m^{-1}) SD = Short day treatment SL = Supplementary lighting ($\mu\text{mol m}^{-2} \text{s}^{-1}$) SL (Fluo) = Fluorescent lamp ($\mu\text{mol m}^{-2} \text{s}^{-1}$) SL (Inc) = Incandescent lamp ($\mu\text{mol m}^{-2} \text{s}^{-1}$) SL (HPS) = High pressure sodium lamp ($\mu\text{mol m}^{-2} \text{s}^{-1}$) SL (M) = Mercury lamp ($\mu\text{mol m}^{-2} \text{s}^{-1}$) SL_{dur} = Supplementary lighting duration (hours) SN = Split night temperature (°C) T_a = Ambient temperature (°C) Atmospheric temperature (°C) T_l = Leaf temperature (°C) T_{opt} = Optimum temperature (°C) Tot = Total Vent = Ventilated VPD = Vapour pressure deficit (kPa) VS = Versus WUE = Water use efficiency ($\text{mol mol}^{-1} \times 10^{-3}$) X = control treatment ½X = plants subjected to half the volume of water in comparison with that of the control treatment 2X = plants subjected to two times the volume of water in comparison with that of the control treatment

Months of the year		Seasons
Jan = January	Jul = July	Spr = Spring
Feb = February	Aug = August	Sum = Summer
Mar = March	Sep = September	Aut = Autumn
Apr = April	Oct = October	Win = Winter
May = May	Nov = November	
Jun = June	Dec = December	

Rose cultivars		Rose rootstocks
Ba = 'Baroness'	Mar = 'Marimba'	R.i = <i>Rosa Indica</i> 'Major'
BP = 'Bianca Parade'	MB = 'Manhattan Blue'	R.m = <i>Rosa manetti</i>
BW = 'Bridal White'	Mc = 'Mercedes'	R.o = <i>R. x odorata</i>
Ca = 'Charming'	Mj = 'Meijikatar'	NB = <i>R. x</i> 'NatalBriar'
CM = 'Cara Mia'	Mo = 'Motrea'	Rdh = <i>R x</i> 'Dr.Huey'
F = 'Frisco'	PS = 'Pink Sensation'	
FR = 'First Red'	R = 'Royalty'	
FY = 'Forever Yours'	RS = 'Red Success'	
Ga = 'Gabriella'	RV = 'Red Velvet'	
GG = 'Grand Gala'	Sa = 'Samantha' (SP)	
GT = 'Golden Times'	So = 'Sonia'	
Io = 'Ilona'	Sou = 'Souvenir'	
Is = 'Ilseta'	SP = 'Sweet Promise'	
K = 'Koba'	Vi = 'Visa'	
L = 'Lambada'	Vo = 'Volare'	
LG = 'Lovely Girl'	WS = 'White Satin'	
Mad = 'Madelon'		

Symbols
↑ = Much Higher
↑ = Higher
↑ = Little Higher
↓ = Much Lower
↓ = Lower
↓ = Little Lower
* = Constant
ε = Elasticity

CHAPTER 1

General Introduction

From ancient times people have had a fascination with roses. It's scent, beauty and splendour bring back a sense of timelessness and beauty to the hurried and grey life of today. Although there is literally thousands of rose lovers growing their own garden roses, the queen of the flowers as it is sometimes called, and rightly so, is so in demand that the largest percentage of cut flower growers all over the world are rose growers. In the year 2001 the production of roses in South Africa varied between 16 and 26 % (on a monthly average) of the total cut flowers sold at the Johannesburg and Pretoria markets. Crysanthemums are a close second with the sales varying between 15 and 22 % (Multiflora report: 2001). The remaining sales comprised of "Fynbos", lilies, tulips, irises, sword lilies, daffodils, greenery and so many more. During the sanction era most of the flowers that had been produced, were sold locally, but since the sanctions have been lifted (1995) the export of cut flowers has doubled. The cut flowers sold locally amount to 40 % while the number of cut flowers sold on international markets amount to 60 % of the South African produce. On a world-wide scale the South African contribution to the world market is less than 1 % of the total cut flowers sales compared to the 4 – 5 % produced by Kenya. At present there is, however, a trend towards the diversification of the cut flower industry i.e. specifically with regard to the species being grown for cut flower purposes. This trend is also manifesting itself in South Africa both in terms of the species being grown and of the export destination. The diversity in cut flower species is moving to a so-called lifestyle-market, putting the accent on flowers that can be used in less formal mixed bouquets. The top 10 flowers auctioned in the Netherlands in 2001 were, however, still roses, chrysanthemum, tulip, lily, gerbera, cymbidium, freesia, dianthus, alstroemeria and gypsophila, with roses still having the highest auction turnover of € 653 013 000 (S.A.G.A., 2002; Pertwee, 2002:20). Destinations that are being targeted include, for example, North America, countries of the Middle East, former Communistic countries as well as the Mediterranean countries. The primary reason for exploring these new market possibilities is the saturation of existing markets in especially Europe, and the unsaturated markets in the countries mentioned above (Boshoff, 2002).

South Africa has the advantage of being classified as a third world country, however unlikely this advantage might seem. The third world status implies inexpensive labour, available surface area as well as less strict or not enforced environmental laws, which are often the limiting factors in the Netherlands. Other third world countries include other African countries, South America and Israel. Some competitive advantage is gained by South Africa because of the climate (high

irradiance levels, relatively long days, warm temperatures), the soil, good infrastructure, the presence of experts in the field and the availability of cut flowers to supply the northern markets during their winter months/low production months. The two primary limiting factors to South African producers are the long distances from the market and the limited cargo/freight space (Boshoff, 2002).

But irrespective of the possibilities and / or limitations posed by the external variables mentioned as well as available infrastructure, the success./ or not achieved by the individual producer is to a large degree a function of the individual's commitment and subsequently horticultural practices employed. Horticultural practices may be defined as the type of production method used (flush or staggering), the number of basil shoots and the number of flowering stems that are allowed to mature per rose plant (single, two or multiple stemmed), the bending of inferior stems to supply the growing marketable stems with photosynthate (bent stem technique), pruning in winter or not, the removal of blind shoots and lateral stems at a very early stage of stem development as well as the removal of weeds. One of the variables that need to be understood and managed in a controlled growth environment is the artificial watering of the crop. For example, when rose plants in greenhouses appear wilted at high noon, the first assumption made, might be that they are not receiving enough water. It is known that rose plants are demanding in terms of the external input variables they require which include: fertiliser, irradiation, carbon dioxide (CO₂) and temperature (Moss, 1984:550; Meyer *et al.*, 1988a:12; Pellett *et al.*, 1998:720). While the first impression that the plants do not receive enough water, might be correct, the first reaction to apply more water, might however not be. Considering only the visual appearance of the plants and not investigating the growth media can have adverse consequences.

Since irrigation in greenhouses is the only source of water for the plants inside, its scheduling (volume and duration) is important. The volume of irrigation water applied to plants is the most overlooked, but also, fortunately, the most easily rectified external input variable of all. This is important, since a plant receiving an insufficient volume of water or none at all, will experience stress. The same is, however, also true for plants receiving an excess supply of water, since it might cause decreased productivity, viz. yield and quality, or even a decrease in rate of photosynthesis and other accompanying processes viz. transpiration rate and stomatal conductance in the leaves. In this regard it is interesting that Nelson (1991:231) stated that "watering is the greenhouse operation that most frequently accounts for loss in crop quality".

Several factors, in conjunction with irrigation, can be involved in the above-mentioned productivity decrease. Generally, when water is applied a bit too frequently, new growth may

become large but soft as a result of high water content, and, as a whole, plants tend to be taller. This situation is undesirable because some of these plants wilt easily under bright light or dry conditions and do not ship or last well. If water is applied even more frequently, the higher average water content will reduce the oxygen content of the growing medium, resulting in damage to the roots. A damaged root system cannot absorb water and essential elements readily. This causes wilting, hardened growth, an overall stunting of the plants, and several deficiency symptoms (Nelson, 1991:232). Oxygen deficiency also causes chlorosis (yellowing) of especially the leaves and leaf shedding. Leaves drop after the main and larger lateral veins become chlorotic; sometimes pinnae fall off first leaving only the skeletonised rachis (roses) (Henning, 2000:13).

The term “well-watered-plants” is seemingly very simple, implying, giving plants enough water. However, the question that arises is, how much is enough and when does enough turn into too much? Different plants have different water requirements, with plants of the same species, or even the same cultivar, requiring varying volumes of water in different growth media under changing environmental conditions. Various factors, such as the number of plants per m², the growth medium, the root depth of the plants, the season and the greenhouse conditions (country) play major roles when determining the volume and frequency of irrigation water to be applied to roses. A summary of related investigations is provided in Table 1.1, to emphasise this apparent uncertainty as to the volume and frequency of irrigation water required for optimal cut-rose production as well as to motivate why specific volumes of water was used in the current experiment. Furthermore, irrigation scheduling may be based on electrical conductivity of the irrigation and drainage water, rate of evapotranspiration, growth medium water content and potential, irrigation frequency, plant growth status, leaf water potential, percentage leaching water, soil water content and potential and solar radiation as well as visual appearance of the plant. The different measures on which cut-rose irrigation has been scheduled related in investigations are summarised in Table 1.2.

Low water quality and even the type of irrigation method used may affect the volume and frequency of water application, not to mention different horticultural practices. Water quality is of importance since the chemical content (composition) may restrict the application volume and frequency of the irrigation water and the growth of the plant when not attended to. Special attention must be given to the electrical conductivity (EC) or total dissolved solids (TDS), the toxicity of specific ions to sensitive crops (absorption by roots or by leaves), and the bicarbonate concentrations in the water (Nelson, 1991:235).

Table 1.1: Volume of irrigation water applied, irrigation frequency, depth in root zone, in different countries in different seasons.

Crop	No. of plants	H ₂ O day ⁻¹ and H ₂ O week ⁻¹	Irrigation frequency	Growth medium	Depth in root zone	Country	Season	Literature reference
Roses garden	1	2.71 - 3.79 ℓ 18.95 – 26.53 ℓ	-	-	-	-	Hot or very dry	Adams, 1999
Roses garden	1 ⁽¹⁾	2.85 ℓ 20ℓ	-	Soil	20 cm	South Africa	-	Bloom, 1988
Roses	1	-	Hydroponic (constant; aerated)	Water Water	4 ℓ pots	California – USA	-	Cabrera <i>et al.</i> , 1995a Cabrera <i>et al.</i> , 1995b
Roses	-	-	1 time day ⁻¹ (subirrigated)	-	Pot depth	South Carolina – USA	Winter – Spring	Clark <i>et al.</i> , 1993
Roses garden	1 ⁽¹⁾	2.857 ℓ day ⁻¹ 20 ℓ	1 time week ⁻¹	Soil	60 cm	South Africa	-	Geldenhuis, 1994
Roses	1 ⁽²⁾	0.08 – 0.68 ℓ 0.56 – 4.72 ℓ	-	Soil	-	South Africa	Winter – Summer	Henning, 2002
Roses	1	0.40 – 1.00 ℓ 2.80 – 7.00 ℓ ----- 0.01 – 0.03 ℓ 0.08 – 0.18 ℓ	1 – 4 times night ⁻¹ 8 – 20 times day ⁻¹ ----- 2 – 4 times day ⁻¹ 25 times day ⁻¹	Coconut fibers + Pecanshells or perlite	-	South Africa	Summer: Cloudy – hot ----- Winter Summer	Henning, 2000
Roses	1	0.50 – 1.25 ℓ 3.50 – 8.75 ℓ	1 – 2 times night ⁻¹ 10 – 25 times day ⁻¹	Coconut fibers	-	Netherlands	Radiation: low – high	Henning, 2000
Roses	1	(0.54 ℓ day?) 3.79 ℓ	-	-	-	-	-	Hessayon, 1995
Roses	-	-	1-2 times day ⁻¹	Rockwool	-	-	-	Hopper, 1996
Roses	1	0.08 – 0.15 ℓ 0.53 - 1.05 ℓ	15 min day ⁻¹		-	-	-	Hopper & Hammer, 1991
Roses garden	1 ⁽¹⁾	16.24 ℓ 113.70 ℓ	-	Soil	-	-	Summer	KarenP2, 1999
Roses	1 ⁽⁴⁾	-	15 times day ⁻¹ (1 hour ⁻¹) (See Table 1.2)	-	Container	Volos – Greece	Summer	Katsoulas <i>et al.</i> , 2001.
Roses	-	-	1 time day ⁻¹	-	-	Israel	-	Khayat & Zieslin, 1986
Roses	1 ⁽³⁾	0.06 – 0.33 ℓ 0.44 – 2.28 ℓ	-	-	-	Netherlands	Winter – Summer	Konings, 1988 (Table 1.2)
Roses	1 ⁽³⁾	0.857 ℓ 6.00 ℓ	2 times week ⁻¹ Abundant irrigation	-	20 cm	South Africa	-	Meyer <i>et al.</i> , 1988a

Table 1.1: Continued

Crop	No. of plants	H ₂ O day ⁻¹ and H ₂ O week ⁻¹	Irrigation frequency	Growth medium	Depth in root zone	Country	Season	Literature reference
Roses	1	-	Watered regularly	Peat Substrate	2 ℓ pot 3 ℓ pot	Norway Norway Norway	Winter Winter Winter	Mortensen, 1995 Mortensen & Fjeld, 1998 Mortensen & Gislerød, 1999
Roses	-	-	Nutrient film technique	Water	-	Australia	Winter – Summer	Moss & Dalgleish, 1984
General	1	0.38 – 1.91 ℓ 2.67 – 13.37 ℓ	-	-	0.2 – 1.0 m	-	-	Nelson, 1991
Roses	-	-	1 time day ⁻¹	-	26 ℓ pots	California - USA	Whole year	Pasian & Lieth, 1989
Roses outside	1 ⁽³⁾	0.45 ℓ 3.13 ℓ	Abundant irrigation	Soil (mainly)	-	USA	-	Pellett <i>et al.</i> , 1998
Roses	-	-	2–3 times week ⁻¹ or daily	-	-	England	Normal to Hot	Pertwee, 1992
Roses	-	By hand	-	Soil Peat moss Perlite	20 ℓ pots	Maryland - USA	Whole year	Shanks <i>et al.</i> , 1986
Roses	1 ⁽⁵⁾	-	Water culture	Water	-	Norway	Winter	Torre & Fjeld, 2001
Roses	1 ⁽⁶⁾	-	Water saturated (aerated) (see Table 1.2)	Rockwool	-	France	Winter	Urban <i>et al.</i> , 1994b
Roses	1	0.21 ℓ 1.50 ℓ	3 times week ⁻¹	Pecan shells Macadamia– Coco- fibres Rockwool	-	South Africa	Winter	Van der Walt, 1999
Roses	1	0.50 ℓ 3.50 ℓ	1 time day ⁻¹ (1 day week ⁻¹ : 4 times) (See Table 1.2)	Volcanic cinder	10 ℓ pot	Israel	Winter simulated	Zeroni & Gale, 1989

⁽¹⁾ assuming the plant density was 1 plant m⁻²

⁽²⁾ plant density was 7.2 plants m⁻²

⁽³⁾ assuming plant density was 8 plants m⁻²

⁽⁴⁾ plant density was 6 plants m⁻²

⁽⁵⁾ plant density was 66 plants m⁻²

⁽⁶⁾ plant density was 8 plants m⁻²

Abbreviations used in Table 1.1 (see List of Abbreviations, page x)

Table 1.2: Irrigation scheduling based on electrical conductivity of the irrigation and drainage water, rate of evapotranspiration, growth medium water content, potential, irrigation frequency, plant growth status, leaf water potential, percentage leaching water, soil water content, potential and solar radiation.

Crop	Irrigation based on...		Country	Literature reference														
Roses	Electrical conductivity (EC)	EC of dripping water minus EC of leaching water $\leq 0.3 \text{ mS.cm}^{-1}$.	South Africa Netherlands	Henning, 2000														
Roses	Evapotranspiration	Evapotranspiration rate from soil and plant		Anon., 2001? Urban <i>et al.</i> , 1994a Williams <i>et al.</i> , 2000														
General	Growth medium water content	Between 20 and 75%		Lieth, 1996														
General	Growth medium water potential	Between -1 and -5 kPa		Lieth, 1996														
Roses		Between -1 and -10 kPa		Raviv & Blom, 2001														
		Between -1 and -1.3 kPa		Raviv <i>et al.</i> , 1999														
Roses	Growth status of the plant (Plant age)			Durkin, 1992 Hopper & Hammer, 1991														
Roses	Irrigation: volume of water	Minimum: 50 ml irrigation ⁻¹	Netherlands	De Greef, 1993														
Roses	Irrigation: frequency (see Table 1.1)	1 irrigation 1 ⁻¹ to 1.5 hours ⁻¹ 1 irrigation 20 min ⁻¹ to 3.5 hours ⁻¹ (High to low irradiation)	South Africa Netherlands	Henning, 2000														
		Maximum: 1 irrigation.20 min ⁻¹	Netherlands	De Greef, 1993														
Roses	Leaf water potential	Between -0.4 and -1.0 MPa Wilting -1.3 MPa (Forever Yours)		Aikin & Hanan, 1975														
General		Between -0.1 and -1.0 MPa		Taiz & Zeiger, 1991														
Roses		Predawn: -0.5 to -0.6 MPa Midday: -1.4 MPa (growth media)	South Africa	Van der Walt, 1999														
		Between -0.6 and -0.9 MPa (soil)																
Roses		-0.6 MPa		Van Doorn & Vojinovic, 1996														
General	Percentage leaching water	10 to 15 % of irrigation water		Anon., 1999?														
General	(Drainage %)	30 % and higher	South Africa	De Greef, 1993														
General		10 to 15 % of irrigation water		Nelson, 1991														
Roses		0 % of 1 st irrigation of the day 15 % of 2 nd irrigation of the day 35 to 45 % in the middle of the day	South Africa	Henning, 2000 (in winter, a lower drainage % is recommended in cocos fibre)														
		50 to 70 % (high irradiation levels)	Netherlands	Henning, 2000														
		30 % of irrigation water	Greece	Katsoulas <i>et al.</i> , 2001														
		40 % of irrigation water	France	Urban <i>et al.</i> , 1994a														
		10 % of irrigation water	France	Urban <i>et al.</i> , 1994b														
		Pots drained 1 hour after irrigation	Israel	Zeroni & Gale, 1989														
Roses	Soil water content	Between 26 and 30 %	South Africa	Van der Walt, 1999														
Roses	Soil water potential	Lower than -10 to -30 kPa	USA	Durkin, 1992														
Roses		Lower than -3 kPa		Terada <i>et al.</i> , 1997														
Roses		Between -1.7 and -2.8 kPa	South Africa	Van der Walt, 1999														
General	Solar radiation ¹	Minimum: increment of 0.4 MJ m ⁻² Increments of 0.8 MJ m ⁻² 1.2 MJ m ⁻² (Rockwool and Coconut fibre)	Netherlands South Africa	De Greef, 1993														
Roses			USA	Durkin, 1992														
Roses		Increments of 1.1 MJ m ⁻²	Netherlands	Henning, 2000														
Roses	Solar radiation ¹	<table><tr><th>Total irradiance (MJ m⁻² day⁻¹)</th><th>Irrigation water (l m⁻² day⁻¹)</th></tr><tr><td>5</td><td>0.75 - 1.10</td></tr><tr><td>10</td><td>1.33 - 1.95</td></tr><tr><td>15</td><td>1.90 - 2.66</td></tr><tr><td>20</td><td>2.48 - 3.55</td></tr><tr><td>25</td><td>3.00 - 4.50</td></tr><tr><td>30</td><td>3.55 - 5.30</td></tr></table>	Total irradiance (MJ m ⁻² day ⁻¹)	Irrigation water (l m ⁻² day ⁻¹)	5	0.75 - 1.10	10	1.33 - 1.95	15	1.90 - 2.66	20	2.48 - 3.55	25	3.00 - 4.50	30	3.55 - 5.30	Netherlands	Konings, 1988
Total irradiance (MJ m ⁻² day ⁻¹)	Irrigation water (l m ⁻² day ⁻¹)																	
5	0.75 - 1.10																	
10	1.33 - 1.95																	
15	1.90 - 2.66																	
20	2.48 - 3.55																	
25	3.00 - 4.50																	
30	3.55 - 5.30																	
Roses	Solar radiation ¹	Increments of 2.8 MJ m ⁻²	France	Urban <i>et al.</i> , 1994a														

¹ assuming that the Solar Radiation is equal to the Total Radiation Spectrum and not only the Visible Light Spectrum used in the process of photosynthesis (PAR).

Abbreviations used in Table 1.2 (see List of Abbreviations, page x)

Irrigation systems vary in the manner by which water is delivered to the plants. There are three major irrigation systems (strategies) into which the different irrigation methods are divided. Overhead irrigation systems wet the entire plant, although the primary aim is to provide water to the roots (hand watering, sprinkler, mist and fog, and irrigation boom system). Surface systems place water directly on the soil surface, avoiding wetting most of the foliage (drip, spaghetti, in-line, spray emitter system). Subsurface or subirrigation systems introduce water directly into the root zone from below (capillary mat, troughs, ebb-and-flood and flooded floor system) (Nelson, 1991:237-249; Durkin, 1992:78; Lieth, 1996:10-23; Ball, 1998:83-96). It is important to know the advantages and disadvantages associated with the different irrigation systems before deciding on a specific one to be used.

When quantifying the volume and frequency of irrigation water to apply, terms like “watered regularly” and “abundant irrigation volumes” is not specific enough when it comes down to quality, yield, photosynthesis rate and production cost. The volume and frequency of irrigation water to apply depends on the water consumption by the plant (mostly transpiration rate), the container size (when growing potted plants), the water-holding capacity of the growth medium and the evaporation rate from the soil surface, during different environmental conditions. The aim is to apply just the right volume of water to keep the water readily available to the plants, while keeping the aeration in the growing medium as optimal as possible (Lieth, 1996:23). Soil drainage is of the utmost importance in this respect. For example, if soil drainage is sub-optimal, an attempt to apply the correct volume of water may result in a decrease in aeration, while the aim to allow sufficient aeration of the soil may result in under-irrigation of the plants. In either case, poor plant quality will result (Nelson, 1991:232). A wide variety of soil amendments may be used to compensate for the characteristic(s) lacking in soil. To improve infiltration rate, hydraulic conductivity, water-holding capacity as well as aeration in soil the following materials may be added in various proportions to the soil; course sand, sphagnum peat moss, perlite, vermiculite, polystyrene beads, haydite, scoria, various seed hulls (pecan nut shells, macadamia nut shells, peanut shells), woodchips, sawdust, coconut fibres rock wool, manure and straw (Durkin, 1992:77; Lieth, 1996:3; Ball, 1998:93; Hayashi 1998:249). One or a combination of two or more of these amendments may also be used as growth media, with or without soil. Several approaches exist on which irrigation scheduling is based; the look-and-feel, gravimetric, timer-based, the sensor-based and the model-based method. The look-and-feel irrigation method is based on the visual appearance of the plant and involves the close inspection of the plant, paying attention to any drooping foliage or slight colour changes that occur in some crops just prior to wilting, or determining the water content of the growth medium by touching the medium or in the instance of potted plants, by picking up the pot and weighing it by hand. In the

gravimetric method, the change in weight of the plant plus the growing medium over time is taken as being equal to water lost due to evapotranspiration, since changes in weight due to plant growth are much smaller. The transpiration rate has been used in the irrigation scheduling. Time-based irrigation scheduling involves the use of a timer to program the volume and frequency of irrigation water that has to be applied. Sensor-based irrigation scheduling is based on the use of sensors to determine the moisture content or related characteristics of growing media, and then using this information to control the irrigation schedule. At the moment tensiometers are widely used for this purpose. Model-based irrigation scheduling involves measuring the volume of water plants has used and then irrigating to replace this volume. This scheduling method attempt to relate the volume of water lost by the plant as well as from the soil, to one or more environmental variable (temperature, light, humidity, wind speed) as well as factors related to the plant (leaf area), so that irrigation can be scheduled to replace the lost water (Lieth, 1996:23-29).

The primary objective of the present investigation was to determine an effective irrigation schedule (by only altering the irrigation volume) that requires the minimum volume of water for maximum flower productivity, with reference to the yield (Chapter 3) and quality (Chapter 4), as well as the photosynthetic rate and other related parameters (Chapter 5) of cut-roses grown in the soil under South African environmental conditions. From an economical point of view, the treatment yielding the highest number of stems achieving the highest price at the market with the lowest production cost will be the best treatment. Long stems are the most desirable from the grower's point of view, since long stems achieve higher prices at the market (Table 1.3).

Table 1.3: Monthly averages ($\pm$ s.d.) of prices (Rand) obtained at the Johannesburg flower market for stems of the cultivar *Grand Gala* in different length classes for the years 1999 and 2000 (Redelinghuys, 1999; Redelinghuys 2000).

In the instances where the s.d. values are not stated, inadequate data was present to determine the s.d.

Only choice grade stems were used; data of stems of lower quality were discarded.

Table 1.3a

1999

Month	Length classes (cm)						
	40	50	60	70	80	90	100
Jan		0.81 $\pm$ 0.27	1.02 $\pm$ 0.23	1.10 $\pm$ 0.29			
Feb		0.45 $\pm$ 0.23	1.69 $\pm$ 1.17	0.89 $\pm$ 0.54	1.32 $\pm$ 1.12		0.86
Mar							
Apr	0.30	0.38 $\pm$ 0.25	0.48 $\pm$ 0.13	0.36 $\pm$ 0.14	0.45 $\pm$ 0.21		
May			0.97 $\pm$ 0.18	1.14 $\pm$ 0.32	1.32 $\pm$ 0.22		
Jun	0.48	0.38	0.67 $\pm$ 0.27	0.64 $\pm$ 0.23	0.68 $\pm$ 0.12		
Jul		1.12	0.90		1.23		
Aug		1.26 $\pm$ 0.01	1.49 $\pm$ 0.45	1.76 $\pm$ 0.52			
Sep							
Oct		1.00 $\pm$ 0.51	0.79 $\pm$ 0.28	1.04 $\pm$ 0.45			
Nov	0.38 $\pm$ 0.04	0.45 $\pm$ 0.11	0.80 $\pm$ 0.20	0.81 $\pm$ 0.21	0.78 $\pm$ 0.17		
Dec	0.46	0.71 $\pm$ 0.17	0.76 $\pm$ 0.29	0.78 $\pm$ 0.22	0.87 $\pm$ 0.19		

Table 1.3b

2000

Month	Length classes (cm)						
	40	50	60	70	80	90	100
Jan		1.18 $\pm$ 0.35	1.23 $\pm$ 0.28	1.37	1.03 $\pm$ 0.20		
Feb	2.05	1.42 $\pm$ 0.60	1.55 $\pm$ 0.67	1.67 $\pm$ 1.18	1.19		
Mar	0.51	0.41 $\pm$ 0.10	0.90 $\pm$ 0.34	0.81 $\pm$ 0.29	0.88 $\pm$ 0.42	1.02	
Apr		0.47 $\pm$ 0.17	0.57 $\pm$ 0.18	0.77 $\pm$ 0.13	0.59 $\pm$ 0.19		
May		0.92 $\pm$ 0.23	0.95 $\pm$ 0.24	1.14 $\pm$ 0.36	0.81 $\pm$ 0.21		
Jun		0.63 $\pm$ 0.23	0.95 $\pm$ 0.27	0.89 $\pm$ 0.12			
Jul	0.67			0.84 $\pm$ 0.07	1.20		
Aug		0.81 $\pm$ 0.04	1.09 $\pm$ 0.17	1.09 $\pm$ 0.10	1.18 $\pm$ 0.06		
Sep	0.54 $\pm$ 0.18	0.77 $\pm$ 0.25	0.96 $\pm$ 0.22	0.91 $\pm$ 0.29	1.22	1.20	
Oct	0.35 $\pm$ 0.18	0.54 $\pm$ 0.20	0.73 $\pm$ 0.36	0.86 $\pm$ 0.34	0.76 $\pm$ 0.59		
Nov		0.64 $\pm$ 0.18	0.84 $\pm$ 0.30	0.76 $\pm$ 0.30	1.28 $\pm$ 0.52		
Dec		0.60	0.84 $\pm$ 0.22	1.03 $\pm$ 0.41	0.78		

Abbreviations used in Table 1.3 (see List of Abbreviations, page x)

CHAPTER 2

Materials and Methods (general)

2.1 Study area

This study was conducted in the Northern Province of South Africa, in the Nylstroom - Warmbaths area. Situated on the 24°27'30" southerly latitude and the 28°8'30" easterly longitude. The greenhouse is situated at the foot of a small hill. The surrounding landscape is mountainous (see Figure 2.1). In Figure 2.1 the greenhouse is in the foreground on the right hand side while the surrounding mountain range, the Waterberg mountains, is visible in the background.



Figure 2.1: *Landscape surrounding the farm where the greenhouse was situated.*

2.2 Plant material used

Rose plants (*Rosa hybrida*, cv. Grand Gala; a vigorously growing, red, long stemmed, thornless rose) were used in this study. The straight and erect growth form of this particular cultivar can be seen clearly in Figure 2.4. The roses were two years old and fully productive when the study initiated in February 1999, at the end of the study the roses were two-and-a-half-years of age. The breeders of 'Grand Gala' roses classified it as follows:

Variety:	Meiqualis
Type:	Hybrid Tea
Colour:	Strawberry Red (Figure 2.2)
Bud:	Conical (Figure 2.2)
Number of Petals:	30 on Average
Vase Life:	10 - 12 days
Foliage:	Dark Green, Glossy (Figures 2.2 and 2.4)
Recommended Stock:	Indica
Yield:	130 - 160 blooms m ⁻² year ⁻¹
Length of the Stems:	60 - 80 cm



Figure 2.2: Flowers of this splendid cultivar at 4 different stages of development. (Meilland Poster, 1992?)

When comparing the number and length of the stems yielded during this experiment with the average yield and stem length obtained by the breeder of the cultivar 'Grand Gala' (summarised above) it was found that the number of stems yielded during the current experiment was higher and the stems longer (see Chapter 3 for more detail). One possible explanation for this is the use of the rootstocks of two different cultivars; in the present experiment the cultivar 'Natal Brier' was used while the breeders of 'Grand Gala' used the cultivar 'Indica'. In trials conducted by the Dutch rose grower, Bill Steenks, it was found that the use of the 'Natal Brier' rootstock contributed to achieving from 15 % to 20 % higher yields, better quality and longer stems than the same cultivars grown on other rootstocks (Pellett *et al.*, 1998:717).

2.3 Horticultural Practices

In this study the rose plants had two or more basal shoots and were multiple-stemmed. A rosebush with two visible basal shoots, as was typical for this investigation, can be seen in Figure 2.7(b).

The stems were harvested continuously, a method known as staggering (stagger harvesting), throughout the year, thus no winter rest period occurred and no winter pruning took place. The developmental stage at harvesting varies with cultivar, season and distance to the market, but generally the stems are harvested at the tightest stage at which the flower will open in neat water. In general the stems of yellow cultivars are harvested with the flower bud tighter than the pink cultivars, which is again harvested tighter than the flower buds of red cultivars. In the instances where the stems were harvested with the flower buds too tight, the flowers will not open. Most stems of the pink cultivars and especially the red cultivars, must be harvested when at least one of the outer petals has started to unfold (Meyer *et al.*, 1988b:13; Pellett *et al.*, 1998:713). Since 'Grand Gala' is a red cultivar the stems were harvested at the latter stage. The stems were harvested three times per day (06h00, 12h00 and 17h00) in the late summer and early autumn and two to three times per day in late autumn and early winter. Whenever possible, stems were harvested in the early morning or late afternoon to prevent dehydration of the stems. High temperatures sometimes necessitated the harvesting of the stems more than the preferable two times a day, since these climatic conditions influenced the water content and subsequently the fresh weight of the stems and lead to a decrease in quality, due to flower buds opening too wide and a decrease in vase life (Meyer *et al.*, 1988b:13; Durkin, 1992:82; Pellett *et al.*, 1998:713). The stems were harvested with the highest possible length. In general, the stems were cut above the second five-pinnated compound leaf above the previous cut, slightly above the node. Thinner stems were cut closer to the previous cut or even below it (Pellett *et al.*, 1998:715).

The bent stem technique was used during this study. In short, this technique entails the bending down of lateral stems to increase the number of leaves (foliage) available for photosynthesis. These lateral stems that are bent down are stems of poor quality: thin and short stems with small or deformed buds. By using this technique, the aisles are filled with foliage and are not very easily distinguishable from the beds itself, giving an overall bushy appearance (see Figure 2.4) (Pellett *et al.*, 1998:716).

The exceptionally long stems of this particular cultivar (Grand Gala) were kept in an upright position while they were growing. They were supported by wire fastened to the wooden poles planted ± 12 m apart at either side of each bed (see Figure 2.3). The wire was fastened at a height

of 45 cm and again at a height of 90 cm from the soil surface. The stems (shoots) were guided periodically to an upright position (see Figure 2.4). This practice reduces the breaking and bending of the long stem roses and thus retaining the quality of the stems.

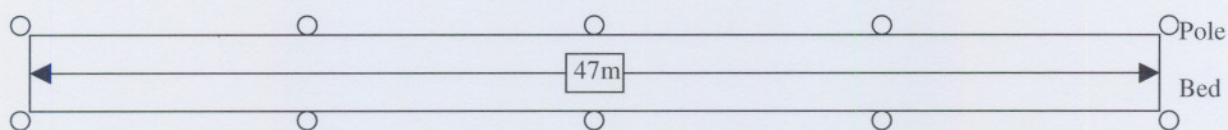


Figure 2.3: Schematic representation of the position of the wooden poles with respect to a bed as seen from above.



Figure 2.4: Two neighbouring beds divided by an aisle, with a very bushy appearance.

Suckers, originating from the rootstock, also called the understock, were removed and secondary buds were pinched off, leaving only the terminal bud to fully develop into a flower. The blind shoots were removed in an early stage of shoot development, since allowing the development of non-marketable stems is too wasteful from a plant energy utilisation perspective. Stems with bent necks were harvested and sold as low-grade stems. Stems originating from the basal shoots, also referred to as 'water shoots' or 'renewal canes', were also harvested for the local market. The beds and aisles of the greenhouse were kept free of weeds, fallen leaves, petals and twigs, minimising the occurrence and spreading of diseases. The dead and sick parts of the rose bushes were also removed for the same reason.

2.4 Greenhouse description

Data collection during this study took place in a commercially productive greenhouse. The greenhouse had a length of 100 m, a width of 50 m and a height of 5 m, covering a surface area of 5000 m² or ½ a hectare. The beds of the greenhouse (72 beds in total) were 47 m long and 1 m wide and raised to a height of 0.40 m, with aisles of 0.40 m in between. Each bed consisted of two rows of roses with a total of 556 rose plants per bed (see Figures 2.5 and 2.6). The beds of each treatment were divided into four equal parts, from which the data of the replicas were obtained. There were a total number of 40 000 rose plants in the greenhouse (8 plants.m⁻² of the greenhouse). The growth medium (soil) was 4 to 6 m deep and had a sandy-loam texture consisting of 84 % sand, 4 % silt and 12 % clay. It had a soil density of ca 1213 kg m⁻³. The greenhouse was covered with a 200 micron, UV-protected polyethylene film (Triclear) (Figure 2.7).

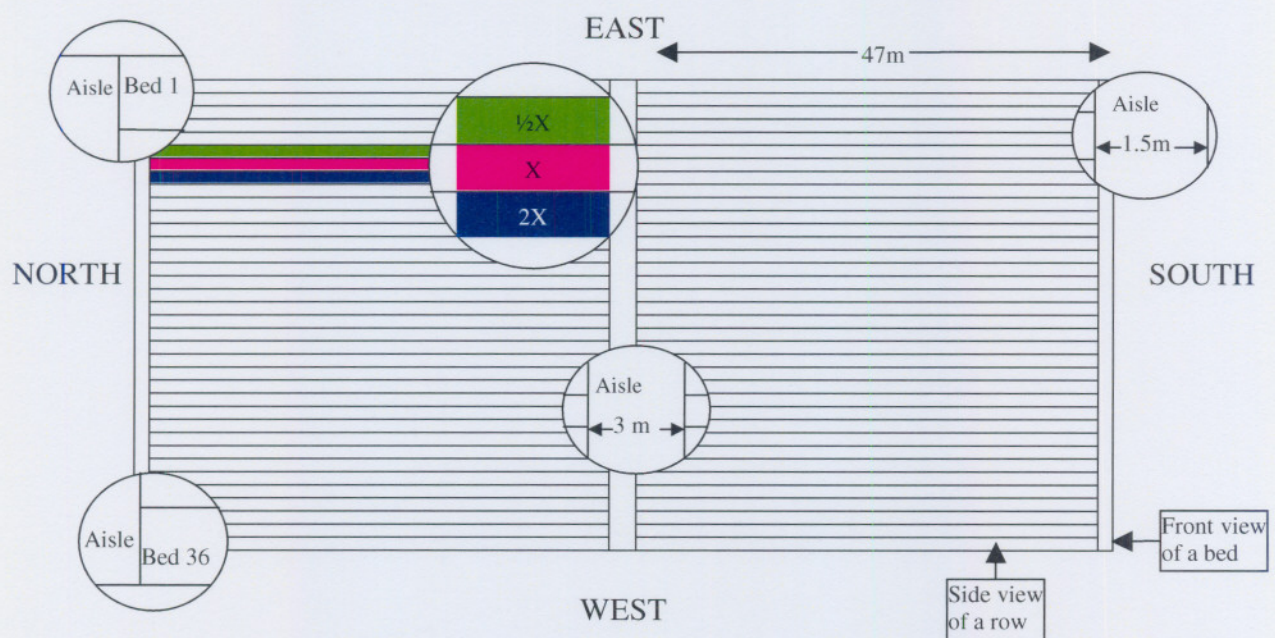


Figure 2.5: Schematic representation of the top view of the greenhouse that was used. The coloured beds indicate the location of the three treatments 2X, X and ½ X, respectively.

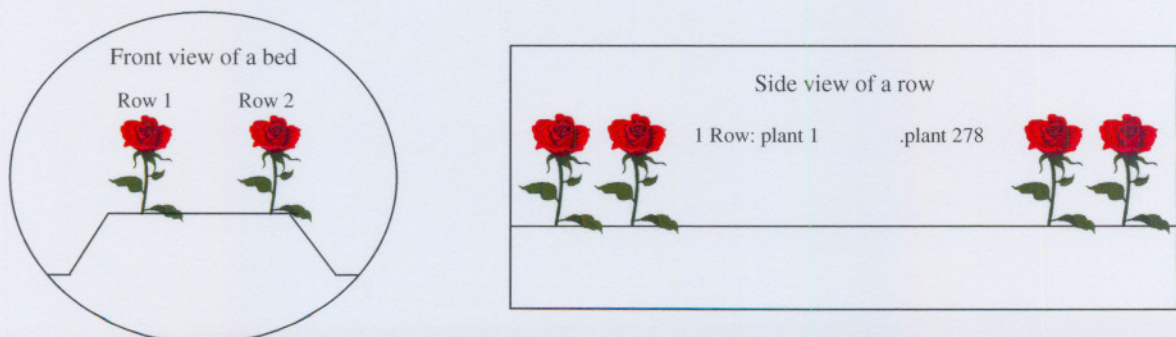


Figure 2.6: Schematic representation of the front view of a bed and a side view of a row

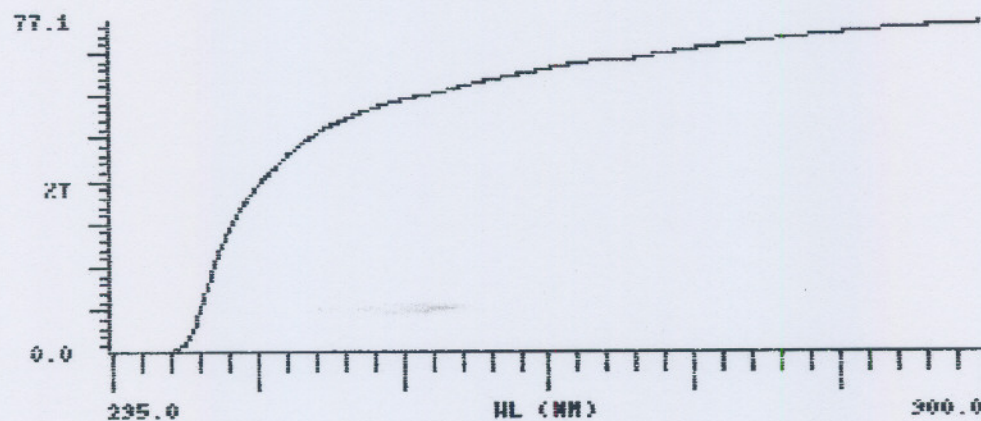


Figure 2.7: Percentage light transmission of the greenhouse covering for the wavelengths in the visible light spectrum ranging from 295.0 nm to 900.0 nm (as measured with a spectrophotometer).

2.5 Irrigation

A drip irrigation system was used to apply water and fertilise the plants simultaneously; a process called fertigation. The fertigation system was completely automated: the timing and volume of irrigation water and fertiliser applied and the EC (electrical conductivity – amount of ions in solution) were thus continually monitored and kept constant. It had the advantage that the water and fertiliser were applied in specific quantities directly to the root zone of the plants. The EC differed between the summer and winter periods; in summer it was set between 1.3 and 1.4 mS cm⁻¹, while in winter it was set between 1.6 and 1.7 mS cm⁻¹. More irrigation cycles were applied in summer than in winter. The water pH (water and fertiliser) was kept constant at 6.5.

The irrigation pipes were 2.5 cm wide plastic pipes with perforations (called drippers in this experiment) 30 cm apart, with no nozzles attached to it. Each bed had one irrigation pipe, running in the middle of the bed and the whole length of the bed except the 2X treatment. The water that was not utilised by the plants presumably leached out of the root zone and deeper into the soil. All the beds of the greenhouse were irrigated with the same volume of water except the 2X and ½X beds that were used for this study, treatment X was used at the control. The three beds that were used for this study were situated next to each other (see Figure 2.5). The 2X treatment had 2 irrigation pipes running in the middle of the bed (the other pipe visible in Figure 2.8 were closed of), the X treatment had 1 irrigation pipe and the ½X treatment had 1 irrigation pipe with distributors at each dripper (see Figure 2.8). Each of the irrigation pipes had an irrigation capacity of 1 litre dripper⁻¹ hour⁻¹ except the irrigation pipe of the ½X treatment that had an irrigation capacity of ½ a litre dripper⁻¹ hour⁻¹ due to the distributors. The X treatment was used as a control, since it received the same volume of water (summer: 10.4 ℓ m⁻² day⁻¹; winter: 8.4 ℓ m⁻² day⁻¹) as the other beds in the greenhouse that were not included in the study. The volume of water applied to the plants of the X treatment was kept at 1.2 ℓ plant⁻¹ day⁻¹ since it was close to the maximum transpiration rate of a rose plant, being 1.5 ℓ m⁻² day⁻¹ (in summer) (Henning, 2000:66). The plants of the 2X treatment received twice as much water as the plants of the X treatment, whilst the plants of the ½X treatment received only half as much. The volume of irrigation water that was applied to the three different treatments (2X, X and ½X) during this study is summarised in Table 2.1. As mentioned earlier, the study period was divided into two main periods (1) the later summer and (2) the early winter period, with a differing number (Figure 2.9) of irrigation cycles applied.

This had an impact on the volume of water applied per unit area per unit time and thus ultimately

the volume of water received by the rose plants of the different treatments per unit time (see Table 1.1, previous Chapter). The volume of irrigation water used and the prevailing conditions during the course of this study has been compared to that of other studies. The volume of irrigation water, the frequency and/or duration of irrigation, the root depth, the country where and the time of year when the similar studies were executed, are presented in Table 1.2 (previous Chapter).



Figure 2.8: Irrigation lines of the 3 treatments (a) treatment 2X, (b) treatment X and (c) treatment $\frac{1}{2}$ X, respectively.

The beds were not irrigated continuously during the day. The rose plants were fertigated for a duration of 15 min every 45 min. During late summer irrigation started at 06h00 and ended at 18h30, while in early winter it started at 07h00 and ended at 17h00. Between 12h00 and 14h00 no fertiliser was added to the irrigation water. This was done to ease osmotic water uptake by

the plants, in order to encourage the transpiration rate of the plants. The electrical conductance (EC) of the irrigation water of the 2X, X and ½X treatments was the same during the study period (1 February to 16 June 1999). The plants were subjected to the different irrigation treatments, from 1 August 1998, 6 months prior to the initiation of the data collection. This ensured enough time for the plants to adapt to the different volumes of irrigation water.

Table 2.1: Volume of irrigation water applied to the 3 different treatments in the late summer and early winter periods.

Treatment	Late Summer (17 irrigation cycles day ⁻¹)		Early Winter (14 irrigation cycles day ⁻¹)	
	H ₂ O m ⁻² day ⁻¹ and H ₂ O m ⁻² week ⁻¹	H ₂ O plant ⁻¹ day ⁻¹ and H ₂ O plant ⁻¹ week ⁻¹	H ₂ O m ⁻² day ⁻¹ and H ₂ O m ⁻² week ⁻¹	H ₂ O plant ⁻¹ day ⁻¹ and H ₂ O plant ⁻¹ week ⁻¹
2X	X x 2 = 2 x 10.2 ℓ = 20.4 ℓ = 142.8 ℓ	X x 2 = 2 x 1.2 ℓ = 2.4 ℓ = 16.8 ℓ	X x 2 = 2 x 8.4 ℓ = 16.8 ℓ = 117.6 ℓ	X x 2 = 2 x 1.0 ℓ = 2.0 ℓ = 14.0 ℓ
X	= 10.2 ℓ = 71.4 ℓ	= 1.2 ℓ = 8.4 ℓ	= 8.4 ℓ = 58.8 ℓ	= 1.0 ℓ = 7.0 ℓ
½X	X ÷ 2 = 10.2 ℓ ÷ 2 = 5.1 ℓ = 35.7 ℓ	X ÷ 2 = 1.2 ℓ ÷ 2 = 0.6 ℓ = 4.2 ℓ	X ÷ 2 = 8.4 ℓ ÷ 2 = 4.2 ℓ = 29.4 ℓ	X ÷ 2 = 1.0 ℓ ÷ 2 = 0.5 ℓ = 3.5 ℓ

[The total surface area of the greenhouse floor, used in the equations to determine the volume of irrigation water is: 0.5 ha – the surface area of the bigger aisles ∴ 5000 m² – 50 m² ((1.5 m x 2) + 3 m)]
= 4950 m²

Abbreviations used in Table 2.1 (see List of Abbreviations, page x).

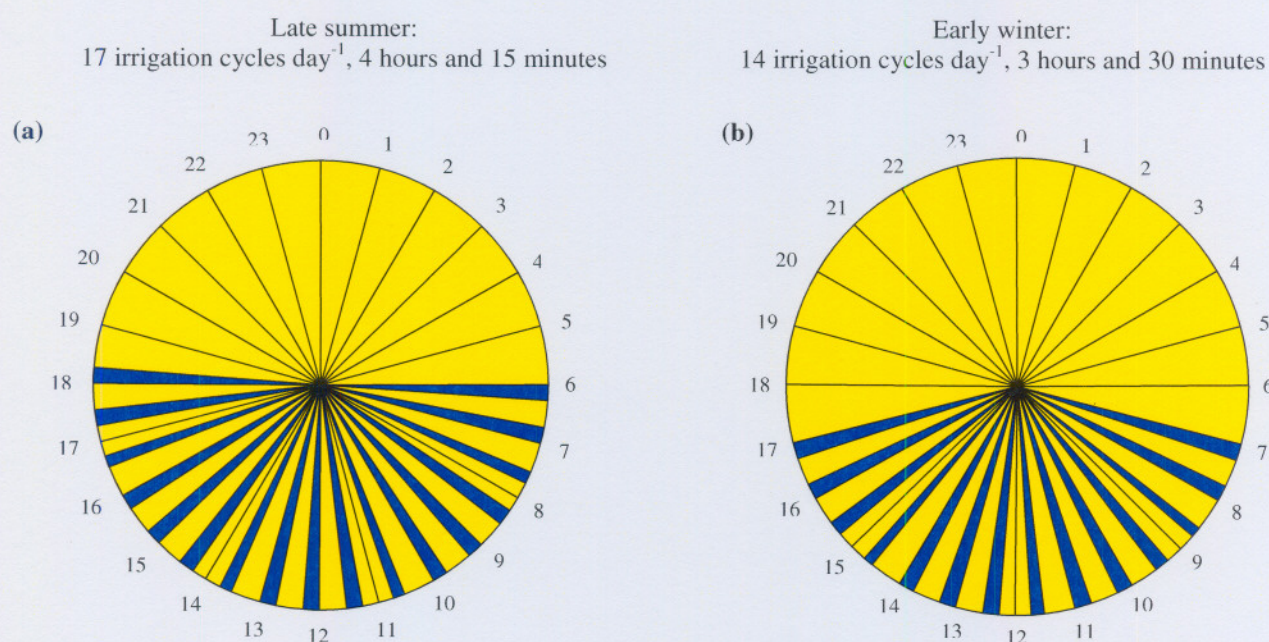


Figure 2.9: Graphical representation of the daily irrigation duration and frequency in (a) the summer and (b) the winter period respectively.

2.6 Fertiliser

Water-soluble fertiliser was used during this study and applied along with the water in the irrigation system. The electrical conductivity (EC) of the water applied to the 3 different treatments 2X, X and $\frac{1}{2}X$ was the same, thus the concentration of the fertiliser in the water was the same. However, the treatments did not receive the same amount of fertiliser due to the different volumes of irrigation water it received. The plants of the 2X treatment received the highest amount of fertiliser, the plants of the X treatment received half of that received by the 2X treatment plants and the plants of the $\frac{1}{2}X$ treatment received only a quarter of the amount of fertiliser.

2.7 Temperature

Climatological data (ambient temperature, time of sunrise and sunset, number of irradiation hours, percentage cloud cover and the number of rainy days) were obtained from the South African Weather Bureau (nearest available and representative weather stations namely Warmbaths and Vaalwater). Temperatures measured at Warmbaths were used to compare the outside ambient temperatures with the ambient temperatures inside the greenhouse. The similarities and differences in the temperatures of the location where the weather station was situated, in comparison with the temperatures measured inside the greenhouse used in this study can be seen from the data presented in Figure 2.10. The basic trend of the temperature changes, a month before and during the course of the study period (1 January – 16 June 1999) can be seen from the maximum and minimum temperatures measured at the weather station. The 12h00 and 15h30 temperatures measured inside the greenhouse were almost identical to the maximum temperatures measured at the weather station, with the 12h00 and 15h30 temperatures being only slightly higher on occasion. However, the 07h00 temperatures measured during this study period were approximately 5 - 7 °C or in some cases, even as high as 10 °C higher than the minimum temperatures measured at the weather station. This phenomenon may be explained by considering that the sun rises much earlier than 07h00 in summer (see Figure 2.11), causing an increase in the temperature inside the greenhouse. During the winter the greenhouse was heated to prevent a further reduction in the number of rose stems as well as frost damage to the roses (see the next section regarding the heating of the greenhouse). The minimum temperatures recorded in the greenhouse (1 May – 16 June) were quite similar to the 07h00 temperatures measured during this investigation. The maximum temperatures recorded in the greenhouse (1 May – 16 June) do not concur with the 12h00 and 15h30 temperatures received from the weather station but were, generally, a few degrees higher than the measured values. This might have been caused by the heated air that was trapped inside the greenhouse, since it could not escape through the ventilation openings or the peak temperature usually measured from 13h00 and 15h00 depending on the location and the time of year, or both. The ventilation openings were closed during most of May and June to prevent heat loss and conserve energy.

