Impact of crop management during plant propagation on yield potential of Junebearer and Everbearer strawberry (*Fragaria x ananassa* Duch.) cultivars

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Declaration

I confirm that this is my own work and the use of material from other sources has been properly and fully acknowledged.

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Abstract

Conditions during the autumn (propagation phase), when plants are developing and flowers are initiated, impact upon subsequent fruit production in strawberry (*Fragaria x ananassa* Duch.). Little is known about the best conditions in which to propagate strawberries, particularly for newly released cultivars from breeding programmes which often struggle to fulfil their yield potential when cropped in a commercial environment. The research presented in this thesis therefore aimed to examine the impact of crop management during the propagation phase on transplant growth, yield potential and the subsequent cropping performance of new Junebearer and Everbearer strawberry cultivars. Five experiments were conducted between September 2013 and 2016 to examine the impact of tipping date, daughter plant position and nitrogen concentration, winter chill accumulation, temperature and light intensity during plant propagation. At the end of the propagation phase for each experiment, a destructive harvest was carried out to analyse treatment effects on transplant growth and yield potential. In the following season, remaining plants were then cropped under conditions designed to replicate a commercial growing system so treatment effects on yield, yield components and cropping profiles could be determined.

The results of the experiments confirmed that conditions during the propagation phase impact on the cropping performance of strawberry and showed that there is the potential improve strawberry yield by improving crop management during this important phase. Results also demonstrated that cropping profiles could be manipulated to enhance valuable early-season strawberry yield, which is an important goal in the soft fruit industry at present.

Abbreviations

The following is a list of abbreviations and symbols used most frequently in this report:

>	More Than
<	Less Than
%	Percent
°C	Degrees Celsius
ANOVA	Analysis of Variance
BN	Berry Number
BW	Berry Weight
cm	Centimetre
CO_2	Carbon Dioxide
CU	Chill Units
D	Days
DW	Dry Weight
EC	Electrical Conductivity
g	Grams
hr(s)	Hour(s)
Inf	Inflorescence
kg	Kilograms
L	Litre
LSD	Least Significant Difference
m	Metre
ml	Millilitre
mm	Millimetre
Mrk	Marketable
N	Nitrogen
P	Probability Value
pers. comm.	Personal Communication
ppm	Parts per Million
S.E.M	Standard Error of the Mean
Un-Mrk	Un-Marketable
UoR	University of Reading

Chapter 1

General Introduction and Literature Review

1.1 Popularity of Soft Fruits

Soft fruits are hugely popular and demand for a year-round supply of fresh, high quality berries continues to grow. The term soft fruit is not a taxonomic designation as it represents a group of species from a wide range of genera including *Rubus*, *Ribes* and *Fragaria*. Soft fruit is best described as a collective term for small edible berries including strawberries, raspberries, blueberries and blackberries (Gilbert 1970).

Consumers enjoy the unique flavours, vibrant colours and overall convenience of soft fruits, and popularity has risen in recent years due to increasing awareness of the health benefits associated with their consumption. Berries are often described as "super foods" not only because they are low in calories, but because they are high in fibre and essential vitamins and minerals (British Summer Fruits 2012). Berries are rich in micro-nutrients essential for human health and contain high levels of anti-oxidants, especially Vitamin C, and can help protect against cardiovascular disease, various cancers and chronic diseases as well as being important for the immune system and cognitive functions (Beattie et al. 2005; Agarwal 2013; Manganaris et al. 2014).

1.2 The Strawberry

The strawberry is one of the most popular soft fruits accounting for 5% of total fruit consumption and 75% of soft fruit consumption in the United Kingdom and worldwide, they have one of the highest growth rates in terms of fruit and vegetable consumption (Boriss et al. 2006).

Strawberries have an appealing glossy red skin, juicy texture and sweet taste; they are consumed both in fresh and processed forms and are a popular health food due to their low calorie content and high Vitamin C content, with only 22 calories and 62 mg of Vitamin C (equating to 77% of an individual's RDA) in an 80 g serving (British Summer Fruits 2012).

1.2.1 Taxonomy

Strawberry belongs to the Rosaceae family which includes other economically important crops such as apple, pears, peaches, plums, cherries and raspberries as well as ornamentals such as roses (Stewart & Folta 2010). The Rosaceae family has four sub-families: Amygdaloideae, Maloideae, Rosoideae and Spiraeoideae and the strawberry belongs to the Rosoideae, plants in this group are characterised as small shrubs or herbs with flowers having a superior ovary and fruit formed as achenes (strawberries) or druplets (raspberries). The family has more than ninety genera and strawberry belongs to the genus *Fragaria* of which there are twenty important species as well as many hybrids and cultivars (Husaini & Neri 2016).

1.2.2 History of Cultivation

Grown worldwide, the most common cultivated strawberry is the garden strawberry (*Fragaria x ananassa* Duch.) a hybrid of two wild American octoploid species, *Fragaria virginiana* found on the east coast of North America and *Fragaria chiloensis,* native to west coast of South America (Darrow 1966; Hancock 1999; Stewart & Folta 2010). The two species were brought to Europe separately, and by the 18th century the first hybrid plants were produced. The hybridisation occurred by chance when a single plant of the dioecious species *F. chiloensis* was gifted to the Director of the Royal Gardens in Paris and planted with *F. virginiana*. The resulting progeny produced fruit of an exceptional size, shape and colour sparking the beginning of the cultivation of *Fragaria x ananassa* (Darrow 1966; Husaini & Neri 2016).

Although the first hybrids were produced in France, English growers and botanists are credited with breeding the first successful cultivars, most notably Michael Keens who produced several cultivars including 'Keen's Seedling' in 1819 and Thomas Laxton who went on to produce even more superior cultivars including 'Royal Sovereign' in 1892 which remained popular for decades (Hyams 1953; Darrow 1966). Continued breeding was facilitated by the hybrid nature of the strawberry, and today new cultivars are continually released with improved fruit quality, disease resistance and plant characteristics adapted to suit a range of climates (Hughes 1980).

1.2.3 Morphology

Figure 1.1A shows the main structures of the strawberry plant including the crown, leaves, stolons, inflorescences and roots (Hancock 1999) .

Crown

The primary stem of the strawberry plant is termed the crown, it is highly compressed (2-3 cm) due to short internodes and covered by leaf stipules which can form up three fifths of its circumferences (Darrow 1966; Savini et al. 2005). The growth of the main axis terminates with the primary inflorescence, and vegetative extension of the plant continues from the bud formed in the axil of the next leaf, referred to as an extension crown axis or branch crown (Figure 1.2). This process continues as secondary, tertiary and further inflorescences are initiated, terminating each branch crown (Savini et al. 2005).

Leaves

Strawberry leaves are formed on long petioles, they are described as compound trifoliate with each leaf comprised of three leaflets. The leaves are hairy with serrated edges and arranged in a 2/5 spiral around the crown to maximise light capture (Darrow 1966).

Axillary Buds

Two to four buds originate from the meristems found in the leaf axils, the development of these is dependent primarily on the photoperiod but this can be modified by temperature. Stolons are produced in long-days, whilst short-days promote branch crown formation and even shorter days promote flower initiation (Le Miere 1997; Hytönen et al. 2004; Savini et al. 2005).

Branch Crowns

Branch crowns are typically formed in late summer through to early autumn, although they may not fully develop until the spring following a period of winter dormancy. Branch crowns are structurally identical to the main crown and can produce leaves, roots, stolons and inflorescences (Savini et al. 2005). Once mature, they can operate independently of the main crown and so can be used as a method of vegetative propagation (Le Miere 1997; Hytönen et al. 2004; Savini et al. 2005).

Roots

The size of the root system varies between cultivars but tends to be relatively shallow (approximately 40 cm). Roots are produced at the base of the crown and a mature strawberry plant typically has 20-35 primary roots and hundreds of secondary and tertiary roots which have a life span of only a few days or weeks and are constantly replaced (Darrow 1966; Hancock 1999).

Inflorescences

The strawberry flower cluster, or inflorescence, is a dichasial cyme (Le Miere 1997; Savini et al. 2005). The general structure of a strawberry inflorescence is shown in Figure 1.1B. Each inflorescence is typically composed of a single primary flower, two secondary flowers, and up to four tertiary flowers and eight quaternary flowers (Darrow 1966; Savini et al. 2005). Further flowers can follow, potentially doubling in number at each progressive stage. Due to this branching habit, the number of flowers is potentially unlimited, but development usually halts once the plant becomes dormant (Le Miere 1997) and breeding programmes have favoured simple inflorescences for increased berry size (Strik 2007). Each individual flower typically has 10 sepals, 5 petals, 20-35 stamen and 60-100 pistils on a conical shaped receptacle; petals are usually white, but can be pink or red (Hancock 1999; Strik 2007).