2.7.1 Heating

A charcoal-fired boiler was used to heat water that was then pumped through a 20 cm wide pipe to the greenhouse where it was converted into warm air by a unit heater. The warm air was distributed with fan-jet tubes. Warm air was blown through the tubes and through holes in the sides of the tubes to heat the whole interior of the greenhouse and maintain a given minimum

temperature as was described by Ball and Zylstra (1998:45). The temperature regulating system in this study was fully automated, turning on at a specific predetermined minimum temperature (15 °C) and off at a specific maximum temperature (18 °C). With the exception of the last 10 days of the study period when the outside temperature dropped to and below freezing point and the minimum temperatures as well as the 07h00 temperatures inside the greenhouse, dropped below 15 °C (see Figure 2.10). The minimum temperature is not always set at 15 °C; in one study the minimum temperature set point was 18 °C (Baile *et al.*, 1996:945) while in another the minimum night time temperature was 13 °C (Urban *et al.*, 1994a:627).

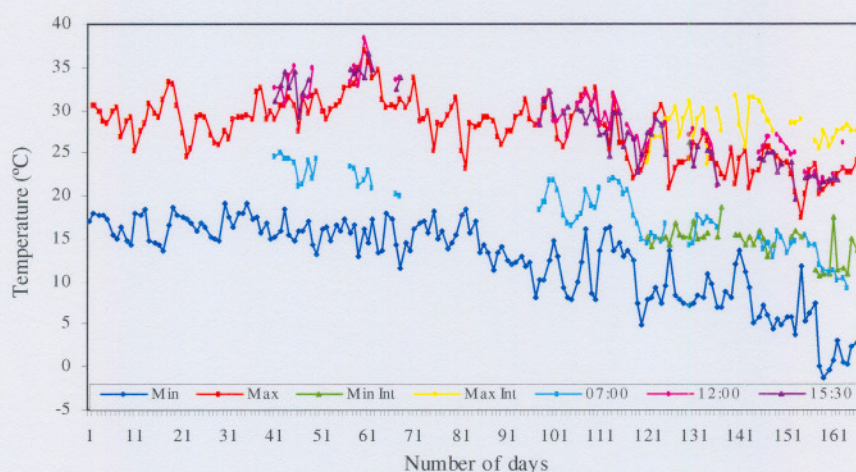


Figure 2.10: Maximum (red) and minimum (blue) Temperatures at Warmbaths,

Maximum (yellow) and minimum (green) Temperatures inside the Greenhouse, and

Temperatures at 07h00 (light blue), 12h00 (pink) and 15h30 (dark pink) from the data collected during this study. (Climatic data of Warmbaths, received from the Weather bureau)

Continuous heating throughout the night started on day 120 (in Figure 2.10) (early in May 1999) when the temperature inside the greenhouse dropped to below 15 °C. The root zone was not warmed during this study, meaning that the roots of the rose plants were exposed to soil at ambient temperatures.

2.7.2 Cooling and ventilation

Natural air movement was used to cool and ventilate the interior of the greenhouse. The ventilation system comprised of six roof flaps that ran parallel with the length of the greenhouse and opened in a westerly direction (see Figure 2.11 as well as Figure 2.5). The ventilation system was computerised using temperature, humidity and wind speed as the determining factors for the aperture size of the ventilation openings. Although the greenhouse had adjustable side-walls, they were never opened for ventilation and cooling purposes. The cooling and ventilation system was not effective in lowering the air temperature of the greenhouse interior. This is very

obvious when one compares the maximum, 12h00 and 15h30 temperatures measured inside the greenhouse, with the maximum temperatures outside the greenhouse (see Figure 2.10).

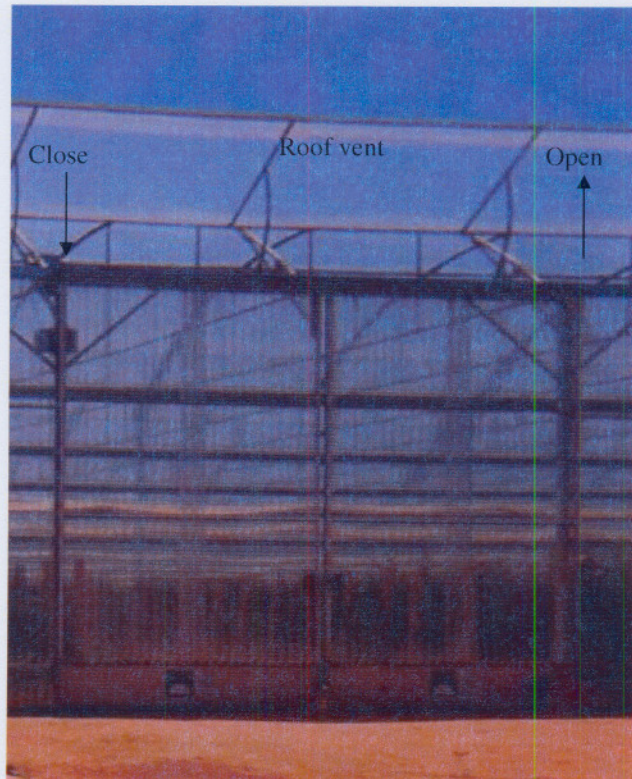


Figure 2.11: *Frontal view of the greenhouse doors. (One of the ventilation openings fully opened.)*

2.8 Irradiance

Natural irradiance was the only form of irradiation the rose plants received. No supplementary lighting was given during the day or night periods. The irradiance data received from the weather bureau consisted of the time of sunrise and sunset (Figure 2.12), the total number of irradiation hours (Figure 2.13). Day length was calculated using the time of sunrise and sunset. Data received from the weather bureau was depicted from 1 January until 16 June 1999, thus beginning a month prior to the commencement of the study and coinciding with the termination of the study. The reason for the figures beginning in January and not in February 1999, was that the assumption was made that the rose stems that were cut in February were initiated in late December 1998 and developed mostly during January 1999. The time span from the initiation of the bud until the fully developed rose stem is finally cut was not determined but calculated as ranging between 37 to 54 days (for the stems harvested in summer) taking the high temperatures, irradiation hours and levels into account (which correlate well with the 37 to 119 days, i.e. minimum and maximum values reported in the literature). The flowering time is discussed in more detail in Chapter 3.

As the sun rose progressively later and set earlier during the course of the experiment (Figure 2.12), the day length shortened from more than 13 hours in January to less than 11 hours in June (Figure 2.13). The slight discrepancy between the actual hours of irradiation received (sunshine hours) and the total day length (Figure 2.13) could be ascribed to the presence of clouds as well as the occurrence of rain. The occurrence of rain (Figure 2.15) and clouds (Figure 2.14) are more common in summer than in winter, since this area receives summer rain. This explains why the number of hours of irradiation received, was nearly the same as the day length hours in winter, but not the case in summer. The days when the hours of irradiation received (sunshine hours) were far less than the day length hours, coincided with the days with a higher percentage cloud cover and/or the occurrence of rain (Figures 2.14 and 2.15). The rain may not have had a direct influence on the growth of the rose stems (plants) since the plants received water by means of the irrigation system. However, the rain accompanied by the clouds, reduced the irradiation hours as well as the irradiance level the plants were subjected to, thereby reducing the photosynthesis rate and growth rate of the rose plants.

The irradiance levels the plants were subjected to in the greenhouse was measured three times a day, at 07h00, 12h00 and 15h30 (see Chapter 5; Figure 5.9a, b and c), from 1 February 1999 until 16 June 1999. The measurements were not taken continuously but they give a good

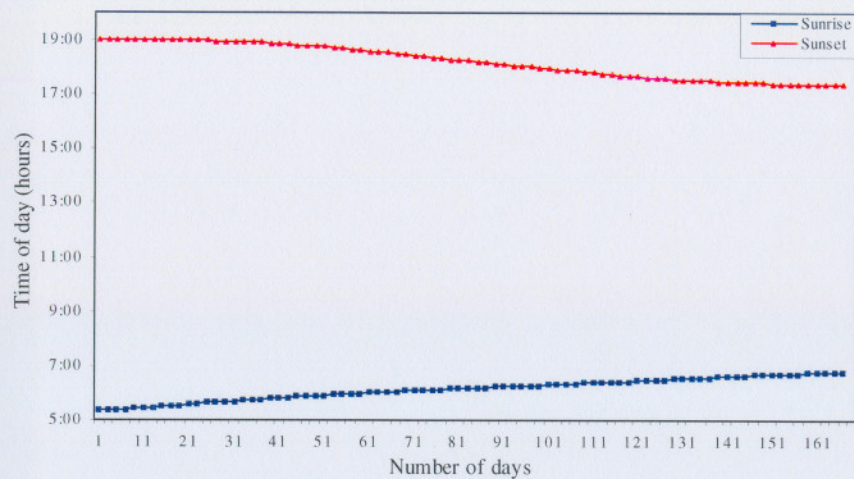


Figure 2.12: Time of sunrise and sunset

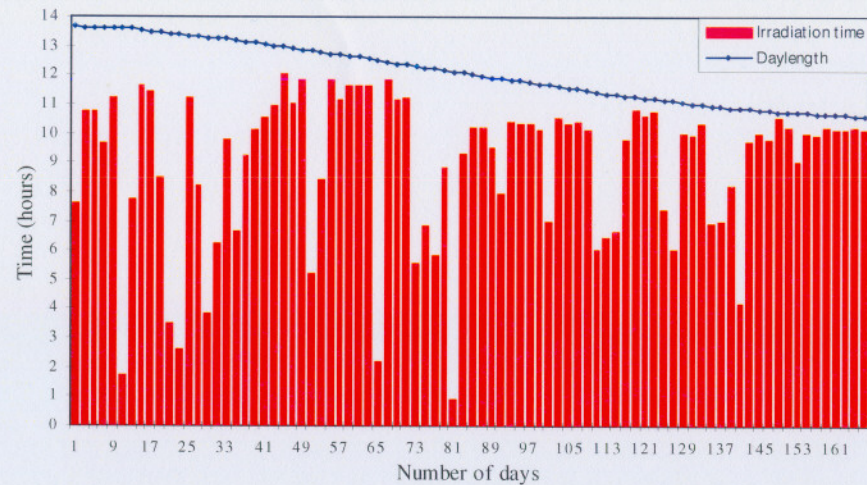


Figure 2.13: Day length as well as number of irradiation hours

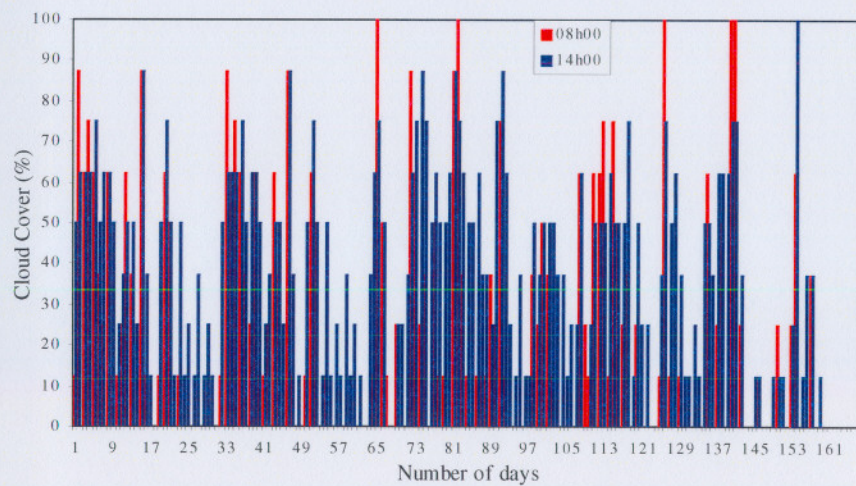


Figure 2.14: Percentage cloud cover at 08h00 and 14h00 (Warmbaths)

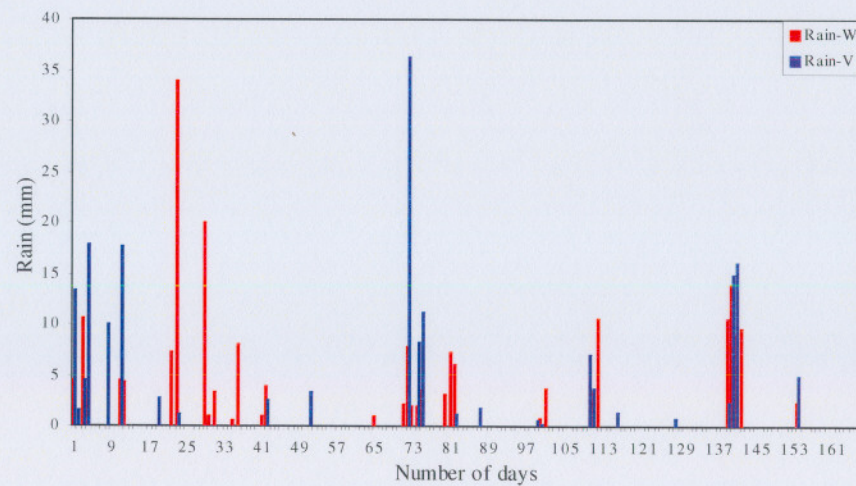


Figure 2.15: Amount of rain received at Warmbaths and Vaalwater

(Climatic data of Warmbaths and Vaalwater, received (courtesy of) from the Weather bureau)

indication of the irradiance level during that part of the year. The presence of clouds and the occurrence of rain are indicated (depicted) as variations in the irradiance levels (Figure 5.9a, b and c). The irradiance level was measured as the number of photons received on a specific area in a specific time interval ($\mu\text{mol m}^{-2} \text{s}^{-1}$) which is referred to as the Photosynthetic Photon Flux (PPF). PPF is always measured in the wavelength region from 400 to 700 nm, the wavelengths most active in photosynthesis (Salisbury & Ross, 1992:613).

As the winter period closed in and the day length as well as the number of irradiation hours decreased (Figure 2.12), the irradiance levels measured at 07h00, 12h00 and 15h30 respectively (Figure 5.9a, b and c), declined gradually. The decrease of the measured irradiance levels at especially 07h00 (Figure 5.9a) coincided with the sun rising later each day. This phenomenon is clearest in the last part of May until 16 of June 1999 when the sun rose at approximately 07h00 (Figure 2.13) and the irradiance level was very low (between 0 and $100 \mu\text{mol m}^{-2} \text{s}^{-1}$) at that specific time (Figure 5.9a).

As expected the irradiance level (I) measured at 07h00 was much lower than that measured at 12h00 and 15h30. The former varied between PPF values of 0 and $800 \mu\text{mol m}^{-2} \text{s}^{-1}$ while the latter varied between PPF values of 150 and $2500 \mu\text{mol m}^{-2} \text{s}^{-1}$. In the case of the 15h30 irradiance data (Figure 5.9c) plants of the 3 different irrigation treatments were not subjected to the same levels of irradiance for the duration of the measurements. The reason for this is that the sun's rays passed through the plastic covering of the greenhouse in the case of the 2X treatment while the sun's rays passed directly through the ventilation openings for a few minutes when the PPF values of the X and $\frac{1}{2}$ X treatments were measured.

In some instances it was more practical to determine the sum of the PPF received on a daily basis, converting the units into the molar range ($\text{mol m}^{-2} \text{day}^{-1}$). The total daily PPF-values as well as the total daily PAR (Photosynthetic Active Radiation) values calculated as weekly averages are summarised in Table 2.2. PAR is used when irradiance is reported in energy units for wavelengths from 400 to 700 nm. The units used for PAR are watts per square meter (W m^{-2} or in other words $\text{J s}^{-1} \text{m}^{-2}$), while the total daily PAR-values are in the MW range (MW m^{-2} or in other words $\text{MJ s}^{-1} \text{m}^{-2}$).

Each of the values presented in Table 2.2 was determined using a graph as depicted in Figure 2.16. The three values used to derive the graph (parabola; polynomial 2) were the weekly averages of the irradiance (I) measured at 07h00, 12h00 and 15h30, respectively. Data collected for the three irrigation treatments were used to determine the weekly averages for the 07h00 and 12h00 points, while only the irradiation measured at 15h30 of the 2X treatment was used to

determine the weekly averages for the 15h30 points. Since the irradiance levels measured for the X and ½X treatments varied significantly and were much higher in most instances than the values measured for the 2X treatment.

Table 2.2: Total Daily PPF and PAR-values.

Week	PPF (mol m ⁻² day ⁻¹)	PAR (MJ m ⁻² day ⁻¹)
1	-	-
2	56.33	12.22
3	59.14	12.83
4	57.58	12.50
5	60.43	13.11
6	60.18	13.06
7	-	-
8	-	-
9	-	-
10	48.12	10.44
11	55.14	11.96
12	46.33	10.05
13	44.63	9.68
14	51.10	11.09
15	43.57	9.46
16	-	-
17	49.33	10.70
18	42.67	9.26
19	51.22	11.11
20	45.84	9.95

Abbreviations used in Table 2.2 (see List of Abbreviations, page x)

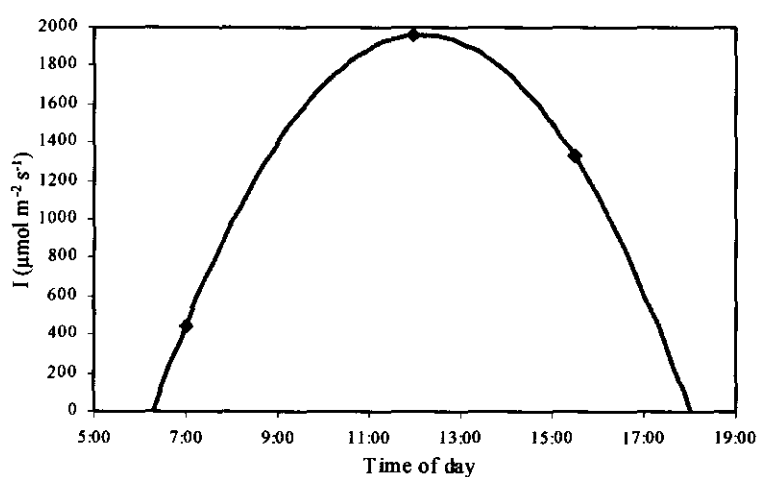


Figure 2.16: Weekly averages of the irradiation measured at 07h00, 12h00 and 15h30 as well as the parabola fitted to the three irradiation values.

The area beneath the parabola was then calculated to determine the Total Daily PPF received. The PAR-values presented in Table 2.2 were calculated using the PPF values just mentioned.

2.9 Collected Data

The data were divided into three categories viz. (1) yield data (2) quality data and (3) photosynthesis-and-related-parameters data.

2.9.1 Yield:

The marketable stems for the four replicas of each irrigation treatment (2X, X and $\frac{1}{2}$ X) were harvested separately from 1 February to June 1999, a period of 20 consecutive weeks. The stems were graded daily in minor length classes ranging from 40 cm to 170 cm with 5 cm intervals (40 cm, 45 cm, 50 cm, etc.). The following data were gathered per replica of each treatment:

- The number of stems harvested per day per minor length class. This data were pooled to form three major length classes viz. short (40 – 80 cm), medium (85 – 105 cm) and long stems (110 – 170 cm). The following data were determined for each of these length classes of the respective treatments as well as for the each treatment as a whole:
- The number of stems harvested per day (short, medium, long stems and total)
- The number of stems harvested per week (short, medium, long stems and total)
- The cumulative number of stems harvested per week (short, medium, long stems and total)
- The number of stems harvested per plant or per m² as well as extrapolated to the number of stems that could be harvested per greenhouse (5000 m²) (short, medium, long stems and total)
- The productivity index (PI) which is a combination between quality (weight length⁻¹) and yield (short, medium, long stems and total).

2.9.2 Quality criteria:

The same stems that were harvested and graded into the minor length classes were used. One representative stem was randomly selected from each minor length class of each irrigation treatment. The following quality criteria were determined:

- Bud length
- Stem fresh weight (flower bud, stem and leaves included)
- Stem diameter at its widest
- Leaf length and width of the third compound leaf from the bud and used to calculate the leaf area

Similar to the production data, the data of the quality criteria of the stems in each length class were combined to form three major length classes viz. short (40 – 80 cm), medium (85 – 105 cm) and long stems (110 – 170 cm). This was done for the replicas of each treatment, respectively. The combined data were then used to determine:

- A daily as well as a weekly average for each quality criterion (short, medium and long stems)
- The average length of the stems harvested per week (short, medium, long and total stems)
- The quality index (QI) as the ratio of the fresh weight to the average length (short, medium, long and total stems)

2.9.3 Photosynthesis and related parameters:

A non-destructive method was used to collect the data of the photosynthesis data and the related parameters as well as the environmental variables at 07h00, 12h00 and 15h30 each day. A rose stem of each treatment was selected at random while the stems were still attached to the respective plants. The stems were of different lengths (short, medium and long). The stems were all at the third stage of shoot development as described by Jiao *et al.* (1989b:246). The fifth compound leaf from the bud, consisting of three to five pinnae, was chosen. A portable Infrared Gas Analyser: IRGA (LCA-2: The Analytical Development Co. Ltd., England) operating in the differential mode was used during this study. An adjoining mast allowed air to be withdrawn continuously at a rate of 350 ml min⁻¹ from a sampling point at a similar height as the plants (bud height), thus determining the CO₂ concentration (external CO₂) in the plant canopy. Data for the following photosynthesis parameters were recorded:

- Assimilation rate
- Transpiration rate
- Stomatal conductance
- Internal CO₂

As well as the following external environmental variables:

- Leaf and ambient air temperatures
- Irradiance level
- External CO₂ concentrations

The photosynthetic data were not recorded continuously from 1 February to 16 July 1999 due to the malfunctioning of the IRGA at times. The data that had been collected were, however,

divided into two major seasonal categories to give a general idea of the effect of the season on the rate of photosynthesis and it's related processes viz. (1) late summer combined with autumn (10 February – 16 May 1999) and (2) early winter (17 May – 16 June 1999).

CHAPTER 3

Yield

Abstract

Plants of the Hybrid Tea rose cultivar 'Grand Gala' were subjected to three different volumes of irrigation water (treatments 2X, X and $\frac{1}{2}X$). Treatment X served as the control treatment since the plants of this treatment received the same volume of water (late summer: $1.2 \text{ l plant}^{-1} \text{ day}^{-1}$, early winter: $1.0 \text{ l plant}^{-1} \text{ day}^{-1}$) as the rest of the plants in the greenhouse. The plants in treatment 2X received twice as much water, whilst the plants in treatment $\frac{1}{2}X$ received half. The number of stems yielded by each of the replicas of the irrigation treatments, over the 20 week experimental period was determined. The data for the stems of the replicas of each irrigation treatment were pooled into three major length classes viz. short (40 – 84.9 cm), medium (85 – 109.9 cm) and long (110 – 165 cm) and the number of stems per length class determined after it was divided into minor length classes ranging from 40 cm to 165 cm in 5 cm intervals. The 2X, X and $\frac{1}{2}X$ treatments yielded 759, 699 and 654 short stems, 2927, 2776 and 2868 medium length stems, 1372, 1409 and 1737 long stems and a total number of stems of 5058, 4884 and 5258 per 556 plants respectively. The number of short stems harvested did not differ significantly. The number of medium stems yielded by the 2X treatment was significantly higher than that yielded by the other two treatments. The $\frac{1}{2}X$ treatment yielded a significantly higher number of long stems as well as the total number of stems than treatment X and 2X. The productivity index (PI) were determined for the different major length classes of each treatment as well as for the total number of stems yielded by each treatment. PI was determined by dividing the fresh weight by the average length and then multiplying the answer with the total number of stems harvested per length class or per treatment. The PI of the total number of stems harvested per treatment were 2388, 2285 and 2401 (g cm^{-1} total number of stems) for the 2X, X and $\frac{1}{2}X$ treatments respectively. As the PI is a function of the total number of stems, it concurs with the yield data, only emphasising the fact that the $\frac{1}{2}X$ treatment yielded significantly higher number of stems than the 2X and X treatments. It can be concluded that the treatment receiving the lowest volume of water ($\frac{1}{2}X$) did not only yield the highest number of stems but also had the highest PI value, implying that the $\frac{1}{2}X$ treatment had the highest productivity and thus the highest stem quality as well.

3.1 Introduction

The growth and development of greenhouse roses are determined by measuring the productivity of the plant. This is constituted by the combined and inter related relationship that exists between the number of stems (yield) and quality of the stems harvested. Generally speaking the higher the yield of the rose plants, the lower the quality, when the quality is defined by leaf area, stem fresh weight, flower bud length, stem diameter and average stem length.

Most growers are of the opinion that the only way to make the highest possible profit when growing roses, or any other cut flower for that matter, is to produce as much roses as possible, no matter what the quality of the stems are. There are, however, exceptions to this rule. Some growers are of the opinion that growing fewer stems of better quality is the better option, since it enables the grower to earn more money per single stem while not overcrowding (dumping) the market with a huge number of lower quality stems. At the end of the day it is not how many stems you produce that matters, but how much money you earn at the market. Higher yields are thus not always equal to higher profits (Pertwee, 1992:37; Pellett *et al.*, 1998:716). The grower must therefore decide which one of the two is more important and whether or not it would be economically feasible to attempt achieving one or both of these goals. An alternative to this white and black approach would be to compromise on a bit of both and consequently produce fewer stems of higher quality. If both high yields as well as high quality stems can be produced, the grower will surely have an advantage. Some serious consideration should therefore be given to the achievable quality and yield before making such an important decision (Nelson, 1991:384).

As in the case of photosynthesis, the growth and development and thus production and quality, of the rose plant are also influenced by various environmental factors (external input variables). These variables include the following: irradiance (duration, level and quality; solar or artificial); temperature (day and night; root zone and air); CO₂ concentration; irrigation (volume and schedule) fertiliser (concentration and schedule); and humidity (Salisbury & Ross, 1992:254; Freeman, 1998:144). The horticultural practices used during the cultivation of the rose plants as well as the location and season also influences the number of stems harvested. A fine interdependence exists between the environmental conditions that result in the highest number of marketable stems as well as the resultant quality of these stems. Consequently, it is important to determine the optimum value or range for each interactive variable.

Greenhouse roses are known for their high-energy (external input variables) requirements, especially in areas where production continue throughout the winter months (Moss, 1984:549;

Zieslin *et al.*, 1987:86). These variables influence the growth and development of greenhouse roses to a greater or lesser extent. The singular effect of each of these individual variables or a combination of two or more of these variables give rise to numerous results, determining the quantity and quality of the roses that are produced.

The next criteria can be used to quantify the production of a single rose plant or a whole crop of rose plants.

- The total number of stems harvested per plant (stems plant⁻¹)
- The total number of stems harvested per unit area (stems m⁻², stems row⁻¹ or stems bed⁻¹)
- in a certain time period (day, week, month or year)
- The fresh or dry weight of harvested flowering stems per unit area (g m⁻²)
- The number of days required by a stem to develop from budbreak until it is harvested (cut) (time until flowering) or any stage in between

The occurrence of “blind shoots¹”, “bullhead²” and “bent-neck³” flowers as well as low quality stems that has to be discarded, reduces the number of marketable stems and thus production.

The process of photosynthesis cannot be detached from yield and quality of the rose stems since they are interdependent. In this chapter the emphasis is placed on the yield of the rose plants. In Chapter 4 and 5 the quality of the harvested stems and the process of photosynthesis and its accompanying processes are discussed in more detail.

¹ “Blind shoots” are stems lacking flower buds that can develop into flowers and are caused by an incomplete development of the flowers, resulting in flower-bud-atrophy/abortion (Zieslin & Moe, 1985:218).

² “Bullhead” flowers are malformed flowers that develop during low temperature conditions. It results from the production of increased numbers of petals, accompanied by a decreased length to width ratio of the petals and the replacement of the nectary ring by a proliferating tissue (Zieslin & Moe, 1985:216).

³ Flowers with “bent necks” also called crooked flowers (Durkin, 1992:89-90) develop during high temperature condition due to a suspected incorrect ratio between calcium and boron (Van Rensburg, 1999). The peduncle as well as the flower bud itself, is bend to one side, causing the so called “bent necks” (Durkin, 1992:89-90).

3.2 Materials and Methods

The production (yield) data was collected as follows. The marketable stems of the replicas of each irrigation treatment (2X, X and ½X) were harvested separately. The stems were harvested when at least one of the outer petals had started to unfold (Meyer *et al.*, 1988:13; Pellett *et al.*, 1998:713). The stems were harvested three times per day (06h00, 12h00 and 17h00) in the late summer and early autumn and two to three times per day in late autumn and early winter. The stems were harvested with the highest possible stem length. In general, the stems were cut above the second five-pinnated compound leaf above the previous cut, slightly above the node. Thinner stems were cut closer to the previous cut or even below it (Pellett *et al.*, 1998:715). The stems were graded daily in minor length classes ranging from 40 cm to 170 cm with 5 cm intervals (40 cm, 45 cm, 50 cm, etc.). The following data was recorded for the four replicates of each treatment:

- The number of stems harvested per day per minor length class.
- This data was pooled to form third major length classes viz. short (40 – 80 cm), medium (85 – 105 cm) and long stems (110 – 170 cm). The stems of the ‘Grand Gala’ cultivar in Figure 3.1 is examples of stems in the short and long length classes respectively (note the straightness of the stems).

The following data was recorded for each of these length classes of the replicates of the respective treatments as well as for the each treatment as a whole:

- The number of stems harvested per day (short, medium, long stems and total)
- The number of stems harvested per week (short, medium, long stems and total)
- The cumulative number of stems harvested per week (short, medium, long stems and total)

The productivity index (PI) which is a combination between quality (QI = fresh weight stem length⁻¹) and yield (short, medium, long stems and total). The yield data was collected continuously from 1 February to 16 June 1999, a period of 20 consecutive weeks (during the latter part of the summer, fall and the first part of the winter).

The data collected for the replicas of each treatment were only used to determine the significance of the differences between the respective irrigation treatments with reference to the stems in the short, medium and long length classes as well as the total number of stems. This data were pooled for the graphs as well as for Table 3.3. The data in this study was analysed by using the Statistica ver. 6® computer software package and the values presented as the mean ± SD

(standard deviation). The probability levels used for statistical significance were $P < 0.05$ and parametric or non-parametric tests were used to compare groups. The four quality criteria as well as the number of stems were analysed with the multivariate analysis method, Principle Component Analysis (PCA), using CANOCO ver. 4.

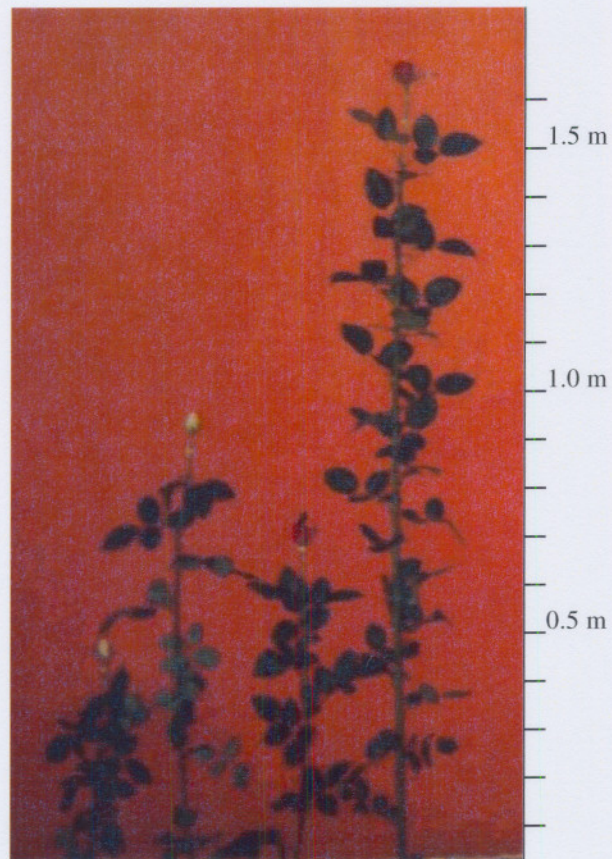


Figure 3.1: *The exceptional long stems of the cultivar 'Grand Gala' (two stems on the right hand side) used in this study vs. the more common stem lengths of another cultivar 'Biance' grown by the same grower.*

3.3 Results and Discussions

3.3.1 Minor length classes

The stems harvested for the replicas of the 2X, X and $\frac{1}{2}$ X treatment over the experimental period varied in length and each was thus divided (classed) into one of the twenty-five minor length classes. The number of stems in the minor length classes had a typical bell shaped (normal) distribution; increasing from a minimum in the 40.0 – 44.9 cm length class to a maximum in the 100.0 – 104.9 cm length class and then decreasing again to a second minimum in the 160.0 – 164.9 cm length class (Figure 3.2). This trend was similar for each of the three irrigation treatments.

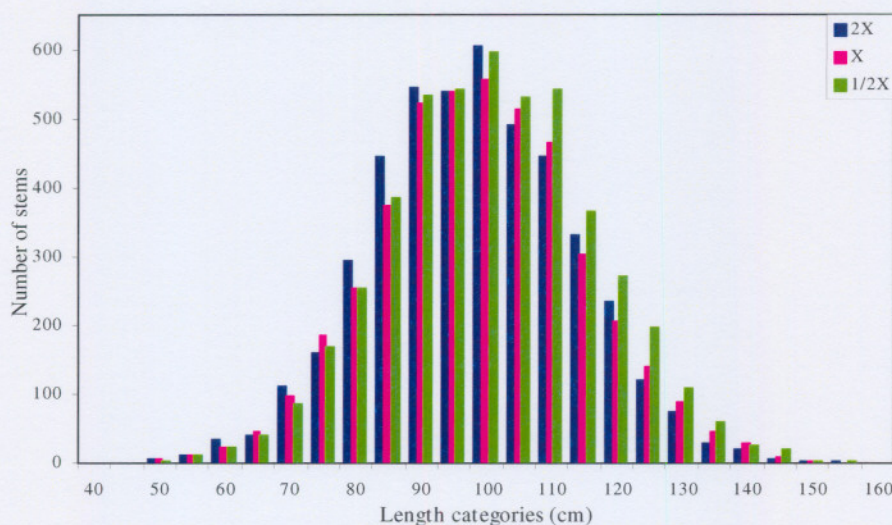


Figure 3.2: The number of stems harvested per minor length class for the 2X, X and $\frac{1}{2}$ X treatments respectively.

At a point of interest, however, the number of stems of the 2X treatment appeared to be the highest until the maximum number of stems was reached (40 – 100 cm), whilst the number of stems of the $\frac{1}{2}$ X treatment appears to be the highest from the 105 cm length class onwards up to the last length class (160 – 164.9 cm). The number of stems yielded by the X treatment was constantly intermediate, being neither the highest nor the lowest in most of the minor length classes.

3.3.2 Major length classes

After the stems of the three irrigation treatments were pooled to form the three major length classes viz. short, medium and long length class, it was plotted over time. The number of stems harvested per week in the three length classes (Figures 3.3a to c) as well as the total number of stems harvested per week (Figure 3.3d) per irrigation treatment depicts the differences in yield between treatments 2X, X and $\frac{1}{2}$ X on a weekly basis, very clearly. The cumulative number of

stems yielded by the 2X, X and $\frac{1}{2}$ X treatments in the short, medium, and long length class (Figures 3.4a to c) as well as the total number of stems (Figure 3.3d) provides the cumulative difference or similarities between the three irrigation treatments over the 20 week period. A general trend of declining yield can be observed in the number of short, medium and long stems as well as the total number of stems as the seasons changed from late summer to early winter over the 20 weeks. The decline in stems yielded by the different irrigation treatments was most pronounced in the last five weeks (Figures 3.3a to d). This decline is also very apparent in the cumulative number of stems where the curves begin to level out (week 16) (Figures 3.4a to d). From the data presented in Figure 3.3a and especially Figure 3.4a, it is evident that treatment 2X yielded the highest number of short stems (759) and treatment $\frac{1}{2}$ X the lowest number (654), whilst the number of stems (699) yielded by the X treatment were intermediate. The differences (in percentage) between the number of stems yielded per week in the different length classes as well as the total number of stems yielded per irrigation treatment are summarised in Table 3.1. No significant difference was, however, found between the number of short stems yielded by any of the irrigation treatments (Table 3.2). The highest number of short stems was harvested during week five and the lowest during week 20 (Figure 3.3a) for each of the three irrigation treatments.

Table 3.1: Summary of the differences (in percentage) between the number of stems yielded per week by the respective irrigation treatments (2X, X and $\frac{1}{2}$ X) in the different length classes as well as the total number of stems harvested for each treatment. (Negative values indicating that the values were smaller than 100 %, while the positive values indicate that the values were bigger than 100 %.)

Week	Short			Medium			Long			Total		
	2X	X	$\frac{1}{2}$ X	2X	X	$\frac{1}{2}$ X	2X	X	$\frac{1}{2}$ X	2X	X	$\frac{1}{2}$ X
1	100	-10.34	-10.34	-38.96	-28.92	100	-21.92	-15.53	100	-28.74	-21.46	100
2	100	1.72	-10.34	-27.92	-24.11	100	-29.40	-20.10	100	-26.18	-19.91	100
3	100	3.53	-15.29	-19.01	-21.90	100	-30.57	-21.02	100	-21.71	-18.40	100
4	100	-14.69	-20.98	-10.50	-15.83	100	-26.54	-17.88	100	-13.92	-14.50	100
5	100	-17.46	-29.76	-0.50	-9.36	100	-24.79	-17.32	100	-4.79	-9.32	100
6	100	-14.37	-25.75	1.07	-10.81	100	-24.85	-19.24	100	-3.46	-10.34	100
7	100	-7.55	-18.33	0.41	-8.84	100	-23.55	-18.18	100	-4.35	-8.88	100
8	100	-3.44	-13.51	-5.48	-8.28	100	-26.67	-18.66	100	-9.36	-8.91	100
9	100	-6.80	-16.89	-2.51	-5.27	100	-27.58	-20.04	100	-7.76	-7.86	100
10	100	-7.51	-18.38	-1.67	-4.95	100	-26.90	-20.25	100	-6.74	-7.56	100
11	100	-10.27	-21.42	0.11	-4.78	100	-24.22	-20.44	100	-4.13	-7.31	100
12	100	-10.65	-21.45	4.05	-3.31	100	-20.35	-17.30	100	-0.52	-5.43	100
13	100	-11.53	-18.56	6.30	-2.99	100	-17.89	-17.64	100	1.17	-5.86	100
14	100	-9.60	-15.76	5.32	-3.38	100	-17.96	-18.20	100	0.14	-6.37	100
15	100	-8.61	-14.58	3.23	-3.40	100	-18.26	-18.26	100	-1.41	-6.49	100
16	100	-7.92	-12.70	0.69	-4.02	100	-20.21	-18.76	100	-3.89	-7.29	100
17	100	-7.11	-13.02	0.77	-3.61	100	-21.90	-19.56	100	-4.61	-7.34	100
18	100	-7.56	-13.66	1.58	-3.19	100	-21.67	-19.13	100	-4.15	-7.05	100
19	100	-7.66	-13.61	1.90	-2.89	100	-21.07	-18.66	100	-3.89	-6.83	100
20	100	-7.91	-13.83	2.06	-3.21	100	-21.01	-18.88	100	-3.82	-7.13	100

Table 3.2: Average number of stems harvested, as well as the Productivity index determined for the four replicates of the different length classes of each treatment ($\pm$ s.d.) for the duration of the study (20 weeks).

^{a-c} Means with the same letter were not significantly different ($P > 0.05$)

Length class	Treatment	Number of stems	Productivity index
Short	2X	189.75 $\pm$ 10.53 ^a	74.00 $\pm$ 6.87 ^a
	X	185.00 $\pm$ 12.77 ^a	66.49 $\pm$ 9.81 ^a
	$\frac{1}{2}$ X	163.50 $\pm$ 17.02 ^a	61.61 $\pm$ 6.69 ^a
Medium	2X	731.75 $\pm$ 23.13 ^a	329.57 $\pm$ 13.98 ^a
	X	694.00 $\pm$ 13.74 ^b	307.98 $\pm$ 4.61 ^b
	$\frac{1}{2}$ X	717.00 $\pm$ 14.00 ^b	316.90 $\pm$ 6.45 ^b
Long	2X	343.00 $\pm$ 20.22 ^a	195.83 $\pm$ 13.05 ^a
	X	352.25 $\pm$ 10.69 ^a	204.75 $\pm$ 2.45 ^a
	$\frac{1}{2}$ X	434.25 $\pm$ 36.94 ^b	249.53 $\pm$ 26.73 ^b
Total Stems	2X	1264.50 $\pm$ 24.66 ^a	594.87 $\pm$ 27.26 ^a
	X	1221.00 $\pm$ 32.07 ^a	572.07 $\pm$ 20.05 ^a
	$\frac{1}{2}$ X	1314.75 $\pm$ 58.95 ^b	610.54 $\pm$ 35.24 ^b

In the instance of the stems in the long length class, the first peak (week 1) was the prominent peak with three less prominent peaks following at weeks 9, 12 and 16, respectively (Figure 3.3c). In three of the four peaks, including the peak at week 1, treatment $\frac{1}{2}$ X had the highest number of long stems with treatment 2X having only the highest number of long stems at week 12 (peak 3), the smallest of the peaks (Figure 3.3c). The difference in the number of long stems yielded by the $\frac{1}{2}$ X treatment compared to that of the X and 2X treatments, is clearly visible in Figure 3.4c. From the onset of the experiment, the number of long stems yielded by the $\frac{1}{2}$ X treatment was the highest. At the end of the experiment the $\frac{1}{2}$ X treatment yielded significantly more long stems (1737) than the 2X (1372) and X treatment (1409), respectively (Figure 3.4c; Table 3.2).

As for the total number of stems (Figure 3.3d) harvested for each treatment, the trend is very similar to that describing the yield of the stems in the medium length class (Figure 3.3b), with the 2X and $\frac{1}{2}$ X treatments having the highest total number of stems on different sides of the normal distribution curve, and the number of stems of the X treatment being intermediate (Figure 3.2). Again, very similar to the trend described for the stems in the medium length class (Figure 3.4b), the curves of the three irrigation treatments were intertwined when the number of stems were cumulatively added, but in this instance, however, the $\frac{1}{2}$ X treatment yielded the highest number of stems (5259) in comparison with the 5058 and 4884 stems yielded by the 2X and X treatments respectively (Figure 3.4d). The total number of stems harvested for the $\frac{1}{2}$ X treatment was significantly higher than that harvested for the 2X and X treatments (Table 3.2). Of interest is to note that where the yield in terms of number of short stems (Figure 3.3a) and to a lesser extent the yield in terms of number of medium stems (Figure 3.3b) were the highest, the corresponding yield in the long stems (Figure 3.3c) were minimal (weeks 5 and 12). The

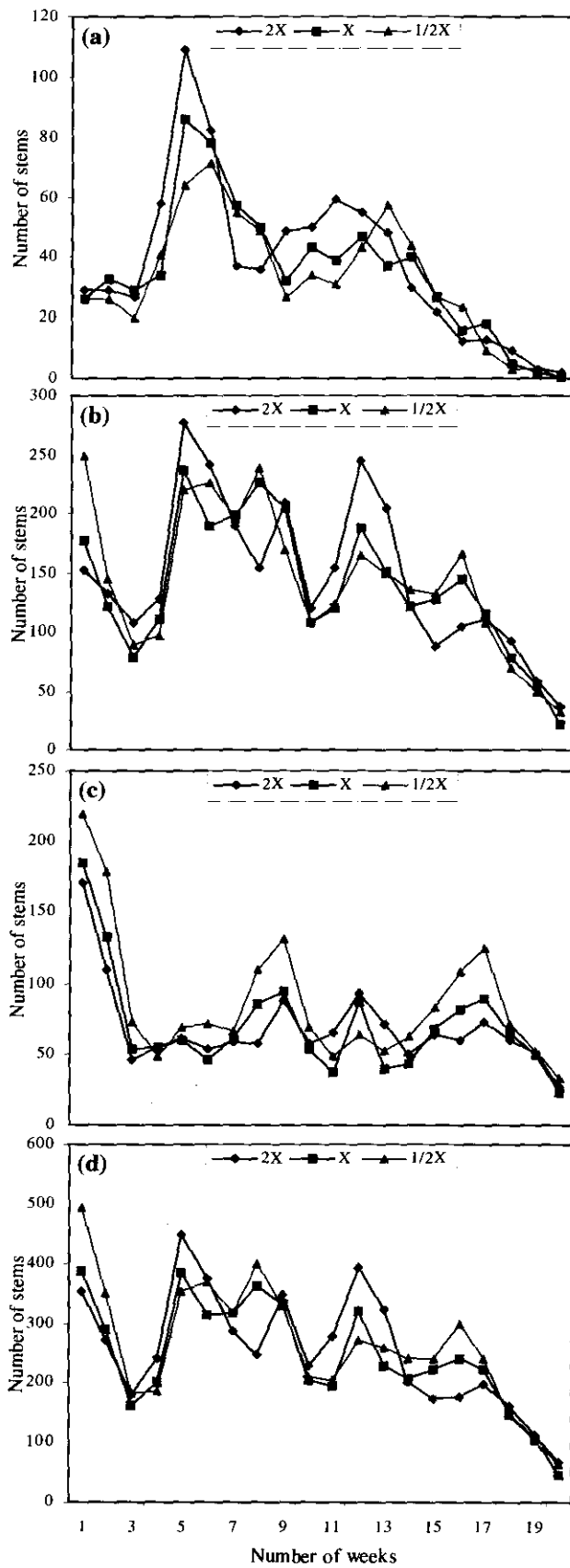


Figure 3.3: Number of (a) short, (b) medium, (c) long and (d) total stems harvested per week per treatment.

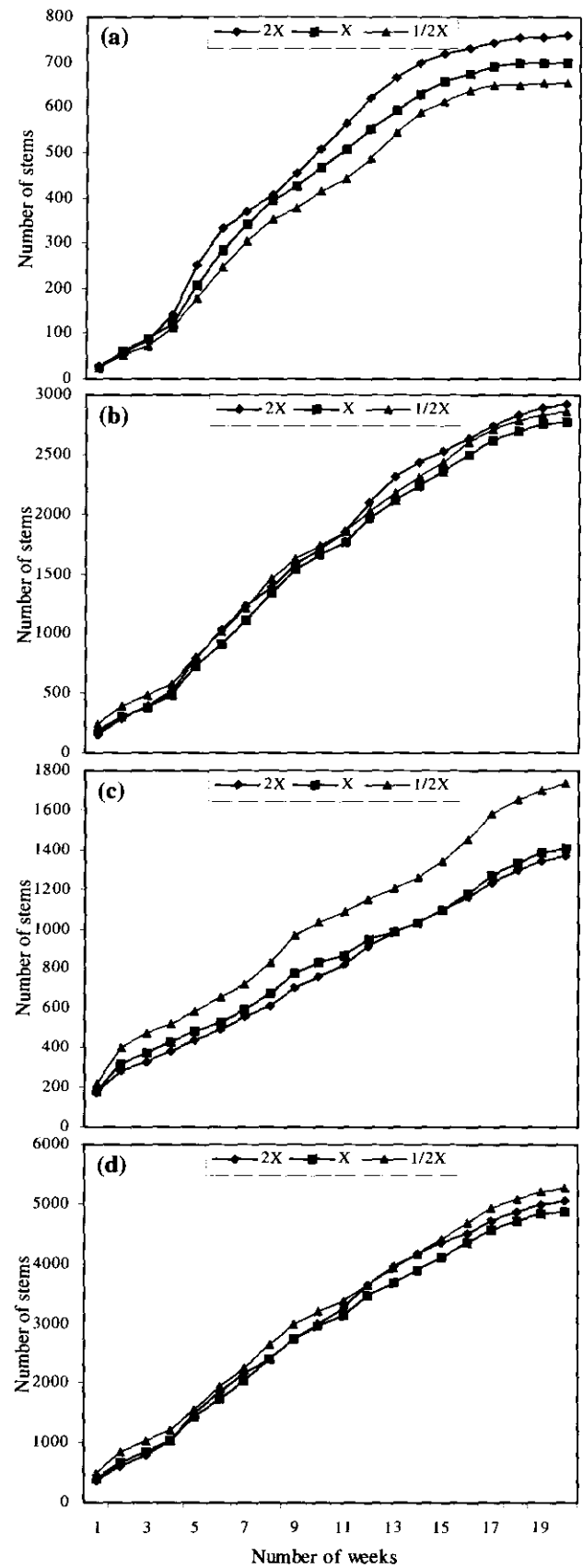


Figure 3.4: Cumulative number of (a) short, (b) medium, (c) long and (d) total stems harvested per week per treatment.

opposite is, however, also true; where the yield in terms of number of medium (Figure 3.3b) and long stems (Figure 3.3c) were the highest (week 1) the corresponding yield in the short stems (Figure 3.3a) were minimal (non existent).

Although there was a marked difference between the flowering cycles of the short (Figure 3.3a), medium (Figure 3.3b) and long stems (Figure 3.3c) as well as the total number of stems (Figure 3.3d) with reference to the amplitude and the frequency of the yield curves when compared too each other, the difference between the amplitude and the frequency of the yield curves of the number of stems harvested in a specific length class for the three irrigation treatments did not vary noticeably. Generally, the amplitudes of the yield curves of the short, medium and long stems as well as the total number of stems diminished with time.

The total number of stems harvested for the 2X, X and $\frac{1}{2}$ X treatments as well as the number of stems in the short, medium and long length classes for the respective treatments are summarised in Table 3.3. The above mentioned are expressed as (1) the total number of stems harvested treatment (per bed; 556 plants) during the 20 weeks, (2) the number of stems harvested per m⁻² during the 20 weeks as well as (3) the number of stems harvested per plant during the 20 weeks. Where possible the number of stems harvested by other researchers are also given for comparison; (note the difference in the duration of the experimental periods for, the season the data was collected, and where mentioned, the plant density in the literature; summarised in more detail in Table 3.4). The yield data was compared by extrapolating or interpolating the values recorded in the literature to the yields expected during an experimental period of 20 weeks. This was done for the number of stems yielded per plant as well as per m². When comparing the total number of stems yielded per plant by the three irrigation treatments over a 20 week period in this experiment (9.1, 8.8 and 9.5) to that of the number of stems recorded by other researchers, the latter was found to be lower in some instances (4.5 – 7.5 (Hopper, 1996:939) and 6.1 – 8.6 (Tsujita & Dutton, 1983:874)) and higher in others (15.2 – 27.3 (Shanks *et al.*, 1986:389); 23.0 – 33.2 (Balazsovits *et al.*, 1988:984); and 9.6 – 12.6 (Van der Walt, 1999:20)), while in still other experiments the minimum value was found to be lower but the maximum value higher than that obtained during this experiment by one or all of the treatments (6.7 – 8.9 (Agbaria *et al.*, 1995:654)) (Table 3.3). The same results were observed when the total number of stems yielded by the 2X, X and $\frac{1}{2}$ X treatments per m² over a 20 week period (72.8, 70.3 and 75.7 respectively) were compared to values obtained in other experiments. Higher numbers of stems ranging from 97.1 to 121.1 and 181.1 to 304.9 were harvested in experiments done by Kool *et al.* (1997:625) and Kool & Van de Pol (1996:137) respectively (Table 3.3); in other experiments where the minimum number of stems harvested was lower but the maximum higher, the values ranged

Table 3.3: Total number of stems harvested per treatment, per plant and per m², the PI of each length class as well as the total number of stems yielded by the 3 irrigation treatments. Values found in the literature for comparison to the above mentioned yield criteria and the flowering time are summarised on the right.