Fruit

Botanically, a strawberry is not a "true" berry since the fleshy part is not derived from the ovary. The fleshy part of the strawberry is the swollen receptacle that holds the ovaries; the strawberry is therefore classed as an aggregate, with the true fruits being the achenes embedded on the surface of the receptacle, with each achene containing a single seed (Hancock 1999; Heide et al. 2013). Once pollinated it takes 20-30 days for a flower to form a ripe berry, however this varies between cultivars and is dependent on weather conditions at the time of ripening and so can be as long as 50 days (Darrow 1966; Strik 2007). The primary flower opens first and produces the earliest and largest berry; the secondary, tertiary and any further flowers then open and produce fruit in succession with the size of the berry reducing at each stage (Darrow 1966; Hansen 1989; Strik 2007). Anderson & Guttridge (1982) showed that the number of flowers that reached anthesis was greater in the primary and secondary flowers (100%) compared to the tertiary (80%) and quaternary flowers (50%).

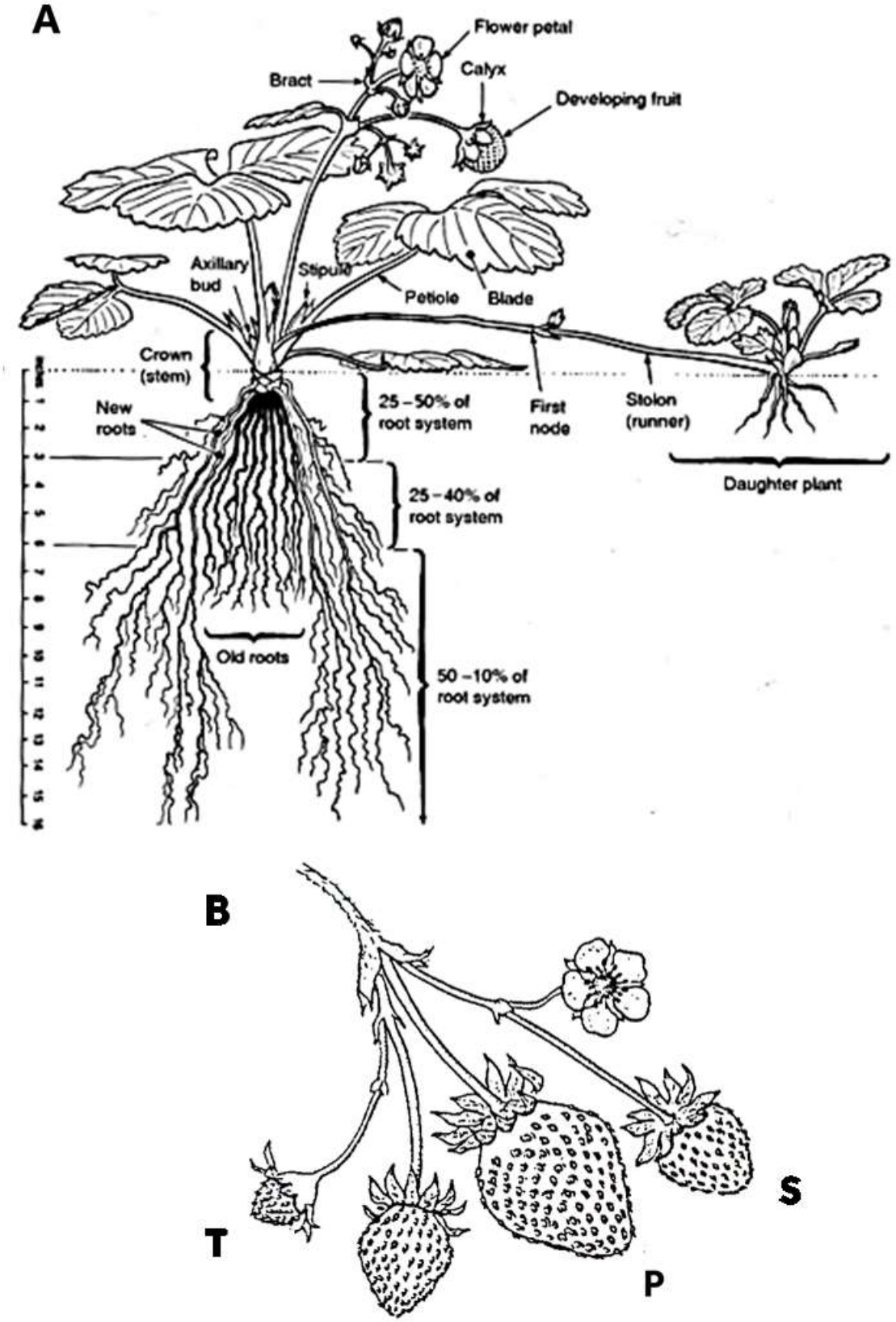

Figure 1.1 Morphological structure of the strawberry plant (A) and a typical inflorescence (B) showing the primary (P), secondary (S) and tertiary fruits (T) (reproduced from Hancock 1999).

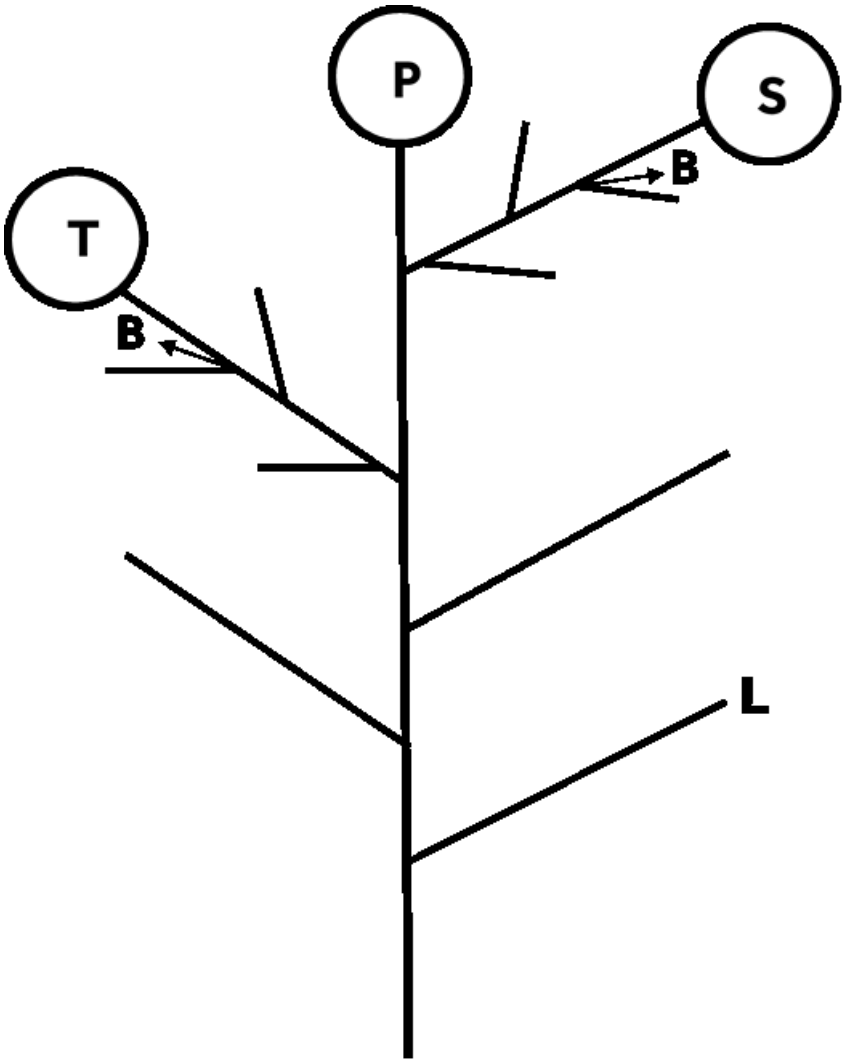

Figure 1.2 Simple diagrammatic representation of a strawberry crown with leaf initials (L) and initiation of the primary (P), secondary (S) and tertiary (T) inflorescences. After a growing axis is terminated by an inflorescence, growth of the crown continues from the bud in the axil of the next leaf which forms a branch crown (B) (re-drawn from Le Miere 1997).