Yield criteria	Length classes			Literature references for comparison	
No. stems treatment ⁻¹ (% of the total number of stems treatment ⁻¹)	Short	2X	759 (15%)		
		X	699 (14%)		
		½X	654 (12%)		
	Medium	2X	2927 (58%)		
		X	2776 (57%)		
		½X	2868 (55%)		
	Long	2X	1372 (27%)		
		X	1409 (29%)		
		½X	1737 (33%)		
	Total	2X	5058		
		X	4884		
		½X	5258		
Stems Plant ⁻¹ 20 Weeks ⁻¹ (Late Summer – Early Winter)	Short	2X	1.365	2.4–2.9 / 2.4–3.2 24.2–34.9 6.1–7.0 / 7.0–8.2 1.5 / 0.9 / 0.9 / 1.3 16.9–23.8 23.2–30.3 9.5–13.5 8.3 / 6.7 / 8.8 / 6.8	Agbaria <i>et al.</i> , 1995 – Is and Mc (49 days) Balazsovits <i>et al.</i> , 1988 – R (21 weeks) Clark <i>et al.</i> , 1993 – Mj (winter (2 months) and summer (2 months)) Hopper, 1996 – Ga, R, Sa and So (winter (4 weeks)) Shanks <i>et al.</i> , 1986 (2 nd year) FY, PS, WS and Vo (5 months) (3 rd year) FY, PS, WS and Vo (5 months) Tsujita & Dutton, 1983 – Ga (7 months) Van der Walt, 1999 – GG (Pecan nut shells, Macadamia nut shells, Coconut fibres and Rockwool – late winter and spring (14 weeks))
		X	1.257		
		½X	1.176		
	Medium	2X	5.264		
		X	4.993		
		½X	5.158		
	Long	2X	2.468		
		X	2.534		
		½X	3.124		
	Total	2X	9.097		
		X	8.784		
		½X	9.459		
Stems m ⁻² 20 Weeks ⁻¹	Short	2X	10.92	565 / 488 / 453 161–166 / 209–222 / 245–271 130–160 30–60 / 48–120 / 55–125 53–112 / 59–244 / 77–200 55–87 / 67–143 / 77–197 30–60 / 44–120 / 55–125 43–82 / 35–173 / 57–136	Kool <i>et al.</i> , 1997 – F (Control, Flush and One stemmed – Feb. 1992 to Oct. 1993) Kool & Van de Pol, 1996 – Mo (Avg. '91–'94: Nov–Feb, Mar–Jun, Jul–Oct) Meilland poster (1992?) (Chapter 2) – GG (1 year) Moss, 1984 Exp 1: Io, Mc and So – 6.67 Plants.m ⁻² (22 weeks) Exp 2: Exp 3: Moss & Dalglish, 1984 (1 st year- 22 week winter) – Io, Mc and So (2 nd year – 17 week summer)
		X	10.06		
		½X	9.41		
	Medium	2X	42.12		
		X	39.94		
		½X	41.26		
	Long	2X	19.74		
		X	20.27		
		½X	24.99		
	Total	2X	72.78		
		X	70.27		
		½X	75.67		

Table 3.3: Continued

Yield criteria	Length classes			Literature references for comparison	
PI Bed ⁻¹ 136 days ⁻¹ (PI Plant ⁻¹ 136 days ⁻¹) (g cm ⁻¹ number of stems)	Short	2X	296 (0.53)	12–15 per plant 8.54–10.49 per plant	Mortensen & Gisterød, 1999 – 14 cultivars (3 flushes – 135 to 160 days) Shanks <i>et al.</i> , 1986 (2 nd year) FY, PS, WS and Vo (112 days)
		X	267 (0.47)		
		½X	248 (0.48)		
	Medium	2X	1323 (2.37)		
		X	1236 (2.25)		
		½X	1265 (2.27)		
	Long	2X	782 (1.41)		
		X	822 (1.47)		
		½X	998 (1.78)		
	Total	2X	2388 (4.31)		
		X	2285 (4.19)		
		½X	2401 (4.47)		
Flowering time (days)	–	–	–	49 41–44 37 45 45–51 40–75 38–79 / 34–77 / 33–75 39–41 44 / 43 45–55 42–56 46–78 54–80 / 54–87 / 62–96 / 58–93 51–116 63–91 45–48 50–65 / 54–65 / 51–62 / 53–65	Agbaria <i>et al.</i> , 1995 – Is and Mc Balazsovits <i>et al.</i> , 1988 – R Cabrera <i>et al.</i> , 1995a – R Cabrera <i>et al.</i> , 1995b – R Clark <i>et al.</i> , 1993 – Mj (late winter-early summer) Durkin, 1992 Hopper & Hammer, 1991 – R (I = 100, 175, 250) Mortensen, 1995 – Sou Mortensen & Fjeld, 1998 – Sou (RH 65 and 90) Mortensen & Gislerød, 1999 – 14 Rose cultivars Pellett <i>et al.</i> , 1998 (General) Shanks <i>et al.</i> , 1986 (1 st year) FY and PS (3 rd year) FY, PS, WS and Vo (3 rd year) FY, PS, WS and Vo Van der Walt, 1999 – GG (14 weeks – late winter and spring) Zeroni & Gale, 1989 – So Zieslin <i>et al.</i> , 1987 – GT, Mc, So and Vi

Abbreviations used in Table 3.3 (see List of Abbreviations, page x)

from 27.3 to 221.8 (Moss, 1984:552 and Moss & Dalgleish, 1984:895). Interesting enough, interpolating the number of stems yielded per m² as recorded by the breeders of the cultivar used in this experiment ('Grand Gala') (values stated on the Meilland Poster (1992?) – Chapter 2) to the expected number of stems that could have been harvested during a 20 week period it was found ranging from 48.8 to 60.0, being less than the number of stems harvested during this experiment for the 2X, X and ½X treatments, respectively (Table 3.3).

A single value, called the Productivity Index in this study, combining the production as well as the quality of the stems harvested for the different irrigation treatments can be useful to compare the productivity of the different irrigation treatments. As the PI is a combined function of the Quality Index (QI = Fresh weight/Length) and the number of stems harvested per time period, the fact that the QI remained relatively constant, means that the fluctuation in the PI of the number of stems harvested per week (Figure 3.5) can be attributed to the variation in the number of stems harvested per length class (Figures 3.5a to c) and the total number of stems harvested (Figure 3.5d). The PI of the stems divided into the different length classes (Figures 3.5a to c) as well as the total number of stems (Figure 3.5d) for each treatment follows the same trend as the number of stems yielded in the different length classes as well as the total number of stems harvested for the different irrigation treatments. The 2X treatment had the highest PI value for the short stems (296) as well as the medium stems (1323), while the ½X treatment had the highest PI value for the long stems (998) as well as the total number of stems (2401) (Table 3.2) when comparing the PI values of the three irrigation treatments determined for the total number of stems harvested per treatment. The PI values found in the literature ranging from 10.4 to 15.0 (Mortensen & Gislerød, 1999:291; Shanks *et al.*, 1986:389), are higher than that calculated for the total number of stems yielded per plant per treatment (4.3, 4.2 and 4.5) (Table 3.3), and may be attributed to the high number of stems harvested during these experiments and/or the high ratio of stem fresh weight to stem length (discussed in more detail in the next Chapter).

The decrease in the number of stems (short, medium and long as well as total) of the three treatments during the course of the experiment can possibly be ascribed to a seasonal effect. Different external input variables may contribute to this seasonal effect viz. day length (irradiance duration), irradiation level, temperature (night, day and root zone), carbon dioxide concentration ([CO₂]) and air humidity not to mention irrigation and fertiliser application (volume and frequency).

Although rose plants are self-inductive, meaning that flower initiation is independent of environmental factors, yield and yield related variables are still influenced by environmental

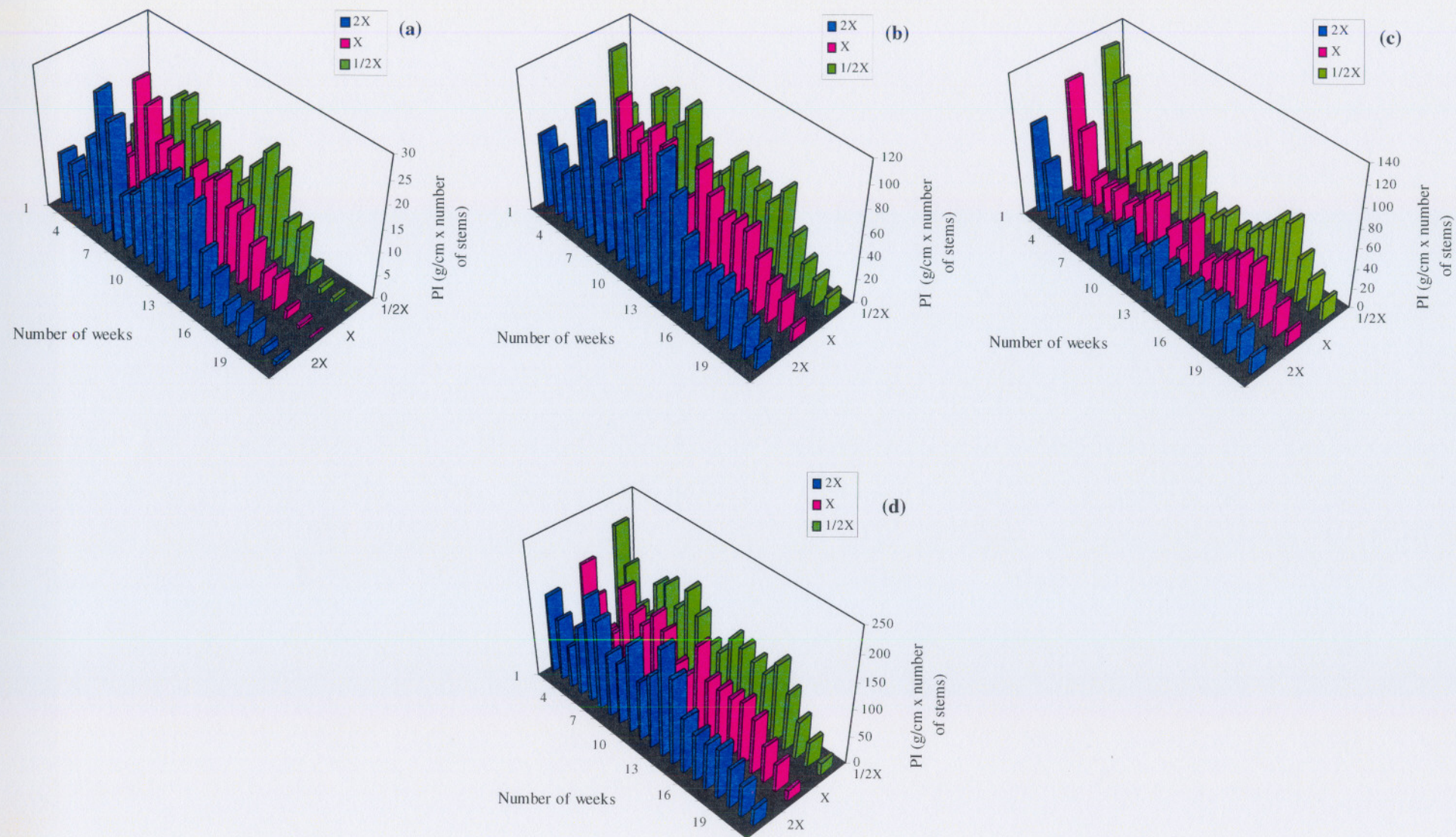


Figure 3.5: Production Indices for the short (a), medium (b) and long stems (c) as well as the total number of stems (d) harvested for the 2X, X and 1/2X treatments.

conditions. Under specific combinations of the environmental variables the yield is maximised. A deviation from these specific conditions may cause a decrease in yield. The interrelated nature of the environmental variables impairs the determination of the optimum environmental conditions, since the increase of one necessitates the increase in the other variables. For example, in the instance where the irradiance is increased, the temperature, CO₂ concentration, irrigation as well as fertiliser application must also be increased. The irradiance may be increased by increasing (1) the amount of irradiance received (usually by applying supplementary irradiation), (2) the irradiance duration (by applying supplementary irradiation and (3) the irradiance quality (ratio of red to far red levels). Increasing the temperature might include the increase of the day temperature as well as the night temperature or the increase of the root zone temperature. Generally, yield increases as the environmental variables increases up to a maximum after which a further increase in the variables causes a decrease in yield. Yield is also decreased with the occurrence of blind shoots (blindness), since blind shoots are shoots without flowers these stems are discarded and cannot attribute to the yield. The increase in the time a stem takes to develop from the auxiliary bud (buddbreak) to anthesis (flowering), expressed in this experiment as the flowering time, also decreases the number of stems harvested per time period. The flowering time also has an effect on the flowering cycles; the longer the flowering time, the less flowering cycles occur over a certain period of time and the less stems are harvested per time period. As for the yield, the number of stems harvested, the flowering time, the number of flowering cycles as well as the number of blind shoots are also influenced by the prevailing environmental conditions, although it varies between different cultivars. Roses are grown under a wide variety of environmental conditions (combinations of environmental variables). The effect of different environmental conditions and experimental location on the number of stems yielded by, the flowering time of, and occurrence of blind shoots in various cultivars of varying ages and plant densities, as well as the harvesting technique used are summarised in Table 3.4

Some rose cultivars are more successful than others when it comes to adapting to higher or lower environmental variables. Generally, the conditions under which the plants were propagated have a profound influence on their adaptability for example, if rose plants were propagated in South Africa, chances are better that it would be more adapted to South African conditions, than plants propagated in Canada and then exported to South Africa, for instance.

Since the PI values of the different irrigation treatments are a function of the yield, it is also influenced by the seasonal changes in the environmental conditions inside the greenhouse,

generally being higher when the environmental conditions favour the increase in growth and development and thus yield as described above.

3.3.3 Flowering time (stem developmental time)

Although the flowering time was not determined in this experiment, the assumption could be made that the flowering time increased as the winter period closed in. The actual flowering time can not, with absolute certainty be said to have ranged between any two specific values. In the literature (Table 3.3) there are some references to the specific flowering time of roses, ranging from a duration as short as 37 days (Cabrera *et al.*, 1995a:62) to as long as 116 days (Shanks *et al.*, 1986:389). These values were however obtained at various environmental conditions using different cultivars (Table 3.4). There exist an uncertainty as to what the combined effect of high environmental variables and the extraordinary long stems would be on the specific duration of flowering time. It is however assumed that the longer the stems are the longer the time it will takes to reach the stage of anthesis.

3.3.4 Principal Component Analysis

The results of the Principal Component Analyses (PCA's) of the yield (number of stems) as well as the four quality criteria (leaf area, fresh weight, bud length and stem diameter) data, for the short, medium and long stems of the three irrigation treatments, are presented in Figures 4.3a to c and Figures 4.4a to c in Chapter 4. As a PCA graph depicts the distribution of a number of points in a multiple axed (multi dimensional) graph on a two dimensional plane (graph) it should be noted that each variable is represented by an arrow, the length of which is representative of the significance of the variable and the distance between arrows are indicative of how closely variables are correlated or not. From the PCA's, when the different length class data was pooled and the yield as well as the four quality criteria analysed per irrigation treatment (Figures 4.4a to c; Chapter 4) it became apparent that, the length classes of each treatment differed distinctly from one another as the data points of each length class grouped together, but in distinctly separate groups. For all three irrigation treatments (Figures 4.4a to c) the data points of the medium stems were the closest to the arrow representing the number of stems (yield) indicating that the stems in this length class had the highest number. The data points of the short stems were the furthest from this arrow, while the data points of the long stems where intermediate. This inclination was found irrespective of the treatment. When the treatment data was pooled and the yield and quality criteria analysed per length class (Figures 4.3a to c) the homogeneity per length class became apparent. This homogeneity may be ascribed to the fact that the data used in the PCA's were the data determined daily, and not the weekly average data (quality

criteria) or the total of the stems harvested per week (yield). As for the yield, the homogeneity of the stems yielded by the different irrigation treatments in a specific length class should not be misinterpreted since the emphasis was put especially on the differences between the total number of short, medium and long stems harvested on a weekly basis. (Not taking the effect of time into account.) Care should, however, be taken with the interpretation of the latter data, as it might to some degree be the consequence of the arbitrary length class divisions made.

Table 3.4: Effect of different environmental variables and horticultural practices used on the number of stems harvested during various experiments.

Irradiance duration (h)	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature ($^{\circ}\text{C}$)	$[\text{CO}_2]$ ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Yield	Literature
Sum-Win 13h45–10h40	Min and Max 43–60 (day)	NT_a / DT_a 10–25/17–39	300–610 (07h00) 290–370 (12h00)		South Africa: Nylstroom Sum – Win 20 weeks	GG 2 Years 8.5 plants m^{-2} Multiple stemmed	$I \uparrow + T_a \uparrow$: Yield $\uparrow$ $\text{Irr}_{s,i} \uparrow^{20.4 \text{ pl m}^{-2}}$: Yield $\downarrow$	This experiment
Cloudy Weather 24 h (Oct–30Apr)	SL(HPS) 50 HPS : $\uparrow$ Red/FR	NT_a / DT_a (Min) 16 / 20 Vent. 25+	330,900,1500 8h–18h 22Nov–1May		Canada: Quebec 12 Jan–7 Jun	R 8 Months 8 plants m^{-2}	$\text{SL} + \text{C}_a \uparrow$: Basal Stems $\uparrow$ Yield $\uparrow$ 69% FT $\downarrow$ $\text{SL} + \text{C}_a$ (900) : Basal Stems $\uparrow$ $\text{SL} \uparrow / \text{C}_a \uparrow$: Yield $\uparrow$ 34/26%	Balazsovits <i>et al.</i> , 1988
Long	17.8–21.0 (day)	High	1000		Denmark: Aarslev	L, MB, RV, So 100 plants m^{-2} (1) 100+ plants m^{-2} (2) 1 stemmed	$I \uparrow$: FT $\downarrow$ Blindness $\downarrow$ Pl density (1) or (2) : FT (1) $\downarrow$, (2) $\downarrow$ Blindness (1) $\downarrow$, (2) $\downarrow$	Bredmose, 1997
	Win 35.9 (day) Spr 66.8 (day) (Total I)	4–16 Shipping temp	350,700,1050		USA: Clemsen 10 Dec–10 Feb (Late Win) 3 Mar–21 Apr (Early Spr)	Mj 472 $\text{cm}^3 \text{pot}^{-1}$	$\text{C}_a \uparrow$: FT $\downarrow$ No. Flowers* $I \uparrow$: No. Flowers $\uparrow$ $\text{C}_a \uparrow$: Shoot + Root growth $\uparrow$ $I \uparrow$: Shoot + Root growth $\uparrow$	Clark <i>et al.</i> , 1993
	1200 SL 50–100	NT_a : 16–21 (LL) 16–27 (HL) NT_a / DT_a 7 7 / 27–30 NT_a 20	900–1000	60–80	USA	General 1 plant 900 cm^{-2}	$T_a \uparrow$: Growth rate $\uparrow$ FT : 40–48 days T_a , I, $\text{C}_a \uparrow$: Yield $\uparrow$ $T_a \uparrow$, I, $\text{C}_a \downarrow$: Yield $\downarrow$ Blindness $\uparrow$ $\text{NT}_a \downarrow$, $\text{DT}_a \downarrow$: FT $\uparrow$ 75days $\text{NT}_a \downarrow$, $\text{DT}_a \uparrow$: FT, 55–60 days $\text{C}_a \uparrow$: Yield $\uparrow$ $I \uparrow$: Yield $\uparrow$ $I \uparrow$: $T_a \uparrow$, RH $\downarrow$ I_1 (shading) : Yield $\uparrow$ $\text{SL} \uparrow$, $\text{NT} \uparrow$ (winter) : Growth $\uparrow$ Yield $\uparrow$ Irr $\uparrow$ Fertiliser $\uparrow$	Durkin, 1992

Table 3.4: Continued

Irradiance duration (h)	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature ($^{\circ}\text{C}$)	$[\text{CO}_2]$ ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Yield	Literature
			Max : 2000				$[\text{CO}_2]\uparrow$ $C_a\downarrow$: Growth $\downarrow$ $C_a\uparrow$: $I\uparrow$ $T_a\uparrow$ Fertiliser $\uparrow$ Irr $\uparrow$	Freeman, 1998
Day + 10h night ⁻¹	Natural Natural + SL (SL = 100)	$\text{NT}_a / \text{DT}_a$ 16 / 23			USA: Colorado 30 Oct–29 Feb 4 Months (Win)	Ga, R, Sa, So 1 Year 10.5 plants m^{-2} Pinched 2 Stemmed	SL : Yield $\uparrow$	Hopper, 1996
Day / Night 12h / 12h	100,175,250	$\text{NT}_a / \text{DT}_a$ 12–22 / 20–25		50–95 Ebb+Flood	USA: Indiana	R 2–3 Months 1 plant 640 ml pot^{-1} 1 Stemmed	$\text{DT}_a\downarrow + \text{NT}_a\downarrow$: FT $\uparrow$ $I\uparrow$: FT $\downarrow$	Hopper & Hammer, 1991
	100–1200	15–30 (Int:5) 22	350–1500 (Int:300–350)		Canada: Guelph	Sa 1 Stemmed	Contributed I (100–1200) : 64% I Duration (8–16) : 31% C_a (350–1500) : 4% DT_a (15–30) : 0.3% NT_a (15–25) : 0.7% to Growth	Jiao <i>et al.</i> , 1991c
		$\text{NT}_a / \text{DT}_a$ 17 / 19 12 / 12 (Nov–Jan)			Netherlands Apr'92–Sep'93	F 3 Months 13.3 plants m^{-2} Control 1 Stemmed Flush	Yield : Con $\uparrow$ /Flush $\uparrow$ /1 ^{Stemmed} $\uparrow$	Kool <i>et al.</i> , 1997
	Very High (Shade)	$\text{NT}_a / \text{DT}_a$ 16 / 27			South Africa	General 8 plants m^{-2}	$T_a\downarrow$: Yield $\downarrow$ $T_a\downarrow_{13}$: Yield $\downarrow$	Meyer <i>et al.</i> , 1988a
18h	Natural 7.3 day SL 11.3 day	Daily Mean 18.7	355	75	Norway (Win)	Sou 1 plant 2 ℓ pot^{-1} 2 Stemmed	Methanol foliar sprays : FT*	Mortensen, 1995
16,20,24h	SL (Fluo) 170	20	800	65 / 95	Norway	Sou	RH $\uparrow$: FT $\uparrow\downarrow$	Mortensen &

Table 3.4: Continued

Irradiance duration (h)	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature ($^{\circ}\text{C}$)	$[\text{CO}_2]$ ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Yield	Literature
20h	SL (HPS) 170	LT 0.5–1.0†		(819 / 234)	12 Mar	6 Months 8 plants 2.5 m^{-2} 2 Stemmed	I† : FT↓	Fjeld, 1998
18,24h	SL : 200 13 / 17 (day) Natural : 4.3,1.8,0.7,1.4, 2.1,6.7 (day) (Oct–Mar)	19	800	75,83,91 550,390,200	Norway Oct'97–Mar'98	14 Cultivars 3.5–4 months 22 plants m^{-2} + 19 plants m^{-2} Flush	RH† : Yield* I _{dur} † : Yield†	Mortensen & Gislerød, 1999
Daytime	Natural 20–64 (day)	RZT : 25 / Ambient NT _a : 18,12,9 18,14,10 DT _a : 21 (25 Vent.)			Australia: Griffith Win–Spr–Sum 22 Weeks	Io, Mc, So 8 plants 1.2 m^{-2} Stagger	RZW : Yield† Growth flush: Amplitude† Frequency* Sum : RZW Yield†	Moss, 1984
Daytime (07h00–16h30)	Natural : 32 (PPF or Total I?)	RZT : 25 / Ambient NT _a : 18,12,9 18,14,10 DT _a : 21 (25 Vent) (27 EvapC)			Australia: Griffith 2 Years : Win–22 Weeks 17 Weeks Sum–5 Weeks	Io, Mc, So 8 plants 1.2 m^{-2} Stagger Light prune Stagger	RZW : % Long stems† Yield† Sum : RZW Yield†	Moss & Dalglish, 1984
		Optimum : NT _a / DT _a 16 / 19–22 (cloudy days) 16 / 24 (clear days) 16 / 27 (C _a enriched)	Limiting : 50–125 Optimum : 1000–1500 – crop specific			General	C _a deficiency : FT† C _a toxicity : Yield↓ C _a † for roses : Blindness↓ FT↓ T _a † ^{+6°C} Fertiliser† I† I† _{full summer} for roses : Growth† I↓ _{optimum} for roses : Blindness† I + SL duration† ^{18h} : FT†	Nelson, 1991

Table 3.4: *Continued*

Irradiance duration (h)	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature ($^{\circ}\text{C}$)	$[\text{CO}_2]$ ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Yield	Literature
SL 16–18h SL 24h SL 18h day ⁻¹	Very high (shaded)	Optimum $\text{NT}_a / \text{DT}_a$ 7–18 / 24–32 Some cultivars: $\text{NT}_{a \text{ min}}$: 4–10			USA	General Plants ha ⁻¹ : Outside 35000–50000	Yield ^{50%} $\text{I} + \text{SL duration}_{18} \uparrow^{24}$: Yield ₁ or ¹ Water quality $\downarrow$: Growth $\downarrow$ Rootstock Natal Brier : Yield 15–20 % $\uparrow$	Pellett <i>et al.</i> , 1998
Sunny days		$\text{NT}_{a \text{ min}}$: 12, 10, 9 $\text{DT}_{a \text{ min}}$: 17 (Vent 24) $\text{NT}_{a \text{ max}}$: 17 for 0, 3, 6, 9, 15h			USA: Maryland: College Park 3 Years Oct'78–Apr'81	FY, PS, WS, Vo 4 Years 20 ℓ Pots Spacing: 35x45	$\text{NT}_{a \text{ dur}} = 17 \uparrow$: FT $\downarrow$ Yield $\uparrow$ FT : February = Min December = Max $\text{NT}_{a \text{ min}}$: FT 9 $\downarrow$, 12 ¹	Shanks <i>et al.</i> , 1986
20 h day ⁻¹	Natural I. $\downarrow$ SL : 75	20	700	70 / 90	Norway	B Cuttings 66 Plants m ⁻² 1 Stemmed	RH $\uparrow$: Growth*	Torre & Fjeld, 2001
12h (06h00–18h00)	Natural Natural + SL (nightly) : 55	RZW : 13, 18, 23 NT_a : 13 DT_a : 21	900–1000 (08h00–16h00)		Canada: Guelph Oct'79–Apr'80	Sa, Ga 5 Months+ Spacing 30 x 30	Samantha SL : Yield $\uparrow$ RZW : Yield* Gabriella SL / RZW : Yield $\uparrow$ SL + RZW : Yield*	Tsujita & Dutton, 1983
Natural	07h00 / 12h00 Inside : 300 / 800 Outside : 800 / 1900	Min / Max 8–15 / 18–27 RZW : Min / Max 15 / 26 (07h00–17h00)	Predawn : 850 07h00 : 630 10h00 : 550 12h00 : 550 15h00 : 440 17h00 : 500		South Africa: Muldersdrift July'96–Oct'96 (14 Weeks)	GG 3 Years 3 plants 10 ℓ pot ⁻¹ Spacing 15 cm	Pecan nut shells : Yield $\uparrow^{\text{max}}$	Van der Walt, 1999
4 h	SL : 7.5 (day)	24h avg. = 19 $\text{NT}_a / \text{DT}_a$ 19 / 19 (1) “Voornachtverhoging” (2)	700 (during lighting)	80–85	Netherlands: Aalsmeer	FR	Treatment (2) : Yield*	Vogelezang & De Hoog, 1998

Table 3.4: Continued

Irradiance duration (h)	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature ($^{\circ}\text{C}$)	$[\text{CO}_2]$ ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Yield	Literature
		$\text{DT}_a - \text{NT}_a = +5$ (3) $\text{DT}_a - \text{NT}_a = -5$ (4)						
06h30–17h15	0–1000	$\text{NT}_a / \text{DT}_a$ 18 / 30 ^{max}	Daytime : 320,600,1200 Nighttime : 350	80 _{min}	Israel (Win)	So 6 Months 1 plant 10 l pot ⁻¹ ; 5 plants chamber ⁻¹	$\text{C}_a + [\text{Salt}]$ (g m^{-2}) 320 + 3436 : Plants died $\uparrow + 3436$: Stopped growing $\uparrow + 1718$: Growth $\uparrow$ $\uparrow + \uparrow$: Yield $\uparrow$ Blindness $\downarrow$ Salt = 2577 : Growth $\downarrow$ but $\uparrow$ than at $[\text{C}_a] = 320$ 1200 + $\uparrow_{1718}$: Side branches $\uparrow$	Zeroni & Gale, 1989
	Natural	DT_a : 18 _{min} (Outside) NT_a : 18 constant 14 constant 18/14 SN 18/14/18/14 P			Israel: Rehovot Oct'81–May'82	GT, Vi, Mc, So 1 Year	Low T_a : FT $\uparrow$ Constant T_a 14 $^{\circ}\text{C}$: Yield $\downarrow_{\text{min}}$	Zieslin <i>et al.</i> , 1987
8h (SD) 8+ 14h (LD)	SL (Fluo) 13.4 + SL (Inc) 4.1 or SL (Fluo) 6.9	15 RZW 20 or 15			General		$\text{T}_a \downarrow$: Bullhead flowers $\uparrow$ $\text{I} \downarrow$: Blindness $\uparrow$ $\text{I} \uparrow + 15^{\circ}\text{C}$: Blindness $\downarrow$ SL (Inc + Fluo) : Blindness $\downarrow$ SL (Fluo + Fluo) : Blindness $\downarrow$ SL (Inc + Fluo) + 21 : Blindness $\uparrow$ than SD (FR) $\uparrow$: Blindness $\uparrow$ (R) $\uparrow$: Blindness $\downarrow$ FR or R (NB) : Blindness* $\text{T}_a \uparrow$: Blindness $\downarrow$ $\text{T}_a \downarrow_{15} + 600$ (I) + SD : Blindness $\uparrow^{100\%}$ RZW ²⁰ $\downarrow_{15}$: Blindness $\uparrow_{28\%}^{50\%}$ Dif. Rootstocks : Blindness $\uparrow$ or $\downarrow$	Zieslin & Moe, 1985

Table 3.4: Continued

Irradiance duration (h)	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature ($^{\circ}\text{C}$)	$[\text{CO}_2]$ ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Yield	Literature
							T_a ↓ for short periods : Bud break↑ NT_a (18) + DT_a (22–30) (Israel) : FC 4–5 (Oct–May) Europe (Win) : Growth + FC = 0 Israel (Sum) : FC 3–5 (Jun–Sep)	

Abbreviations used in Table 3.4 (see List of Abbreviations, page x)

3.4 Conclusion

From the results presented above it can be concluded that the treatment receiving the lowest volume of water ($\frac{1}{2}X$ treatment) was the treatment that yielded the highest number of good quality stems as well as the highest number of the total stems harvested. This would seem to indicate that roses grown under similar growth conditions as prevailing in this experiment (described in Chapter 2), might be receiving too high a volume of irrigation water. It is also evident from the results presented that the volume of irrigation water applied to the rose plants is just as important as the other environmental variables that were discussed.

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CHAPTER 4

Quality

Abstract

Rose plants of the cultivar Grand Gala (*Rosa hybrida*), grown in soil as growing medium, were subjected to three different (volume) irrigation treatments (2X, X and ½X). The X treatment served as the control treatment with the rose plants receiving the same volume of irrigation water (late summer: 1.2 l plant⁻¹ day⁻¹, early winter: 1.0 l plant⁻¹ day⁻¹) as the rest of the greenhouse plants (plants not included in the experiment). The plants of the 2X treatment received twice the volume of water applied to the X treatment while the ½X treatment received only half the volume. The experimental period started in the middle of summer and ended in early winter (1 February 1999 – 16 June 1999). The stems yielded by the 2X, X and ½X treatments were divided into three length classes, the short- (40 – 80 cm), medium- (85 – 105 cm) and long (110 – 165 cm) length classes. The quality of the stems in the “long” length class was found to be of the highest quality whilst the stems in the short length class were of the lowest quality and that of the stems in the medium length class to be of intermediate quality. The quality criteria measured were the leaf area, fresh weight, flower bud length and the stem diameter. It was also observed that the quality of the leaf area, fresh weight and flower bud length increased as the winter period was closing in. The stem diameter of the short stems also increased as the experiment continued, while the stem diameter of the medium and long stems decreased slightly. When the stems within a certain length class were compared, no significant difference was found between the different irrigation treatments with respect to the four mentioned quality criteria, however, the stems in the long length class had the highest QI, while the short stems had the lowest. The quality index ($QI = \text{weight length}^{-1}$) was determined for the stems of the three irrigation treatments in each length class by dividing the average fresh weight by the average stem length of the stems of that specific length class. The general trend was a slight inclination in the QI over the 20 week period.

4.1 Introduction

As mentioned in the previous chapter (Chapter 3) there are three approaches regarding the growing of any cut flower, with roses being no exception. The first approach is to grow roses in such a way as to harvest the highest number of stems possible, the second approach puts the emphasis on the quality of the stems that are harvested while the goal of the third approach is to compromise a bit of both (yield and quality) to achieve less stems but of a higher quality. As stated earlier, higher yields are not always equal to higher profits. Concentrating on growing stems of a higher quality may therefore be just as rewarding or even more rewarding with respect to the profit that are made at the market or retail outlets. Before making a decision to follow one of the three approaches, some serious consideration should be given to the achievable yield and quality. In this chapter the emphasis will be placed on the quality of the harvested stems as well as the effect of the different environmental variables and horticultural practices on the quality.

Post harvest- as well as visual quality is very important aspects to consider, as these aspects often determine the keenness (preference) of the consumers to buy the flowers of a specific grower, and consequently the success of the grower. The next criteria may be used to quantify the quality of the harvested stems:

- Number of deformed flowers (“bullhead” flowers or flowers with “bent necks” (see Chapter 3))
- Flower bud and flower (colour – not faded, shape – malformed, and size typical for cultivar), petals (adequate quantity; firm and bright)
- Leaves (attractive; leaf surface, gloss and colour, adequate in quantity and size)
- Stem (length, standard or longer; straight and in proportion to flower, diameter, thorn less or not, soft)
- Fresh and dry weights of stems, leaves, flower buds or the sum of these weights
- Impulse
- Price
- Acceptable vase life, (vitality, wilted)
- Reliable opening of flowers
- Display
- Fragrance
- Cultivar authenticity
- Disease free
- Without blemish and mechanical damage

- No residue on leaves or flowers
- Transportability (fresh weight, endurance, shoot etiolation and leaf chlorosis, flower and flower bud abscission, flower malformation, flower discoloration)
- Uniformity of the bunches (flower size, stem length, above-mentioned qualities, bunch size)
- Quality Index (QI), also known as the Specific weight (SW) or Weight to Length ratio (W/L) in some experiments
- Productivity Index (PI), also known as the Quality Index (QI) in some experiments (W/L x Number of stems harvested)

The most important quality criterion is the length of the stems. The value of the rose flower is determined by its “category” which is a function of the length of the flower stem. At the auction, long thick stems with big flower buds are considered as being of top quality. As Pertwee (1992:37) stated “There is a rule of thumb on the Dutch auctions that every 1 cm of stems brings you 1 guilder cent.” (Meyer *et al.*, 1988b:13; Nelson, 1991:349 & 366; Pertwee, 1992:37; Clark *et al.*, 1993:613; Hessayon, 1995:5, 112; Oelofse, 1996:14 & 15; Pellett *et al.*, 1998:705-8; Pertwee, 2002:20).

4.2 Materials and Methods

The data for the quality criteria was collected as follows. The marketable stems for the four replicates of each irrigation treatment (2X, X and ½X) were harvested separately. The stems were classed daily in length classes ranging from 40 cm to 170 cm with 5 cm intervals (40 cm, 45 cm, 50 cm, etc.). One representative stem was taken at random from each length class. The following quality criteria was collected:

- Leaf length and -width for each pinna of the third compound leaf from the bud, which consisted of three to five pinnas. The leaf lengths and -widths of the respective pinnas were then used to calculate the leaf area of each pinna measured. A slightly adapted formula, originally after Masarovicova and Pozgaj (1988) were used:

$$A_1 = [1.42 + 0.57 \times (L_1 \times W_1)] \times F$$

$$A_2 = [1.42 + 0.57 \times (L_2 \times W_2)] \times F$$

$$A_3 = [1.42 + 0.57 \times (L_3 \times W_3)] \times F$$

Etc.

(Formula 1)

With A being the leaf area of a specific pinna, L and W the leaf length and width respectively and F the factor with the value of 1.14908747. The total leaf area of the compound leaf was then calculated by adding the respective leaf areas of each pinna.

$$A_{\text{Total}} = A_1 + A_2 + A_3 \text{ etc.}$$

(Formula 2)

(The reader's attention is drawn to the fact that the leaf area of a single compound leaf was calculated per stem, irrespective of the stem length. Thus the longer the stem, the more leaves it will have and the bigger the total leaf area of the specific stem will be.)

- Stem fresh weight (flower bud, stem and leaves included)
- Flower bud length
- Stem diameter at its widest point

The leaf length and width, flower bud length and stem diameter were measured in centimetres by using a vernier calliper, determining the values to the third decimal (Figures 1a to c). The stem fresh weight was determined by weighing the stems with a cantilever scale in grams (accurate to the first decimal).

This data for the stems of each length class were pooled to form three major length classes viz. the short (40 – 84.9 cm), medium (85 – 109.9 cm) and long length classes (110 – 170 cm).

The indentation in the bud length data corresponding to indentation 3 in the other quality criteria, occurred at week 14 and 15 for the short, medium and long stems (Figures 4.7a, b and c), while a fourth indentation followed at week 18 and 19. A fourth indentation was also present in the leaf area of the long stems, week 20 (Figure 4.5c).

The occurrence of the changes in the quality criteria data (the steady increase in quality as well as the occurrence of the indentations) of the 3 treatments may be ascribed to 3 factors: being firstly, the variation in the external input variables (temperature, irradiation hours, -intensity and day length, CO₂ concentration, relative air humidity (RH), volume and quality of the irrigation water and fertilisers applied) over time. Secondly, the number of stems harvested (yield) and thirdly the occasional application of pesticides could have caused the fluctuation in the quality data.

(1) Variation in the external input variables

The best quality roses are produced under cool night and sunny, warm day conditions. Roses grow well under full summer irradiance levels in most areas, but in areas where excessively high irradiance levels prevail, even during the winter as in South Africa ($5000 \mu\text{mol m}^{-2} \text{s}^{-1}$), the partial reduction in irradiance enhances the quality of cut roses. In areas where the irradiance levels are minimal, especially during the winter, the application of supplementary lighting to increase the irradiance levels and/or the duration the plants are subjected to irradiance, increases the quality of the stems harvested. Excessively high temperatures, the generally result faster growth rates but is normally accompanied by a reduction in quality (flower bud size, the number of petals, vase-life of the stem/flower, faded flower and leaf colour and longer but thinner stems). When rose plants are subjected to very low temperatures, production and quality decreases and the shape of the flowers may be in jeopardy. Under conditions of sub optimal air temperatures, an increase in the root zone temperature positively effect the quality of the cut roses. In most instances the quality of the rose stems are enhanced by the CO₂ enrichment of the greenhouse atmosphere. Although vase life of the stems was not determined in this experiment the effect of the relative air humidity (RH) on vase life is worth mentioning. The maintenance of RH in the moderate to high region (65 – 95 %) in a greenhouse do not have a direct effect on the visual quality criteria (stem length, fresh weight, stem diameter, etc.) but the effect becomes evident only later when the vase life of the stems are determined. At too high (maintained at 90 % to 95 %) or low a RH both the vase life as well as the visual quality of the stems may be reduced. Too high an electrical conductivity (EC) of the irrigation water, caused by either a low water quality (high salinity) or an over application of fertiliser, may also reduce the quality of the



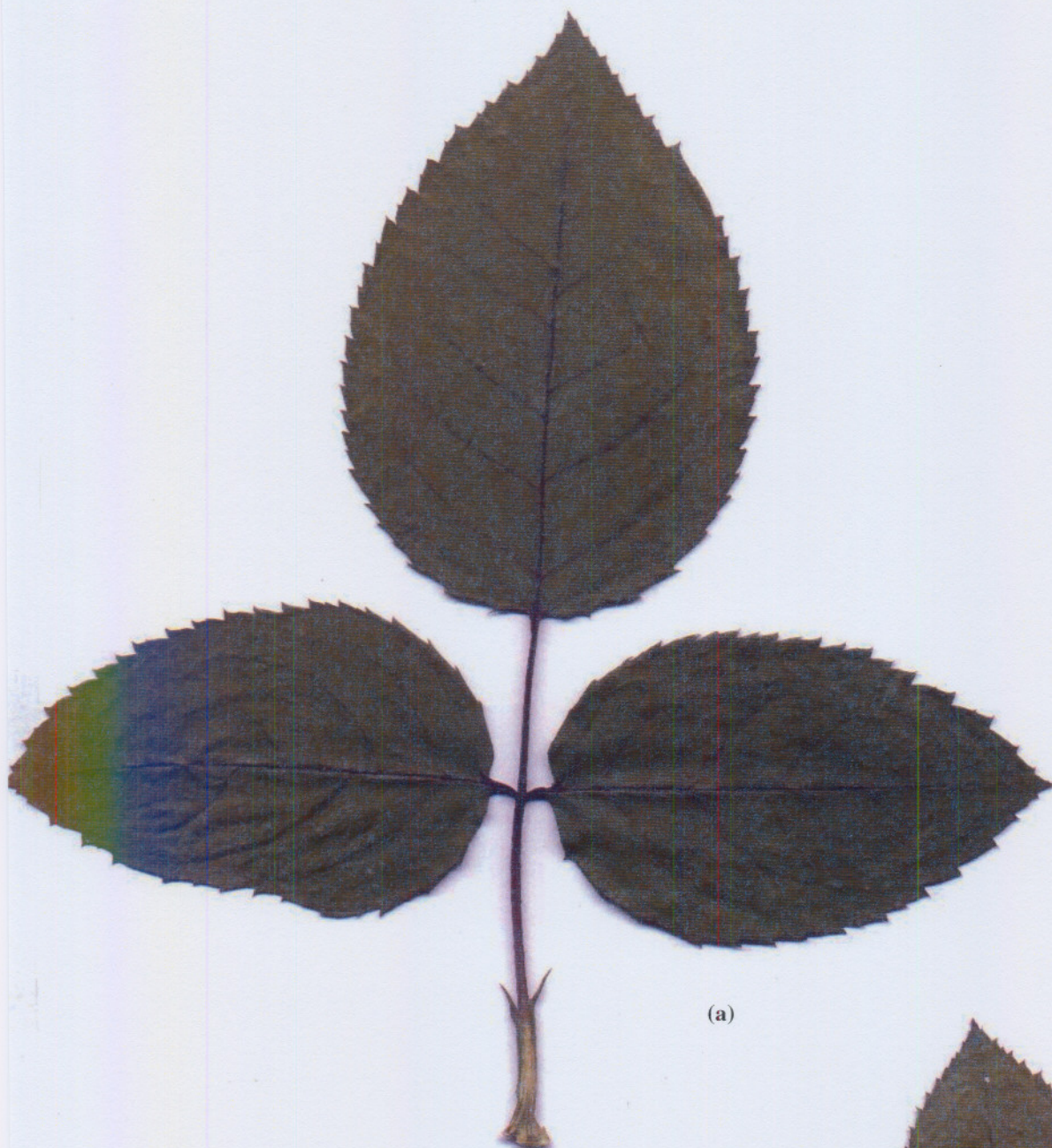
Figure 4.1: Measurement of (a) leaf length, (b) flower bud length and (c) stem diameter.

The stems grouped into the different classes are referred to as short, medium and long stems. An example of stems in the short and long stem classes can be seen in Figure 3.1 (previous Chapter). The combined data of the stems in a specific length class were then used to determine a daily as well as a weekly average for each quality criterion. The ratio of total fresh weight per stem to stem length (W/L), called the Quality index in this experiment ($QI = W/L$), were also calculated for each of the respective length classes of each treatment and for each irrigation treatment (2X, X and $\frac{1}{2}X$) as a whole, as well as an average length per treatment.

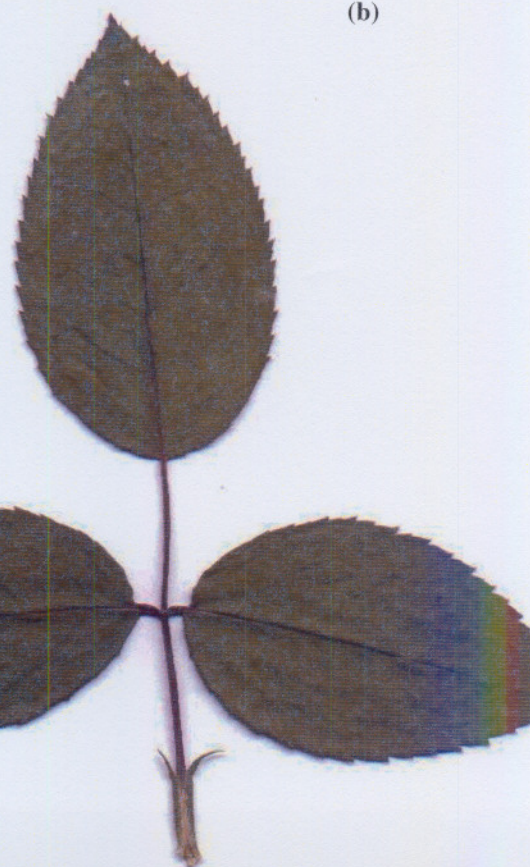
The data collected for the replicates of each treatment were only used to determine the significance of the differences between the respective irrigation treatments with reference to the quality criteria of the stems in the short, medium and long length classes. This data were pooled for the graphs as well as for Table 4.3. The data in this study was analysed by using the Statistica ver. 6[®] computer software package and the values presented as the mean $\pm$ SD (standard deviation). The probability levels used for statistical significance were $P < 0.05$ and parametric or non-parametric tests were used to compare groups. The four quality criteria and the yield (number of stems harvested per day) (described in more detail in Chapter 3) were analysed with the multivariate analysis method Principle Component Analysis (PCA) using CANOCO ver. 4.

Data collection started from 1 February until 16 June 1999 for a period of 20 consecutive weeks.

Of interest is to note the size of the leaves of the cultivar Grand Gala. At first glance the leaf size (length and width) of the short stem, when compared to that of the long stem, seems to be similar (Figure 3.1). Variability in leaf area was, however, a reality as can be seen by the two examples presented in Figure 4.2 and quantitatively indicated in Figures 4.5a to c.



(a)



(b)

Figure 4.2: Actual leaf size of compound leaves collected in
(a) the winter and (b) the summer period.

4.3 Results and Discussion

4.3.1 Principal Component Analysis

The results of the Principal Component Analyses (PCA) of the yield (number of stems harvested) combined with the four quality criteria (stem diameter, leaf area, bud length and fresh weight) data, for the short, medium and long stems of the three irrigation treatments, are presented in Figures 4.3a to c and Figures 4.4a to c. As a PCA graph depicts the distribution of a number of points in a multiple axed (multi dimensional) graph on a two dimensional plane (graph) it should be noted that each variable is represented by an arrow, the length of which is representative of the significance of the variable and the distance between arrows are indicative of how closely variables are correlated or not.

When the treatment data was pooled and the yield and four quality criteria (stem diameter, leaf area, bud length and fresh weight) analysed per length class, the homogeneity per length class becomes apparent (Figures 4.3a to c). A close correlation was found to exist between the stem diameter and fresh weight of a stem and an even closer correlation between the leaf surface area of the foliage leaves and the length of the flower bud. The close correlation found between the leaf surface area and the length of the flower bud may possibly be ascribed to the fact that the leaf surface area is a function of the length- and width of the pinnae of the third compound leaf, while the bud length is based on the length of the flower petals, which is also basically leaves. The correlation would perhaps appear slightly different if the total surface area of all the leaves per stem was determined and this value compared with the bud length. With reference to the length of the arrows, it appears that the yield (number of stems harvested per day) were only the most significant variable in the short stems (Figure 4.3a), while the stem diameter were the most significant variable in both the medium and long stems (Figures 4.3b and c). The second most significant variable in the three length classes was the fresh weight of the stems (Figures 4.3a to c).

From the PCA's when the different length class data was pooled and the yield as well as the four quality criteria analysed per irrigation treatment (Figures 4.4a to c) it became apparent that, irrespective of the irrigation volume, a close correlation was always found to exist between the stem diameter and fresh weight of a stem as well as between the leaf surface area of the foliage leaves and the length of the flower bud. Also, the length classes of each treatment differed distinctly from one another as the data points of each length class grouped together but in distinctly separate groups. For the three irrigation treatments the data points of the long stems were the closest to the heads of the arrows depicting the quality criteria. In contrast, the data

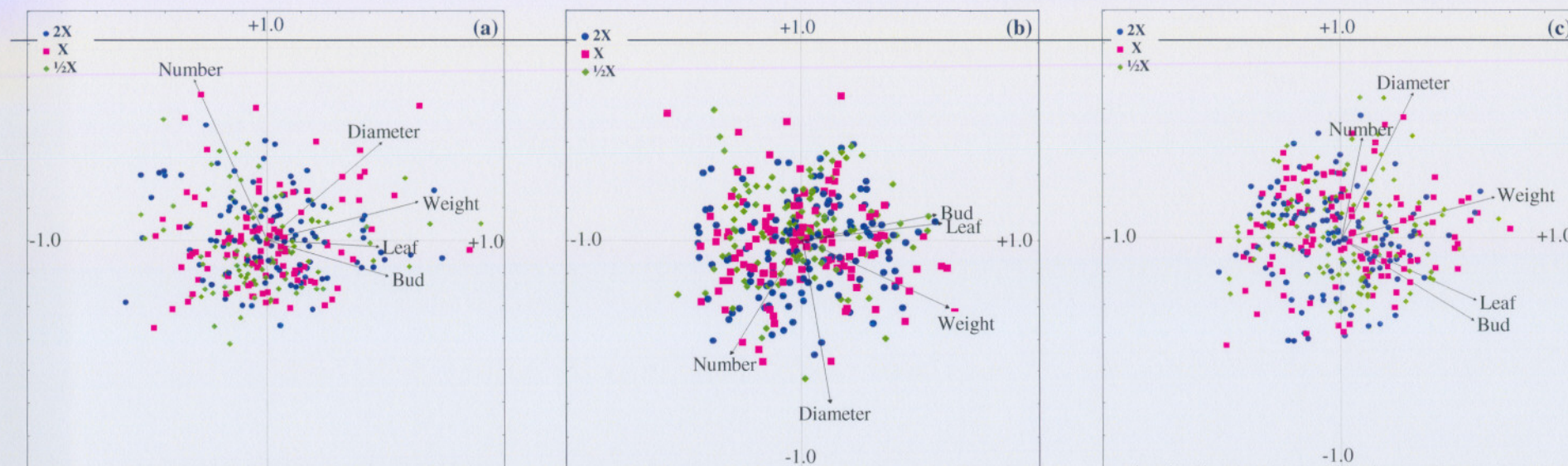


Figure 4.3: Principle component analysis of the yield and quality criteria of (a) the short, (b) medium and (c) long stems of the 2X, X and 1/2X treatments combined.