1.2.4 Flowering and Fruiting

There are several stages in the process of flowering: induction, initiation, differentiation and finally macroscopic development (Durner & Poling 1985). Day-length is perceived by the leaves and if the photoperiod and temperature conditions are appropriate for floral induction, a floral stimulus is translocated from the leaves through the phloem to the apical meristem causing it to transform from a vegetative to a floral apex. This process is known as photoperiodic induction and once the meristem is induced it becomes "florally determined" which means that it cannot revert back to a vegetative state (Durner & Poling 1985; Taiz & Zeiger 2002). Early indication that a meristem has become florally determined can be seen under a microscope as the apex becomes broad and flat. Following on from induction, floral initiation describes the physiological and morphological changes occurring at the meristem once it has been induced to flower. Differentiation leads to the formation of individual flowers within an inflorescence and the floral organs including the sepals, petals, stamens and pistils (Darrow 1966; Jahn & Dana 1970a). The final stage is the development of inflorescences and flowers within the bud leading to eventual anthesis (Durner & Poling 1985). Fruit formation occurs once a flower has been fertilised and strawberries are capable of both self-pollination and cross-pollination. Once fertilised, achenes produce auxin which causes the receptacle to swell and form the berry; the number of achenes therefore influences berry size (Janick & Eggert 1968; Webb et al. 1974; Hansen 1989) and adequate pollination is important, otherwise small and misshapen berries are produced.

1.2.5 Strawberry Yield

Like many other commercial crops, the economic success of strawberry production depends primarily on the yield. Berries must be produced of a marketable standard; a marketable berry in the EU (Class 1) is described as one being over 22 mm in diameter at the shoulder, free from damage from pests and diseases and of a uniform shape and colour (UNECE 2010).

The total yield of a strawberry plant is a function of various components which directly or indirectly influence the yield; these include the number of crowns and inflorescences per plant, the number of flowers per inflorescence, the number of these flowers that set fruit and the individual berry weight (Lacey 1973; Hortynski 1989; Shokaeva 2008). These components are interrelated, excessive flowering for example can cause a reduction in berry weight (Sønsteby et al. 2013).

1.2.6 Classification of Plants

Strawberries can be classified into three groups based on the photoperiod and temperature requirements for floral initiation. Further details on the effect of temperature are given in Section 1.4.2 but in broad terms Junebearers are short-day plants, typically initiating flowers during the short-days of late summer and through the autumn until temperatures become too low and the plants become dormant. A single crop of fruit is usually harvested between late May and the end of June or middle of July due to the availability of early, mid and late-season cultivars (Hyams 1953; Stewart & Folta 2010; Heide et al. 2013).

Everbearers are long-day plants as flowering is intensified under longer photoperiods. Flower initiation occurs in both the autumn and the spring and so Everbearers fruit over a longer period, typically through to mid-October. Often there are two distinct cropping peaks, the first from autumn-initiated flowers which tends to coincide with a Junebearer crop, and a second often larger peak in August-September (Hyams 1953; Stewart & Folta 2010; Heide et al. 2013).

The third type are termed Day Neutral, these are insensitive to photoperiod and so flower and fruit continuously in small flushes throughout the summer (Stewart & Folta 2010). High temperatures promote vegetative growth and so there can be a reduction in yield after periods of high temperature (Domoto et al. 2008).

1.2.7 Plant Propagation

Since the cultivated strawberry is a hybrid, plants are not propagated from seed because they would not come true to type (Hyams 1953). To produce a new stock of genetically identical plants from one generation to the next, strawberries are propagated vegetatively using daughter plants which form on stolons (runners) and are genetically identical to the mother plant (Darrow 1966; Hancock 1999). Many different plants types have been developed and are supplied to fruit growers from specialist nurseries; growers typically use a combination of plant types in a programmed production system to extend the fruiting season. The types of plants available can broadly be split into two types: bare-root plants and plug plants. Bare-roots are currently the most common, but plug plants (plants rooted in substrate) are increasing in popularity particularly in Northern Europe as, although costlier to produce, they have a great uniformity and reduced disease risk compared to bare-roots (Durner et al. 2002; Husaini & Neri 2016).