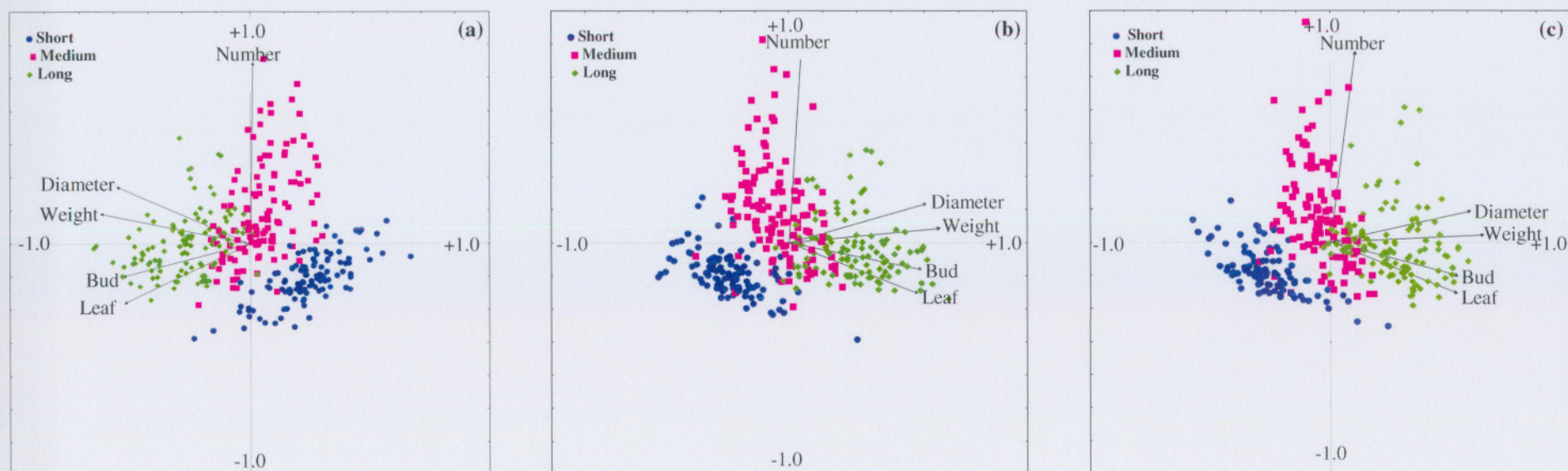


Figure 4.4: Principle component analysis of the yield and quality criteria of (a) the 2X, (b) X and (c) 1/2X respectively.

points of the short stems were the furthest away from the heads of the arrows, while the data points of the medium length stems were situated between the two mentioned extremes. This indicates that the quality of the long stems was the highest, the quality of the medium stems intermediate and that of the short stems the poorest. The number of stems harvested per day (yield) was the variable with the highest significance in the 2X, X and $\frac{1}{2}$ X treatment (Figures 4.4a to c), since it had the longest arrow (as discussed in Chapter 3). The fresh weight of the three irrigation treatments was the variable with the second highest significance and also the quality criterion with the highest significance. It would thus appear that the stems of different lengths of a specific irrigation treatment might be identified by the yield first, and secondly by the fresh weight.

4.3.2 Quality criteria plotted over time

When the four quality criteria (leaf area, fresh weight, bud length and stem diameter (Figures 4.5 to 4.8)) for the short, medium and long stems are plotted over time, its homogeneity is still apparent, since it does not differ when comparing the average data determined per week. The data of all the quality criteria is however not constant over the monitoring period, but vary to a more or lesser extent. The general trend in the quality of the leaf area, fresh weight and flower bud length is an increase over time, irrespective of length class or irrigation treatment (Figures 4.5a, b and c) (Figures 4.6a, b and c) (Figures 4.7a, b and c). The stem diameter, on the other hand, increased ever so slightly in the short stems, remained relatively constant in the medium stems and decreased slightly in the long stems over the 20 week period (Figures 4.8a, b and c). These general trends are, however, not without variation. Three indentations occurred in the quality criteria when the leaf area (most prominent), stem fresh weight, flower bud length and stem diameter data were plotted over (Figures 4.5a, b and c). For the other quality criteria the indentations are less prominent or negligible. Generally the indentations reached its lowest points during week 2 to 4 or week 5 to 7 (indentation 1), week 12 and 13 (indentation 2) as well as week 17 and 18 (indentation 3). The indentations in the bud length data did not correspond to that occurring in the other quality criteria. The first indentation occurred in almost all the quality criteria data except for the stem diameter criteria (where it was less prominent in the medium stems and undetectable in the short and long stems). The second indentation was only prominent in the leaf area data and visible to a very limited extent, in the stem fresh weight data. The third indentation was most prominent in the leaf area data of the short, medium and long stems (Figures 4.5a, b and c) as well as the stem fresh weight and stem diameter of the medium stems (Figures 4.6b and 4.8b). Indentation 3 is very vague in both the fresh weight and stem diameter data of the short (Figures 4.6a and 4.8a) as well as the long stems (Figures 4.6c and 4.8c).

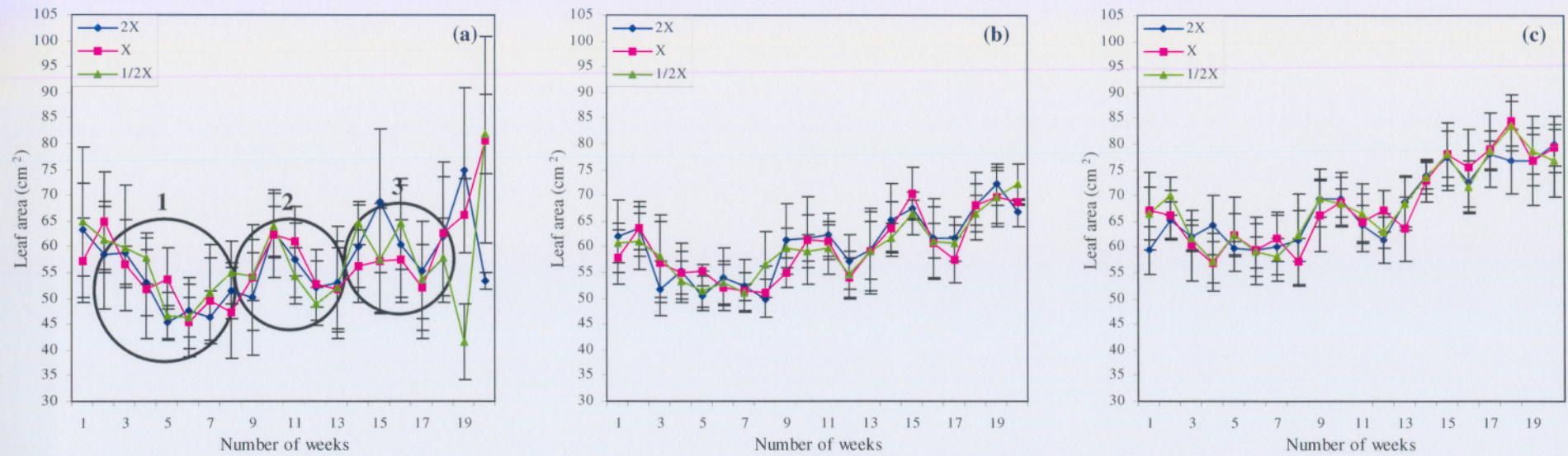


Figure 4.5: Leaf area for the short (a), medium (b) and long stems (c) of treatment 2X, X and $\frac{1}{2}X$. (1, 2 and 3 denotes indentations in the data over time.)

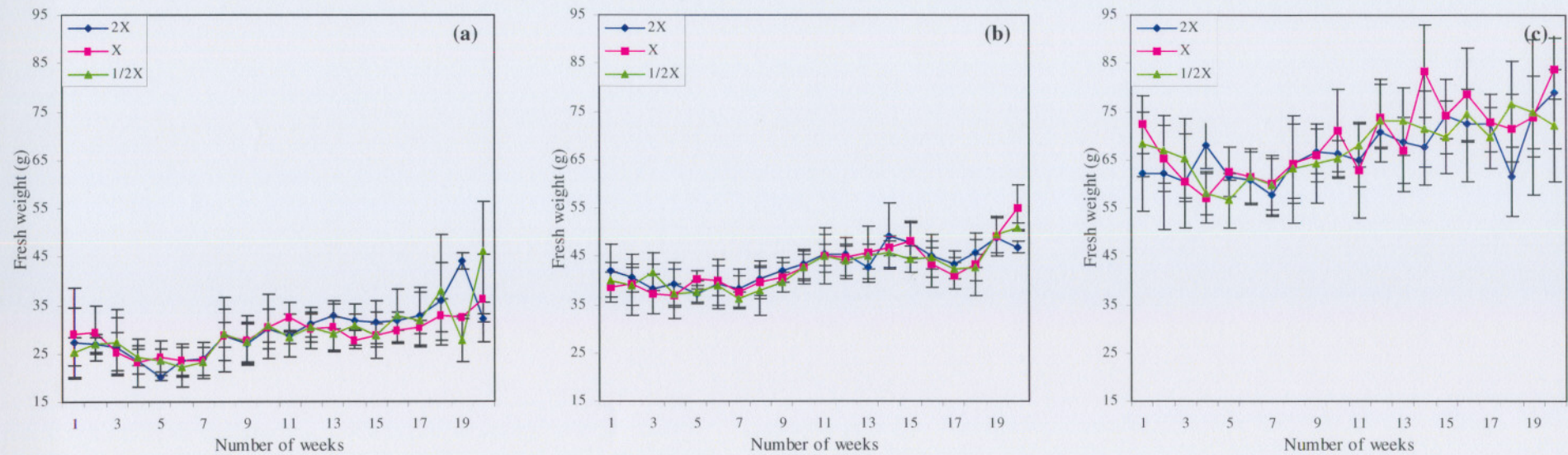


Figure 4.6: Stem fresh weight for the short (a), medium (b) and long stems (c) of treatment 2X, X and $\frac{1}{2}X$.

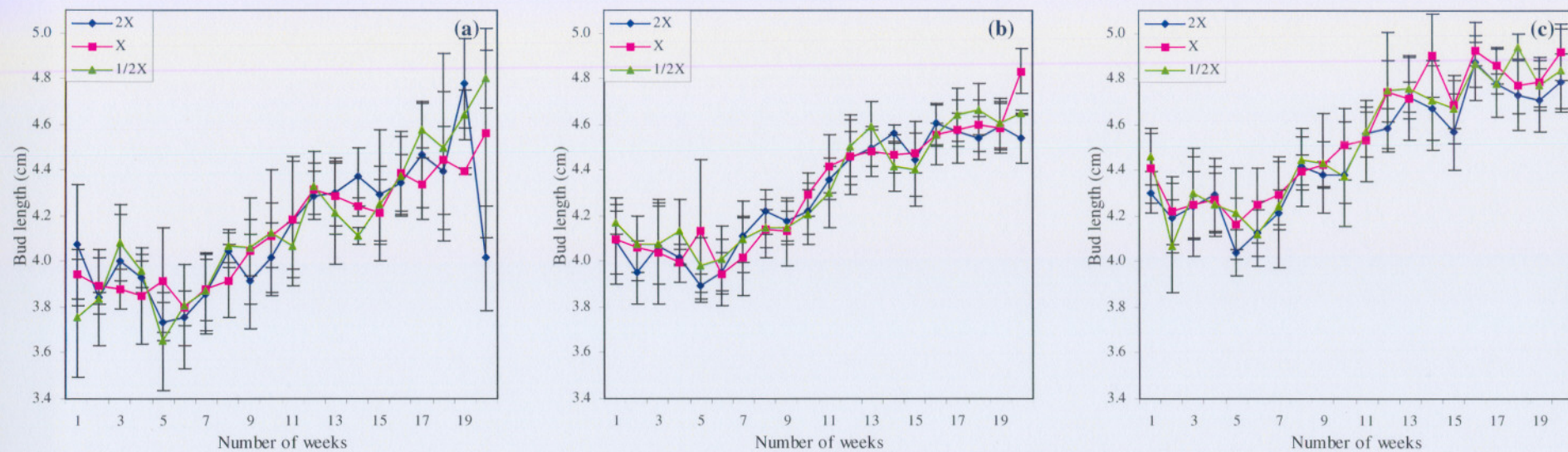


Figure 4.7: Flower bud length for the short (a), medium (b) and long stems (c) of treatment 2X, X and $\frac{1}{2}X$.

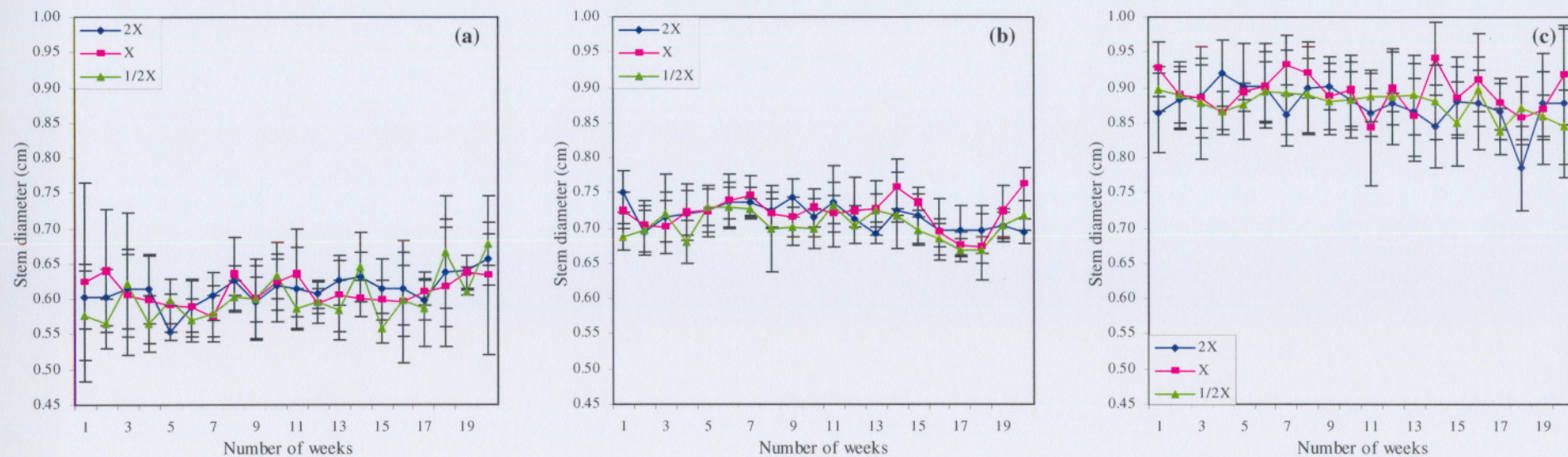


Figure 4.8: Stem diameter for the short (a), medium (b) and long stems (c) of treatment 2X, X and $\frac{1}{2}X$.

rose stems. Optimisation of a single or combination of the above-mentioned external input variables may lead to the enhancement of the quality of the stems. There are however considerable cultivar differences in terms of their response to a certain environmental variable or a combination of variables, complicating the prediction of response of a specific cultivar. The effect of the different external input variables on various stem quality criteria is summarised in Table 4.4. Since the season changed from the end of summer to mid winter during the course of this experiment, the conclusion that this factor could be responsible for the steady increase in quality observed to occur as the experiment progressed.

(2) The number of stems harvested (yield)

The occurrence of the highest number of stems that were harvested corresponds very well with especially the first indentation in the quality criteria data (compare Figures 3.3a to d (previous chapter) with Figures 4.5a to c; Figures 4.6a to c; Figures 4.7a to c; Figures 4.8a to c and Figure 4.9). The leaf area and the bud length were more affected than the fresh weight and the stem diameter. Since a rose plant produces stems of more than one length, the effect of a high yield of, for example short stems, may not necessarily only be on the quality of the short stems but may influence the quality of the medium- and long stems as well. This phenomenon occurs irrespective of the irrigation treatment. A decrease in the number of stems that were harvested in combination with the changes in the external input variables as the experiment progressed, also had an effect of the stem quality.

(3) The occasional application of pesticides

The application of specific pesticides may have caused some of the observed indentations in the quality criteria data especially the leaf surface area (Figures 4.5a to c) and the bud length (Figures 4.7a to c) as well as to a lesser extent the fresh weight and stem diameter data. The reason for this is the distortion of the leaves and the flower petals (also being leaves). The fresh weight of the stems are not influenced severely since not all the leaves of a certain stem are distorted, but only a few (three to five) and the distortion of the leaves does not necessarily result in a decrease in the fresh weight of these leaves. Since only the surface area of the third compound leaf from the bud were measured per stem, only the surface areas of these leaves might have indicated distortion while the distorted leaves lower down on the stem might not have influenced the leaf surface area at all but might have influenced the fresh weight. A decrease of the bud length a week or so before a decrease occurred in the leaf surface area may also indicate leaf distortion since the flower buds of stems will be damaged first while the leaf surface area of the corresponding week(s) are still normal and visa versa. Durkin (1992:88)

stated that rose leaves grow to maturity in 10 to 12 days from the embryonic size and that spray applications during this period can damage the leaf and prevent normal growth, resulting in distortion. Comparing the indentations in especially the leaf surface area and the bud length data to the dates (Table 4.1) of pesticide application the possibility of leaf distortion becomes apparent.

Table 4.1: *Effect of pesticide application on the number and position of distorted leaves of the harvested stems.*

Week	Day of the week pesticide was sprayed	Leaves affected
1	-	-
2	-	-
3	1 and 4	-
4	-	-
5	-	-
6	-	-
7	-	-
8	-	-
9	-	-
10	-	-
11	1	-
12	-	(7) Nearest to the bud
13	1	(2) 6 – 9 th from the bud
14	2	(4) Some leaves still burnt
15	4	(5–6) Minimum leaves burnt
16	-	(5) Some leaves nearest to the bud burnt (6) Most leaves nearest to the bud, burnt (7) 3 rd Leave of most stems burnt
17	5	(4) 3–6 th leave from the top in most stems
18	-	(1) 5 th leave from the top in most stems (5) 7 – 12 th leave from the top slightly effected
19	3	(1) Minimum leaves effected (2) Lowest leaves affected (5) Leaves not burnt
20	-	-

4.3.3 Average stem length

Stem length is the first quality criterion that is focused on at the auction (market), since the stems are graded into different length classes (categories) and longer stems are more popular (Pertwee, 1992:37). Besides personal preferences, other reasons may be that longer stems are more versatile, display better and are generally of a higher quality than shorter stems.

As already mentioned, the quality of the stems appeared to increase as the stem length increased (Figures 4.3a to c). This tendency become even more apparent when the leaf area, stem fresh weight and flower bud length, (plotted over time, Figures 4.5a to c, Figures 4.6a to c and Figures

4.7a to c) are compared to the average stem length for the total number of stems harvested per treatment (Figure 4.9). The stem diameter also had the tendency to increase as the stem length increased (compare Figures 4.8a, b and c) but in this instance the stem diameters per stem length class remains constant in contrast with the average stem length that tended to vary over time.

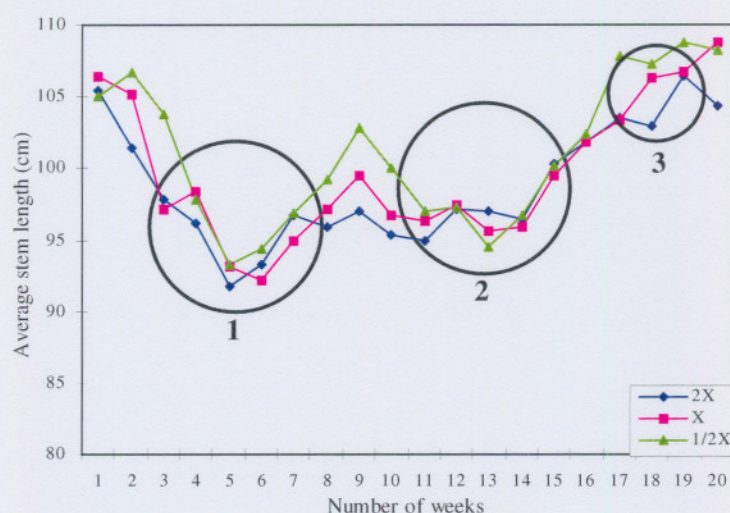


Figure 4.9: Weekly average stem length for the total number of stems per treatment (2X, X and 1/2X).

Since being a function of the length of the stems and the number of the stems, the weekly average stem length of an irrigation treatment was influenced by the number of stems in the different length classes (Chapter 3). For example, the larger the percentage of short stems in comparison with the other stem lengths, the shorter the average stem length for the total number of stems harvested.

It appears as if the stems of the 1/2X treatment generally yielded the highest number of long stems compared to its medium and short stems, while the 2X treatment was typified by the lowest number of long stems with the X treatment yielding an intermediate number of long stems (Figure 4.9).

No significant differences were found between the average values determined for the three irrigation treatments in a specific length class, irrespective of the quality criterion (Table 4.2). Four replicates were used to determine the average values summarised in Table 4.2. These results corroborate with the results obtained with the PCAs of the respective length classes (Figures 4.3a to c) as well as that as weekly average values depicted over time (Figures 4.5a to c, Figures 4.6a to c, Figures 4.7a to c and Figure 4.8a to c).

Although no differences per specific quality criterion in a certain length class (short, medium or long) across the irrigation treatments were observed (Table 4.2), it is most likely that when the

values of a specific quality criterion were compared between the three length classes of a specific irrigation treatment significant differences would be found (see Table 4.2).

Since the quality criteria of stems in a certain length class did not differ significantly, irrespective of the treatment, the stems are only referred to as short, medium and long stems in Table 4.3, thus general minimum and maximum values were determined for the different length classes of each quality criterion, with no distinction made between the different irrigation treatments.

Table 4.2: Average values ($\pm$ s.d.) for the quality criteria measured for the four replicas of the different length classes of each irrigation treatment.

^a Means with the same letter were not significantly different ($P > 0.05$)

Length class	Treatment	Leaf area (cm ²)	Fresh weight (g)	Bud length (cm)	Stem diameter (cm)	Quality Index (g cm ⁻¹)
Short	2X	56.55 $\pm$ 2.42 ^a	29.08 $\pm$ 1.65 ^a	4.12 $\pm$ 0.06 ^a	0.61 $\pm$ 0.01 ^a	0.39 $\pm$ 0.02 ^a
	X	55.58 $\pm$ 1.49 ^a	28.37 $\pm$ 0.48 ^a	4.10 $\pm$ 0.02 ^a	0.61 $\pm$ 0.01 ^a	0.38 $\pm$ 0.01 ^a
	½X	56.42 $\pm$ 2.72 ^a	28.25 $\pm$ 0.64 ^a	4.11 $\pm$ 0.06 ^a	0.59 $\pm$ 0.02 ^a	0.38 $\pm$ 0.01 ^a
Medium	2X	60.09 $\pm$ 0.82 ^a	42.99 $\pm$ 0.66 ^a	4.30 $\pm$ 0.04 ^a	0.72 $\pm$ 0.01 ^a	0.45 $\pm$ 0.01 ^a
	X	59.39 $\pm$ 0.87 ^a	42.41 $\pm$ 0.87 ^a	4.31 $\pm$ 0.01 ^a	0.72 $\pm$ 0.01 ^a	0.44 $\pm$ 0.01 ^a
	½X	59.72 $\pm$ 0.76 ^a	42.12 $\pm$ 0.62 ^a	4.32 $\pm$ 0.02 ^a	0.70 $\pm$ 0.02 ^a	0.44 $\pm$ 0.01 ^a
Long	2X	67.81 $\pm$ 1.82 ^a	66.59 $\pm$ 1.73 ^a	4.48 $\pm$ 0.04 ^a	0.88 $\pm$ 0.02 ^a	0.57 $\pm$ 0.01 ^a
	X	68.23 $\pm$ 1.92 ^a	68.49 $\pm$ 2.06 ^a	4.55 $\pm$ 0.04 ^a	0.89 $\pm$ 0.01 ^a	0.58 $\pm$ 0.02 ^a
	½X	68.59 $\pm$ 1.67 ^a	67.68 $\pm$ 2.36 ^a	4.53 $\pm$ 0.01 ^a	0.88 $\pm$ 0.01 ^a	0.57 $\pm$ 0.02 ^a
Tot. Stems	2X	61.48 $\pm$ 1.50 ^a	46.22 $\pm$ 1.20 ^a	4.30 $\pm$ 0.04 ^a	0.74 $\pm$ 0.01 ^a	0.47 $\pm$ 0.01 ^a
	X	61.07 $\pm$ 0.60 ^a	46.43 $\pm$ 0.62 ^a	4.32 $\pm$ 0.02 ^a	0.74 $\pm$ 0.00 ^a	0.47 $\pm$ 0.01 ^a
	½X	61.58 $\pm$ 1.13 ^a	46.02 $\pm$ 0.83 ^a	4.32 $\pm$ 0.02 ^a	0.73 $\pm$ 0.01 ^a	0.46 $\pm$ 0.01 ^a

Abbreviations used in Table 4.2 (see List of Abbreviations, page x)

The minimum and maximum values of the leaf surface area for the stems in the short (41 – 82 cm²), medium (50 – 72 cm²) and long (57 – 85 cm²) length classes calculated for the leaves in the current experiment compares very well to the values determined by Costa and Challa (2002: 113) (58 – 93 cm²) (Table 4.3). The values of the current experiment were however determined for a three pinnated compound leaf while Costa and Challa (2002: 113) used five pinnated compound leaves.

The fresh weight of the short stems (20 – 47 g) of this experiment compares well to the values given in the literature 10 – 54 g (Hopper & Hammer, 1991:612) and 20 – 40 g (Tsujita & Dutton, 1983:874), while that of the medium- (36 – 55 g) does not compare that well and that of the long stems (56 – 84 g) are much higher (Table 4.3).

Only the maximum values for the flower bud lengths of the short (4.7 cm), medium (4.8 cm) and long stems (4.9 cm) compare well with the values found determined by Van der Walt (1999:25)

Table 4.3: Minimum and maximum values for the leaf area, fresh weight, bud length, stem diameter, stem length and quality index of the length divided by the fresh or dry weight of the stem and values from literature references for comparison.

Quality Criteria	Length class	Min - Max	Literature references for comparison	
Leaf area (cm ²) Single compound leaf Figures 4.5a to c	Short Medium Long Average	(41) – 82 50 – 72 57 – 85 49 – 80	Single leaf, 5 pinnated: 58 / 93 1 Stem: 0–261 / 219–273 / 326–339 / 327 184–253 / 284–463 1 Stem + 1 shoot: 387–447 / 547–598 Total plant: 4000–7000 970–1268 1600–2400	Costa & Challa, 2002 – Mad (Exp.1 and Exp.2) (0, 14, 39, 58 Leaf area of cutting) Marcelis-Van Acker, 1995 – Mo and So (Parent shoot or shoot) (1 Stemmed + 1 shoot) Baille <i>et al.</i> , 1996 – So Clark <i>et al.</i> , 1993 – Mj (Late winter–Early summer) Raviv & Blom, 2001 – Mc (High EC–Low EC)
Fresh weight (g) Figures 4.6a to c	Short Medium Long Average	20 – (47) 36 – 55 56 – 84 37 – 62	14 / 22 / 19 / 18 10–39 / 15–47 / 21–54 18 / 14 / 20 7–18 / 11–26 28 / 27 20–24 14–27 20–28 / 33–40 11–35	Hopper, 1996 – Ga, R, Sa and So Hopper & Hammer, 1991 – R (I = 100, 175, 250) Kool <i>et al.</i> , 1997 – F (Control, Flush and One stemmed) Marcelis-Van Acker, 1995 – Mo and So Mortensen & Fjeld, 1998 – Sou (RH 65 and 90) Mortensen & Gislerød, 1999 – 14 Rose cultivars Shanks <i>et al.</i> , 1986 – FY, PS, WS and Vo Tsujita & Dutton, 1983 – Ga and Sa Zeroni & Gale, 1989 – So
Bud length (cm) Figures 4.7a to c	Short Medium Long Average	3.6 – 4.7 3.8 – 4.8 4.0 – 4.9 3.8 – 4.8	4.8 / 4.8 / 4.7 / 5.0	Van der Walt, 1999:– GG (Pecan, Macadamia, Coconut and Rockwool)
Stem diameter (cm) Figures 4.8a to c	Short Medium Long Average	0.55 – 0.68 0.67 – 0.77 (0.78) – 0.94 0.67 – 0.80	0.58–0.62 0.39–0.63 0.43–0.52 0.60–0.80 / 0.60–0.70 / 0.90–1.30 0.38–0.48 / 0.47–0.56 0.40–0.50 / 0.38–0.49 / 0.36–0.51 0.41–0.54 0.84 / 0.77 / 0.74 / 0.72 0.49–0.55 / 0.59–0.61	Balazsovits <i>et al.</i> , 1988 – R Hopper & Hammer, 1991 – R (I = 175) Jiao <i>et al.</i> , 1991a– Sa Kool <i>et al.</i> , 1997 – F (Control, Flush and One stemmed) Marcelis-Van Acker, 1995 – Mo and So Moss, 1984. Exp. 1 to 3 (Winter /Spring) (Summer) – Io, Mc and So (Min - Max) Van der Walt, 1999 – GG (Pecan, Macadamia, Coconut and Rockwool) Tsujita & Dutton, 1983 – Ga and Sa
Stem length (cm) Average values (Min and Max values) Figure 4.9	2X X ½X Short (40–84) Medium (85 – 109) Long (110–165)	98 (82 – 107) 99 (92 – 109) 101 (92 – 109) 75 96 118	35–47 / 30–40 64–67 32 / 33 / 34 / 31 64 60 0–34 / 27–37 / 43–46 / 47 58–78 81 : 63 / 84 : 55 38 / 49 / 48 / 43 44–57	Agbaria <i>et al.</i> , 1995 – Is and Mc Balazsovits <i>et al.</i> , 1988 – R Cabrera, 2002 – BW (4 different rootstocks) Cabrera <i>et al.</i> , 1995a – R Cabrera <i>et al.</i> , 1995b – R Costa & Challa, 2002 – Mad (Original leaf area 0, 14, 39, 58) Erwin <i>et al.</i> , 1997 – R and LG (Cutting Position: 13 to 1) R and LG (Fall : Spring) Hopper, 1996 – Ga, R, Sa and So Jiao <i>et al.</i> , 1991a – Sa

Table 4.3: Continued

Quality Criteria	Length class	Min - Max	Literature references for comparison	
			25-34 / 41-59 60-80 28-31 46 / 49 45-70 29-42 / 30-43 / 27-49 28-47 25-55 36-46 44-51 / 68-72 100 / 91 / 87 / 90 15-77 47-56 / 46-54 / 61-76 / 76-92	Marcelis-Van Acker, 1995 – Mo and So Meilland poster, 1992? (Chapter 2) – GG (1 year) Mortensen, 1995 – Sou Mortensen & Fjeld, 1998 – Sou (RH 65 and 90) Mortensen & Gislerød, 1999 – 14 Rose cultivars Moss, 1984 Exp. 1 to 3 (Winter /Spring) (Summer) – Io, Mc and So (Min – Max) Moss and Dalglish, 1984 – Io, Mc and So Shanks <i>et al.</i> , 1986 – FY, PS, WS and Vo Tsujita & Dutton, 1983 – Ga and Sa Van der Walt, 1999 – GG (Pecan, Macadamia, Coconut and Rockwool) Zeroni & Gale, 1989 – So Zieslin <i>et al.</i> , 1987 – GT, Mc, So and Vi
QI = Fresh weight Length ⁻¹ (g cm ⁻¹) Figures 4.10a to d	Short Medium Long Average	0.38 – 0.39 0.44 – 0.45 0.57 – 0.58 0.46 – 0.47	0.36 / 0.45 / 0.40 / 0.42 0.39–0.55 / 0.38–0.5 0.61 / 0.55 0.39–0.43 0.33–0.61 0.44–0.53 / 0.48–0.55 0.42–0.85	Hopper, 1996 – Ga, R, Sa and So Marcelis-Van Acker, 1995 – Mo and So Mortensen & Fjeld, 1998 – Sou (RH 65 and 90) Mortensen & Gislerød, 1999 – 14 Rose cultivars Shanks <i>et al.</i> , 1986 – FY, PS, WS and Vo Tsujita & Dutton, 1983 – Ga and Sa Zeroni & Gale, 1989 – So

Abbreviations used in Table 4.3 (see List of Abbreviations, page x)

The values in parenthesis is anomalies

Value with question mark at the end is an estimated value.

⁽¹⁾ Authors quoted by Morisot *et al.*, 1998

(4.7 – 5.0 cm); the minimum values (3.6; 3.8 and 4.0 respectively) are much lower (Table 4.3).

Most values found in the literature for the stem diameter are lower (0.39 – 0.63 cm) (Hopper & Hammer, 1991:612) and (0.38 – 0.56 cm) (Marcelis-Van Acker, 1995:246) than even the stem diameter values measured for the short stems (0.55 – 0.68 cm). Values that did compare well with that of the medium (0.67 – 0.77 cm) and long stems (0.78 – 0.94 cm) were measured in stems harvested from single stemmed plants (0.90 – 1.30 cm) (Kool *et al.*, 1997:627) and from plants of the same cultivar as used in this experiment (0.74 – 0.84 cm) (Van der Walt, 1999) (Table 4.3).

The length of the stems determined in other experiments (64 – 67 cm) (Balazsovits *et al.*, 1988:982), (45 – 70 cm) (Mortensen & Gislerød, 1999:291) and (46 – 92 cm) (Zieslin *et al.*, 1987:87) generally fell into the length class of the short stems (40 – 84 cm); again only the stems yielded by the same cultivar as used in this experiment (87 – 100 cm) (Van der Walt, 1999:25) compared well to the length categories of the medium (85 – 109 cm) and long stems (110 – 165 cm) (Table 4.3).

The weekly average QI values determined for each length class of all the irrigation treatments as well as that of the total number of stems harvested per treatment, decreased for the first four to five weeks and then started increasing for the remainder of the monitoring period (Figures 4.10a to d). The average QI value calculated for the short stems of each treatment ranged from 0.38 to 0.39 g cm⁻¹; that of the medium stems ranged from 0.44 to 0.45 g cm⁻¹ and that of the long stems ranged from 0.57 to 0.58 g cm⁻¹, while the average of the total number of stems ranged from 0.46 to 0.47 g cm⁻¹ (Table 4.3). These values are in the range of values reported in the literature: 0.38 – 0.43 g cm⁻¹ for ‘Royalty’, ‘Samantha’, ‘Sonia’ and ‘Gabriella’ roses (Hopper, 1996) and 0.33 – 0.61 g cm⁻¹ for ‘Forever Yours’, ‘Pink Sensation’, ‘White Satin’ and ‘Volare’ roses (Shanks *et al.*, 1986). These values for the different length classes emphasise the fact that the long stems were the stems typified by the highest quality whilst the short stems were of lowest quality (Table 4.3). When comparing QI values it is important to keep either the weight or the stem length in mind, since stems with high QI values are usually long stems, but could be short but heavy stems, and stems with low QI values could just as well be long with a low fresh weight than short with an even lower fresh weight. There is, however, an obvious difference in the QI determined for the short, medium and long stems of this experiment.

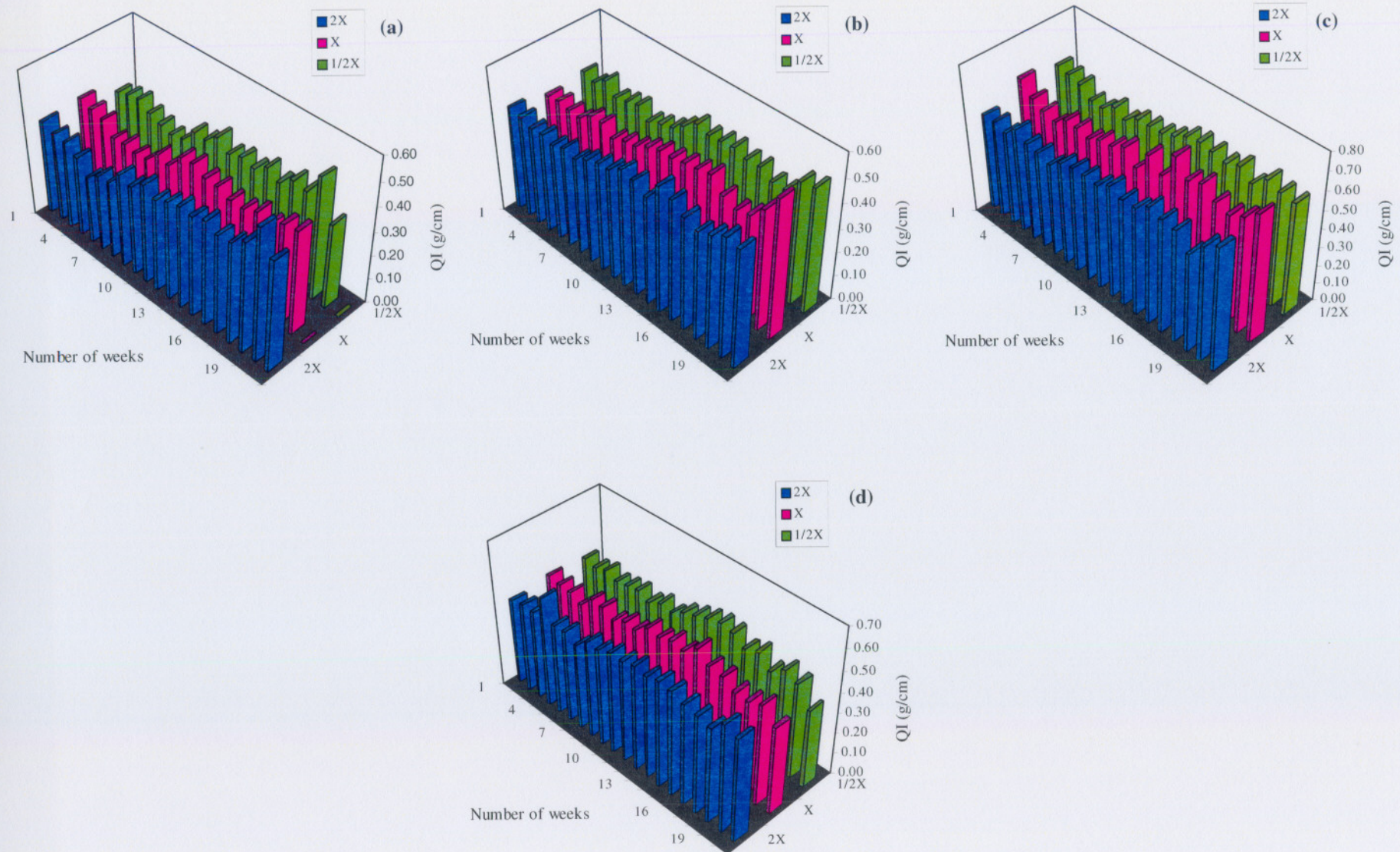


Figure 4.10: Quality indices for (a) the short, (b) medium and long stems as well as for (c) the total number of stems (d) of treatment 2X, X and 1/2X.

Table 4.4: Effects of the external input variables as well as some horticultural practices on the quality of the stems produced during various experiments.

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO ₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Quality	Literature
Sum 13h45 Win 10h40	Min and Max 43–60 (day)	NT _a / DT _a 10–25/17–39	300–610 (07h00) 290–370 (12h00)		South Africa: Nylstroom Sum – Win 20 weeks	GG 2 Years 8.5 plants m ⁻² Multiple stemmed	Sum to Win : Leaf area↑ Bud length↑ Fresh weight↑ Stem diameter* Irr – Sum 0.6↑ ^{2.4 t pl.₁ day +} Win 0.5↑ ^{2.0 t pl.₁ day :} Length class quality : Quality↓ Short↑ Medium↑ Long↑	This experiment
Cloudy Weather 24 h (Oct–30Apr)	SL(HPS) 50 HPS : ↑Red/FR	NT _a / DT _a (Min) 16 / 20 Vent. 25+	330,900,1500 8h–18h 22Nov–1May		Canada: Quebec 22 Nov–7 Jun	R 8 Months 8 plants m ⁻²	SL + C _a ↑ : Quality↑	Balazsovits <i>et al.</i> , 1988
12 hours SL: 0, 4, 8h	50, 100, 150	NT _a / DT _a 18 / 20		70		Mad, So 9 Weeks 1 t pots	I ₅₀ ↑ ¹⁵⁰ : SL _{dur} 4 or 8 h : Fresh weight↑ Fresh weight*	Blom-Zandstra <i>et al.</i> , 1995
							T _{a21} ↑ ³² : Stem length ⁴² ↓ ₂₅ Node number↓ Petal number↓	Byrne <i>et al.</i> , 1978 (Quoted by Erwin <i>et al.</i> , 1997)
	Win 35.9 (day) Spr 66.8 (day) (Total I)	4 – 16 Shipping temp	350,700,1050		USA: Clemson 10 Dec–10 Feb (Late Win) 3 Mar–21 Apr (Early Spr)	Mj 472 cm ³ pot ⁻¹	C _a ↑ : I↑ : C _a ↑ : I↑ : C _a /T _a – 350/4 : 1050/16 : Spr/16 : Win/4 : Plant height↑ Bud size* Plant height↑ Bud size↑ Shoot + Root growth↑ Shoot + Root growth↑ Etiolated↓ Etiolated↑ Leaf Chlorosis↑ Leaf Chlorosis↑	Clark <i>et al.</i> , 1993

Table 4.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO ₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Quality		Literature
	1200 SL 50–100	NT _a 16–21 (LL) 16–27 (HL) NT _a / DT _a 7 7 / 27–30 NT _a 20	900–1000	60–80	USA	General 1 plant 900 cm ⁻²	Soil compaction + aeration↓ : Soil moisture↓ : T _a ↑ : T _a , I, C _a ↑ : T _a ↑, I, C _a ↓ : NT _a ↓, DT _a ↑ : C _a ↑ : I↑ : I↑ : I _l (shading) : SL↑, NT _a ↑ (winter) :	Chlorosis Rootgrowth↓ Stem length↓ Stem length↓ Flower size↓ Petal no.↓ Bud size↓ Quality↑ Quality↓ Bud Size↑ Stem Length↑ Quality↑ Quality↑ T _a ↑, RH↓ Quality↑ Growth↑ Plant vigor↑ Irr↑ Fertiliser↑ C _a ↑	Durkin, 1992
Natural + SL: 18 h	Natural + SL (SL = 100) Daily = 10–20	NT _a / DT _a 16 / 21			USA: Minnesota Fall: Nov–Jan Spr: Feb–Apr	R, LG 4 Years	Aut to spr : Cut. position 1–13 : Cut. position 1–5 : Cut. position 5–13 : Leaves removed :	Node number↓ Stem length↓ Stem length↓ Node number↑ Node number↓ Stem length↓	Erwin <i>et al</i> , 1997
							C _a ↓ : C _a ↑ :	Growth↓ I↑ T _a ↑ Fertiliser↑ Irr↑	Freeman, 1998
Day + 10h night ⁻¹	Natural Natural + SL	NT _a / DT _a 16 / 23			USA: Colorado	Ga, R, Sa, So 1 Year	SL : Yield :	FW↑ Stem Length↓	Hopper, 1996

Table 4.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO ₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Quality	Literature
	(SL = 100)				30Oct–29 Feb 4 Months(Win)	10.5 plants m^{-2} Pinched 2 Stemmed	FW↓	
Day / Night 12h / 12h	100,175,250	NT _a / DT _a 12–22 / 20–25		50–95 Ebb+Flood	USA: Indiana	R 2–3 Months 1 plant 0.64 ℓ pot ⁻¹ 1 Stemmed	DT _a ↓ + NT _a ↓ : I↑ : Stem diameter↑ DW↑ FW↑ Stem diameter↑ DW↑ FW↑	Hopper & Hammer, 1991
	0–1400 400	22 18 / 22 (14h/10h)	350 350		Canada: Guelph	Sa	C _a : Stem Length↑ Diameter↑ Bud size* DW*	Jiao <i>et al.</i> , 1991a
	100 – 1200	15–30 (Int:5) 22	350–1500 (Int:300–350)		Canada: Guelph	Sa 1 Stemmed	I (100–1200) : I _{dur} (8–16) : C _a (350–1500) : DT _a (15–30) : NT _a (15–25) : Contributed 64% 31% 4% 0.3% 0.7% to Growth	Jiao <i>et al.</i> , 1991c
		NT _a / DT _a 17 / 19 12 / 12 (Nov–Jan)			Netherlands Apr'92–Sep'93	F 3 Months 13.3 plants m^{-2}	Weight : June '92 to Sept '93: 1 Stemmed↑ Flush↑ Con↑ Stem diameter↑	Kool <i>et al.</i> , 1997
Day: 16	184	17, 21, 25 21		70		Mo,So 1 Stemmed	T _{a17} ↑ ²⁵ Mo : (2 nd order lateral) Stem length↓ Stem diameter↓ FW↓ Total no leaves↓ Leaf area↓ T _{a17} ↑ ²⁵ So : (2 nd order lateral) Stem length↑ Stem diameter* FW↑ Total no leaves↓ Leaf area↑	Marcelis-Van Acker, 1995

Table 4.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO ₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Quality	Literature
	Very High (Shade)	NT _a / DT _a 16 / 27			South Africa	General 8 plants m ⁻² Control 1 Stemmed Flush	T _a ↓ : T _a ↑ : Quality↓ Bud Size↓ Petal no.↓ Vaselifel	Meyer <i>et al.</i> , 1988b
	270-bright day Protruding Br: 1 st Bud 260	NT _a ^{min} /DT _a ^{max} 16 / 30 Growth Cham 18/24			Israel	Mar 5 Years 5 Months 3+ Branches 1 Branch	1 st bud – 3 rd bud : Stem length↓	Mor & Halevy, 1984
					France 2 Years	So,K 1.5 to 3.5 Years Continuesly	Stem length grade↑ : Aut : Spr : I _↑ ^{max} : W/L↑ W/L _↓ ^{min} W/L _↑ ^{max} W/L _↑ [↓]	Morisot <i>et al.</i> , 1998
18h	Natural 7.3 day SL 11.3 day	Daily Mean 18.7	355	75	Norway (Winter)	Sou 1 plant 2ℓ pot ⁻¹ 2 Stemmed	Methanol foliar sprays : Stem length*	Mortensen, 1995
16,20,24h,20h	SL (Fluo) 170 SL (HPS) 170	20 LT 0.5–1↑	800	65 / 95 (819 / 234)	Norway 12 Mar	Sou 6 Months 1 ℓ pots 2 Stemmed	RH↓ : I↓ : RH↑ : I _{dur} ↑/65 RH : Stem length↑ Stem length↓ FW* Vase life↓ Vase life↓	Mortensen & Fjeld, 1998
18,24h	SL : 200 13 / 17 (day) Natural : 4.3,1.8,0.7,1.4, 2.1,6.7 (day) (Oct–Mar)	19	800	75,83,91 550,390,200	Norway Oct'97–Mar'98	14 Cultivars 3.5–4 months 22 plants m ⁻² + 19 plants m ⁻² Flush	RH ₈₃ ↑ ⁹¹ : I _{dur} ↑ : RH ₇₅ ↑ ⁹¹ /I _{dur} 18h : RH ₇₅ ↑ ⁹¹ /I _{dur} 24h : FW↓ FW↑ Vase life↓ Vase life↓	Mortensen & Gislerød, 1999
Daytime	Natural 20–64 (day)	RZT : 25 / Ambient NT _a : 18,12,9 18,14,10			Australia: Griffith Win–Spr–Sum 22 Weeks	Io, Mc, So 8 plants 1.2 m ⁻² Stagger	RZW : Stem length↑ Stem diameter↑	Moss, 1984

Table 4.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature ($^{\circ}\text{C}$)	$[\text{CO}_2]$ ($\mu\text{mol mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Quality	Literature
		DT _a : 21 (25 Vent.)						
Daytime (07h00–16h30)	Natural : 32 (PPF or Total I?)	RZT : 25 / Ambient NT _a : 18,12,9 18,14,10 DT _a : 21 (25 Vent. (27 EvapC)			Australia: Griffith 2 Years : Win–22 Weeks 17 Weeks Sum–5 Weeks	Io, Mc, So 8 plants 1.2 m ² Stagger Light prune Stagger	RZW : % Long stems↑	Moss & Dalglish, 1984
		Optimum : NT _a / DT _a 16 / 19–22 (cloudy days) 16 / 24 (clear days) 16 / 27 (CO ₂ enriched)	Limiting : 50–125 Optimum : 1000–1500 – crop specific			General	C _a deficiency : Quality↓ C _a toxicity : Leaf chlorosis Leaf necrosis C _a ↑ for roses : Stem length↑ Stem weight↑ No. Petals↑ Temp↑ ^{+6°C} Fertiliser↑ I↑ HL I↑ for roses : Growth↑ I↓ ^{opt} for roses : Bud size↓ Stem diameter↓ Stem length↑ T _a ↑ _{min} : Stem length↑ T _a ↓ ^{opt} : Stem diameter↓ Bud size↓	Nelson, 1991
SL 18h day ⁻¹	Very high (shaded)	NT _a / DT _a 7–18 / 24–32 Some cultivars: NT _{a min} : 4–10			USA	General Plants ha ⁻¹ : Outside 35000–50000	NT _a ↓ _{min} : Bud deformed↑ High I [↓] / High T _a ↓ : Stem length↑ Bud size↑ Colour fading↓ Leaf size↑ Foliage gloss↑ Water quality↑ : Foliage residue↓	Pellett <i>et al.</i> , 1998

Table 4.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO ₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Quality	Literature
							Foliage quality↑ Growth Leaf drop Rootstock Natal Brier : Quality↑ Stem length↑ RH↑, NT _a ↓, I↓ :	
							EC _{2.5} ↑ ^{7.5} : Leaf area↓ Stem length↓ Shoot diameter*	Raviv & Blom, 2001
							NT _{a dur} = 17↑ : Stem length↑ Weight↑	Shanks <i>et al.</i> , 1986
20 h day ⁻¹	Natural I. ↓ SL : 75	20	700	70 / 90	Norway	Ba Cuttings 66 Plants m ⁻² 1 Stemmed	RH↑ : Shoot length* Fresh weight* No of leaves* Leaf area* Vase life↓	Torre & Fjeld, 2001
12h (06h00–18h00)	Natural Natural + SL (nightly) : 55	RZW :13,18,23 NT _a :13 DT _a :21	900–1000 (08h00– 16h00)		Canada: Guelph Oct'79–Apr'80	Sa, Ga 5 Months+ Spacing 30x30	Samantha SL : RZW : RZW ₂₃ : Gabriella SL / RZW : SL + RZW : Stem length↑ Weight↑ W/L↑ Bud diameter↑ Stem diameter* Stem diameter* W/L↓ Bud diameter↓ Stem length↑ Stem length↑ Stem diameter↑ Weight↑ W/L↑ Bud diameter↑ Stem diameter↓ Stem length↓	Tsujita & Dutton, 1983

Table 4.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO ₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Quality	Literature	
							Weight↓ W/L↓ Bud diameter↓		
09h00–19h00	SL : HPS + M 783.41 (PPF or Total I?)	21		80	France: Sophia-Antipolis	SP (So) 6 Months 8 plants m ⁻²	Pl water content↓ : Stem diameter↓ : Stem diameter↑ : Nutrient solution :	Stem diameter↓ ε Leaves↓ Basal stems↓ Young stems↓ Basal stems↑ Young stems↑ Stem diameter↓ _{1 day}	Urban <i>et al.</i> , 1994
Natural	07h00 / 12h00 Inside : 300 / 800 Outside : 800 / 1900	Min / Max 8–15 / 18–27 RZW : Min / Max 15 / 26 (07h00–17h00)	Predawn :850 07h00 : 630 10h00 : 550 12h00 : 550 15h00 : 440 17h00 : 500		South Africa: Muldersdrift July'96–Oct'96 (14 Weeks)	GG 3 Years 3 plants 10 ℓ pot ⁻¹ Spacing 15 cm	Rockwool : Pecan nut shells :	Bud length↑ ^{max} Bud diameter↑ ^{max} Stem length↑ ^{max} Stem diameter↑ ^{max}	Van der Walt, 1999
4 hours	SL : 7.5 (day)	24h avg. = 19 NT _a / DT _a 19 / 19 (1) “Voornachtver hoging” (2) DT _a –NT _a =+5 (3) DT _a –NT _a =-5 (4)	700 (during lighting)	80–85	Netherlands: Aalsmeer	FR	Treatment (2) : [Starch]* o r ↑ : Treatment (1,2,3) : Treatment (4) : I↑ :	Stem length↓ Bud length↓ Blueing of bud↑ Bud size* Vase life* [Starch]↑ [Starch]↓ Vase life*	Vogelezang & De Hoog, 1998
06h30–17h15	0–1000	NT _a / DT _a 18 / 30 ^{max}	Daytime : 320,600,1200 Nighttime : 350	80 _{min}	Israel Winter	So 6 Months 1 plant 10 ℓ pot ⁻¹ ; 5 plants chamber ⁻¹	C _a + [Salt] (g m^{-2}) 320 + 3436 : ↑ + 3436 : ↑ + ↓ : ↑ + 1718 : ↑ + ↑ : Salt = 2577 :	Plants died Stopped growing Stem length↑ FW +DW↑ Growth↑ Stem length↑ Growth↓ but ↑ than at [C _a]=320	Zeroni & Gale, 1989

Table 4.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO ₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Quality	Literature
							320 + $\uparrow_{2577}$: Bud length↓ Petals – dark + deformed 320 + $\uparrow$: Stem length↓ 1200 + 0 : Bud size↑ Fresh weight↑ Normal flowers 1200 + $\uparrow$: Bud size↑ FW + DW↑	
	Natural	DT _a : 18 _{min} (Outside) NT _a : 18 constant 14 constant 18/14 SN 18/14/18/14 P			Israel, Rehovot Oct'81–May'82	GT, Vi, Mc, So 1 Year	T _a ↓ ^{opt} : Stem length _l or *	Zieslin <i>et al.</i> , 1987
					General		T _a ↑ : No Petals↓ T _a ↓ ^{min} : No Petals↑ Bullhead flowers↑ Bud length↓ Bud diameter↓ Long day + 15 °C : Stem length↑ No Leaves↓	Zieslin & Moe, 1985

Symbols and abbreviations used in Table 4.4 (see List of Abbreviations, page x)

4.4 Conclusion

As the seasons change from late summer to mid winter the quality increased (leaf area, fresh weight and flower bud length). The only quality criterion that differs from the rest is the stem diameter. The quality of stems is a function of the stem length rather than the irrigation treatment, with the longest stems having the highest quality and the shortest stems the poorest. Since the average stem length is the highest for the stems yielded by the $\frac{1}{2}X$ treatment, the general quality of the stems in this treatment will also be the highest.

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CHAPTER 5

Photosynthesis and Related Parameters

Abstract

The current experiment was conducted in a commercial greenhouse under South African conditions, from late summer to early winter (1 February – 16 June 1999). The greenhouse consisted of 72 raised beds with a total number of 40 000 in-ground rose plants of the cultivar Grand Gala (*Rosa hybrida*). Three beds were irrigated with three different volumes of irrigation water. The plants in the first bed each received 1.2 ℓ day⁻¹ in summer and 1.0 ℓ day⁻¹ in winter (treatment X), plants in the second bed received twice the above-mentioned volumes (2X treatment), while the plants in the third bed received only half the volumes (treatment $\frac{1}{2}$ X). Measurements of the photosynthesis parameters as well as the environmental variables were taken at 07h00, 12h00 and 15h30 daily. The photosynthesis and related parameters included the rate of photosynthesis (A), transpiration rate (E), stomatal conductance (G) and the internal CO₂ concentration (C_i), while the environmental variables included the irradiance level (I), atmospheric (ambient) temperature (T_a) and atmospheric (ambient) CO₂ concentration (C_a). The water use efficiency (WUE) was determined by calculating the ratio between A and E, while the irradiance saturation point (I_{sp}) was determined. Correlations between the different parameters were determined by means of principal component analyses (PCAs) as well as the fitting of linear regression lines. No significant differences were found between the respective photosynthesis parameters of the three irrigation treatments at 07h00, 12h00 and 15h30 respectively.

5.1 Introduction

The objective of growing plants in greenhouses is to maximise plant growth by optimising the growing conditions as far as possible. Since plant growth is dependent on the rate of CO₂ assimilation (photosynthesis rate), the conditions maximising/optimising the photosynthesis rate also favour plant growth. Processes accompanying photosynthesis, such as the rate of transpiration, respiration and stomatal conductance influence the rate or effectiveness of photosynthesis either directly or indirectly. These processes are again influenced directly or indirectly by environmental variables such as water application, CO₂ concentrations, irradiance levels and -duration, availability of elements (fertiliser application), temperature (night and day; root zone and ambient air) and air humidity (vapour pressure deficit) to a greater or lesser extent. Each of these variables has a range of optimum values at which maximum photosynthesis rates can be achieved. Maximum photosynthesis rates can, however, only be achieved when all the environmental variables (external input variables) fall in their optimum ranges since all the variables are linked. Any one of these variables can therefore be the factor limiting the photosynthesis rate (limiting factor). Under certain conditions there can be more than one limiting factor, e.g. a low I-level can prevent the shade leaves of a specific plant to reach its full photosynthesis potential, while the ambient air CO₂ concentration has a negative effect on the photosynthesis potential of sun leaves. Normally when one considers the limiting factor, the assumption is made that the value of this variable is lower than the values falling in the optimum range for this specific variable. This assumption is sometimes incorrect, since the value of the limiting factor, e.g. temperature, may just as well be greater than the values in the optimum range, but nevertheless limiting.

Plant related factors such as plant species genetics and age as well as horticultural practices used such as plant densities (Nelson, 1991:365), harvesting methods, bent stem technique, removal of blind shoots and stems with bent necks also influence the maximum achievable photosynthesis rate and the photosynthesis related processes. Plants of the same species, such as rose plants for example, or even the same cultivar react differently when subjected to various combinations of environmental variables as well as horticultural practices under controlled or semi-controlled conditions in greenhouses.

The maximum rate of photosynthesis ($A_{\max}$) vary markedly both within and between C₃ species. $A_{\max}$ varies with almost all environmental variables which influence photosynthesis, even when the plants within the same genotype (cultivar) are considered. In this instance preconditioning, leaf age and ontogeny may have a marked influence on $A_{\max}$. Considerable variations may even

be found between leaves within the same plant (plant canopy) (Long & Hällgren, 1993:159). When comparing the photosynthesis rates (expressed per unit leaf area) of single leaves to that of the whole plant canopy of C_3 plants in general, the tendency to increase hyperbolically with an increase in irradiance (I) levels to the irradiance saturation point (I_{sp}) stays the same. In the instance of the latter, however, higher I -levels are required to reach this point. The reason for this difference is that the single leaves are generally exposed to high levels of Irradiance when measurements are made. In single plants (canopies) or stands of plants only the upper leaves (sun leaves) are exposed to high levels of Irradiance and thus absorb much of the incident light, leaving less for the lower leaves (shade leaves). When single plants or stands of plants are then exposed to higher I -levels, the upper leaves (sun leaves) may be saturated, while more light is transmitted and reflected toward the shaded leaves below that are not saturated. Exposing the whole plant or a stand of plants to I -levels high enough as to bring the shaded leaves to irradiance saturation point (I_{sp}) and maximise their photosynthesis rate, would probably supersaturate the upper leaves (sun leaves) decreasing their rate of photosynthesis with photo-inhibition (Salisbury & Ross, 1992:259–60).

Plants adapted to shaded habitats (shade plants) have a lower capacity for CO_2 assimilation (photosynthesis) than plants adapted to habitats where they are exposed to high I -levels (sun plants) (Schulze & Hall, 1982:183). Sun and shade plants have the ability to acclimatise to conditions of respectively lower or higher I -levels than it were grown at to a certain extent. When shade plants are exposed to higher I -levels, the photosynthetic capacity is higher than that of the same plants exposed to low I -levels equal to that of its native habitat (cultivation conditions). Exposing sun plants to lower I -levels than it is adapted to causes the photosynthesis rate to decrease. Adaptation of sun plants to lower I -levels is more common than adaptation of shade plants to higher I -levels. The reason for this is that leaves/plants grown under low I -levels are usually damaged when exposed to high I -levels, a phenomenon called photo-inhibition. Any leaf/plant can undergo photo-inhibition when exposed to unusually high I -levels, but photo-inhibition is most common in plants growing in the shade that are suddenly exposed to high I -levels. Photo-inhibition lowers photosynthetic rates and impairs electron transport and photophosphorylation (Taiz & Zeiger, 1991:253).

There are marked differences between sun- and shade leaves, corresponding to characteristics of true sun- and shade plants. In dicots, shade leaves are typically larger in area but thinner than sun leaves, with sun leaves having longer palisade cells or an additional layer of these cells and weighing more per unit leaf area. Sun leaves have a more developed epidermis, spongy mesophyll, and vascular systems. Sun leaves are also more densely distributed on the stem with

shorter petioles, shading each other more. On the other hand, the petioles of shaded leaves also respond to the direction and intensity of the Irradiance received, by bending, causing the leaf blades to move into less shaded regions. "On a weight basis, shade leaves also generally have more chlorophyll *b*, mainly because each chloroplast has more grana than do those of sun leaves." In some instances some shade plants develop far more thylakoids in the grana, up to 100 per granum. "On the other hand, chloroplasts of shade leaves have less total stroma protein, including rubisco, and probably less thylakoid electron transport protein than do sun leaves." Thus, shade leaves invest more energy in producing light-harvesting pigments, allowing maximum utilisation of the limited Irradiance it receives. Chloroplasts rearrange in such a way to maximise light absorption in leaves subjected to lower I-levels than normal and to prevent (minimise) damage to the photosynthetic apparatus of leaves subjected to excessively high I-levels (Taiz & Zeiger, 1991:251–2; Salisbury & Ross, 1992:257 & 570).

When exposed to increasing I-levels, the net photosynthesis rate (*A*) of rose plants, as with other *C*₃ plants, tend to increase hyperbolically (Pasian & Lieth, 1989:584; Jiao *et al.*, 1991a:241; Jiao *et al.*, 1991b:247; Forseth & Norman, 1993:214; Long & Hällgren, 1993:158; Baille *et al.*, 1996:947; Raviv & Blom, 2001:267). *A* increases from a negative value obtained in the dark (dark respiration; *R*_d), reaching a plateau where these plants are no longer able to use additional irradiance above a critical value after which *A* remains constant (*A*_{max}) or even decreases again as a result of photo-inhibition and chloroplast-injury (Nelson, 1991:360). This value is known as the light (irradiance) saturation point (*I*_{sp}). The irradiance level between darkness and light saturation, where the net *A* is zero, is known as the light (irradiance) compensation point (*I*_{cp}). Differences in *I*_{cp} are caused primarily by differences in *R*_d rates. When respiration is low, the light compensation point will also be low since the leaf requires less light to photosynthesise rapidly enough to balance the CO₂ being lost. This value is critical since no net growth will occur at I-levels lower than this point (Nelson, 1991:382; Salisbury & Ross, 1992:255; Long & Hällgren, 1993:158). The level of *I* required to saturate whole-plant net *A* for roses is higher than that required for individual leaves (Jiao *et al.*, 1991b:248), however, *A*_{max} remains the same in both instances (Nelson, 1991:361).

No clear differences were found in *A* when rose leaves at different ages, ranging from 10 to 40 days, were subjected to increasing I-levels. A possible explanation for these results could be that leaves younger than 10 days and older than 40 days would exhibit lower *A*-rates. Suggesting that 10-day-old rose leaves have an almost completely developed photosynthetic mechanism, and that senescence does not begin until rose leaves are older than 40 days for the plants used in this specific experiment (Pasian & Lieth, 1989:583).

As with irradiance level, the duration of the I-period also has a profound influence on daily carbon gain (C gain). In general, the longer the I-period the longer the photosynthesis period and the higher the daily carbon gain, since a shorter dark period results in less daily carbon loss due to respiration during the dark. Increasing the I-period to 24 h decreases the C loss during the dark period due to dark respiration to 0 (Jiao *et al.*, 1991b:248-50). Increasing the I-duration to up to 18 h is beneficial for roses, a further increase to 24 h may, however, result in a reduction in postproduction life (vase life) of these and other crops (Nelson, 1991:371).

A is also influenced by the partial pressures of the CO₂ in the ambient air (C_a) and in the intercellular spaces of the leaf (C_i), as well as the stomatal conductance of water (G) (adapted) and the atmospheric pressure (Taiz & Zeiger, 1991:258). An increase in the atmospheric CO₂ concentrations (C_a) results in an increase in A in roses (Zieslin & Moe, 1985:218; Jiao *et al.*, 1991a:242; Nelson, 1991:349). A exhibits a hyperbolic response curve when plotted against increasing C_a (Jiao *et al.*, 1991b:250; Baille *et al.*, 1996:949). The C_a at which the CO₂ fixation by photosynthesis balances the CO₂ loss by respiration is known as the CO₂ compensation point (C_{cp}). The C_a at which A is saturated and a further increase in the C_a does not result in an increase in A, is known as the CO₂ saturation point (C_{sp}) i.e. where RuBP regeneration rate is limiting (Taiz & Zeiger, 1991:258). In some instances A keeps on increasing and no C_{sp} is reached, while in other instances it is. The additional CO₂ decreases photo respiration by increasing the ratio of CO₂ to O₂ reacting with rubisco, leading to higher A-rates (Porter & Grodzinski, 1985 quoted by Jiao *et al.*, 1991b:251; Salisbury & Ross, 1992:260).

A is influenced by E since a net efflux of gas, predominantly water vapour, from a photosynthesising leaf normally exceeds the total influx creating a pressure gradient, causing a mass flow of gases including CO₂ out of the leaf and so depressing C_i relative to C_a (Long & Hällgren, 1993:154).

The response of A to C_i exhibits a hyperbolic or asymptotic reaction curve under saturating irradiance conditions. On the initial slope of the curve A_{sat} is limited by the carboxylation efficiency and is therefore RuBP (ribulose-1,5-bisphosphate) saturated. Beyond the inflection of the curve, A_{sat} is assumed to be limited by the potential rate of regeneration of RuBP and is therefore RuBP limited (Long & Hällgren, 1993:156–7).

When A-rates are plotted as a function of temperature, the curve exhibits a parabolic shape (Taiz & Zeiger, 1991:261). The A rates increases as the temperature increases, reaches maximum values and then decreases again at still higher temperatures (Jiao *et al.*, 1991a:242; Nelson, 1991:382; Taiz & Zeiger, 1991:261). The temperatures at which the maximum rates of A is

reached is called the optimum temperatures, known collectively as the optimum temperature range (Nelson, 1991:382; Taiz & Zeiger, 1991:261). Since rose plants are evergreen shrubs that become deciduous when the night air temperature falls below 10 °C (Tashner, 2001:11) to 12 °C (Romer, 1993:79 quoted by Van der Walt, 1999:38), assuring that the minimum temperature is kept above these temperatures are a necessity for continues production during the winter, with the corresponding day air temperatures varying from 18 to 25 °C (Tashner, 2001:11).

Night air temperatures (NT_a) also influences A obtained during the day; when rose plants were grown under three different NT_a regimes, the regime where the plants were continuously exposed to 18 °C had the highest A-rate while the plants that were subjected to 12 °C had the lowest. The plants subjected to alternating temperatures (12 °C and 18 °C every 2 hours) had intermediate A-rates, being almost just as high as the A-rate of the plants subjected to the 18 °C regime (Khayat & Zieslin, 1986:610).

In the instance where rose plants were subjected to a nutrient solution of which the EC gradually increased, A was minimally effected. This phenomenon can be ascribed to the gradual acclimatisation of these rose plants to the increasing EC (Raviv & Blom, 2001:266–7).

Optimum temperatures, where A is maximal, increases with increasing C_a -levels as well as increasing I-levels, and even further when the plants are subjected to a combination of higher C_a and I-levels (Jiao *et al.*, 1991a:239; Jiao *et al.*, 1991c:257–8). It was found that the influence of C_a -level on A increases, while the relative contribution of temperatures to A decreases with increasing I-levels. It was also found that the relative contribution of the different environmental variables to plant daily growth was 64, 31, 4, 0.3 and 0.7 % for the I-level (100 – 1200 $\mu\text{mol m}^{-2} \text{s}^{-1}$), day length (8 – 16 h), C_a (350 – 1500 $\mu\text{mol mol}^{-1}$), DT_a (15 – 30 °C) and NT_a (15 – 25 °C) respectively (Jiao *et al.*, 1991c:255–6).

Respiration rates (R) increase as the temperature increases (Jiao *et al.*, 1991a:238–42; Nelson, 1991:360; Taiz & Zeiger, 1991:262) especially during the day when more C is lost due to photo-respiration (Salisbury & Ross, 1992:262). In an experiment where the R was determined for the different parts of a rose shoot at stage 3 of shoot development (see the Materials and Methods of this Chapter), it was found that the R (on a dry weight basis) of the flower bud was three to four times higher than that of the leaves (Jiao *et al.*, 1991a:238). A reduction in night air temperature results in a reduction in dark R rates (Jiao *et al.*, 1991a:241; Nelson, 1991:382), however, too low night temperatures (e.g. 12 °C) have been found to effect the daytime A-rates negatively (Jiao *et al.*, 1991a:241). Determining R in the dark is the only way to quantify the amount of CO_2 (C) that is lost during the day by respiration. The assumption that R rates measured during

the light period are the same as that measured in the dark is most probably incorrect (Salisbury & Ross, 1992:570). Even if the temperature is kept constant during the light and dark period when the measurements take place, the application of high I-levels during the light period and the occurrence of photo-respiration increases the amount of CO₂ lost in comparison of that lost during the dark period (Jiao *et al.*, 1991a:243).

The transpiration rate (E) is influenced by the stomatal conductance of water vapour, the difference in the partial pressures of water inside the leaf and in the ambient air (VPD) and the atmospheric pressure (P) (Taiz & Zeiger, 1991:258). Air humidity and thus air water vapour concentrations have an important influence on stomatal opening. The water vapour pressure deficits (VPD) that can be withstood, without detriment to the CO₂ assimilation rate (A), vary between species. In many mesophytes stomatal closure, sufficient to depress A, begins at a VPD of > 1.0 kPa (Long & Hällgren, 1993:154). An increase in the stomatal aperture does not necessarily result in an increase in A. Under conditions where the air surrounding the leaves are very still an increase in the stomatal aperture may have little effect on E. Under these conditions the thickness of the boundary layer controls the rate of E. On a windy day, however, the stomatal aperture has the largest control over E; an increase in the stomatal aperture drastically increases the E-rate (Taiz & Zeiger, 1991:93). When rose plants are subjected to increasing I-levels E increases hyperbolically (Baille *et al.*, 1996:950). The E-rate of rose plants decrease with an increase in C_a (Baille *et al.*, 1996:950) and increase as the VPD increases (Baille *et al.*, 1996:950–3). Leaf temperature plays a very important, although indirect, role in the rate of E through its effect on the water potential (or VPD) (Raviv & Blom, 2001:262). The exposure of rose plants to irrigation water having different electrical conductance (EC) (levels of salinity) had an effect on the E-rate of the plants. Generally the E-rate decreased with an increase in the EC-levels (Zeroni & Gale, 1989:506). Withholding water from previously well-watered rose plants causes a decrease in maximum E-rates reached during the day as well as minimum E-rates reached at night (Urban *et al.*, 1994b:672). When rose plants were subjected to a nutrient solution with a gradually increasing EC, the specific E-rate decreased sharply (Raviv & Blom, 2001:267–8). The E-rate of young leaves is much higher than that of mature leaves (Jones, 1992 quoted by Raviv & Blom, 2001:264)

The opening and closing of stomata and thus the resulting increase and decrease in stomatal conductance (G) have been found to respond to root signals, to I-levels, VPD, CO₂ levels and to plant hormones in a complex interaction (Raviv & Blom, 2001:263). The capacity of the mesophyll to fix CO₂ influences G, rather than G influencing the rate of CO₂ assimilation (Long & Hällgren, 1993:157). G is effected by the I-level, as G increases hyperbolically with an

increase in the I-level (Forseth & Norman, 1993:214). The minimum I-level for the opening of stomata in most plants is just beyond the I_{cp} . Subjecting plants to higher I-levels causes wider stomatal apertures and thus higher Gs. When plants are suddenly exposed to darkness, the stomata closes more rapidly than when the I-level declines gradually. When the wavelengths of light that were most effective in causing stomata to open were examined, it was found that blue light was nearly 10 times as effective as red light in producing a given stomatal aperture. Apparently the red light responses are caused by light absorbed by chlorophyll, but the blue light effect is independent of photosynthesis (Salisbury & Ross, 1992:74–5). The blue-light photoreceptor has yet to be established. The blue-light activity is not restricted to the stomata, but include common photoresponses such as phototropism, solar tracking as well as the movement of chloroplast within photosynthetic cells (Taiz & Zeiger, 1991:135).

When rose plants were grown at three levels of daytime ambient $[CO_2]$ and four levels of salinity (irrigation water ECs), G decreased as the salinity levels as well as the ambient $[CO_2]$ increased (Zeroni & Gale, 1989:506).

In an experiment where rose plants were grown at two different air humidities (65 and 90 %, RH) combined with three lighting periods (16, 20 and 24 h day⁻¹), the G measured at the beginning of the lighting period / new cycle (06h00) was lower than that measured at 12h00, irrespective of the lighting period or % RH. The plants subjected to the 90 % RH had higher G-values than the corresponding G-values of plants subjected to 65 % RH, irrespective of the lighting period or measuring time. In general, the G of the rose plants increased as the lighting period increased with reference to the two different % RH as well as the different measuring times (Mortensen & Fjeld, 1998:33). When rose plants were subjected to three supplementary lighting treatments of different duration in addition to the 12 h light period, it was found that G decreased at the end of the light period irrespective of the duration of the supplementary lighting (SL) treatment. For one rose cultivar the decrease in G did not depend on the duration of the SL treatment, but for the other cultivar it did. In both cultivars the Gs measured in the light period were enhanced by the SL treatments. Strangely enough the SL treatment of 4 h resulted in higher G than the SL treatment of 8 h measured during the light period as well as during the period when SL was applied. In general G (measured in the light period) decreases as the I-level of the I applied during the light period decreases. The sensitivity of different rose cultivars to the I-level received during the light period, with reference to G, is cultivar-dependent as well as dependent on the developmental stage of the specific leaves used for the measurements (Blom-Zandstra *et al.*, 1995:256–7). When rose plants were subjected to SL treatments with different qualities (control, white, orange and blue respectively); the G of the plants treated with the

orange SL were the highest during the light period and those treated with the white SL the second highest. The G measured during the light period of the blue SL treatment corresponded with that of the control (Blom-Zandstra *et al.*, 1995:257–8). When the light was switched on, or off after light treatment of 2.5 h or 3.5 h, the Gs were as follows: G decreases instantaneously when the light is switched off after which it increases, at first the increase is very sharp with a more gradual increase later on. The reduction in G when the light was switched off depended on the I-level during the day and the duration of the light period. The G of the plants grown at high I-levels ($150 \mu\text{mol m}^{-2} \text{s}^{-1}$) decreased much faster when the light was switched off than that of the plants grown at low I-levels ($50 \mu\text{mol m}^{-2} \text{s}^{-1}$) (Blom-Zandstra *et al.*, 1995:257).

The stomata of most plants respond to C_i -levels but not to the CO_2 concentration at the leaf surface and in the stomatal pore. Low C_i -levels cause stomata to open, while high C_i -levels can cause the stomata to close partially; occurring in the light as well as the dark. When the stomata are slightly open, CO_2 -free air blown across the leaf results in the stomata opening even wider, even in the dark. On the other hand, blowing CO_2 -free air over completely closed stomata has no effect (Salisbury & Ross, 1992:74). High temperatures (30 to 35 °C) usually cause stomatal closing. This might either be an indirect response to water stress, or a rise in respiration rate causing an increase in C_i . The latter is most probably the correct explanation, since it can be prevented by flushing the leaf continuously with CO_2 -free air (Salisbury & Ross, 1992:75).

Stomata of many species are highly sensitive to atmospheric humidity, closing when the difference between the vapour content of the air and that of the intercellular spaces exceeds a critical level. A large gradient tends to induce oscillations in opening and closing with a periodicity of about 30 minutes, probably because, as the steep vapour gradient induces closing, C_i is depleted, and this in turn leads to opening. The most rapid responses to lowered humidity occur under low I-levels (Salisbury & Ross, 1992:75).

Stomatal opening and closing is also influenced by the water potential within the leaf. As water potential becomes more negative, the stomata close, overriding the effect of low CO_2 levels and bright light (Salisbury & Ross, 1992:75). When plants are supplied with abundant volumes of water, and the I-level is such that high rates of A is favoured, stomatal apertures are maximal, as well as the E-rate. On the other hand, when the water supply becomes insufficient, but the plants are still subjected to high I-levels, the stomata will open less or will even remain closed (Taiz & Zeiger, 1991:94).

To quantify the effectiveness of the volume of water applied to a crop, with reference to the production of the specific crop the water use efficiency (WUE) is calculated. The (WUE) can be

defined in four different ways: (i) photosynthetic WUE as the ratio of leaf net assimilation and leaf transpiration; (ii) biomass WUE as the ratio of cumulative aboveground dry weight biomass of a crop canopy to cumulative evapotranspiration used by the crop; (iii) yield WUE as the product of yield dry mass and evapotranspiration or (vi) effective WUE as the yield dry weight biomass per volume of the water input (precipitation and irrigation) (Baille *et al.*, 1996:948; Raviv & Blom, 2001:258–9). The water use efficiency (WUE) of rose plants decreases when the plants are subjected to increasing I-levels, while the WUE increases when the plants are subjected to increasing C_a concentrations (Baille *et al.*, 1996:951–2). The WUE also decreases with an increase in the leaf to air vapour pressure deficit (VPD) (Baille *et al.*, 1996:952). Subjecting rose plants to gradually increasing salinity levels (2.5 – 7.5 mS cm⁻¹) resulted in an increase in the WUE (Raviv & Blom, 2001:267). The WUE of well-watered plants is usually low, increasing during early stages of water stress, and decreasing again as stress becomes more severe (Taiz & Zeiger, 1991:353). The reciprocal of the photosynthetic WUE, the so-called transpiration ratio, is determined to quantify the effectiveness of plants in moderating water loss while allowing sufficient CO₂ uptake for photosynthesis (Taiz & Zeiger, 1991:97). Some other ways in which effectiveness can be quantified is by calculating the photosynthetic efficiency (ratio of the total I-energy absorbed by a crop from planting to harvest to the total chemical-bond energy of the sucrose produced in photosynthesis), as well as calculating the harvest index (percentage of weight in the harvestable product compared with aboveground plant biomass as a function of e.g. the I received) (Salisbury & Ross, 1992:263–4). Photosynthetic efficiency can further be expressed on the basis of incident I, intercepted I, or absorbed I (Pasian & Lieth, 1989:583; Wilson *et al.*, 1992:368; Baille *et al.*, 1996:947) or on the basis of the C_a (Baille *et al.*, 1996:948). In some instances the photosynthetic efficiency is also called the quantum yield (Long & Hällgren, 1993:160).

Photosynthetic capacity is also controlled internally; removing carbon sinks e.g. developing fruits (opening flowers) typically reduces leaf photosynthetic capacity after a few days, especially in adjacent leaves that normally translocate substances to these organs. If some leaves are removed, the photosynthetic capacity of the remaining leaves often increases. It appears that leaf A capacity is determined primarily by the availability of photosynthetic enzymes, Rubisco in particular. There is evidence suggesting that stomatal conductance adjusts to this capacity rather than being a strong component of the capacity itself (Salisbury & Ross, 1992:263 & 569).

Canopy architecture also has an influence on plant production. Structure of the leaf canopy determines how much light will be absorbed by individual leaves in a plant community. The determination of the leaf area index (LAI) of a crop is of importance, since the ratio of leaf area

of a crop to the ground area upon which that crop stands determines the leaf area receiving direct (full) irradiation and the leaf area subjected to lower, modified I-levels. This will be the case in the instance where the leaves in the plant canopy are arranged nearly horizontally and irradiance comes mostly from above. If leaves are nearly vertical, however, as are those of most grasses, and irradiance still comes predominantly from above, the light rays will be more or less parallel to the leaf surfaces, subjecting the leaves to lower I-levels, while the light penetrates deeply into the canopy. Ideally, a plant should have a LAI that allows for optimum photosynthesis of the plant as a whole. If the index is too low, not enough light will be absorbed; if too high, lower leaves will not get enough light and will not photosynthesise effectively. The LAI of a crop depends on the specific plant species and the planting density of the crop (Salisbury & Ross, 1992:260 & 571). The LAI is very helpful when extrapolating the photosynthesis rate, transpiration rate, stomatal conductance etc. (usually measured per m² leaf area) to that measured for the crop per m² ground surface area.

5.1.1 Changes of photosynthesis parameters during the course of a typical day.

The changes of the different photosynthesis parameters during a typical day in an arid environment can be categorised as being either one-peaked or two-peaked. These daily courses vary with different species and environmental conditions. Well-watered C₃ plants frequently exhibit one-peaked daily courses of CO₂ (A) and water vapour exchange (G or/and E) with high A- and G/E-rates even under dry atmospheric conditions. Some of these peaks are, however, irregular (Schulze & Hall, 1982:203–5). For example, when rose plants were grown in summer in Greece, under evaporative cooling conditions and cooling using only natural ventilation, the G in both cases increased sharply in the morning reaching a maximum at 13h00 and 11h00 respectively, and declined steadily during the rest of the day. The maximum G-value reached under evaporative cooling conditions was almost double the value reached under natural cooling conditions alone. Under these conditions the daily course of E is much more symmetrical than that of G. The rate of E under natural cooling conditions is higher in the morning than that under evaporative cooling conditions, with corresponding rates during the afternoon (Katsoulas *et al.*, 2001:241–3). The same one-peaked patterns were exhibited for G and E by *Prunus armeniaca* grown in an arid environment early in the wet season, receiving adequate irrigation. The rates of G and E as well as A were high under these conditions. Under more severe environmental conditions, two-peaked patterns were exhibited for G, E and A with the rates of each being lower than the corresponding values at more favourable conditions. During a two-peaked diurnal course, A increases to high rates in the early morning, decreases at noon and increases again in the late afternoon before decreasing again. The mid-day depression at noon is caused by the

closing of the stomata, resulting in a decrease of A. The second peak results from the reopening of the stomata in the late afternoon. E may also decrease, but this may not be generally observed since the increased difference in VPD between the leaf and the atmosphere (air) at noon compensates for the effect of stomatal closure (Schulze & Hall, 1982:205–8).

The daily course of the transpiration rate of rose plants can be depicted as a hyperbola, increasing sharply during the morning and decreasing again during the late afternoon and the beginning of the dark period, reaching a maximum rate in the early afternoon (Urban *et al.*, 1994b:670). When well-watered rose plants are suddenly subjected to desiccation, the plants still exhibit a one-peaked daily course with reference to the transpiration rate, but the peak becomes more irregular as the days passes. The transpiration rate still increases sharply in the first part of the morning, but starts to decrease again later during the morning. The transpiration rate decreases sharply at first and then more gradually until darkness falls and it decreases sharply again to a minimum value (Urban *et al.*, 1994b:672).

The rate of photosynthesis of C₃ plants usually corresponds with the change in I-levels during the course of a typical day, with the maximum CO₂ assimilation occurring at noon and the minimum during the night (Salisbury & Ross, 1992:255).

5.2 Materials and Methods

The photosynthesis data was recorded at 07h00, 12h00 and 15h30 each day. The bed of each treatment was divided into four equal parts, and the measurements of each part taken as a replica, thus each treatment had four replicas. A non-destructive method was used to collect the photosynthesis data. The method used was as follows. A rose stem of each irrigation treatment was selected at random while the stems were still attached to the respective plants. These stems had different lengths and were at the third stage of shoot development as described by Jiao *et al.* (1991b:246). At this stage, also called the 'colour bud stage', the shoots are $\pm$ six weeks old, all leaves fully expanded, the flower bud ca. 20 mm in diameter with petals visibly red, being in the last week of development before harvesting would take place. The fifth compound leaf from the bud, consisting of three to five pinnae, was chosen. Being the fifth compound leaf, the leaf was rarely shaded by other leaves. A portable Infrared Gas Analyser: IRGA (LCA-2: The Analytical Development Co. Ltd, England) operating in the differential mode was used for the measurements. An adjoining mast allowed air to be withdrawn continuously at a rate of 350 ml min⁻¹ from a sampling point at a similar height as the plants (bud height), thus determining the CO₂ concentration in the plant canopy. Three readings were taken per stem; each reading on a different pinna of the same leaf. The readings were taken 30 seconds after the cuvette was clamped shut, directly after the readings had stabilised. This was done to minimise the effect of the artificially dried air moving over the leaf inside the cuvette; no humidity control was otherwise applied. The cuvette was tilted as to expose the leaves to the maximum irradiance level possible; perpendicular to the incoming rays of the sun. The plants were not subjected to rapidly changing environmental variables, but were measured under prevailing environmental conditions.

Data for the following photosynthesis parameters were recorded:

- Net CO₂ assimilation rate (Photosynthesis rate) (A ; $\mu\text{mol m}^{-2} \text{s}^{-1}$)
- Internal CO₂ (C_i ; $\mu\text{mol mol}^{-1}$)
- Transpiration rate (E ; $\text{mmol m}^{-2} \text{s}^{-1}$)
- Stomatal conductance of water (G ; $\text{mol m}^{-2} \text{s}^{-1}$)

As well as for the following external environmental (input) variables:

- Leaf temperature (T_l ; °C)
- Ambient air temperature (T_a ; °C)
- Incident irradiance level (photosynthetic photon flux; PPF) (I ; $\mu\text{mol m}^{-2} \text{s}^{-1}$)
- External CO₂ concentrations (C_a ; $\mu\text{mol mol}^{-1}$)

Note that the photosynthesis parameters are all expressed, as properties per unit leaf area (were determined per unit leaf area). Furthermore note that the leaf temperature (T_l) was determined, but is not referred to further in this chapter since the leaf temperature and the air temperature did not differ more than 2 °C at any time, with the air temperature generally being the higher of the two.

The following variables were measured by the IRGA (LCA), (1) photon flux density incident on the cuvette (I) and (2) cuvette air temperature (T_a), while the remaining variables (A, E, G, T_l , C_i and C_a) were calculated automatically.

The photosynthetic water use efficiency (WUE) was calculated by determining the ratio of A to E, while the irradiance saturation point (range) was determined.

The photosynthesis data was not recorded continuously. The recorded data was divided into two global seasonal categories to give a general idea of the effect of the season on the photosynthetic parameters as well as the environmental variables. In the first category the late summer and autumn data was combined (10 February – 16 May 1999), while in the second category the early winter data was combined (17 May – 15 June 1999).

The data of the replicates for each measurement time (07h00, 12h00 and 15h30) were pooled for the PCAs and other graphs to demonstrate the general trends.

The data in this study was analysed by using the Statistica ver. 6[®] computer software package and all values presented as the mean $\pm$ SD (standard deviation). The probability levels used for statistical significance were $P < 0.05$ and parametric or non-parametric tests were used to compare groups. The four photosynthesis parameters as well as the three environmental variables were analysed with the multivariate analysis method Principle Component Analysis (PCA) using CANOCO ver. 4.

The following formulas were used to transform results obtained in other experiments to units used in this experiment for comparison:

$$A (\mu\text{mol m}^{-2} \text{ s}^{-1}) = \frac{\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1} \times 1000}{44 \text{ g mol}^{-1}} \quad \begin{array}{l} \text{See Pasion \& Lieth, 1989} \\ \text{Formula 5.1} \end{array}$$

$$A (\mu\text{mol m}^{-2} \text{ s}^{-1}) = \frac{\text{mmol C dm}^{-2} \text{ h}^{-1} \times 100 \times 44 \text{ g mol}^{-1}}{3600 \text{ s} \times 12 \text{ g mol}^{-1}} \quad \begin{array}{l} \text{See Khayat \& Zieslin, 1986} \\ \text{Formula 5.2} \end{array}$$

$$R (\mu\text{mol s}^{-1}) = \frac{\mu\text{mol CO}_2 \text{ min}^{-1}}{60 \text{ s}} \quad \begin{array}{l} \text{See Jiao et al., 1991a} \\ \text{Formula 5.3} \end{array}$$

$$R (\mu\text{mol s}^{-1}) = \frac{\mu\text{mol CO}_2 \text{ g}^{-1} \text{ Dry weight min}^{-1} \times \text{g Total dry weight}}{60 \text{ s}} \quad \begin{array}{l} \text{See Jiao et al., 1991a} \\ \text{Formula 5.4} \end{array}$$

$$R (\mu\text{mol m}^{-2} \text{ s}^{-1}) = \frac{\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1} \times 1000}{44 \text{ g mol}^{-1}} \quad \begin{array}{l} \text{See Pasion \& Lieth, 1989} \\ \text{Formula 5.5} \end{array}$$

$$E (\text{mmol m}^{-2} \text{ s}^{-1}) = \frac{\text{mg H}_2\text{O s}^{-1}}{18 \text{ mg mmol}^{-1} \times 2} \quad \begin{array}{l} \text{See Urban et al., 1994b} \\ \text{Formula 5.6} \end{array}$$

$$\begin{aligned} E (\text{mol m}^{-2} \text{ day}^{-1}) &= \frac{\text{cm}^3 \text{ H}_2\text{O cm}^{-2} \text{ Leaf area day}^{-1} \times 10000}{18 \text{ g mol}^{-1}} \\ &= \frac{\text{g H}_2\text{O cm}^{-2} \text{ Leaf area day}^{-1} \times 10000}{18 \text{ g mol}^{-1}} \end{aligned} \quad \begin{array}{l} \text{See Raviv \& Blom, 2001} \\ \text{Formula 5.7} \end{array}$$

$$E (\ell \text{ plant}^{-1} \text{ day}^{-1}) = \frac{\text{cm}^3 \text{ H}_2\text{O cm}^{-2} \text{ Leaf area day}^{-1} \times \text{cm}^2 \text{ plant}^{-1}}{1000} \quad \begin{array}{l} \text{See Raviv \& Blom, 2001} \\ \text{Formula 5.8} \end{array}$$

$$E (\ell \text{ plant}^{-1} \text{ day}^{-1}) = \frac{\text{m}\ell \text{ H}_2\text{O plant}^{-1} \text{ day}^{-1}}{1000} \quad \begin{array}{l} \text{See Cabrera et al., 1995a} \\ \text{Formula 5.9} \end{array}$$

$$E (\text{mmol m}^{-2} \text{ s}^{-1}) = \frac{\text{W H}_2\text{O m}^{-2} \text{ Ground area} \times 1000}{2440 \text{ J g}^{-1} \times 18 \text{ g mol}^{-1} \times 4 \text{ m Leaf area}} \quad \begin{array}{l} \text{See Katsoulas et al., 2001} \\ \text{Formula 5.10} \end{array}$$

$$G (\text{cm s}^{-1}) = \frac{1}{\text{s cm}^{-1}} \quad \begin{array}{l} \text{See Mortensen \& Fjeld, 1998} \\ \text{Formula 5.11} \end{array}$$

$$G (\text{cm s}^{-1}) = \text{mm s}^{-1} \times 10 \quad \begin{array}{l} \text{See Katsoulas et al., 2001} \\ \text{Formula 5.12} \end{array}$$

$$G (\text{mol m}^{-2} \text{ s}^{-1}) = \frac{(E) \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1} \times 100 \text{ kPa}}{\text{kPa} \times 1000} \quad \begin{array}{l} \text{See Katsoulas et al., 2001} \\ \text{Formula 5.13} \end{array}$$

$$\text{EC (mS cm}^{-1}) = \frac{\text{dS m}^{-1} \times 100}{100} \quad \begin{array}{l} \text{See Raviv \& Blom, 2001} \\ \text{Formula 5.14} \end{array}$$

$$\text{WUE (mol mol}^{-1}) = \frac{\text{g CO}_2 \div 44 \text{ g mol}^{-1}}{\text{g H}_2\text{O} \div 18 \text{ g mol}^{-1}} \quad \begin{array}{l} \text{See Baille et al., 1996} \\ \text{Formula 5.15} \end{array}$$

Abbreviations used see List of Abbreviations, page x

5.3 Results and Discussion

5.3.1 Principal Component Analysis

The results of the Principal Component Analyses (PCAs) of the photosynthetic parameters (A, E, G, C_i) combined with the environmental variables (I, T_a, C_a), for the three irrigation treatments, are presented in Figures 5.1a to c to Figures 5.6a to c. It should be noted that in the next section the photosynthetic parameters as well as the environmental variables are simply referred to as variables.

A PCA-graph depicts the distribution of a number of points in a multiple axed (multi-dimensional) graph on a two-dimensional plane (graph). Each variable is represented by an arrow, the length of which is representative of the significance of the variable and the distance between arrows are indicative of how closely variables are correlated or not. A small angle between two variables indicates a very close positive correlation, while an angle of approximately 180° indicates a very close negative correlation between two variables. An angle of 90° indicates a weak correlation between two variables.

The first three PCAs (Figures 5.1a to c to Figures 5.3a to c) depicts the seasonal effect (late summer and early winter, respectively and combined) on the relations (correlation) between (of) the different variables at different times of the day (07h00, 12h00 and 15h30) per irrigation treatment.

Data points of different times of the day (07h00, 12h00 and 15h30) grouped (concentrated) into distinct (separate) groups. The groups are more distinct from one another during the winter period than during the summer period. This was observed irrespective of the irrigation treatment (Figures 5.1a and b; Figures 5.2a and b and Figures 5.3a and b). These groups are still distinct even when the summer and winter data points are combined onto a single graph (Figure 5.1c; Figure 5.2c and Figure 5.3c). The variables also formed distinct groups, in this case only two groups, irrespective of the season or irrigation treatment (Figures 5.1a to c; Figures 5.2a to c and Figures 5.3a to c). The variables in each group are positively correlated to a greater or lesser extent. The one group consists of variables A, I, T_a and E, while the other group consists of C_i, C_a and G. The 07h00 data points are situated closer to the arrowheads of the second variable group, while the 12h00 data points are situated closer to the arrowheads of the first group. The 15h30 data points are situated between the other two groups of data points, exhibiting a tendency more to the location of the 12h00 data points. Effectively this indicates that the values of C_i, C_a and G are the highest (most significant) for the 07h00 data points of each irrigation treatment

(summer or winter), while the values of A, I, T_a and E are the lowest (least significant). For the 12h00 data points the exact opposite tendency is exhibited and again the values of the 15h30 data points are intermediate.

In the instances of all the PCAs, the most significant variable, determined by the length of the arrows, are either G or E (Figures 5.1a to c; Figures 5.2a to c and Figures 5.3a to c; Table 5.1). In two instances, C_i was combined with G as the most significant variable. Practically this indicates that when one wants to distinguish between data points of the 07h00, 12h00 or 15h30 measurements (readings), the variables to concentrate on are G or E, irrespective of the irrigation treatment. Thus, the stomatal conductance and the rate of transpiration are the two indicative variables.

Table 5.1: Most significant, second most significant and third most significant variable (s) according to the length of the arrows in the respective PCAs (Figure 5.1a to c; Figure 5.2a to c and Figure 5.3a to c).

Treatment	Summer			Winter			Summer and winter		
	1	2	3	1	2	3	1	2	3
2X	G	E	C _i	G and C _i	T _a	C _a	G	E	C _i
X	G and C _i	E	T _a	E	C _i	T _a and I	E	C _i and T _a	C _a
½X	E	C _i	T _a	G and E	C _i	T _a	E	T _a	C _i

Abbreviations used in Table 5.1 (see List of Abbreviations, page x)

The correlation between the different photosynthetic variables are summarised in Table A.1 and A.2 (Annexure A) (first value, squared correlation coefficient). These values only indicate the correlation between the variables in the PCAs where the summer and winter data were combined (Figure 5.1c; Figure 5.2c and Figure 5.3c). It also only indicates the degree of correlation between the variables, but does not indicate whether the correlation is positive or negative. The variable-combinations with the strongest positive correlation ($R^2 > 0.7$) are C_i vs C_a, E vs T_a and the variable-combinations with the strongest negative correlation ($R^2 > 0.7$) are A vs C_i, C_i vs I (Annexure A: Table A.1 and A.2). Strangely enough, the correlations of some of the variable-combinations having either small angles or angles of nearly 180° on the PCAs (Figure 5.1c, 5.2c and 5.3c) are not as strong as expected. The WUE variable was excluded from the PCAs since WUE is only a relationship between two of the other variables, viz. A and E.

5.3.2 Seasonal effect on photosynthesis parameters and environmental variables

The photosynthesis parameters as well as the environmental variables were effected differently by the climatic changes brought about by the changing of the seasons from summer to winter. The photosynthesis parameters as well as the environmental variables of the three irrigation

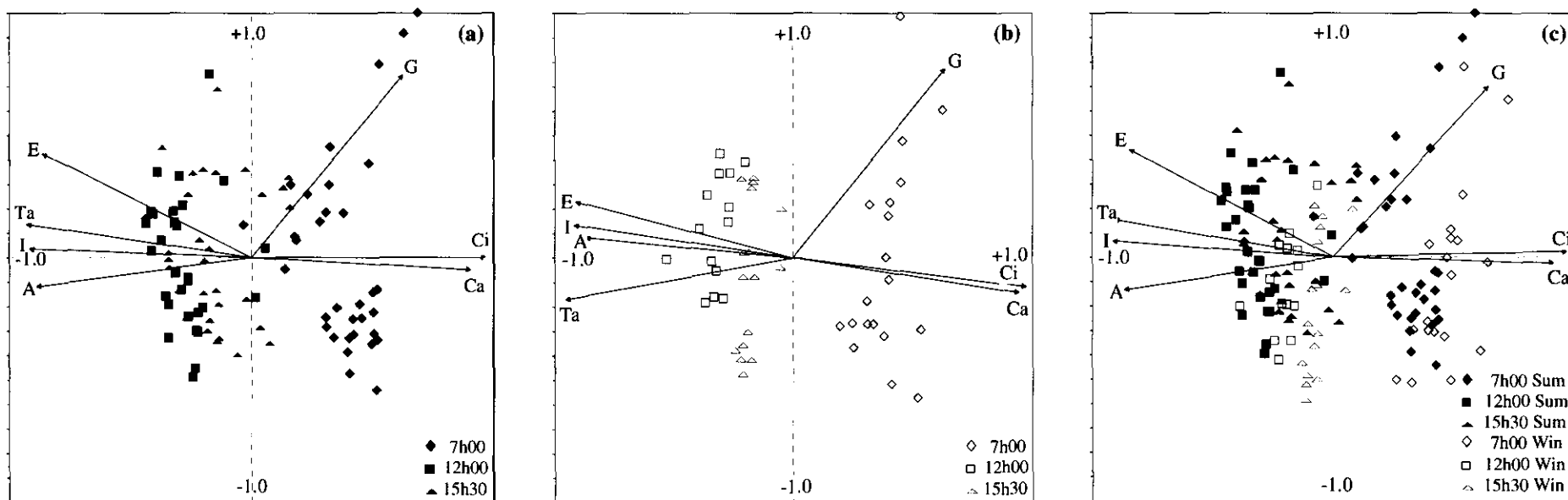


Figure 5.1: Photosynthesis parameters and environmental variables of treatment 2X at 07h00, 12h00 and 15h30 during (a) summer and (b) winter, respectively and (c) combined.