Bare-Root Plants

Bare-root plants are traditional strawberry transplants that can be supplied as fresh plants directly after being dug in the nursery or after being cold stored. Plants are graded using crown size as the primary quality marker, but root length can also be used. High quality plants termed "A+" have a crown diameter of 12-15 mm, "A" plants have a crown diameter of 8-12 mm and "A-" plants 6-8 mm. Extra-large plants termed "A++" or "AA+" are also available (Husaini & Neri 2016). There are four main types of bare-root plants: fresh dug plants, green plants, frigo plants and waiting bed plants.

Fresh Dug and Green Plants

Fresh dug and green plants are lifted prior to dormancy induction and the soil is removed from the roots; the plants are supplied with leaves (green plants) or without leaves (fresh dug). The plants are dispatched and transplanted immediately. Flower induction occurs in the autumn and fruit is produced in the following May-June (Durner et al. 2002; Husaini & Neri 2016).

Frigo Plants

Cold stored (frigo) plants are lifted once they have become dormant, the soil is removed from the roots and the plants are defoliated. Plants are usually lifted in January-February and cold stored at -1.5 to -2°C for up to 6 months (Durner et al. 2002; Husaini & Neri 2016). Flower induction has already taken place in these plants, they are transplanted in late summer (July to August) and produce a short late crop in the same year (Husaini & Neri 2016).

Waiting Bed Plants

Waiting bed plants are large multi-crowned plants (18-22 mm crown diameter) with a high yield potential. They originate as bare-roots but are then planted in a raised bed known as a "waiting bed" to increase crown size. They are typically transplanted from April to mid-July with fruiting commencing 6-8 weeks later, meaning fruit can be harvested from late summer through to autumn (López et al. 2002; Husaini & Neri 2016).

1.2.7.1 *Plug Plants*

There are many advantages of using plug plants over bare-roots; the production cycle is shorter and since the plants are pre-rooted in substrate there is reduced risk of damage to the root system during transport and transplanting. Plant establishment is also quicker and survival rates higher. Plug plants require less irrigation and fewer pesticide applications after planting as there is a reduced disease risk, but the production costs are greater and at present these plants are limited in availability (Crawford et al. 2000; Durner et al. 2002; Bish et al. 2003; Takeda et al. 2004; Cocco et al. 2010; Husaini & Neri 2016).

Misted Tips

Misted tips are small, single crowned plants produced within 5 weeks in late summer. Flower induction begins once the tips are planted and fruit is produced in the following April to June. In areas with mild winters production can start early (planting January to March) if the plants are grown under protection. Instead of being established in a field, mother plants are grown hydroponically on raised gutters in either a polytunnel or glasshouse. The gutters are elevated higher than that for fruit production so the stolons hang down but do not reach the ground, preventing the daughters from rooting. When two or three root nodules are visible on the underside of the crown, and two to three leaves are beginning to emerge, the daughter plants are cut and quickly planted (using a section of stolon as an anchor) into multi-celled trays filled with substrate (usually a mix of peat or coir). The trays are then overhead misted typically for three to four weeks in a high humidity environment to promote rooting (Crawford et al. 2000; Durner et al. 2002; Bish et al. 2003; Takeda et al. 2004; Cocco et al. 2010; Husaini & Neri 2016).

Tray Plants

Tray plants can be produced from freshly harvested daughter plants, misted tips or small bare-root plants. The plants are typically single crowned with two or three inflorescences and produce up to six more once transplanted. They are grown in multi-celled trays (7-8 cm diameter) and can be cold stored at -1.5 to -2°C for up to 6 months. They are transplanted at various times of the year as they are periodically dispatched from cold stores, and typically the plants flower and fruit within 60 days (Husaini & Neri 2016). Mini-tray plants are also available, these are produced in smaller celled trays (5-6 cm diameter) and cost less to produce but are not as high yielding.