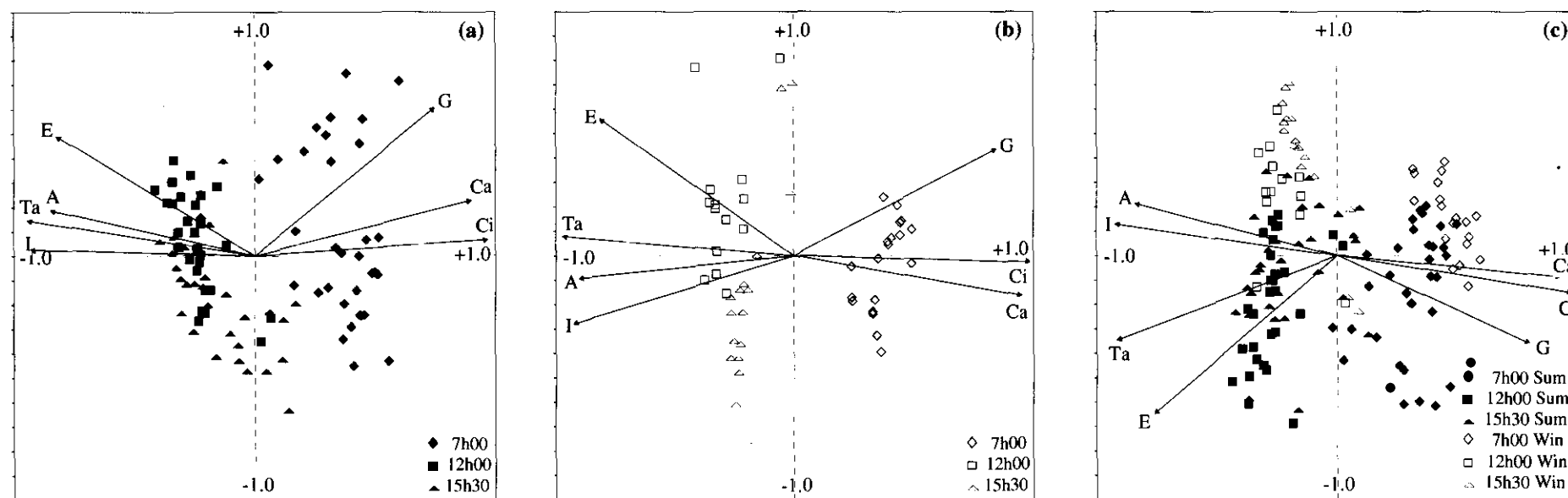


Figure 5.2: Photosynthesis parameters and environmental variables of treatment X at 07h00, 12h00 and 15h30 during (a) summer and (b) winter, respectively and (c) combined.

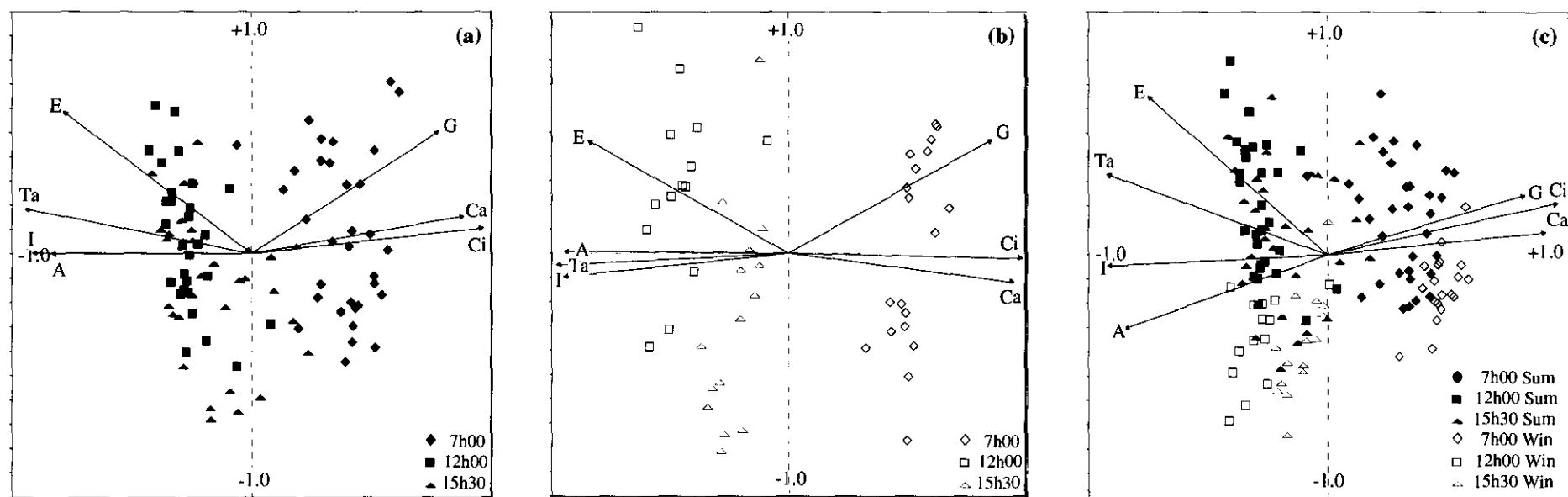


Figure 5.3: Photosynthesis parameters and environmental variables of treatment $\frac{1}{2}X$ at 07h00, 12h00 and 15h30 during (a) summer and (b) winter, respectively and (c) combined.

treatments were plotted over time and general trends were established by fitting straight lines through the data points (Figures 5.4a to c to Figures 5.10a to c).

As the different irrigation treatments (2X, X and ½X) exhibited the same basic trends for the measurements taken at 07h00, 12h00 and 15h30 respectively, each irrigation treatment is not discussed separately. The data of the photosynthesis parameters as well as the environmental variables for the different irrigation treatments measured at a specific time (07h00, 12h00 or 15h30) are homogeneous (Annexure C; Figures C.1 and C.2).

As the season changes from summer to winter the photosynthesis rate (A) decreased at 07h00, while A increased slightly at 12h00, and remained constant at 15h30 (Figures 5.4a to c). On average A measured at 12h00 had the highest values and A measured at 07h00 had the lowest, while A measured at 15h30 was intermediate (Figure 5.4 and Table 5.3). During the first two weeks the values determined at 07h00 were mostly positive, and during the rest of the experiment mostly negative. As the season changed, the irradiance level (I) (Figure 5.9a) and the atmospheric temperature (T_a) (Figure 5.10a) decreased gradually. When comparing the values of A determined at 07h00 to values found in the literature, the minimum value of A ($-22.0 \mu\text{mol m}^{-2} \text{s}^{-1}$) was found to be much lower than that found in the literature ($-1.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Jiao *et al.*, 1991b:247)) (Table 5.2). Even values for respiration rates found in the literature and determined in the dark ($5.9 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Jiao *et al.*, 1991a:242)) were not as low as the minimum A values measured at 07h00 (Table 5.2 and Figure 5.4a). The maximum values of A at 07h00 ($12.4 \mu\text{mol m}^{-2} \text{s}^{-1}$), however, compares well to the values found in the literature (10.8 to $14.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Agbaria *et al.*, 1995:653)) where measurements were done on the leaves while the plants were subjected to relative low I and/or T_a -levels (Table 5.2). The maximum values of A measured at 12h00 ($18.8 \mu\text{mol m}^{-2} \text{s}^{-1}$) compare well to maximum values (17.0 to $17.8 \mu\text{mol m}^{-2} \text{s}^{-1}$) obtained by Pasian and Lieth (1989:582) and Raviv and Blom (2001:266) at leaf-level under high I and T_a -levels. (The terms high and low I-levels and T_a is relative, since I and T_a -values are normally very high in South Africa where I-levels of $2500 \mu\text{mol m}^{-2} \text{s}^{-1}$ (PPF) and T_a -values of 40°C measured inside a greenhouse are not uncommon. When accustomed to these high values, maximum I-values of 25 to $150 \mu\text{mol m}^{-2} \text{s}^{-1}$ and T_a -values of 20°C applied in some experiments are almost unthinkable.)

At 07h00 the C_a and C_i -values (Figure 5.5a) were higher than that measured during the rest of the day ($350 \mu\text{mol mol}^{-1}$) (Figure 5.5b and c) since A was minimal at that time of the morning (Figure 5.4a). As the season changed the C_i -values increased (Figure 5.5a) as A decreased

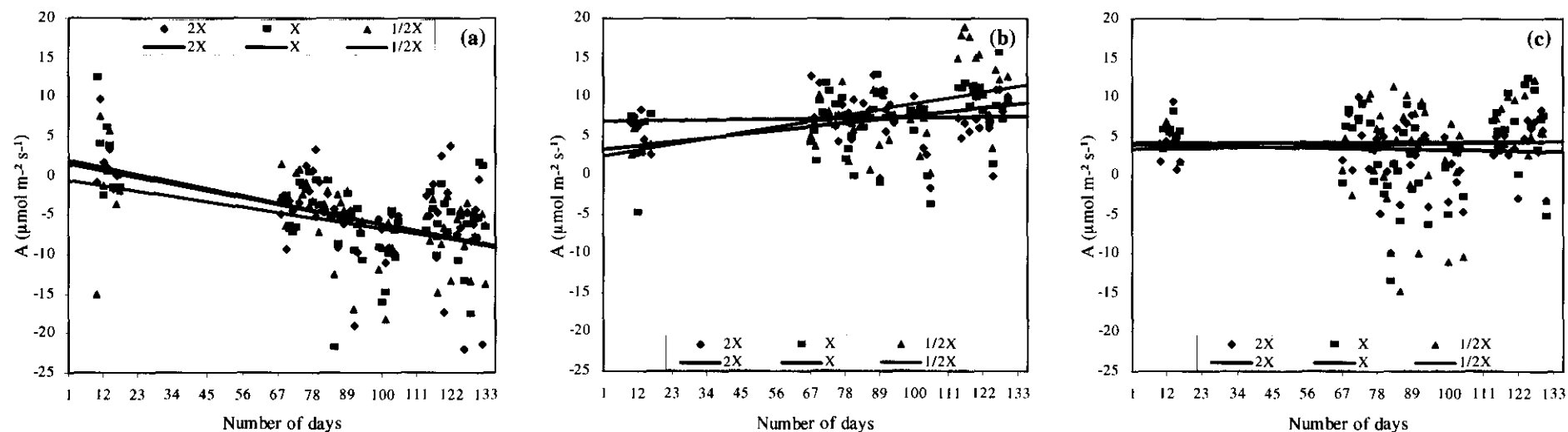


Figure 5.4: Rate of photosynthesis (A ; $\mu\text{mol m}^{-2} \text{s}^{-1}$) measured at (a) 07h00, (b) 12h00 and (c) 15h30 for the 2X, X and 1/2X treatments.

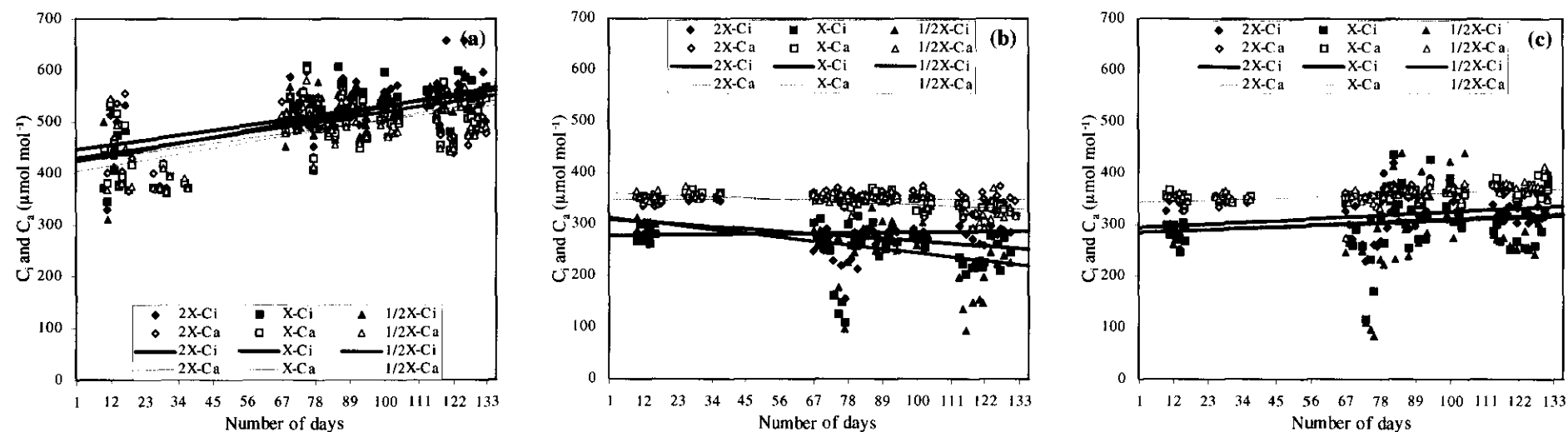


Figure 5.5: Internal (C_i ; $\mu\text{mol mol}^{-1}$) and external CO_2 (C_a ; $\mu\text{mol mol}^{-1}$) concentrations, measured at (a) 07h00, (b) 12h00 and (c) 15h30 for the 2X, X and 1/2X treatments.

(Figure 5.4a), thus having a negative correlation (Annexure A: Figure A.6). The C_a -values corresponded with the C_i -values, with C_a being constantly about $30 \mu\text{mol mol}^{-1}$ lower than C_i .

The assumption was made that the C_a inside the greenhouse was in equilibrium with the C_a outside, since the ventilation openings were already open before measurements were done at 07h00. This assumption was made based on the temperatures (T_a) measured at 07h00 inside the greenhouse (Figure 5.10a) since the optimum night air temperature was set at 15°C to 18°C and the measured T_a -values were higher than these values until the 89th day. This assumption is supported by the fact that the C_a -values in the closed greenhouse were lower during the last three weeks than the C_a -values when the ventilation openings were open (Figure 5.5a). It is also assumed that the ventilation openings were closed at 12h00 and 15h30 during this period when the average T_a dropped below the optimum day air temperature of 25°C (Figures 5.10b and c), hence causing the decrease in the C_a -levels at 12h00 and 15h30 (Figures 5.5b and c). During the last three to four weeks the sun rose just before 07h00 (Figure 2.11). The C_a -values measured in the greenhouse were, however, lower than it normally was during that time of the morning (Figure 5.5a). As the A-rates were not high (Figure 5.4a), the low C_a -values indicate that the ventilation openings were closed. The assumption is also made that the rate of dark respiration (R_d) (not measured) was low during the latter part of this experiment (see Table 5.2 for corresponding values found in the literature).

The transpiration rate (E) decreased as the study period progressed, irrespective of the time of measurement (07h00 (Figure 5.6a), 12h00 (Figure 5.6b) and 15h30 (Figure 5.6c)). The minimum and maximum values for E determined at 07h00 (2.77 and $8.73 \text{ mmol m}^{-2} \text{ s}^{-1}$), 12h00 (5.33 and $11.53 \text{ mmol m}^{-2} \text{ s}^{-1}$) and 15h30 (4.37 and $10.27 \text{ mmol m}^{-2} \text{ s}^{-1}$) respectively, are all higher than the corresponding values found in the literature, with the highest value being $4.81 \text{ mmol m}^{-2} \text{ s}^{-1}$ (Urban *et al.*, 1994b:672). It would seem as if rose plants have a higher E-rate under conditions where the plants receive ample irrigation volumes in comparison with those where the plants were desiccated, with E increasing as the % RH inside the greenhouse decreases (Table 5.2) (Urban *et al.*, 1994b:672; Katsoulas *et al.*, 2001:239).

The stomatal conductance (G) increased gradually as the season progressed from summer to winter irrespective of the time the measurements were taken (07h00, 12h00 or 15h30) (Figure 5.7a to c). The G was high in the morning (07h00) (Figure 5.7a) and lower at 12h00 (Figure 5.7b) and 15h30 (Figure 5.7c). The minimum G-values measured at 07h00 ($0.42 \text{ mol m}^{-2} \text{ s}^{-1}$), 12h00 ($0.07 \text{ mol m}^{-2} \text{ s}^{-1}$) and 15h30 ($0.15 \text{ mol m}^{-2} \text{ s}^{-1}$) (Figure 5.7a to c; Table 5.2) compare well to the maximum G-values found in the literature ranging from $0.07 \text{ mol m}^{-2} \text{ s}^{-1}$ (Agbaria *et al.*,

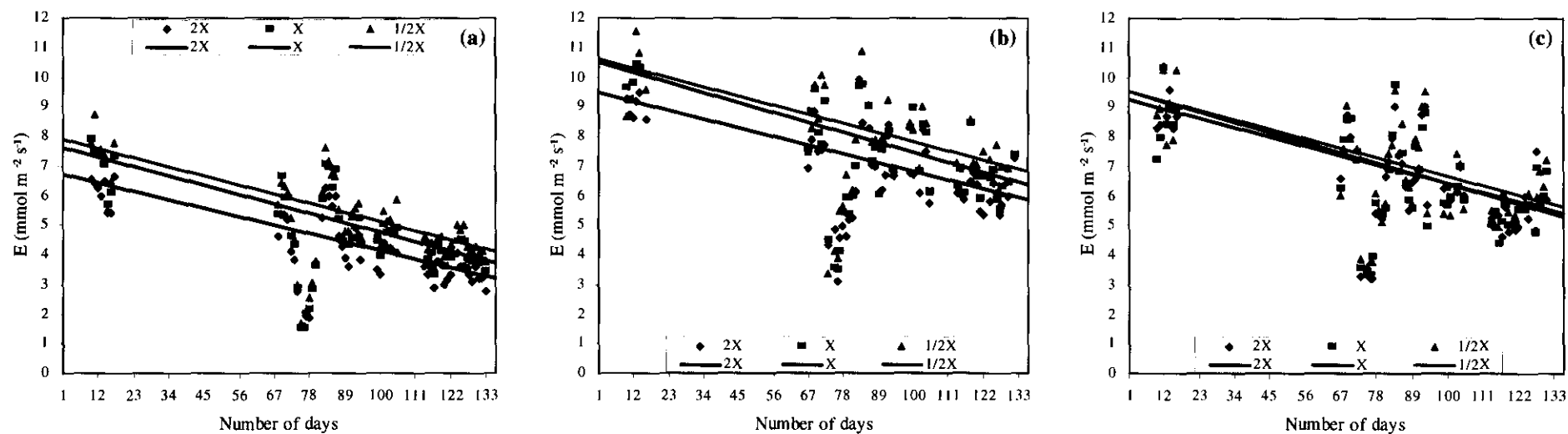


Figure 5.6: Rate of transpiration (E ; $\text{mmol m}^{-2} \text{s}^{-1}$) measured at (a) 07h00, (b) 12h00 and (c) 15h30 for the 2X, X and $1/2X$ treatments.

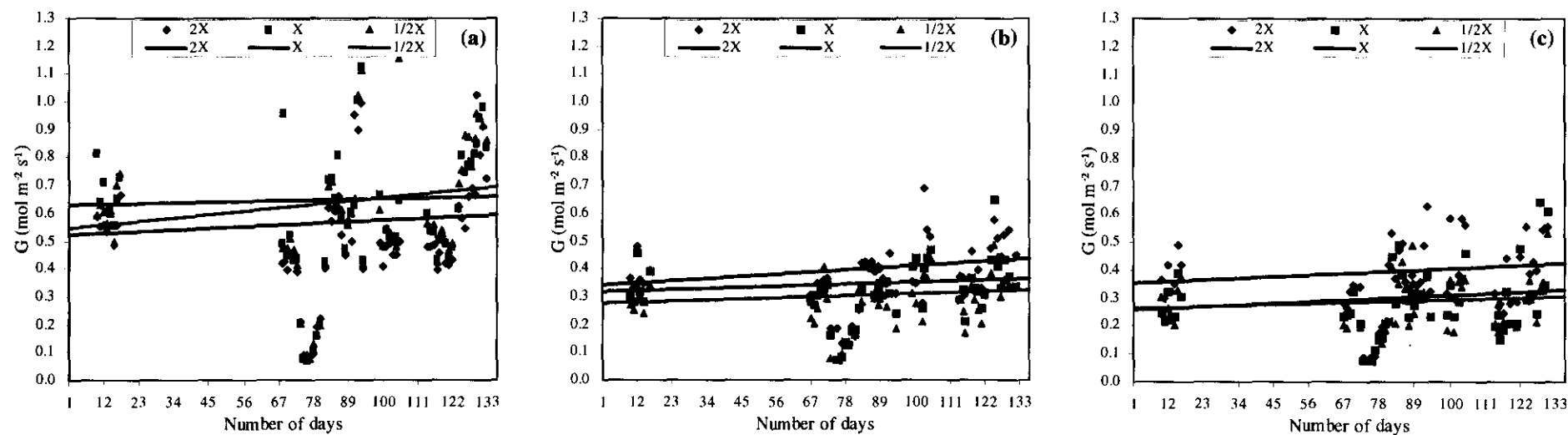


Figure 5.7: Stomatal conductance (G ; $\text{mol m}^{-2} \text{s}^{-1}$) measured at (a) 07h00, (b) 12h00 and (c) 15h30 for the 2X, X and $1/2X$ treatments.

1995: 652) to $0.42 \text{ mol m}^{-2} \text{ s}^{-1}$ (Blom-Zandstra *et al.*, 1995:257) (Table 5.2) and determined on a leaf basis. The maximum G-values measured at 07h00 ($1.15 \text{ mol m}^{-2} \text{ s}^{-1}$), 12h00 ($0.69 \text{ mol m}^{-2} \text{ s}^{-1}$) and 15h30 ($0.64 \text{ mol m}^{-2} \text{ s}^{-1}$) (Figure 5.7a to c; Table 5.2) are, however, much higher than these maximum G-values obtained from the literature. From the data collected during the current experiment it would appear as if G is very sensitive to high I-levels, or rather, quickly changing I-levels. The G (Figure 5.7c) of leaves suddenly subjected to higher I-levels (Treatment X and $\frac{1}{2}$ X; Figure .9) were lower than that of the leaves not subjected to a sudden increase in I (Treatment 2X; Figure 5.9).

The WUE measured at 07h00 (Figure 5.8a) decreased as the season progressed, while the WUE measured at 12h00 (Figure 5.8b) and 15h30 (Figure 5.8c) increased. The minimum WUE-values were all negative (-6.6 , -0.6 and $-2.0 \text{ } \mu\text{mol mol}^{-1}$) irrespective of the time of measurement (Table 5.2). Negative values were obtained where the A was negative. The maximum WUE-values (1.6 , 3.2 and $2.8 \text{ } \mu\text{mol mol}^{-1}$) do not compare well to the values obtained by other researchers (3.3 to $14.2 \text{ } \mu\text{mol mol}^{-1}$ (Agbaria *et al.*, 1995:652 and Baille *et al.*, 1996:951)) (Table 5.2). The former are much lower than the latter, comparing only well with values obtained where the plants were subjected to the sub-normal CO_2 concentration, $250 \text{ } \mu\text{mol mol}^{-1}$ (2.3 to 3.7 (Baille *et al.*, 1996:951)) (Table 5.2). The WUE-values are most probably low as a result of the extremely high E-values (Figure 5.6; Table 5.2).

Although not determined during the current experiment, the resistance of the boundary layer may be of great importance under greenhouse conditions where, in the absence of active air movement, air may be still, resulting in a very high boundary layer resistance (Raviv & Blom, 2001:263). This phenomenon might explain the high transpiration rates measured during the current experiment, since the cuvette with which the measurements were done had a fan that ensured the movement of air around the leaf portion inside the cuvette. This air movement may have reduced the boundary layer resistance (Raviv & Blom, 2001:263) (enhanced the boundary layer conductance) which resulted in higher total conductance (stomatal and boundary layer conductance) and thus increased E-rates. On the other hand, the high E-rates could be the result of the great volumes of irrigation water applied to the rose plants used in this experiment, since well-watered plants have a high E-rate (Taiz & Zeiger, 1991:255), causing the WUE to be very low.

The relative humidity (% RH) of the ambient air (Annexure B, Figures B.1a to c) as well as the vapour pressure deficit (VPD) between the ambient air and the stomatal cavities of the leaves (Annexure B, Figure B.2a to c) were calculated using the T_a (Figures 5.10a to c) as well as E-

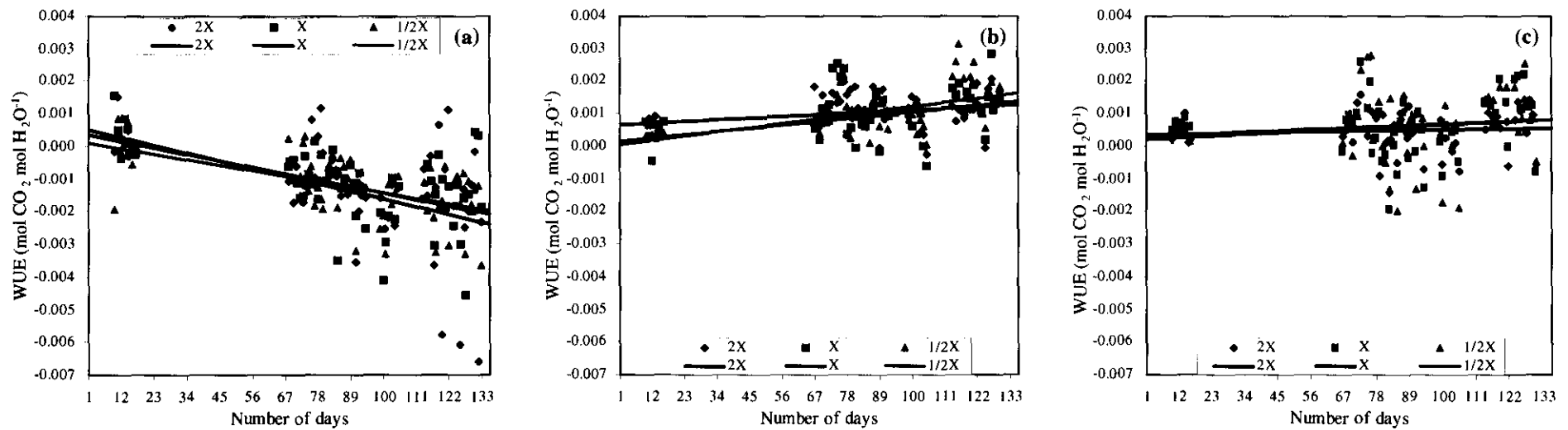


Figure 5.8: Water use efficiency (WUE; $\text{mol CO}_2 \text{ mol H}_2\text{O}^{-1}$) calculated for photosynthesis and transpiration rates measured at (a) 07h00, (b) 12h00 and (c) 15h30 for the 2X, X and $1/2X$ treatments.

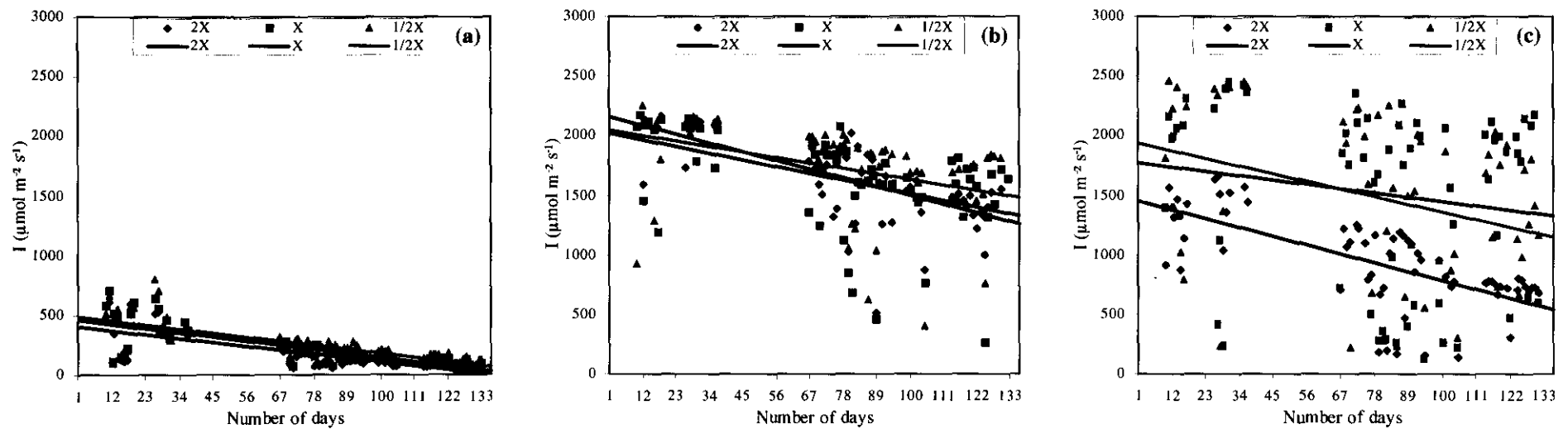


Figure 5.9: Irradiance level (I ; $\mu\text{mol m}^{-2} \text{ s}^{-1}$) measured at (a) 07h00, (b) 12h00 and (c) 15h30 for the 2X, X and $1/2X$ treatments.

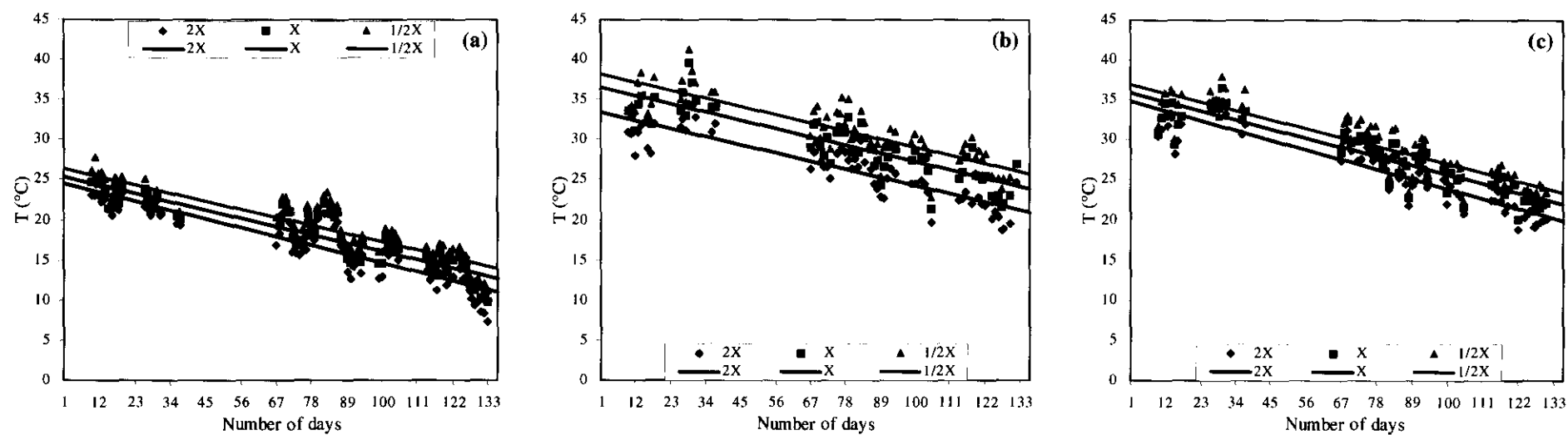


Figure 5.10: Air temperature (T_a ; $^{\circ}\text{C}$) measured at (a) 07h00, (b) 12h00 and (c) 15h30 for the 2X, X and 1/2X treatments.

Table 5.2: Minimum and maximum values for the photosynthesis parameters as well as the environmental variables and values from literature references for comparison.

Photosynthesis Parameters	Time	Min-Max	Literature references
A ($\mu\text{mol m}^{-2} \text{s}^{-1}$) (Fig. 5.4a-c)	07h00 12h00 15h30	-22.0-12.4 -4.7-18.8 -14.7-12.3	10.0 / 11.2 / 10.1 / 11.8 (leaf) 14.6 / 10.7 / 12.6 / 10.8 (leaf) 6.9 (leaf; max) 6.4 / 8.6 / 13.5 (plant; max) -1.5 / 8.3 / 11.7 / 13.5 (plant; max) 3.2-11.4 (leaf) 9.7-13.0 (leaf) 20.0 / 15.0 (leaf; max) 8.5-9.0 (leaf) 3.8-6.6 (plant; min & max) 6.9 / 6.3 (plant) 0.7-6.2 / -0.6-7.3 / -1.1-6.4 (plant; min & max) 4.2-6.3 / 8.0-9.3 (plant; min & max) -1.6-7.2 (plant; min & max) 3.0 (plant) 1.7 / 3.9 (plant) 5.4-12.0 (plant; min & max) -0.5-1.9 / 0.2-3.5 / 1.5-4.8 / 3.0-6.8 / 4.0-8.8 / 4.2-11.0 (plant; min & max) 1.2-1.7 12.4 / 15.6 / 17.8 / 17.3 (leaf; max) 2.0-17.0 (leaf) 3.0-2.0 / 15.0-17.0 (leaf) 9.0 (leaf) Agbaria <i>et al.</i>, 1995 - (I = 450; T_a = 26; RH = 50) Mc (Scions = non grafted / Mc / Is / R.i) Is (Scions = non grafted / Is / Mc / R.i) Aikin & Hanan, 1975 - FY³ Baille <i>et al.</i>, 1996 - So (C_a = 235 / 375 / 1050; I = 0-1000) (C_a = 0 / 350 / 700 / 1050; I = 1500) Beeson, 1990 - R, RS (I = 150-500; T_a = 28-33, 18) Bozarth <i>et al.</i>, 1982 - Sa³ Bozarth <i>et al.</i>, 1982 - Sa⁵ (I = 500; Young leaves / older and shaded leaves) Jiao <i>et al.</i>, 1991a - Sa (T_a = 15-30; I = 700) Sa (T_a = 15-35; I = 1200; C_a = 350) Sa (NT_a = 17 / 27; DT_a = 27) Sa (T_a = 16 / 22 / 28; I = 0-1350; C_a = 350) Sa (C_a = 350 / 1000; T_a = 15-35) b - Sa (I = 0-1500; T_a = 22; C_a = 350) Sa (I = 400; T_a = 22; C_a = 350) Sa (I = 204 x 24 h / 410 x 12 h - dark respiration) Sa (C_a = 300-1200; I = 1200; T_a = 22) c - Sa (I = 100 / 200 / 300 / 500 / 700 / 1200; T_a = 15-30; C_a = 350-1450) Khayat & Zieslin, 1986 - So, GT (I = low; DT_a = 18-30; NT_a = 12-18) Pasian & Lieth, 1989 - CM (I = 0-1200; T_l = 10 / 20 / 30 / 37) Raviv & Blom, 2001 - Mc (I = 100-1300) Mc (EC = 1-10; I = 100 / 1300) Williams <i>et al.</i>, 2000 - Ca, BP (I = 613; T_l = 24.8; C_a = 318)
R ($\mu\text{mol s}^{-1}$)	-	-	0.06 / 0.03 / 0.03 / 0.12 (dark) 0.03-0.09 / 0.02-0.09 (dark) 0.02-0.11 (day) Jiao <i>et al.</i>, 1991a - Sa (flower bud / leaves / stem / shoot; T_a = 25) Sa (flower bud / leaves; T_a = 15-35) Sa (flower bud; NT_a = 10-36)
R ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	-	-	0.9 1.5-5.6 (plant) 1.3 / 2.6 (plant; dark) 1.0-5.9 / 1.0-5.3 (plant) 1.7 (plant; dark) 2.0 (plant; dark) 0.3-1.4 (leaf; dark) Bozarth <i>et al.</i>, 1982 - Sa⁴ Jiao <i>et al.</i>, 1991a - Sa (I = 1200; C_a = 350; NT_a = 10-35) Sa (NT_a = 17 / 27; DT_a = 27) Sa (C_a = 350 / 1000; T_a = 15-35) b - Sa (T_a = 18) Sa (T_a = 22; C_a = 350) Pasian & Lieth, 1989 - CM (I = 0-1200; T_l = 10-37)
E ($\text{mmol m}^{-2} \text{s}^{-1}$) (Fig. 5.6a-c)	07h00 12h00 15h30	2.77-8.73 5.33-11.53 4.37-10.27	2.46 / 0.88 / 1.64 / 0.83 (leaf) 1.77 / 0.80 / 1.15 / 1.07 (leaf) Agbaria <i>et al.</i>, 1995 - (I = 450; T_a = 26; RH = 50) Mc (Scions = non grafted / Mc / Is / R.i) Is (Scions = non grafted / Is / Mc / R.i)

Table 5.2: Continued

Photosynthesis Parameters	Time	Min-Max	Literature references	
			0–2.60 (plant) 2.38 / 2.23 / 1.98 (plant) 0.06–3.37 / 0.06–3.24 (canopy; min & max) 0.31–4.81 / 0.06–0.36 (canopy; night-day) 0.40–0.62 / 0.31–0.43 / 0.15–0.35 (plant; min & max)	Baille <i>et al.</i> , 1996 – So (I = 0–1000) (C _a = 440 / 860 / 1090; I = 0–1000) Katsoulas <i>et al.</i> , 2001 – FR (VPD = 0.2–4.7 / 0.1–2.3; I = 0–1843) Urban <i>et al.</i> , 1994b – So (T _a = 21; RH = 80; well watered / desiccated) Zeroni & Gale, 1989 – So (I = 0–1000; T _a = 18–30; C _a = 320 / 600 / 1200; EC = 0.84–4.70)
E (mol m ⁻² day)			227.8–388.9 (plant)	Raviv & Blom, 2001 – Mc (EC = 7–3)
E (l plant ⁻¹ day ⁻¹)			0.01–1.11 (plant, min & max) 1.5 (plant) 0.7–1.5 (plant)	Cabrera <i>et al.</i> , 1995a – R (I = natural; DT _a = 25; NT _a = 18) Henning, 2000 – General (Dutch conditions) Raviv & Blom, 2001 – Mc (EC = 7–3)
G (mol m ⁻² s ⁻¹) (Fig. 5.7a–c)	07h00 12h00 15h30	0.42–1.15 0.07–0.69 0.15–0.64	0.17 / 0.08 / 0.14 / 0.07 (leaf) 0.13 / 0.08 / 0.11 / 0.09 (leaf) 0.02–0.08, 0.04–0.33, 0.03–0.21 / 0.02–0.11, 0.02–0.35, 0.01–0.27 (leaf; night-day) 0.14–0.42, 0.03–0.23 / 0.01–0.27 / 0.01–0.27 (leaf; night-day) 0.02–0.08, 0.02–0.26, 0.04–0.32, 0.04–0.11 / 0.02–0.12, 0.02–0.19, 0.03–0.36, 0.02–0.08 (leaf; night-day) 0.16–0.23 / 0.17–0.31 (leaf; min-max) 0.02–0.12 / 0.02–0.21 (canopy) 0.03–0.04 (leaf)	Agbaria <i>et al.</i> , 1995 – (I = 450; T _a = 26; RH = 50) Mc (Scions = non grafted / Mc / Is / R.i) Is (Scions = non grafted / Is / Mc / R.i) Blom-Zandstra <i>et al.</i> , 1995 – (DT _a = 20; NT _a = 18; RH = 70) (Mad / So; I = 150; SL = 25; SL D = 0, 4, 8) (Mad / So; I = 50, 100, 150; SL = 25; SL D = 8; Leaf age = 3 and 6 weeks) (Md / So; I = 150; SL = 0, white, orange, blue) (Md; I = 50 – 1300; Plants adapted to I = 50 / I = 150) Katsoulas <i>et al.</i> , 2001 – FR (VPD = 0.2–4.7 / 0.1–2.3; I = 0–1566) Williams <i>et al.</i> , 2000 – Ca, BP (I = 613; T _l = 24.8; C _a = 318; Control / drought-grown)
G (cm s ⁻¹)			0.03–2.35 / 0.18–3.18 (canopy) <0.04–0.20 / 0.08–0.50 (leaf) 0.09–1.00 / <0.07–0.83 / <0.07–0.50 (leaf; min & max)	Katsoulas <i>et al.</i> , 2001 – FR (VPD = 0.2–4.7 / 0.1–2.3; I = 0–1566) Mortensen & Fjeld, 1998 – Sou (I = 170; I D = 16–24; T _a = 20; C _a = 800; RH = 65 / 90) Zeroni & Gale, 1989 – So (I = 0–1000; T _a = 18–30; C _a = 320 / 600 / 1200; EC = 4.70–0.84)
WUE (mol mol ⁻¹ x 10 ⁻³) (Fig. 5.8a–c)	07h00 12h00 15h30	-6.6–1.6 -0.6–3.2 -2.0–2.8	4.1 / 12.7 / 6.2 / 14.2 (leaf) 8.3 / 13.4 / 11.0 / 10.1 (leaf) 2.3–3.7 / 3.3–5.7 / 4.9–7.7 / 5.9–13.5 (plant; min & max)	Agbaria <i>et al.</i> , 1995 – (I = 450; T _a = 26; RH = 50) Mc (Scions = non grafted / Mc / Is / R.i) Is (Scions = non grafted / Is / Mc / R.i) Baille <i>et al.</i> , 1996 – So (C _a = 250 / 470 / 580 / 900; I = 0–1000)
I _{cp} (μmol m ⁻² s ⁻¹)			29 / 21 / 18 (plant) 46.1–50.7 30.0–100.0 3.3–22.9 (leaf)	Baille <i>et al.</i> , 1996 – So (C _a = 350 / 700 / 1050; I = 1500) Hand & Cockshull, 1975 – So ² Jiao <i>et al.</i> , 1991b – Sa (I = 0–1500; T _a = 22; C _a = 350) Pasian & Lieth, 1989 – CM (I = 0–1200; T _l = 10–37)
C _{cp} (μmol mol ⁻¹)			88 / 46 / 39 / 33 / 30	Baille <i>et al.</i> , 1996 – So (I = 100 / 300 / 500 / 1000 / 1500; C _a = 1050)
I _{sp} (μmol m ⁻² s ⁻¹)	12h00	1500–1840	450–500 680	Aikin & Hanan, 1975 – FY ³ Aikin & Hanan, 1975 – FY ⁶

Table 5.2: Continued

Photosynthesis Parameters	Time	Min-Max	Literature references	
		450–500 1200 500 800 / 1050 / 1100 (plant) 1000–1300 (plants) 308–626 1100–1300 (leaf)	Bozarth <i>et al.</i> , 1982 – Sa ³ Durkin, 1992 – Roses in general Jiao, 1989 – Sa Jiao <i>et al.</i> , 1991a – Sa ($T_a = 16 / 22 / 28$; $I = 0$ –1500; $C_a = 350$) b – Sa ($I = 0$ –1500; $C_a = 350$; $T_a = 22$) Pasian & Lieth, 1989 – CM ($I = 0$ –1200; $T_i = 10$ –37) Raviv & Blom, 2001 – Mc ($I = 100$ –1300; $EC = 1$ –10)	
C_{sp} ($\mu\text{mol mol}^{-1}$)		800	Jiao <i>et al.</i> , 1991b – Sa ($C_a = 300$ –1200; $I = 1200$; $T_a = 22$)	
I_{ue} (mol mol^{-1}) Quantum yield		0.063 / 0.085 / 0.095 (plant) 0.052 (leaf) 0.075 (leaf) 0.024 (canopy)	Baille <i>et al.</i> , 1996 – So ($C_a = 350 / 700 / 1050$; $I = 1500$) Bozarth <i>et al.</i> , 1982 ($C_a = 350$) ¹ Pasian & Lieth, 1989 ($C_a = 350$) ¹ Wilson <i>et al.</i> , 1992 ($C_a = 350$) ¹	
C_{ue} ($\text{mol m}^{-2} \text{s}^{-1}$)		0.014 / 0.030 / 0.036 / 0.042 / 0.046	Baille <i>et al.</i> , 1996 – So ($I = 100 / 300 / 500 / 1000 / 1500$; $C_a = 1050$)	
$T_{a \text{ opt}}$ (°C)		16 / 32 20–25 / 15–37 (plant / leaf) 16 / 22 (plant) 23.5 / 25.5 (plant) 19–23.5 (plant; min & max) 20 / 15 (plant; DT_a / NT_a) 27 / 16 (DT_a / NT_a) 19–25, 24–27 / 16 (DT_a (cloudy day, clear day) / NT_a) 22–35 (leaf) 25–30 / 15.5 (DT_a / NT_a)	Billett, 1996 ⁶ – (winter – min/ summer – max) Jiao <i>et al.</i> , 1991a – Sa ($I = 1200$; $C_a = 350$; $T_a = 15$ –35) Sa ($I = 0$ –300 / 300–1350; $C_a = 350$; $T_a = 16, 22, 28$) Sa ($C_a = 350 / 1000$; $T_a = 15$ –35) c – Sa ($I = 100$ and $C_a = 350 / I = 1200$ and $C_a =$ and 1450; $T_a = 16$ –26) c – Sa ($I = 200$ –700; $C_a = 350$ –1000; $DT_a = 15$ –30 / $NT_a = 15$ –25) Meyer <i>et al.</i> , 1988a – Roses in general (South African conditions) Nelson, 1991 – Roses in general Pasian & Lieth, 1989 – ($C_a = 350$) ⁶ Romer, 1993 ⁶	
C_{opt} ($\mu\text{mol mol}^{-1}$)		900–1000 1000–2000	Durkin, 1992 – Roses in general Romer, 1993 ⁶	
RH_{opt} (%)		60–80	Durkin, 1992 – Roses in general	
C_i ($\mu\text{mol mol}^{-1}$)		250 / 260 (leaf)	Williams <i>et al.</i> , 2000 – Ca, BP ($I = 613$; $T_i = 24.8$; $C_a = 318$; Control / drought-grown)	

Abbreviations used in Table 5.2 (see List of Abbreviations, page x)

¹ quoted by Baille *et al.*, 1996

² quoted by Wilson *et al.*, 1992

³ quoted by Beeson, 1990

⁴ quoted by Pasian & Lieth, 1989

⁵ quoted by Raviv & Blom, 2001

⁶ quoted by Van der Walt, 1999

(Figures 5.6a to c) values measured at 07h00, 12h00 and 15h30 respectively.

An indentation in the data occurred from day 70 to day 85 and was most probably caused by pesticide damage to the leaves since it coincides with the second indentation occurring in the leaf surface area data plotted over time (Table 4.2 and Figure 4.5). Evidently the distortion of the leaves had an effect on the photosynthesis parameters with E (Figures 5.6a to c) and G (Figures 5.7a to c) being the most affected during the largest part of the day (07h00, 12h00 and 15h30). C_i (Figures 5.5a to c) was effected to a lesser extent (12h00 and 15h30), while A (Figures 5.4a to c) appears not to be effected at all. This was the case irrespective of the irrigation treatment. Note that the specific days during which the indentation in the data of the photosynthesis parameters occurred might vary slightly from the days during which the indentation occurred in the leaf surface area data since two different compound leaves were used to determine the respective data. The fifth compound leaf was used in the former, while the third compound leaf was used in the latter.

No significant differences were found between the respective photosynthesis parameters of the three irrigation treatments measured at 07h00, 12h00 and 15h30 respectively, except between the G values measured at 15h00 (Table 5.3). These differences can, however, be ascribed to the difference in I-levels the plants of the different irrigation treatments were subjected to and the apparent sensitivity of G to changes in I-levels (as mentioned earlier in this Chapter). The plants of the 2X treatment were subjected to lower I-levels than the plants of the other two treatments for that fleeting moment.

Table 5.3: Average photosynthesis parameter values ($\pm$ s.d.) recorded for the duration of the study (20 weeks).

^{a, b} Means with the same letter were not significantly different ($P > 0.05$).

Time of day	Treatment	A ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	E ($\text{mmol m}^{-2} \text{s}^{-1}$)	G ($\text{mol m}^{-2} \text{s}^{-1}$)	C_i ($\mu\text{mol mol}^{-1}$)	WUE ($\text{mol mol}^{-1} \times 10^{-3}$)
07h00	2X	-5.86 ± 5.02^a	4.35 ± 1.06^a	0.57 ± 0.16^a	526.56 ± 52.38^a	-1.47 ± 1.43^a
	X	-5.83 ± 5.59^a	4.93 ± 1.20^a	0.64 ± 0.16^a	519.93 ± 58.79^a	-1.31 ± 1.18^a
	1/2X	-6.56 ± 4.71^a	5.26 ± 1.20^a	0.65 ± 0.19^a	511.99 ± 53.50^a	-1.35 ± 0.98^a
12h00	2X	7.18 ± 3.12^a	6.98 ± 1.17^a	0.41 ± 0.09^a	285.56 ± 22.53^a	1.06 ± 0.51^a
	X	7.28 ± 3.55^a	7.62 ± 1.29^a	0.35 ± 0.07^a	269.21 ± 34.81^a	1.00 ± 0.60^a
	1/2X	8.50 ± 4.79^a	7.87 ± 1.27^a	0.31 ± 0.07^a	249.92 ± 58.71^a	1.14 ± 0.76^a
15h30	2X	3.03 ± 3.76^a	6.66 ± 1.30^a	0.41 ± 0.10^a	324.22 ± 29.10^a	0.47 ± 0.62^a
	X	4.08 ± 4.42^a	6.55 ± 1.32^a	0.31 ± 0.11^b	308.40 ± 41.58^a	0.65 ± 0.78^a
	1/2X	3.69 ± 5.69^a	6.85 ± 1.49^a	0.29 ± 0.09^b	307.40 ± 50.99^a	0.58 ± 0.93^a

Abbreviations used in Table 5.3 see List of Abbreviations (page x)

Table 5.4: Effects of the external input variables as well as some horticultural practices on the photosynthesis parameters investigated during various experiments.

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO ₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Photosynthesis and related parameters	Literature
Sum 13h45 Win 10h40	Natural Min and Max 43–60 (day)	NT _a / DT _a 10–25/17–39	300–610 (07h00) 290–370 (12h00)		South Africa, Nylstroom Sum – Win 20 weeks	GG 2 Years 8.5 plants m ⁻² Multiple stemmed	A/E/G/C _i /WUE 07h00 : 2X = X = ½X 07h00 sum-win : A↓, C _i ↑, E↓, G↑, WUE↓ 12h00 sum-win : A↑, C _i ↓*, E↓, G↑, WUE↑ 15h30 sum-win : A*, C _i , E↓, G↑, WUE↑	This experiment
	450	26		50	Israel	Is, Mc 1 Year	Grafted & non grafted : A, E, G, WUE↑↓	Agbaria <i>et al.</i> , 1995
	0–1000	16–33 (T _i)	200–1000	(200–2000)	France: Nice Nov'93– Mar'94	So 10–14 Months 5 plants m ⁻²	I ₀ ↑ ¹⁰⁰⁰ : A↑, E↑, WUE↓ I ₁₀₀ ↑ ¹⁵⁰⁰ : C _a cp↓, C _a uc↑ C _a 235↑ ¹⁰⁵⁰ : A↑, I _{cp} ↓, I _{uc} ↑ C _a 440↑ ¹⁰⁹⁰ : E↓ C _a 250↑ ⁹⁰⁰ : WUE↑ VPD ₀ ↑ ^{2.4} : WUE↓	Baille <i>et al.</i> , 1996
12 h SL: 0, 4, 8h	50, 100, 150 SL: 25	NT _a / DT _a 18 / 20	-	70	Netherlands: Wageningen	Mad, So 12 Weeks 1 plant dm ⁻³ pot	SL _{dur} 0h & 4h : E* I _{dur} ↑ : G↑ I↑ : E _{daily} ↑ G _{SL} & G _{Dark} * Week 3 & 6 Mad/So : G↓ / G*	Blom-Zandstra <i>et al.</i> , 1995
	Sep : 17 (day ⁻¹) Nov 2 : 16 Dec 22 : 12 Feb 10 : 11 Apr 1 : 14 May 21 : 19 Jul 10 : 22 Aug 29 : 17	NT _a / DT _a 18 / 25			California: Davis 1Sept 1990	R Flush 1 plant 7 dm ⁻¹ pot	Stem length (growing) : E↑	Cabrera <i>et al.</i> , 1995a
							C _a ↑ : A↑ I↑ T _a ↑ Fertiliser↑ Irr	Freeman, 1998

Table 5.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature ($^{\circ}\text{C}$)	$[\text{CO}_2]$ ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Photosynthesis and related parameters	Literature
SL: 24h	Natural + SL SL = 150 700 1200 0–1350	NT _a / DT _a 18 / 25 15–35 15–35	350, 1000 350 350	70	Canada: Guelph Oct–Mar	Sa 1 Stemmed 1 plant 1.4dm ⁻¹ pot	T _a ↑ : T _a 15↑ ²² : T _a 22↑ ³⁵ : I↑ : C _a 350↑ ¹⁰⁰⁰ : R _{dark} ↑ A* A↑ ^{max} A↓ A (T _a =16)↑ A (T _a =22)↑ A (T _a =28)↑ A↑	Jiao <i>et al.</i> , 1991a
24h or 12h	0–1400 204 / 410 = 17.6 (day) 1200	22 22	350 350 350–1200		Canada: Guelph	Sa	I ₀ ↑ ¹⁰⁰⁰ : I ₁₀₀₀ ↑ ¹⁴⁰⁰ : I _{dur} = 24h / I _{dur} = 12h : C _a 350↑ ¹²⁰⁰ : A↑ A↓ A↑ / A↑ Daily C gain↑/↓ A↑	Jiao <i>et al.</i> , 1991b
	100 – 1200	15–30 (Int:5) 22	350–1450 (Int:300–350)		Canada: Guelph	Sa 1 Stemmed	I (100–1200) : I _{dur} (8–16) : C _a (350–1500) : DT _a (15–30) : NT _a (15–25) : I ₁₀₀ ↑ ¹²⁰⁰ : C _a 350↑ ¹⁴⁵⁰ : T _a 15↑ ²¹ : T _a 21↑ ³⁰ : Contributed 64% 31% 4% 0.3% 0.7% to Growth A↑ A↑ A↑ A↓	Jiao <i>et al.</i> , 1991c
06h00–21h00	0–1566	DT _a max 35+ Natural Vent : Natural Vent + Evap C : 09h00–19h00	Natural level ± 350	75↓ / 75↑ (550)	Greece: Volos Sum 19–27Aug	FR 6 Months 6 plants m ⁻²	Misting / no misting : I ₀ ↑ ³⁴⁰ : E _t / ↑ G↑ / ↑ E↑ G↑	Katsoulas <i>et al.</i> , 2001
16,20,24,20h	SL (Fluo) 170 SL (HPS) 170	20 LT _a = 0.5–1↑	800	65 / 95 (819 / 234)	Norway 12 Mar	Sou 6 Months	RH↑ : I _{dur} ↑ : G↑ G↑	Mortensen & Fjeld, 1998

Table 5.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO ₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Photosynthesis and related parameters	Literature
						8 plants 2.5 m ⁻² 2 Stemmed	Time 06h00 / 12h00 : G _t / ↑	
		Optimum: NT _a / DT _a 16 / 19–22 (cloudy days) 16 / 24 (clear days) 16 / 27 (CO ₂ enriched)	Limiting : 50–125 Optimum : 1000–1500 – crop specific			General	I + SL _{dur} ↑ ^{18h} : A↑ in sum	Nelson, 1991
	0–1200	T _l : 10, 20, 30, 37	320–340		California, Davis Aug'85–Aug'86	CM 11–13 Months	I↑ : T _l 10 / 20 / 30 / 37 : T _l ↑ : Different leaf ages : A↑ A _{avg} ↑ / ↑ / ↑ / ↓ I _{cp} ↑ I _{sp} ↑ A↑↓ I _{cp} ↑↓	Pasian & Lieth, 1989
	100–1300				Israel	Mc	EC↑ : I↑ : A* E↓ A↑	Raviv & Blom, 2001
09h00–19h00	SL : HPS + M 783.41 (PPF or Total I?)	21		80	France: Sophia-Antipolis	SP (So) 6 Months 8 plants m ⁻²	Night / Day : Watering / no watering : E _t / ↑ E↑ / ↓	Urban <i>et al.</i> , 1994b
	613	LT _a : 24.8	318			BP, Ca 30 plant m ⁻²	Watering / no watering : A* G↑ / ↓ C _i ↑ / ↓ WUE _t / ↑	Williams <i>et al.</i> , 2000
06h30–17h15	0–1000	NT _a / DT _a 18 / 30 ^{max}	Daytime : 320,600,1200 Nighttime : 350	80 _{min}	Israel Win	So 6 Months 1 plant 10 l pot ⁻¹ : 5 plants chamber ⁻¹	C _a ↑ : [Salt]↑ : E↓ G↓ E↓ G↓	Zeroni & Gale, 1989
8h (SD)	SL (Fluo) 13.4	15			General		T _a ↓ : LD + 15 °C : Anthocyanin↑ Cytokinin↑ Gibb. In No Leaves↓	Zieslin & Moe, 1985

Table 5.4: Continued

Irradiance duration	Irradiance intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) ($\text{mol m}^{-2} \text{day}$)	Temperature (°C)	[CO₂] ($\mu\text{mol.mol}^{-1}$)	RH (%) or VPD (Pa)	Location Season Duration	Cultivar Plant age Plant density Harvesting method	Effect on Photosynthesis and related parameters	Literature
8+ 14h (LD)	+ SL (Inc) 4.1 or SL (Fluo) 6.9							

Symbols and abbreviations used in Table 5.4 (see List of Abbreviations, page x)

5.3.3 Visual observations

- (1) Irrigation water collected in the allies between the beds where the plants were subjected to the different irrigation treatments, especially in the allies next to the bed of the 2X treatment.
- (2) At high noon (12h00) the orientation of the leaves of the rose plants differed from that of the normal position. All the leaves seemed wilted, but in addition the young leaves, with the abaxial sides still reddish, twisted at the leaf petioles to expose the abaxial sides to the sun. A possible explanation for this phenomenon is that the orientation of the leaves is changed to avoid the high levels of irradiance it was subjected to and thus possible damage to the photosynthesis systems.

5.4 Conclusion

From the data in this Chapter it would appear that if the application of the specific irrigation volumes used in this experiment did not cause any significant differences between the respective photosynthesis parameters measured at different times during the day. These parameters were, however, expressed per unit leaf area (m^2), and not per plant or as a function of the LAI. This will be discussed in the next Chapter (Chapter 6).

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CHAPTER 6

General Discussion

From the photosynthesis data presented in Chapter 5 the deduction are made that the photosynthesis parameters (measured per unit leaf area) are not influenced by the difference in irrigation volumes applied to the rose plants. Examining this data in conjunction with the quality data (Chapter 4) and the yield data (Chapter 3) gives quite another picture. As stated in Chapter 4, no significant differences were found in the quality of the stems in a specific length class, with reference to flower bud length, fresh weight, stem diameter, leaf area and the QI determined for the respective irrigation treatments. The stems in the 'long' length class were of the highest quality, while the quality of the stems in the 'short' length class were of the lowest, irrespective of the irrigation treatment the plants were subjected to. The difference between the three irrigation treatments is, however, found in the number of stems produced (Chapter 3). Plants subjected to the lowest volume of irrigation water (treatment $\frac{1}{2}X$) produced the highest number of long stems and plants subjected to the highest irrigation volume (treatment $\frac{1}{2}X$) produced the lowest number, while that of the X treatment was intermediate. Treatment $\frac{1}{2}X$ also yielded the highest total number of stems (short + medium + long), but in this instance treatment X yielded the lowest total number of stems and treatment 2X the intermediate number of stems. No significant difference was found between the number of long stems yielded by the 2X and X treatments, but the number of long stems yielded by these two treatments differed significantly from that of the $\frac{1}{2}X$ treatment. The same results were obtained when the significant differences between the total number of stems yielded by the 2X, X and $\frac{1}{2}X$ treatments were determined. The productivity (expressed as a single value defined as the Productivity Index; PI) of the plants in the $\frac{1}{2}X$ treatment is thus the highest, with these plants yielding not only the highest number of stems but also the highest number of stems of the highest quality (stems in the 'long' length class).

The number of stems harvested per week had a negative effect on the quality of the stems irrespective of the length class and the irrigation treatment. The week in which stems of the lowest quality were produced, were also the week in which the highest number of stems in the "short" and "medium" length classes were harvested.

The longest stems do not only have the biggest leaves (a single compound leaf), but also the highest number of leaves; the opposite is true for the short stems (compare the two stems of the cultivar Grand Gala in Figure 3.1; Chapter 3). This effectively means that the plants producing

the highest number of long stems (plants of treatment $\frac{1}{2}X$) have the highest leaf area index (LAI) and thus, the highest photosynthesis rates per plant. Higher photosynthesis rates are, however, associated with higher stomatal conductance, respiration rates and transpiration rates.

(Note that the internodes of the long stem in Figure 3.1 are not longer in comparison with that of the short stem and that the number of leaves per stem is a function of the stem length; increasing as the stem length increases. Interesting enough, it appears as if the application of to high a volume of water (treatment 2X) does not result in a shortening of the internodes of the stems, but that the length of the internodes remains practically the same as that of the long stems. The stems yielded by the plants of the 2X treatment are generally shorter with fewer leaves per stem.)

It makes total business sense to grow Grand Gala roses under the $\frac{1}{2}X$ irrigation regime, when subjected to the same environmental variables and horticultural practices, since more stems of higher quality are produced with less water, fertiliser, etc. These stems achieve the highest prices at the market (see Chapter 1) and are more versatile, since the stems may be cut shorter if shorter stems are in demand, but still achieving higher prices since the stems are of the highest grade (choice grade).

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ANNEXURE A

Photosynthesis and related parameters

The following abbreviations are used in this Appendix:

- (1) A = Photosynthesis rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
- (2) C_a = Ambient air CO_2 concentration ($\mu\text{mol mol}^{-1}$)
- (3) C_i = Internal CO_2 concentration ($\mu\text{mol mol}^{-1}$)
- (4) E = Transpiration rate ($\text{mmol m}^{-2} \text{s}^{-1}$)
- (5) G = Stomatal conductance ($\text{mol m}^{-2} \text{s}^{-1}$)
- (6) I = Irradiance level ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
- (7) T_a = Ambient air temperature ($^{\circ}\text{C}$)
- (8) WUE = Water use efficiency (mol mol^{-1})

The following values and equation were determined: (1) the square of the correlation coefficient of the two variables involved, determined by fitting a straight line through the data points; (2) the square of the correlation coefficient of the two variables involved as determined by fitting a linear regression line with the highest squared correlation coefficient (R^2 value); (3) the equation of the latter. Only the square of the correlation coefficient of the straight line was determined for the last three combinations of variables. The same values and equation mentioned above were also determined for the respective measurement times, 07h00, 12h00 and 15h30. These values and equations are summarised in Table A.1 and A.2.

Symbols representing the respective irrigation treatments and the corresponding curves in Figures A.1 to A.25 in this Appendix:

Treatment 2X ● —

Treatment X ■ —

Treatment $\frac{1}{2}\text{X}$ △

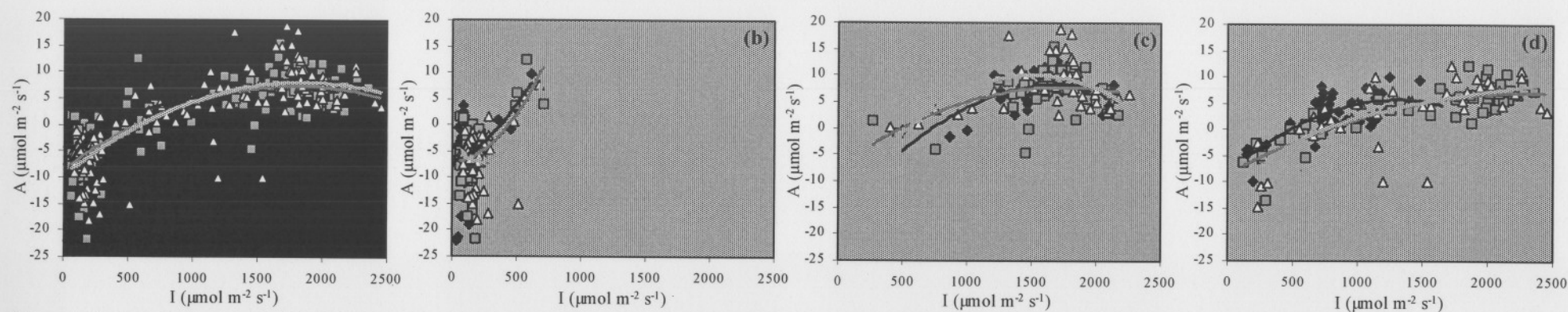


Figure A.1: A vs. I measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

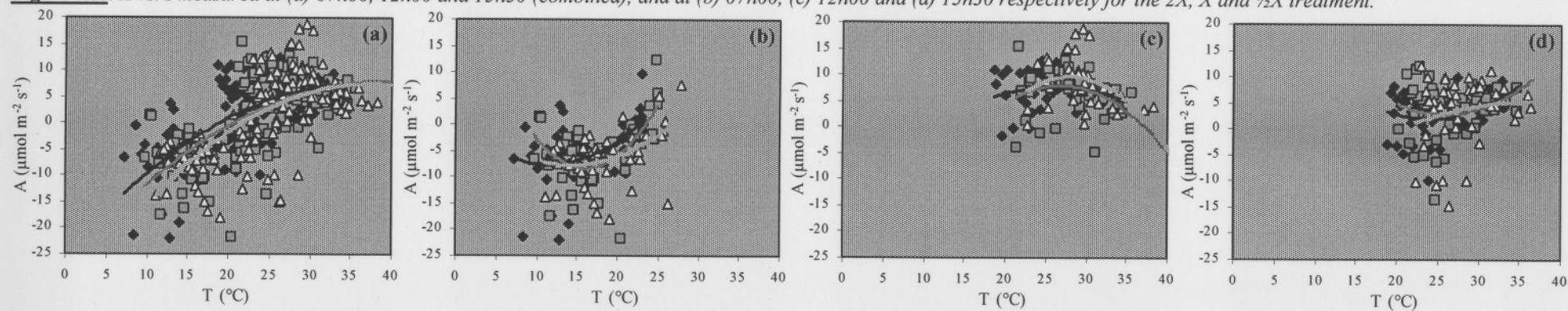


Figure A.2: A vs. T_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

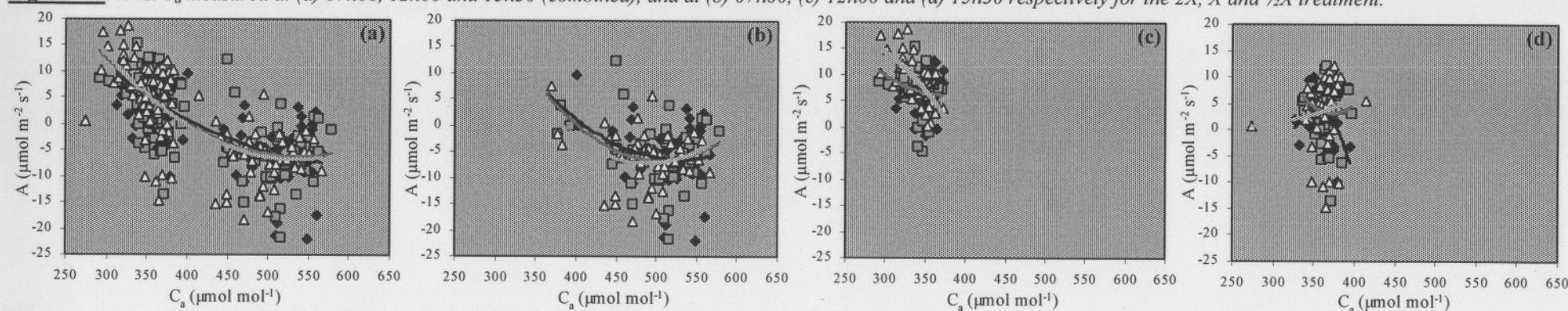


Figure A.3: A vs. C_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

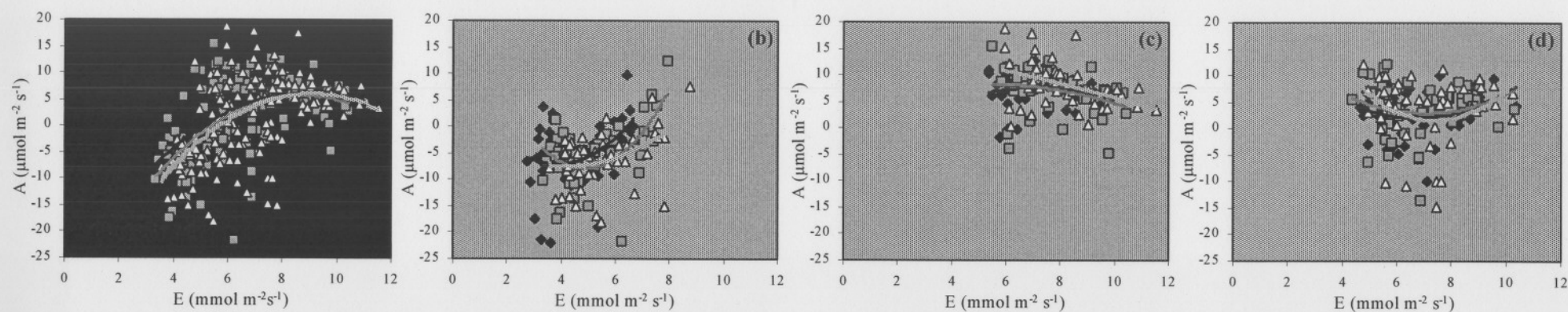


Figure A.4: A vs. E measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

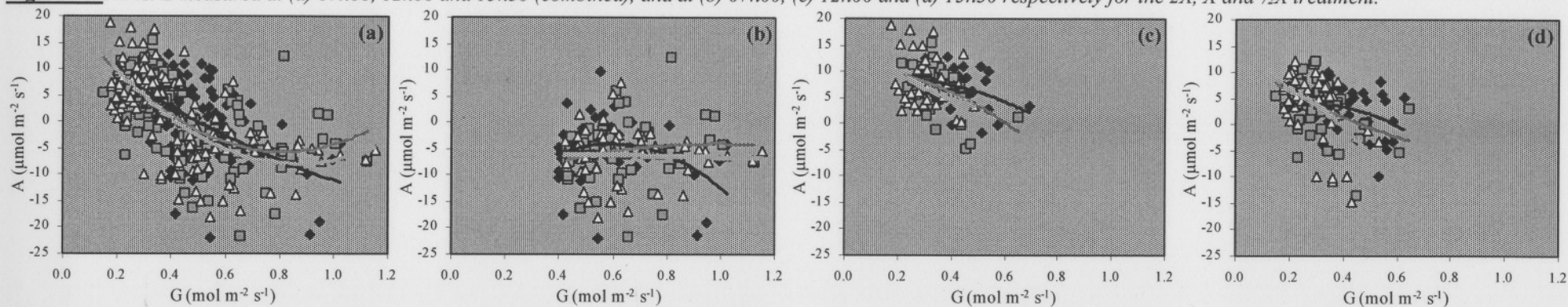


Figure A.5: A vs. G measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

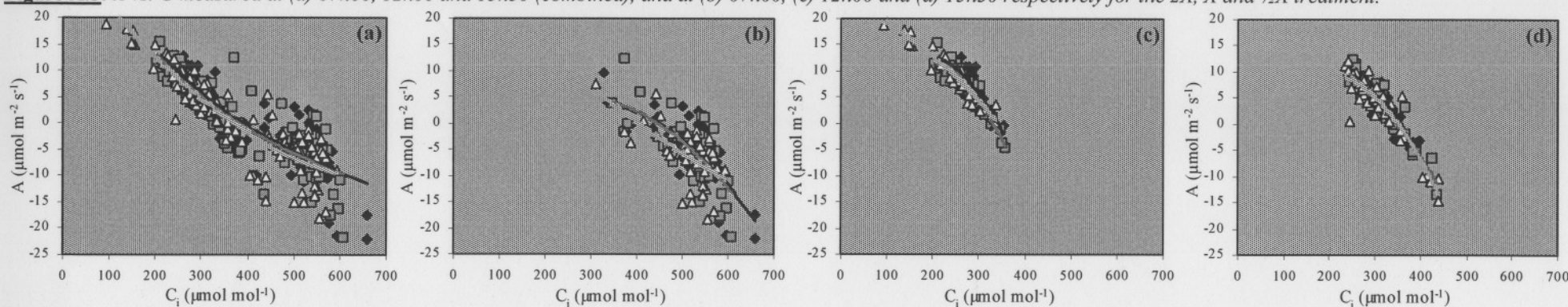


Figure A.6: A vs. C_i measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

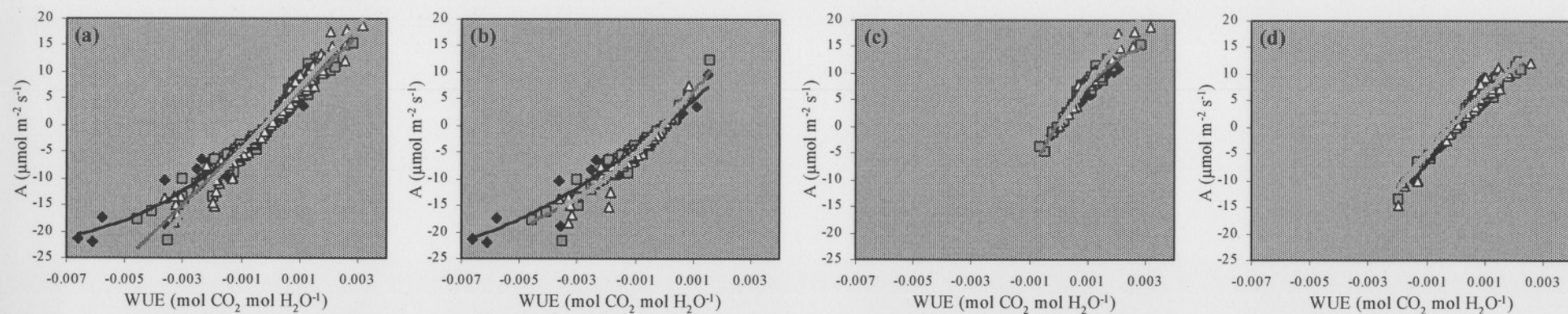


Figure A.7: A vs. WUE measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}X$ treatment.

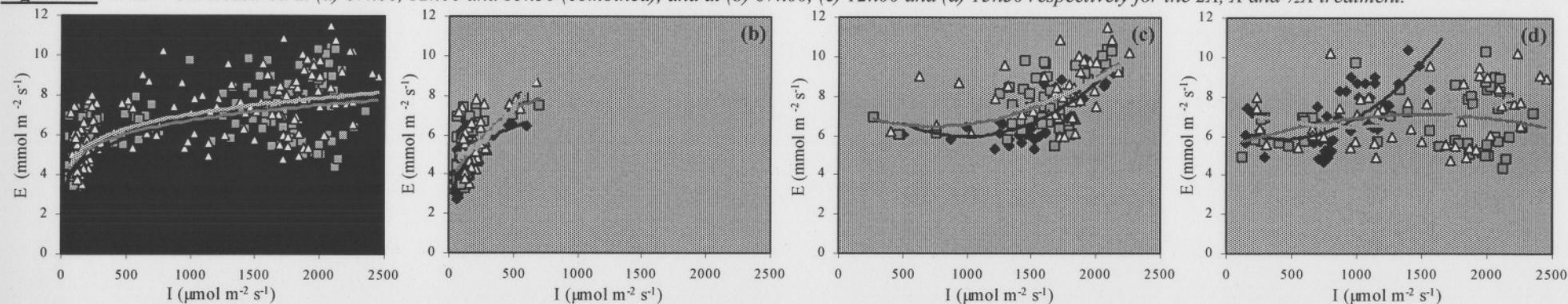


Figure A.8: E vs. I measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}X$ treatment.

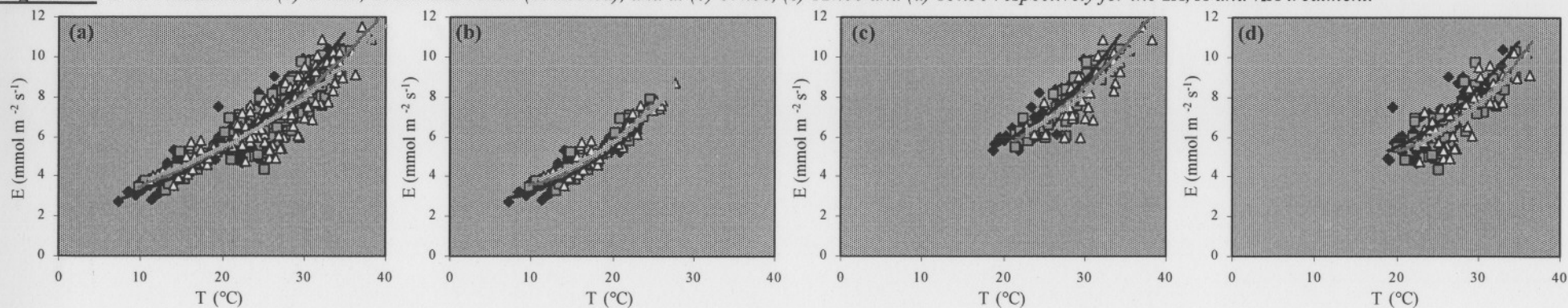


Figure A.9: E vs. T_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}X$ treatment.

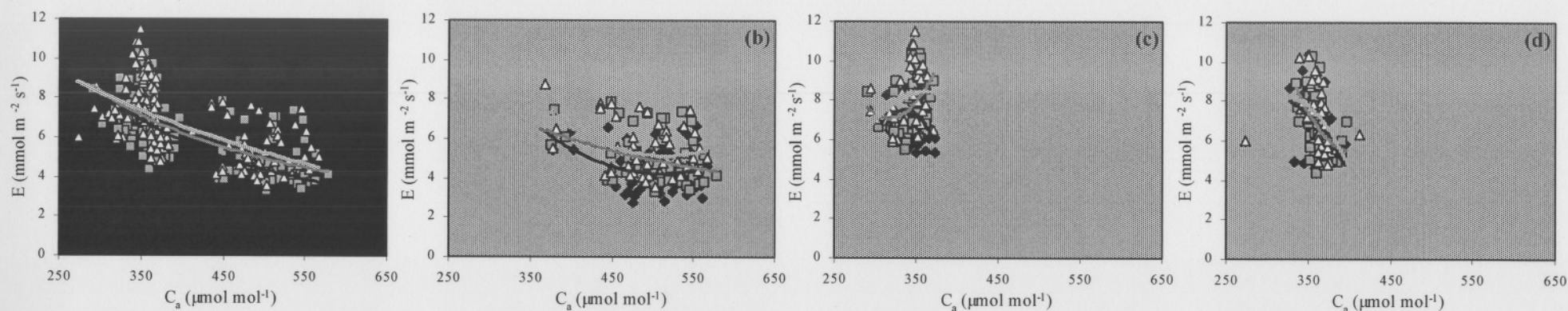


Figure A.10: E vs. C_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

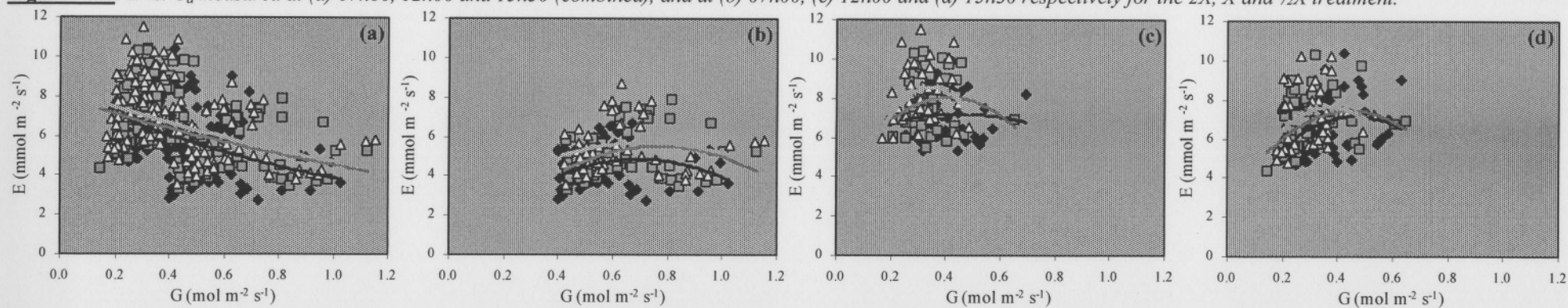


Figure A.11: E vs. G measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

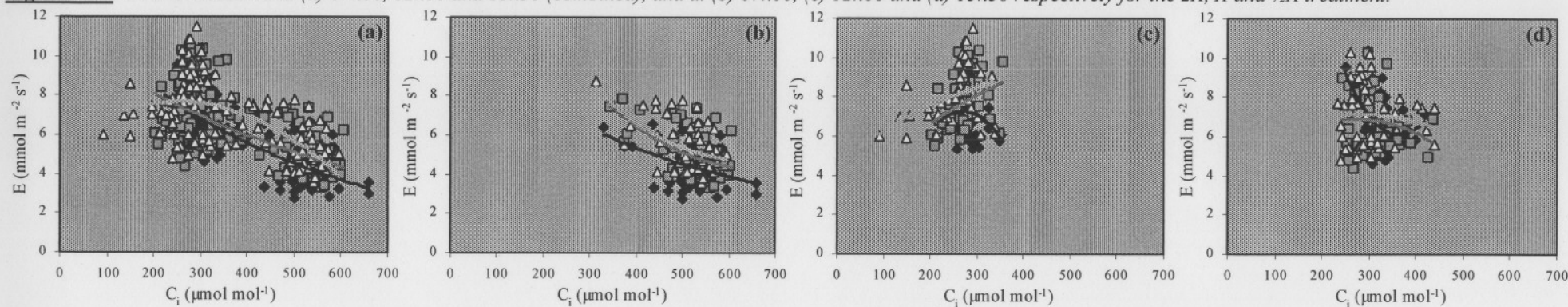


Figure A.12: E vs. C_i measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

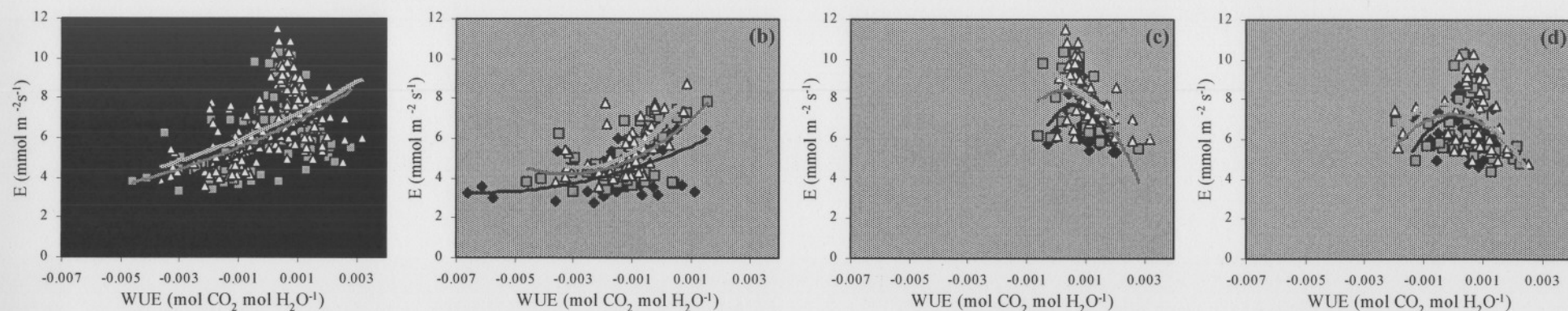


Figure A.13: E vs. WUE measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}X$ treatment.

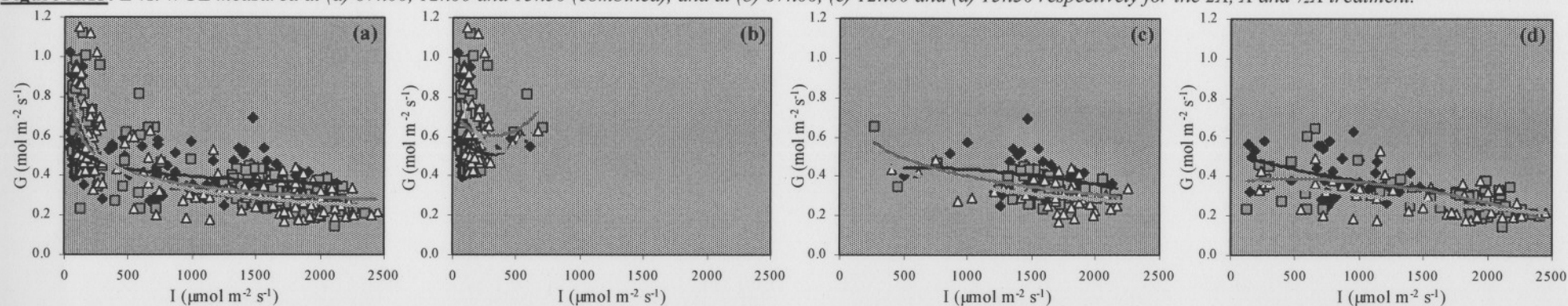


Figure A.14: G vs. I measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}X$ treatment.

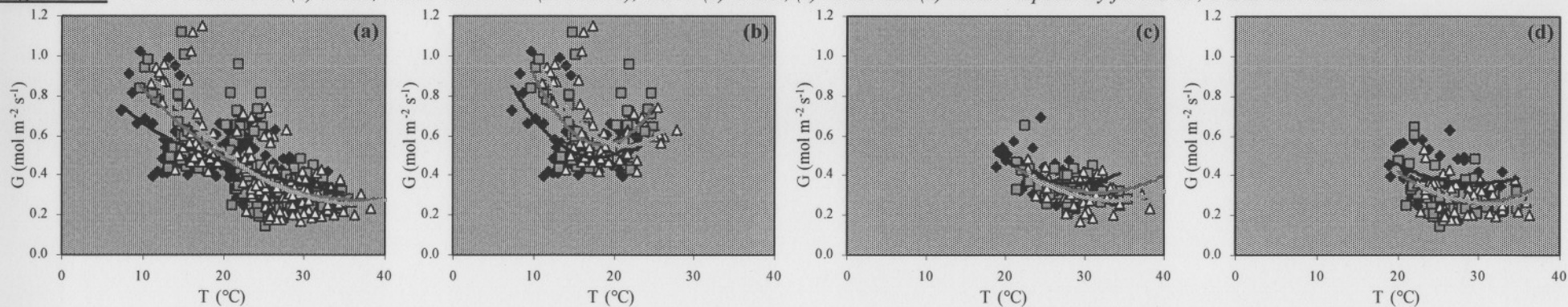


Figure A.15: G vs. T_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}X$ treatment.

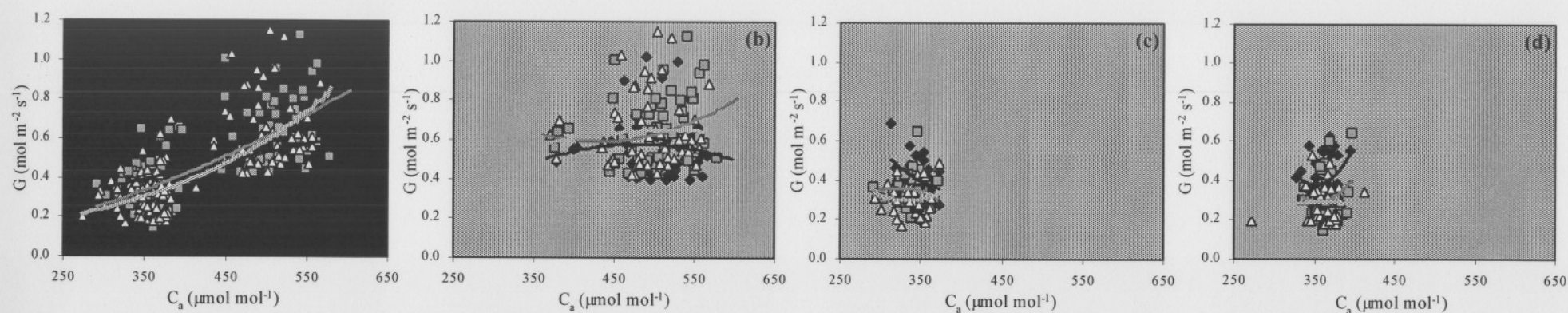


Figure A.16: G vs. C_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

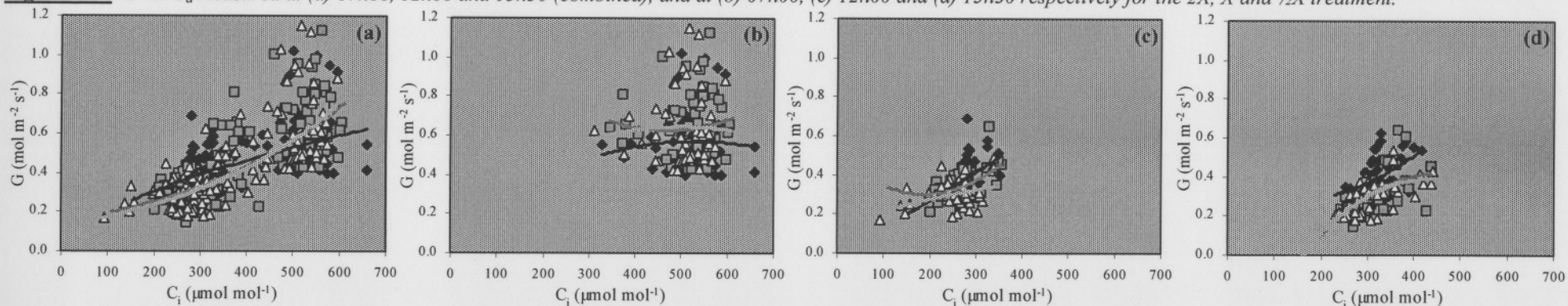


Figure A.17: G vs. C_i measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

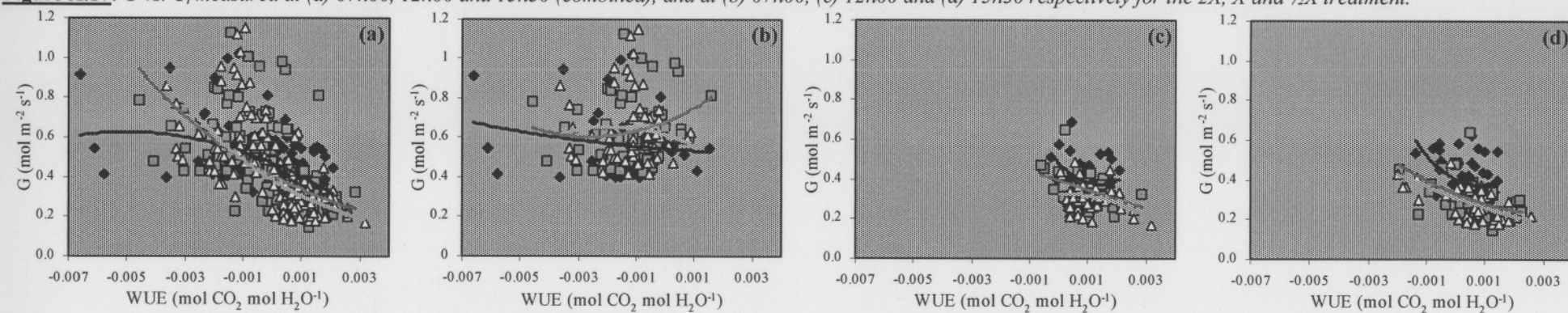


Figure A.18: G vs. WUE measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

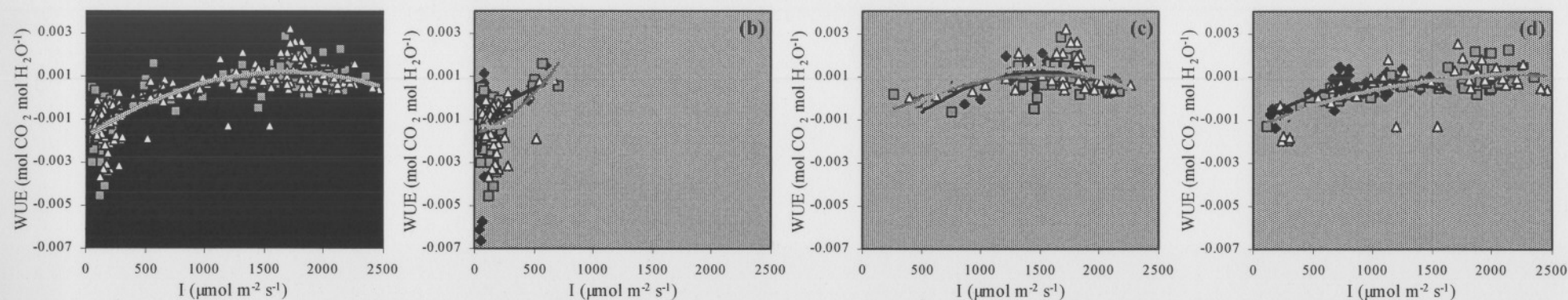


Figure A.19: *WUE vs. I measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}X$ treatment.*

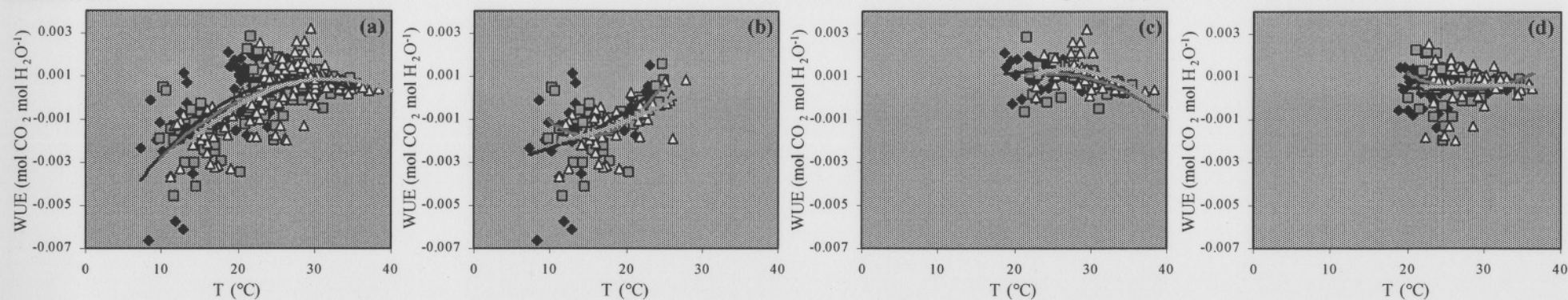


Figure A.20: *WUE vs. T_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}X$ treatment.*

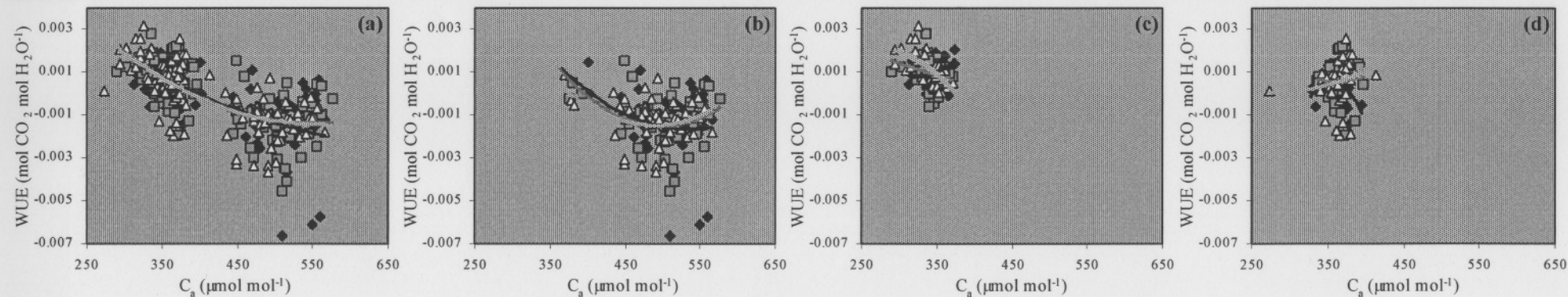


Figure A.21: *WUE vs. C_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}X$ treatment.*

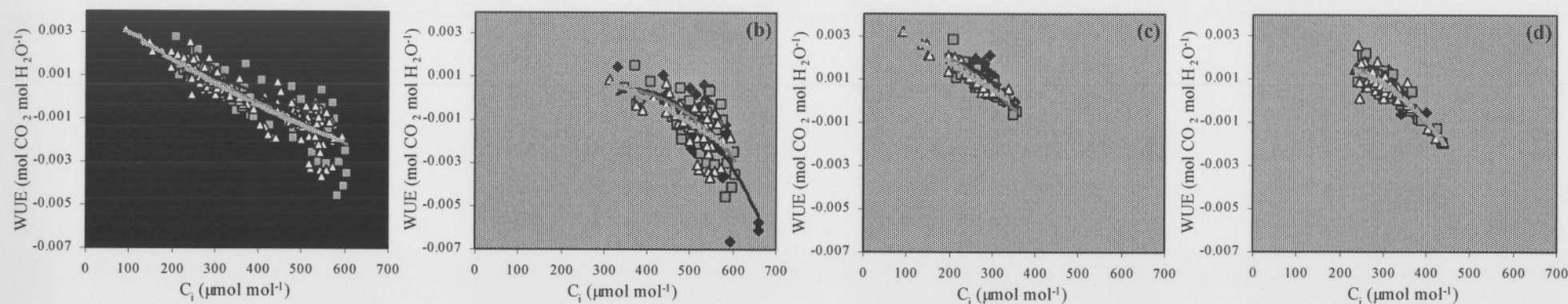


Figure A.22: WUE vs. C_i measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

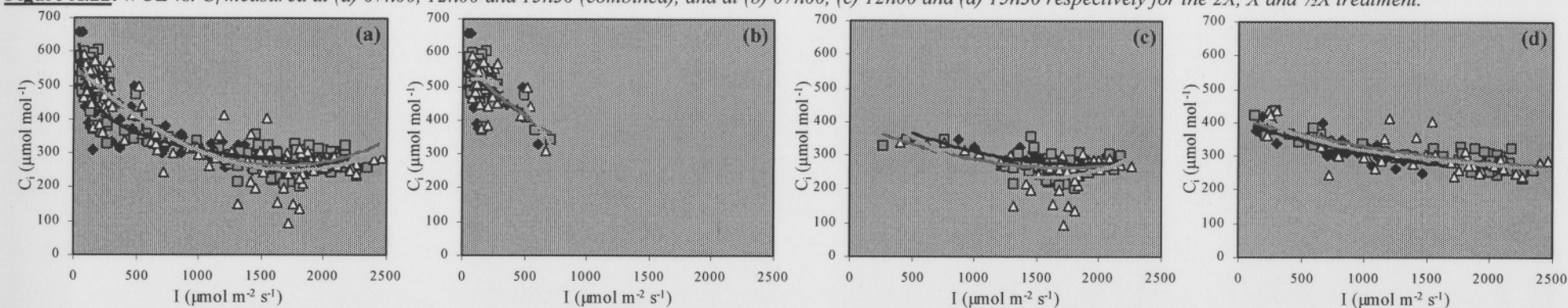


Figure A.23: C_i vs. I measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

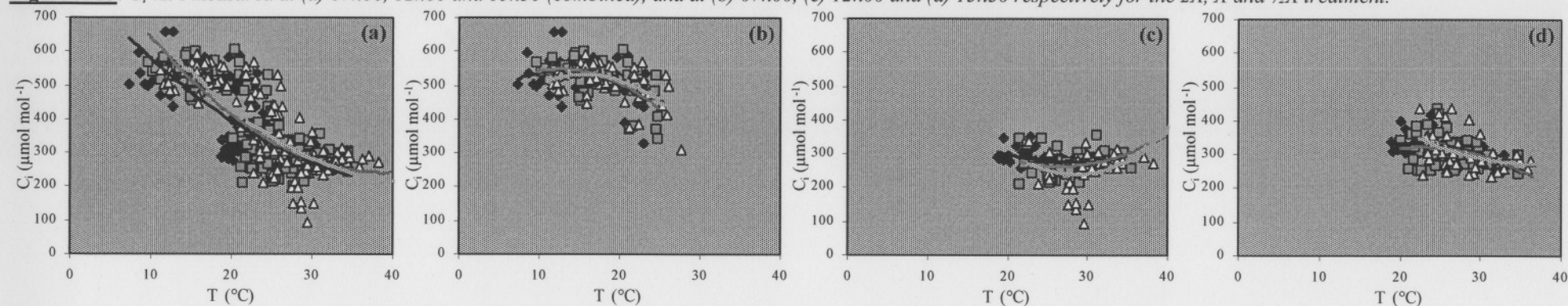


Figure A.24: C_i vs. T_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

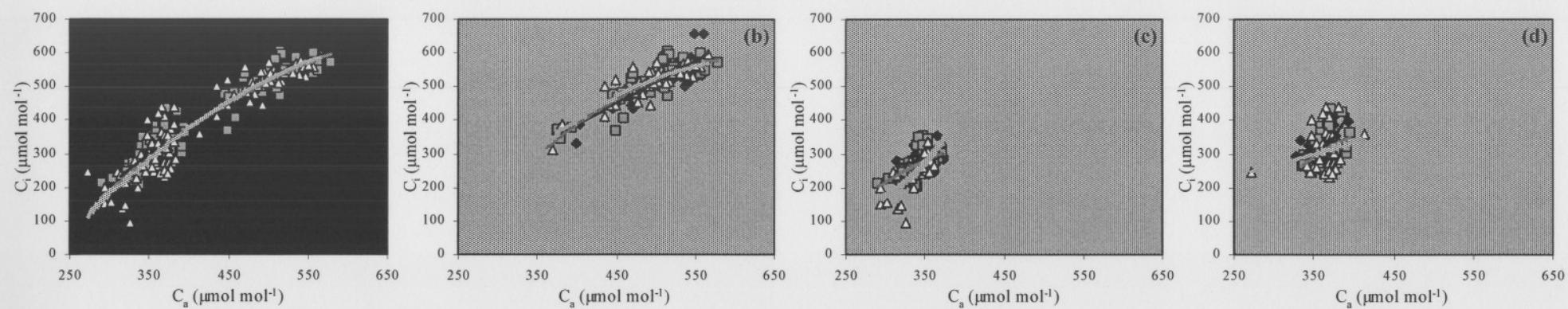


Figure A.25: C_i vs. C_a measured at (a) 07h00, 12h00 and 15h30 (combined), and at (b) 07h00, (c) 12h00 and (d) 15h30 respectively for the 2X, X and $\frac{1}{2}$ X treatment.

Table A.1: Squared correlation coefficients (R^2) for the straight line as well as the linear curve fitting the best to the data points of each combination of variables, and the equation for the latter. The data points used are a combination of the 07h00, 12h00 and 15h30 data of each variable for the respective irrigation treatments.

Variables	2X	Treatment X	$\frac{1}{2}X$
A vs I	$R^2 = 0.641$ $R^2 = 0.667$ $y = 4.4782\ln(x) - 25.855$	$R^2 = 0.649$ $R^2 = 0.702$ $y = -5E-06x^2 + 0.0176x - 8.4437$	$R^2 = 0.618$ $R^2 = 0.677$ $y = -5E-06x^2 + 0.0191x - 9.7735$
A vs T_a	$R^2 = 0.437$ $R^2 = 0.459$ $y = -0.025x^2 + 1.8072x - 25.186$	$R^2 = 0.406$ $R^2 = 0.422$ $y = -0.0229x^2 + 1.7975x - 27.323$	$R^2 = 0.427$ $R^2 = 0.454$ $y = -0.0302x^2 + 2.2724x - 35.219$
A vs C_a	$R^2 = 0.534$ $R^2 = 0.544$ $y = 0.0002x^2 - 0.2423x + 65.64$	$R^2 = 0.501$ $R^2 = 0.532$ $y = 0.0003x^2 - 0.357x + 89.634$	$R^2 = 0.507$ $R^2 = 0.546$ $y = 0.0004x^2 - 0.3888x + 96.976$
A vs E	$R^2 = 0.358$ $R^2 = 0.413$ $y = -0.457x^2 + 8.0156x - 29.063$	$R^2 = 0.260$ $R^2 = 0.321$ $y = -0.5377x^2 + 9.3477x - 34.857$	$R^2 = 0.230$ $R^2 = 0.285$ $y = -0.5224x^2 + 9.5557x - 37.656$
A vs G	$R^2 = 0.287$ $R^2 = 0.288$ $y = 8.9879x^2 - 35.462x + 15.378$	$R^2 = 0.323$ $R^2 = 0.393$ $y = 40.182x^2 - 65.325x + 20.827$	$R^2 = 0.402$ $R^2 = 0.482$ $y = 39.114x^2 - 67.878x + 21.468$
A vs C_l	$R^2 = 0.772$ $R^2 = 0.778$ $y = -21.703\ln(x) + 129.45$	$R^2 = 0.775$ $R^2 = 0.789$ $y = -20.854\ln(x) + 123.88$	$R^2 = 0.814$ $R^2 = 0.831$ $y = 8E-05x^2 - 0.1187x + 32.974$
A vs WUE	$R^2 = 0.927$ $R^2 = 0.962$ $y = 322982x^2 + 5356.9x + 0.7402$	$R^2 = 0.954$ $R^2 = 0.954$ $y = 5304.7x + 1.22$	$R^2 = 0.957$ $R^2 = 0.957$ $y = 5743.2x + 1.1902$
E vs I	$R^2 = 0.574$ $R^2 = 0.655$ $y = 1.7703x^{0.1921}$	$R^2 = 0.384$ $R^2 = 0.486$ $y = 2.3017x^{0.1557}$	$R^2 = 0.417$ $R^2 = 0.457$ $y = 2.3104x^{0.161}$
E vs T_a	$R^2 = 0.871$ $R^2 = 0.897$ $y = 1.9796e^{0.0497x}$	$R^2 = 0.815$ $R^2 = 0.843$ $y = 2.3191e^{0.042x}$	$R^2 = 0.780$ $R^2 = 0.809$ $y = 2.5397e^{0.0379x}$
E vs C_a	$R^2 = 0.479$ $R^2 = 0.533$ $y = 11675x^{-1.2693}$	$R^2 = 0.393$ $R^2 = 0.445$ $y = 2833.2x^{-1.0219}$	$R^2 = 0.371$ $R^2 = 0.406$ $y = 16.435e^{-0.0023x}$
E vs G	$R^2 = 0.108$ $R^2 = 0.123$ $y = 8.0888e^{-0.7425x}$	$R^2 = 0.138$ $R^2 = 0.159$ $y = 7.9679e^{-0.5644x}$	$R^2 = 0.174$ $R^2 = 0.197$ $y = 8.3288e^{-0.5705x}$
E vs C_l	$R^2 = 0.517$ $R^2 = 0.562$ $y = 12.587e^{-0.002x}$	$R^2 = 0.395$ $R^2 = 0.442$ $y = 11.075e^{-0.0015x}$	$R^2 = 0.342$ $R^2 = 0.399$ $y = -3E-05x^2 + 0.0166x + 5.5739$
E vs WUE	$R^2 = 0.320$ $R^2 = 0.385$ $y = 5.7857e^{129.3x}$	$R^2 = 0.235$ $R^2 = 0.283$ $y = 6.1719e^{110.03x}$	$R^2 = 0.215$ $R^2 = 0.260$ $y = 6.5006e^{100.34x}$
G vs I	$R^2 = 0.258$ $R^2 = 0.348$ $y = 0.9642x^{-0.1287}$	$R^2 = 0.554$ $R^2 = 0.600$ $y = 2.1135x^{-0.2599}$	$R^2 = 0.545$ $R^2 = 0.669$ $y = 3.2188x^{-0.3305}$
G vs T_a	$R^2 = 0.343$ $R^2 = 0.368$ $y = -0.2799\ln(x) + 1.3059$	$R^2 = 0.470$ $R^2 = 0.498$ $y = 0.0008x^2 - 0.0576x + 1.3305$	$R^2 = 0.555$ $R^2 = 0.601$ $y = 0.001x^2 - 0.0731x + 1.5745$
G vs C_a	$R^2 = 0.250$ $R^2 = 0.272$ $y = 0.0028x^{0.8456}$	$R^2 = 0.548$ $R^2 = 0.550$ $y = 2E-06x^2 + 0.0002x + 0.027$	$R^2 = 0.527$ $R^2 = 0.542$ $y = 0.0627e^{0.0045x}$
G vs C_l	$R^2 = 0.305$ $R^2 = 0.3449$ $y = 0.0127x^{0.6005}$	$R^2 = 0.556$ $R^2 = 0.5803$ $y = 0.1487e^{0.0027x}$	$R^2 = 0.568$ $R^2 = 0.630$ $y = 0.1321e^{0.0029x}$
G vs WUE	$R^2 = 0.253$ $R^2 = 0.2566$ $y = -6197.3x^2 - 62.313x + 0.4693$	$R^2 = 0.310$ $R^2 = 0.3533$ $y = 0.4053e^{-184.45x}$	$R^2 = 0.422$ $R^2 = 0.479$ $y = 0.3841e^{-230.51x}$
WUE vs I	$R^2 = 0.488$ $R^2 = 0.579$ $y = 0.0009\ln(x) - 0.0055$	$R^2 = 0.602$ $R^2 = 0.661$ $y = -1E-09x^2 + 3E-06x - 0.0017$	$R^2 = 0.577$ $R^2 = 0.669$ $y = -1E-09x^2 + 4E-06x - 0.0019$
WUE vs T_a	$R^2 = 0.418$ $R^2 = 0.499$ $y = -1E-05x^2 + 0.0006x - 0.0075$	$R^2 = 0.396$ $R^2 = 0.452$ $y = -8E-06x^2 + 0.0005x - 0.0069$	$R^2 = 0.443$ $R^2 = 0.521$ $y = -9E-06x^2 + 0.0006x - 0.0082$

Table A.1: Continued

Variables	Treatment		
	2X	X	½X
WUE vs C _a	R ² = 0.498 R ² = 0.501 y = 2E-08x ² - 3E-05x + 0.0098	R ² = 0.493 R ² = 0.523 y = 5E-08x ² - 6E-05x + 0.0151	R ² = 0.507 R ² = 0.538 y = 5E-08x ² - 6E-05x + 0.0145
WUE vs C _i	R ² = 0.711 R ² = 0.735 y = -2E-08x ² + 1E-05x + 0.0002	R ² = 0.751 R ² = 0.753 y = 3E-09x ² - 1E-05x + 0.0041	R ² = 0.797 R ² = 0.801 y = 6E-09x ² - 1E-05x + 0.0044
C _i vs I	R ² = 0.739 R ² = 0.866 y = 1298.5x ^{-0.207}	R ² = 0.777 R ² = 0.871 y = 0.0001x ² - 0.3536x + 557.72	R ² = 0.744 R ² = 0.842 y = 0.0001x ² - 0.359x + 564.21
C _i vs T _a	R ² = 0.607 R ² = 0.619 y = 0.3014x ² - 27.383x + 822.2	R ² = 0.640 R ² = 0.667 y = 0.4806x ² - 37.358x + 967.71	R ² = 0.628 R ² = 0.648 y = 0.4025x ² - 34.804x + 966.15
C _i vs C _a	R ² = 0.930 R ² = 0.932 y = -0.0014x ² + 2.647x - 459.76	R ² = 0.907 R ² = 0.912 y = -0.0022x ² + 3.3812x - 626.9	R ² = 0.877 R ² = 0.885 y = -0.0026x ² + 3.7774x - 724.34
C _a vs T _a	R ² = 0.547	R ² = 0.619	R ² = 0.613
I vs T _a	R ² = 0.573	R ² = 0.598	R ² = 0.648
I vs C _a	R ² = 0.618	R ² = 0.617	R ² = 0.603

Table A.2: Squared correlation coefficients (R^2) for the straight line as well as the linear curve fitting the best to the data points of each combination of variables, and the equation for the latter. These values and equation were determined separately for the 07h00, 12h00 and 15h30 data of each variable for the respective irrigation treatments.

Variables	2X	X	$\frac{1}{2}X$
A vs I (07h00)	$R^2 = 0.218$ $R^2 = 0.223$ $y = 2E-05x^2 + 0.0107x - 7.355$	$R^2 = 0.293$ $R^2 = 0.312$ $y = 4E-05x^2 + 0.0007x - 7.0647$	$R^2 = 0.101$ $R^2 = 0.178$ $y = 7E-05x^2 - 0.0303x - 3.6408$
(12h00)	$R^2 = 0.165$ $R^2 = 0.425$ $y = -9E-06x^2 + 0.0293x - 16.814$	$R^2 = 0.166$ $R^2 = 0.252$ $y = -5E-06x^2 + 0.0174x - 7.4005$	$R^2 = 0.074$ $R^2 = 0.319$ $y = -1E-05x^2 + 0.033x - 14.916$
(15h30)	$R^2 = 0.487$ $R^2 = 0.586$ $y = -8E-06x^2 + 0.0215x - 8.3192$	$R^2 = 0.703$ $R^2 = 0.732$ $y = -3E-06x^2 + 0.0132x - 8.418$	$R^2 = 0.421$ $R^2 = 0.519$ $y = 7.2058\ln(x) - 47.603$
A vs T_a (07h00)	$R^2 = 0.193$ $R^2 = 0.234$ $y = 0.0632x^2 - 1.4501x + 0.6466$	$R^2 = 0.155$ $R^2 = 0.371$ $y = 0.1532x^2 - 4.9028x + 30.915$	$R^2 = 0.167$ $R^2 = 0.205$ $y = 0.0516x^2 - 1.484x + 2.8726$
(12h00)	$R^2 = 0.004$ $R^2 = 0.021$ $y = -0.0332x^2 + 1.72x - 14.627$	$R^2 = 0.023$ $R^2 = 0.088$ $y = -0.0723x^2 + 3.869x - 43.757$	$R^2 = 0.079$ $R^2 = 0.207$ $y = -0.0971x^2 + 5.4356x - 66.428$
(15h30)	$R^2 = 0.038$ $R^2 = 0.073$ $y = 0.05x^2 - 2.3646x + 30.074$	$R^2 = 0.018$ $R^2 = 0.047$ $y = 0.0593x^2 - 3.0531x + 42.175$	$R^2 = 0.037$ $R^2 = 0.039$ $y = -0.0183x^2 + 1.3783x - 20.377$
A vs C_a (07h00)	$R^2 = 0.085$ $R^2 = 0.122$ $y = 0.0005x^2 - 0.4865x + 122.25$	$R^2 = 0.046$ $R^2 = 0.137$ $y = 0.0006x^2 - 0.6369x + 153.81$	$R^2 = 0.021$ $R^2 = 0.129$ $y = 0.0006x^2 - 0.5729x + 132.98$
(12h00)	$R^2 = 0.069$ $R^2 = 0.082$ $y = 0.0015x^2 - 0.942x + 156.85$	$R^2 = 0.045$ $R^2 = 0.049$ $y = 0.0007x^2 - 0.5114x + 101.69$	$R^2 = 0.434$ $R^2 = 0.439$ $y = -0.0008x^2 + 0.3846x - 28.082$
(15h30)	$R^2 = 0.062$ $R^2 = 0.197$ $y = -0.0061x^2 + 4.2757x - 749.29$	$R^2 = 0.007$ $R^2 = 0.020$ $y = 0.0024x^2 - 1.7518x + 329.56$	$R^2 = 0.017$ $R^2 = 0.018$ $y = 0.0002x^2 - 0.0996x + 12.38$
A vs E (07h00)	$R^2 = 0.133$ $R^2 = 0.175$ $y = 1.0863x^2 - 8.348x + 8.9404$	$R^2 = 0.188$ $R^2 = 0.321$ $y = 1.541x^2 - 15.016x + 28.67$	$R^2 = 0.167$ $R^2 = 0.192$ $y = 0.4917x^2 - 4.1328x + 1.1512$
(12h00)	$R^2 = 0.001$ $R^2 = 0.014$ $y = -0.2614x^2 + 3.7831x - 6.0409$	$R^2 = 0.084$ $R^2 = 0.088$ $y = -0.1577x^2 + 1.6501x + 4.0192$	$R^2 = 0.159$ $R^2 = 0.160$ $y = -0.0372x^2 - 0.6522x + 16.055$
(15h30)	$R^2 = 0.020$ $R^2 = 0.074$ $y = 0.4429x^2 - 5.9268x + 21.86$	$R^2 = 0.0003$ $R^2 = 0.030$ $y = 0.4091x^2 - 5.7579x + 23.156$	$R^2 = 0.003$ $R^2 = 0.087$ $y = 0.8249x^2 - 12.223x + 46.857$
A vs G (07h00)	$R^2 = 0.047$ $R^2 = 0.116$ $y = -51.937x^2 + 62.14x - 22.588$	$R^2 = 0.025$ $R^2 = 0.028$ $y = -9.7338x^2 + 19.234x - 13.501$	$R^2 = 0.001$ $R^2 = 0.001$ $y = -0.5458x^2 - 0.2318x - 5.6751$
(12h00)	$R^2 = 0.132$ $R^2 = 0.139$ $y = -24.813x^2 + 8.7588x + 7.8779$	$R^2 = 0.183$ $R^2 = 0.189$ $y = -27.656x^2 - 1.0183x + 10.837$	$R^2 = 0.068$ $R^2 = 0.104$ $y = 20.062e^{-3.6443x}$
(15h30)	$R^2 = 0.094$ $R^2 = 0.101$ $y = -40.669x^2 + 22.73x + 0.7773$	$R^2 = 0.202$ $R^2 = 0.204$ $y = 15.836x^2 - 34.776x + 12.785$	$R^2 = 0.274$ $R^2 = 0.281$ $y = -55.322x^2 - 2.7735x + 9.4106$
A vs C_i (07h00)	$R^2 = 0.531$ $R^2 = 0.568$ $y = -0.0002x^2 + 0.1012x - 11.052$	$R^2 = 0.472$ $R^2 = 0.488$ $y = -0.0002x^2 + 0.0847x - 6.2844$	$R^2 = 0.388$ $R^2 = 0.389$ $y = 3E-05x^2 - 0.0899x + 30.646$
(12h00)	$R^2 = 0.650$ $R^2 = 0.674$ $y = -0.0005x^2 + 0.1673x - 1.5255$	$R^2 = 0.826$ $R^2 = 0.878$ $y = -0.0005x^2 + 0.1945x - 5.581$	$R^2 = 0.898$ $R^2 = 0.907$ $y = -0.0001x^2 - 0.0303x + 23.249$
(15h30)	$R^2 = 0.797$ $R^2 = 0.809$ $y = -0.0003x^2 + 0.0612x + 9.9088$	$R^2 = 0.862$ $R^2 = 0.872$ $y = -0.0002x^2 + 0.0266x + 14.999$	$R^2 = 0.826$ $R^2 = 0.862$ $y = -0.0004x^2 + 0.1392x - 3.3141$
A vs WUE (07h00)	$R^2 = 0.918$ $R^2 = 0.939$ $y = 197332x^2 + 4529.4x + 0.0983$	$R^2 = 0.922$ $R^2 = 0.938$ $y = 337252x^2 + 5619.3x + 0.4816$	$R^2 = 0.907$ $R^2 = 0.922$ $y = 449283x^2 + 6075.5x + 0.383$
(12h00)	$R^2 = 0.886$ $R^2 = 0.908$ $y = -1E+06x^2 + 8131.5x + 0.4421$	$R^2 = 0.918$ $R^2 = 0.956$ $y = -1E+06x^2 + 8263.1x + 0.6611$	$R^2 = 0.944$ $R^2 = 0.960$ $y = 4845.9x^{0.9291}$

Table A.2: Continued.

Variables	2X	Treatment X	1/2X
(15h30)	$R^2 = 0.936$ $R^2 = 0.942$ $y = -609646x^2 + 6508.4x + 0.4271$	$R^2 = 0.946$ $R^2 = 0.930$ $y = -208168x^2 + 5496.9x + 0.9157$	$R^2 = 0.9475$ $R^2 = 0.913$ $y = -276016x^2 + 5793.2x + 0.9617$
E vs I (07h00)	$R^2 = 0.368$ $R^2 = 0.431$ $y = 1.2066\ln(x) - 1.1114$	$R^2 = 0.394$ $R^2 = 0.406$ $y = -6E-06x^2 + 0.0103x + 3.6569$	$R^2 = 0.365$ $R^2 = 0.379$ $y = 7E-06x^2 + 0.0018x + 4.6918$
(12h00)	$R^2 = 0.487$ $R^2 = 0.590$ $y = 3E-06x^2 - 0.0054x + 8.6485$	$R^2 = 0.216$ $R^2 = 0.290$ $y = 2E-06x^2 - 0.0023x + 7.3113$	$R^2 = 0.125$ $R^2 = 0.202$ $y = 2E-06x^2 - 0.0035x + 8.8461$
(15h30)	$R^2 = 0.343$ $R^2 = 0.477$ $y = 3E-06x^2 - 0.003x + 6.4759$	$R^2 = 0.034$ $R^2 = 0.060$ $y = -7E-07x^2 + 0.0022x + 5.4429$	$R^2 = 0.086$ $R^2 = 0.147$ $y = 1E-06x^2 - 0.0019x + 7.4002$
E vs T _a (07h00)	$R^2 = 0.862$ $R^2 = 0.883$ $y = 0.0087x^2 - 0.0415x + 2.767$	$R^2 = 0.879$ $R^2 = 0.913$ $y = 0.013x^2 - 0.1811x + 4.1067$	$R^2 = 0.874$ $R^2 = 0.902$ $y = 0.0109x^2 - 0.1402x + 4.1064$
(12h00)	$R^2 = 0.783$ $R^2 = 0.802$ $y = 0.0135x^2 - 0.3566x + 7.5001$	$R^2 = 0.794$ $R^2 = 0.801$ $y = 0.0078x^2 - 0.0834x + 4.0259$	$R^2 = 0.663$ $R^2 = 0.677$ $y = 0.0094x^2 - 0.229x + 6.5773$
(15h30)	$R^2 = 0.728$ $R^2 = 0.743$ $y = 0.012x^2 - 0.3003x + 6.684$	$R^2 = 0.662$ $R^2 = 0.680$ $y = 0.0131x^2 - 0.4095x + 8.2032$	$R^2 = 0.643$ $R^2 = 0.650$ $y = 0.0085x^2 - 0.1714x + 5.0455$
E vs C _a (07h00)	$R^2 = 0.034$ $R^2 = 0.086$ $y = 0.0001x^2 - 0.1073x + 31.54$	$R^2 = 0.112$ $R^2 = 0.116$ $y = 1062.9x^{0.8648}$	$R^2 = 0.097$ $R^2 = 0.159$ $y = 0.0001x^2 - 0.1129x + 34.235$
(12h00)	$R^2 = 0.022$ $R^2 = 0.084$ $y = -0.0012x^2 + 0.8287x - 132.15$	$R^2 = 0.102$ $R^2 = 0.147$ $y = 0.0008x^2 - 0.4901x + 84.74$	$R^2 = 0.077$ $R^2 = 0.092$ $y = -0.0004x^2 + 0.2541x - 37.638$
(15h30)	$R^2 = 0.158$ $R^2 = 0.162$ $y = -0.0004x^2 + 0.2087x - 22.129$	$R^2 = 0.212$ $R^2 = 0.227$ $y = 0.0007x^2 - 0.5424x + 115.07$	$R^2 = 0.115$ $R^2 = 0.260$ $y = -0.0006x^2 + 0.3689x - 50.898$
E vs G (07h00)	$R^2 = 0.003$ $R^2 = 0.071$ $y = -9.98x_2 + 13.874x + 0.023$	$R^2 = 0.024$ $R^2 = 0.093$ $y = -10.045x^2 + 15.439x - 0.4288$	$R^2 = 0.001$ $R^2 = 0.042$ $y = -6.9238x^2 + 10.035x + 2.0488$
(12h00)	$R^2 = 0.00006$ $R^2 = 0.004$ $y = -7.0357x^2 + 6.3684x + 5.7453$	$R^2 = 0.001$ $R^2 = 0.048$ $y = -26.17x^2 + 21.51x + 3.6299$	$R^2 = 0.027$ $R^2 = 0.119$ $y = -66.663x^2 + 45.99x + 0.6228$
(15h30)	$R^2 = 0.027$ $R^2 = 0.043$ $y = -23.273x^2 + 21.634x + 2.1292$	$R^2 = 0.052$ $R^2 = 0.117$ $y = -24.214x^2 + 21.514x + 2.6734$	$R^2 = 0.074$ $R^2 = 0.141$ $y = -42.289x^2 + 31.409x + 1.8019$
E vs C _l (07h00)	$R^2 = 0.146$ $R^2 = 0.150$ $y = -3.5461\ln(x) + 26.584$	$R^2 = 0.285$ $R^2 = 0.297$ $y = 3E-05x^2 - 0.0404x + 17.826$	$R^2 = 0.248$ $R^2 = 0.264$ $y = 3E-05x^2 - 0.0439x + 18.7$
(12h00)	$R^2 = 0.022$ $R^2 = 0.043$ $y = -9E-05x^2 + 0.0399x + 2.7396$	$R^2 = 0.112$ $R^2 = 0.134$ $y = 0.5344x^{0.4764}$	$R^2 = 0.152$ $R^2 = 0.180$ $y = 1.6948x^{0.2824}$
(15h30)	$R^2 = 0.109$ $R^2 = 0.188$ $y = 0.0002x^2 - 0.1769x + 38.287$	$R^2 = 0.024$ $R^2 = 0.031$ $y = -4E-05x^2 + 0.0238x + 3.6564$	$R^2 = 0.008$ $R^2 = 0.011$ $y = -3E-05x^2 + 0.0147x + 5.0475$
E vs WUE (07h00)	$R^2 = 0.219$ $R^2 = 0.248$ $y = 45765x^2 + 563.81x + 5.0118$	$R^2 = 0.277$ $R^2 = 0.349$ $y = 153816x^2 + 1003.9x + 5.8395$	$R^2 = 0.316$ $R^2 = 0.418$ $y = 288102x^2 + 1558.4x + 6.6085$
(12h00)	$R^2 = 0.117$ $R^2 = 0.283$ $y = -1E+06x^2 + 1527.4x + 7.2493$	$R^2 = 0.230$ $R^2 = 0.336$ $y = -697877x^2 + 327x + 8.4054$	$R^2 = 0.302$ $R^2 = 0.307$ $y = 9.2631e^{-133.88x}$
(15h30)	$R^2 = 0.004$ $R^2 = 0.083$ $y = -782694x^2 + 174.38x + 7.1765$	$R^2 = 0.025$ $R^2 = 0.180$ $y = -441537x^2 - 40.686x + 7.2799$	$R^2 = 0.034$ $R^2 = 0.192$ $y = -430844x^2 - 253.16x + 7.7285$
G vs I (07h00)	$R^2 = 0.002$ $R^2 = 0.020$ $y = 1E-06x^2 - 0.0008x + 0.6247$	$R^2 = 0.0003$ $R^2 = 0.019$ $y = 1E-06x^2 - 0.0007x + 0.7078$	$R^2 = 0.036$ $R^2 = 0.104$ $y = 2E-06x^2 - 0.0018x + 0.8694$
(12h00)	$R^2 = 0.070$ $R^2 = 0.081$ $y = -3E-08x^2 + 3E-05x + 0.4417$	$R^2 = 0.366$ $R^2 = 0.400$ $y = -0.1315\ln(x) + 1.309$	$R^2 = 0.221$ $R^2 = 0.239$ $y = -0.1038\ln(x) + 1.0713$

Table A.2: Continued.

Variables	2X	Treatment X	$\frac{1}{2}X$
(15h30)	$R^2 = 0.146$ $R^2 = 0.147$ $y = 4E-08x^2 - 0.0002x + 0.5163$	$R^2 = 0.289$ $R^2 = 0.314$ $y = -5E-08x^2 + 5E-05x + 0.3753$	$R^2 = 0.257$ $R^2 = 0.260$ $y = 0.3877e^{-0.0002x}$
G vs T_a (07h00)	$R^2 = 0.088$ $R^2 = 0.239$ $y = 0.0033x^2 - 0.1168x + 1.5238$	$R^2 = 0.030$ $R^2 = 0.274$ $y = 0.0047x^2 - 0.1759x + 2.1819$	$R^2 = 0.129$ $R^2 = 0.261$ $y = 0.0035x^2 - 0.1496x + 2.144$
(12h00)	$R^2 = 0.182$ $R^2 = 0.236$ $y = 0.0016x^2 - 0.0896x + 1.6403$	$R^2 = 0.141$ $R^2 = 0.190$ $y = 0.0012x^2 - 0.0732x + 1.4692$	$R^2 = 0.164$ $R^2 = 0.232$ $y = 0.0011x^2 - 0.0732x + 1.5112$
(15h30)	$R^2 = 0.099$ $R^2 = 0.108$ $y = 0.001x^2 - 0.0588x + 1.2324$	$R^2 = 0.099$ $R^2 = 0.148$ $y = 0.0015x^2 - 0.0925x + 1.6535$	$R^2 = 0.095$ $R^2 = 0.123$ $y = 0.001x^2 - 0.0659x + 1.3225$
G vs C_a (07h00)	$R^2 = 0.0002$ $R^2 = 0.007$ $y = -6E-06x^2 + 0.0053x - 0.7034$	$R^2 = 0.040$ $R^2 = 0.054$ $y = 7E-06x^2 - 0.0063x + 1.9418$	$R^2 = 0.004$ $R^2 = 0.006$ $y = -3E-06x^2 + 0.003x - 0.1304$
(12h00)	$R^2 = 0.139$ $R^2 = 0.145$ $y = 2E-05x^2 - 0.0175x + 3.8454$	$R^2 = 0.012$ $R^2 = 0.022$ $y = -2E-05x^2 + 0.0141x - 1.9176$	$R^2 = 0.00009$ $R^2 = 0.016$ $y = 2E-05x^2 - 0.0149x + 2.7796$
(15h30)	$R^2 = 0.023$ $R^2 = 0.068$ $y = 9E-05x^2 - 0.0612x + 11.147$	$R^2 = 0.028$ $R^2 = 0.055$ $y = 7E-05x^2 - 0.0462x + 8.5035$	$R^2 = 0.0048$ $R^2 = 0.014$ $y = -9E-06x^2 + 0.0062x - 0.8301$
G vs C_i (07h00)	$R^2 = 0.001$ $R^2 = 0.006$ $y = -2E-06x^2 + 0.0018x + 0.0836$	$R^2 = 0.0008$ $R^2 = 0.007$ $y = 3E-06x^2 - 0.0028x + 1.2843$	$R^2 = 0.0009$ $R^2 = 0.003$ $y = -2E-06x^2 + 0.0017x + 0.2132$
(12h00)	$R^2 = 0.161$ $R^2 = 0.177$ $y = 0.0009x^{1.0824}$	$R^2 = 0.226$ $R^2 = 0.242$ $y = 6E-06x^2 - 0.0021x + 0.501$	$R^2 = 0.160$ $R^2 = 0.182$ $y = 0.0354x^{0.3871}$
(15h30)	$R^2 = 0.180$ $R^2 = 0.179$ $y = 3E-06x^2 - 0.0007x + 0.3063$	$R^2 = 0.299$ $R^2 = 0.315$ $y = -5E-06x^2 + 0.0044x - 0.5809$	$R^2 = 0.410$ $R^2 = 0.448$ $y = -5E-06x^2 + 0.0045x - 0.5951$
G vs WUE (07h00)	$R^2 = 0.031$ $R^2 = 0.032$ $y = 1409.1x^2 - 10.746x + 0.5436$	$R^2 = 0.034$ $R^2 = 0.056$ $y = 11382x^2 + 59.579x + 0.6834$	$R^2 = 0.002$ $R^2 = 0.010$ $y = -11641x^2 - 42.879x + 0.6164$
(12h00)	$R^2 = 0.103$ $R^2 = 0.173$ $y = 54601x^2 - 149.22x + 0.477$	$R^2 = 0.169$ $R^2 = 0.169$ $y = -48.789x + 0.3933$	$R^2 = 0.101$ $R^2 = 0.123$ $y = -15104x^2 + 10.358x + 0.321$
(15h30)	$R^2 = 0.107$ $R^2 = 0.169$ $y = 48090x^2 - 73.436x + 0.4029$	$R^2 = 0.201$ $R^2 = 0.263$ $y = 8425.9x^2 - 59.237x + 0.3304$	$R^2 = 0.310$ $R^2 = 0.382$ $y = 2381.4x^2 - 52.092x + 0.3132$
WUE vs I (07h00)	$R^2 = 0.174$ $R^2 = 0.189$ $y = 0.0011\ln(x) - 0.0065$	$R^2 = 0.225$ $R^2 = 0.232$ $y = 4E-09x^2 + 1E-06x - 0.0017$	$R^2 = 0.115$ $R^2 = 0.150$ $y = 9E-09x^2 - 3E-06x - 0.0011$
(12h00)	$R^2 = 0.053$ $R^2 = 0.363$ $y = -2E-09x^2 + 5E-06x - 0.0028$	$R^2 = 0.102$ $R^2 = 0.215$ $y = -9E-10x^2 + 3E-06x - 0.0012$	$R^2 = 0.038$ $R^2 = 0.263$ $y = -2E-09x^2 + 5E-06x - 0.0022$
(15h30)	$R^2 = 0.334$ $R^2 = 0.589$ $y = -8E-06x^2 + 0.0211x - 8.1885$	$R^2 = 0.636$ $R^2 = 0.657$ $y = -5E-10x^2 + 2E-06x - 0.0014$	$R^2 = 0.356$ $R^2 = 0.474$ $y = 0.0011\ln(x) - 0.0069$
WUE vs T_a (07h00)	$R^2 = 0.268$ $R^2 = 0.272$ $y = 5E-06x^2 + 2E-05x - 0.0031$	$R^2 = 0.230$ $R^2 = 0.368$ $y = 3E-05x^2 - 0.0008x + 0.004$	$R^2 = 0.313$ $R^2 = 0.319$ $y = 4E-06x^2 - 3E-05x - 0.0022$
(12h00)	$R^2 = 0.050$ $R^2 = 0.062$ $y = -4E-06x^2 + 0.0002x - 0.0008$	$R^2 = 0.105$ $R^2 = 0.144$ $y = -9E-06x^2 + 0.0004x - 0.0041$	$R^2 = 0.140$ $R^2 = 0.231$ $y = -1E-05x^2 + 0.0007x - 0.008$
(15h30)	$R^2 = 0.0003$ $R^2 = 0.020$ $y = 6E-06x^2 - 0.0003x + 0.0041$	$R^2 = 0.001$ $R^2 = 0.037$ $y = 1E-05x^2 - 0.0006x + 0.0085$	$R^2 = 0.003$ $R^2 = 0.003$ $y = -2E-06x^2 + 0.0001x - 0.001$
WUE vs C_a (07h00)	$R^2 = 0.070$ $R^2 = 0.093$ $y = 1E-07x^2 - 0.0001x + 0.026$	$R^2 = 0.032$ $R^2 = 0.139$ $y = 1E-07x^2 - 0.0001x + 0.0339$	$R^2 = 0.019$ $R^2 = 0.125$ $y = 1E-07x^2 - 0.0001x + 0.0264$
(12h00)	$R^2 = 0.075$ $R^2 = 0.113$ $y = 4E-07x^2 - 0.0003x + 0.0456$	$R^2 = 0.077$ $R^2 = 0.078$ $y = -0.0037\ln(x) + 0.0223$	$R^2 = 0.409$ $R^2 = 0.419$ $y = -2E-07x^2 + 9E-05x - 0.0104$

Table A.2: Continued.

Variables	2X	Treatment X	$\frac{1}{2}X$
(15h30)	$R^2 = 0.023$ $R^2 = 0.177$ $y = -1E-06x^2 + 0.0007x - 0.1259$	$R^2 = 0.0001$ $R^2 = 0.003$ $y = 1E-07x^2 - 0.0001x + 0.0192$	$R^2 = 0.0356$ $R^2 = 0.035$ $y = 6E-08x^2 - 4E-05x + 0.0049$
WUE vs C_i (07h00)	$R^2 = 0.492$ $R^2 = 0.583$ $y = -7E-08x^2 + 5E-05x - 0.0098$	$R^2 = 0.424$ $R^2 = 0.454$ $y = -5E-08x^2 + 3E-05x - 0.0046$	$R^2 = 0.364$ $R^2 = 0.365$ $y = -7E-09x^2 - 4E-06x + 0.0028$
(12h00)	$R^2 = 0.499$ $R^2 = 0.517$ $y = -7E-08x^2 + 2E-05x - 0.0002$	$R^2 = 0.819$ $R^2 = 0.822$ $y = -2E-08x^2 - 4E-06x + 0.0037$	$R^2 = 0.904$ $R^2 = 0.904$ $y = 4E-09x^2 - 1E-05x + 0.0045$
(15h30)	$R^2 = 0.664$ $R^2 = 0.707$ $y = -8E-08x^2 + 4E-05x - 0.003$	$R^2 = 0.783$ $R^2 = 0.780$ $y = -3E-08x^2 + 2E-06x + 0.0027$	$R^2 = 0.765$ $R^2 = 0.793$ $y = -5E-08x^2 + 2E-05x - 0.0004$
C_i vs I (07h00)	$R^2 = 0.258$ $R^2 = 0.288$ $y = 556.7e^{-0.0006x}$	$R^2 = 0.419$ $R^2 = 0.449$ $y = 571.37e^{-0.0006x}$	$R^2 = 0.288$ $R^2 = 0.324$ $y = -0.0005x^2 + 0.0783x + 519.97$
(12h00)	$R^2 = 0.298$ $R^2 = 0.464$ $y = 5E-05x^2 - 0.1948x + 452.42$	$R^2 = 0.159$ $R^2 = 0.249$ $y = 5E-05x^2 - 0.1562x + 398.78$	$R^2 = 0.083$ $R^2 = 0.279$ $y = 0.0001x^2 - 0.355x + 507.33$
(15h30)	$R^2 = 0.663$ $R^2 = 0.675$ $y = 2E-05x^2 - 0.1187x + 402.95$	$R^2 = 0.754$ $R^2 = 0.767$ $y = 2E-05x^2 - 0.0993x + 412.96$	$R^2 = 0.477$ $R^2 = 0.535$ $y = -62.218\ln(x) + 748.32$
C_i vs T_a (07h00)	$R^2 = 0.161$ $R^2 = 0.229$ $y = -0.8376x^2 + 21.447x + 406.62$	$R^2 = 0.324$ $R^2 = 0.377$ $y = -0.7729x^2 + 19.508x + 424.58$	$R^2 = 0.242$ $R^2 = 0.345$ $y = -0.9246x^2 + 28.927x + 306.06$
(12h00)	$R^2 = 0.090$ $R^2 = 0.127$ $y = 0.3479x^2 - 19.507x + 549.83$	$R^2 = 0.023$ $R^2 = 0.066$ $y = 0.5208x^2 - 27.547x + 627.86$	$R^2 = 0.030$ $R^2 = 0.123$ $y = 0.9799x^2 - 55.907x + 1037$
(15h30)	$R^2 = 0.215$ $R^2 = 0.264$ $y = -0.4891x^2 + 21.164x + 106.5$	$R^2 = 0.122$ $R^2 = 0.143$ $y = -0.4584x^2 + 20.778x + 86.935$	$R^2 = 0.172$ $R^2 = 0.183$ $y = 0.3912x^2 - 28.457x + 790.65$
C_i vs C_a (07h00)	$R^2 = 0.738$ $R^2 = 0.769$ $y = 0.2412x^{1.2333}$	$R^2 = 0.726$ $R^2 = 0.752$ $y = -0.0034x^2 + 4.4431x - 839.12$	$R^2 = 0.740$ $R^2 = 0.770$ $y = -0.0034x^2 + 4.2714x - 769.76$
(12h00)	$R^2 = 0.066$ $R^2 = 0.074$ $y = 158.01e^{0.0017x}$	$R^2 = 0.283$ $R^2 = 0.285$ $y = -0.0038x^2 + 3.7769x - 570.63$	$R^2 = 0.577$ $R^2 = 0.586$ $y = 0.0127x^2 - 6.3285x + 927.59$
(15h30)	$R^2 = 0.377$ $R^2 = 0.459$ $y = 0.0391x^2 - 26.417x + 4760.9$	$R^2 = 0.147$ $R^2 = 0.149$ $y = -0.0089x^2 + 7.9162x - 1384.5$	$R^2 = 0.056$ $R^2 = 0.056$ $y = 0.0001x^2 + 0.5915x + 78.643$
C_a vs T_a (07h00)	$R^2 = 0.040$	$R^2 = 0.184$	$R^2 = 0.106$
(12h00)	$R^2 = 0.0007$	$R^2 = 0.133$	$R^2 = 0.089$
(15h30)	$R^2 = 0.191$	$R^2 = 0.265$	$R^2 = 0.208$
I vs T_a (07h00)	$R^2 = 0.336$	$R^2 = 0.367$	$R^2 = 0.354$
(12h00)	$R^2 = 0.486$	$R^2 = 0.375$	$R^2 = 0.234$
(15h30)	$R^2 = 0.476$	$R^2 = 0.111$	$R^2 = 0.237$
I vs C_a (07h00)	$R^2 = 0.110$	$R^2 = 0.210$	$R^2 = 0.203$
(12h00)	$R^2 = 0.0007$	$R^2 = 0.010$	$R^2 = 0.008$
(15h30)	$R^2 = 0.203$	$R^2 = 0.036$	$R^2 = 0.001$

ANNEXURE B

Percentage relative humidity and Vapour pressure deficit

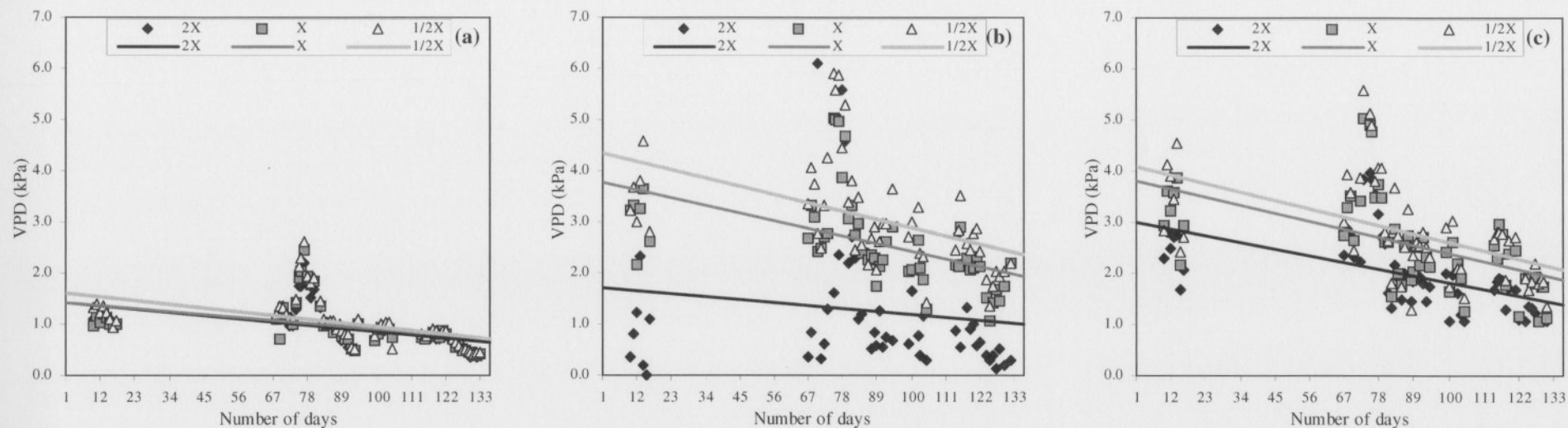


Figure B.1: Vapour pressure deficit (kPa) calculated using transpiration rates and temperature measured at (a) 7h00, (b) 12h00 and (c) 15h30 for the 2X, X and 1/2X treatments

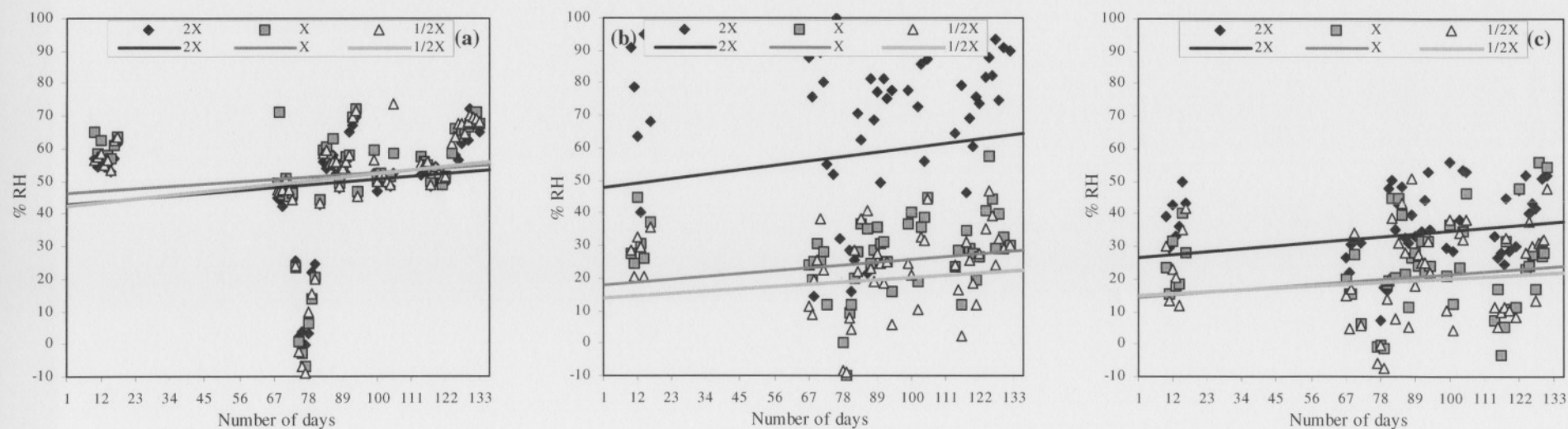


Figure B.2: Relative air humidity (%) calculated using transpiration rates and temperature measured at (a) 7h00, (b) 12h00 and (c) 15h30 for the 2X, X and 1/2X treatments

ANNEXURE C

Principal component analyses of photosynthesis and related parameters

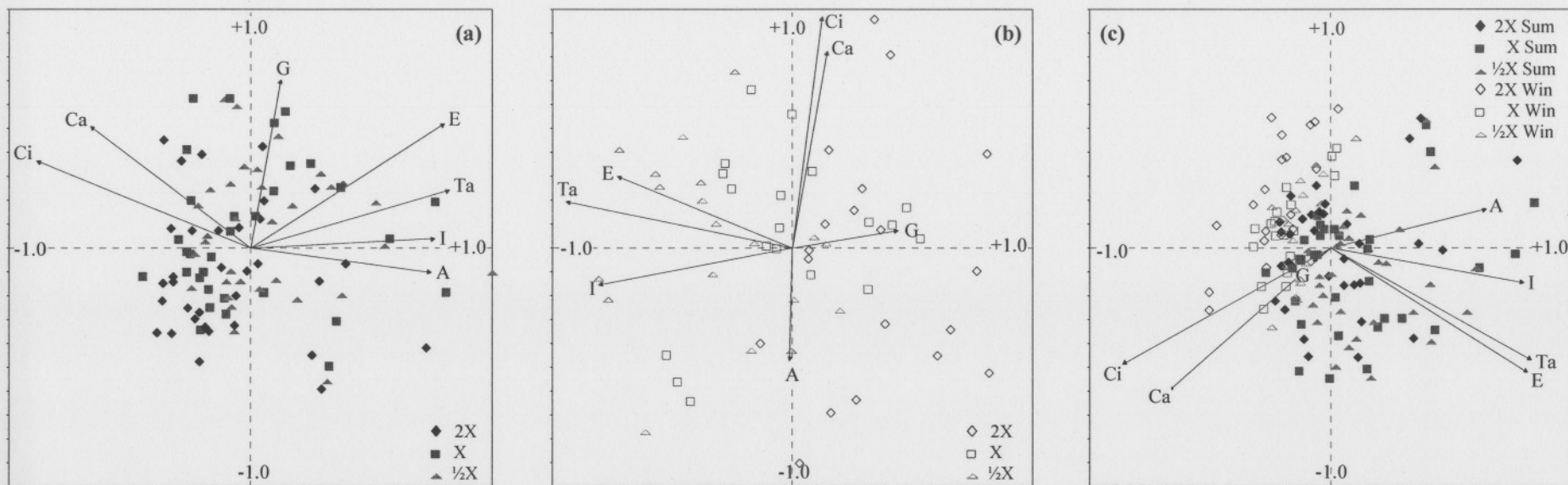


Figure C.1: PCA of the photosynthesis data collected for the 2X X and 1/2X treatments at 07h00 during (a) summer and (b) winter, respectively and (c) combined.

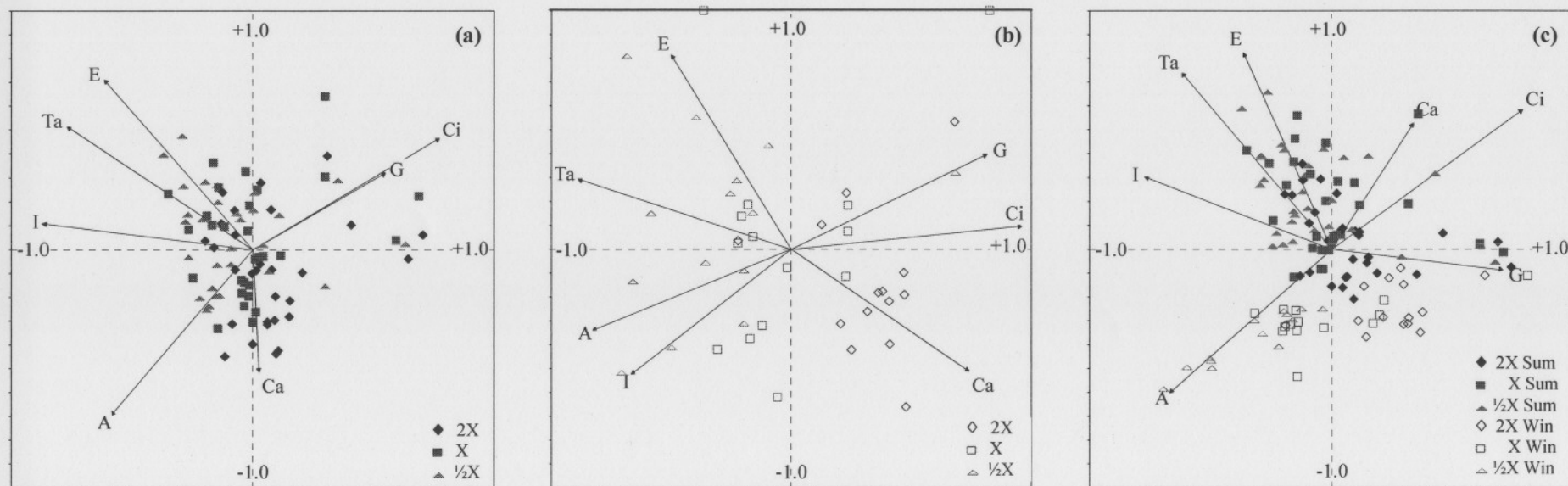


Figure C.2: PCA of the photosynthesis data collected for the 2X X and 1/2X treatments at 12h00 during (a) summer and (b) winter, respectively and (c) combined.

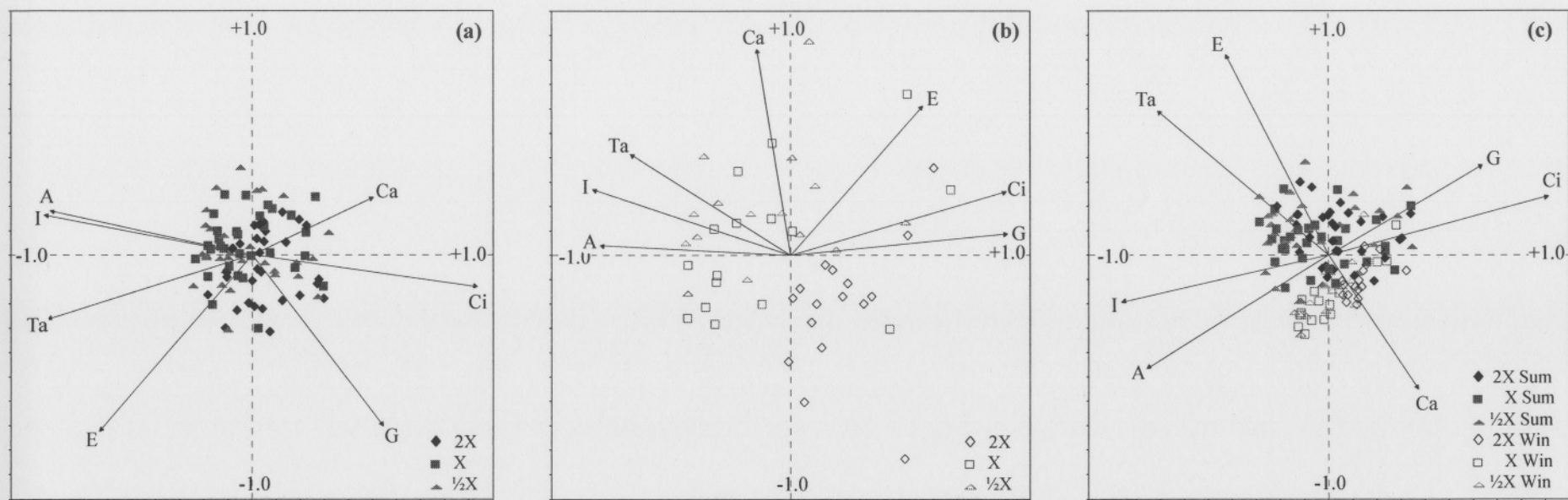


Figure C.3: PCA of the photosynthesis data collected for the 2X X and 1/2X treatments at 15h30 during (a) summer and (b) winter, respectively and (c) combined.