1.3 The Strawberry Industry

1.3.1 Worldwide

Soft fruits have been cultivated by humans for centuries; raspberry cultivation, for example, dates back to the Middle Ages and woodland relatives of the modern garden strawberry were grown by the Romans (Beattie et al. 2005). Today cultivation and trade of soft fruit occurs worldwide with strawberries, raspberries and currants being the most important commercial crops. There are a number of different ways in which the fruit is marketed and sold including pick-your-own, where consumers pick and buy the fruit on farm, or where the growers harvest the crop which is then sold as fresh produce via retail outlets or to manufacturing industries where the fruit is then processed (frozen, dried, pureed, juiced) to make secondary products including jams, juices and desserts (Strik 2007).

In 2014, total worldwide production of berries amounted to approximately 11.9 million tonnes, 68% of which was supplied by strawberries making them the most valuable soft fruit (FAOSTAT 2017). Approximately 7.7 million tonnes of strawberries were produced in 2013, and the top five producers were China (2.99 million tonnes), USA (1.36 million tonnes), Mexico (380 thousand tonnes) Turkey (373 thousand tonnes) and Spain (313 thousand tonnes) (FAOSTAT 2017).

1.3.2 United Kingdom

In 2015, the UK horticultural industry was valued at £3.1 billion, with a £695 million contribution from outdoor and glasshouse fruit (DEFRA 2016). The most important soft fruit crops are strawberries and raspberries, but blueberries are increasing in value year on year. Strawberries accounted for 62% of the value of the soft fruit industry in 2014 (£244 million) and were the 8th most valuable crop in the UK overall (Table 1.1).

Table 1.2 shows the crop area, yield, total production quantity and value of the British strawberry industry in five-year periods from 1985 to 2014; production increased 147% from 1985-89 to 2010-14, with an increase in yield per hectare of 213%. However, the UK only currently supplies 68% of its total demand for strawberries, with imported fruit primarily to satisfy out-of-season demand. In 2014, 49 thousand tonnes of strawberries were imported primarily from Spain, The Netherlands and Morocco whilst one thousand tonnes was exported to countries including The Netherlands, Ireland, and Spain (DEFRA 2016; FAOSTAT 2017).

Table 1.1 Top ten crops by production value, UK 2014 (FAOSTAT 2017).

Rank	Crop	Production Value (thousand $)
1	Potatoes	881,036,820
2	Wheat	788,594,440
3	Rapeseed	590,983,100
4	Barley	431,666,700
5	Sugar Beet	344,112,000
6	Carrots and Turnips	173,701,200
7	Mushrooms and Truffles	143,438,510
8	Strawberries	128,090,490
9	Apples	91,873,840
10	Onions	77,313,150

Table 1.2 Total crop area, yield, production quantity and value of home-grown UK strawberries in five-year periods from 1985 to 2014. Provisional data for 2015 is also included (DEFRA 2016).

Period	Crop Area (thousand ha)	Yield (tonnes / ha)	Total Quantity (thousand tonnes)	Total Value (£ million)
1985-1989	5.7	8.2	46.8	60.8
1990-1994	5.1	8.8	44.5	69.9
1995-1999	4.3	8.9	38.3	75.0
2000-2004	3.3	12.9	43.0	93.6
2005-2009	4.0	20.6	82.3	167.1
2010-2014	4.6	21.6	98.1	233.2
2015 (prov.)	4.5	25.5	115.5	284.1

1.3.3 Challenges and Changes in the UK Strawberry Industry

Strawberries are the primary soft fruit crop in the UK and production levels have increased rapidly, particularly in the last fifteen years (Figure 1.3). Despite a decline in the crop area dedicated to strawberries between 1985 and 2004, production levels remained stable and from 2001 there has been a continuous and rapid upward trend in production with levels from 2004 surpassing that ever previously recorded (Figure 1.3).

Strawberry production occurs primarily in the South East of England but in recent years other areas, particularly the West Midlands, have increased their contribution to the industry which is in part due to the move to out of soil production and the introduction of polytunnels allowing growers to create a suitable microclimate in which to produce fruit (Calleja 2011).

Figure 1.3 UK home production of strawberries (solid black) and crop area (broken grey) from 1985 to 2014. Provisional data for 2015 is also included (DEFRA 2016).

From an initial period of six to eight weeks in the summer months of June and July, the main British strawberry season has been extended to six months from May to October. Season extension has partly been achieved through the introduction of polythene greenhouses (polytunnels) in the mid-1990s as well as the increased use of improved Everbearer varieties (Armstrong 2004; Tunnel Facts 2004). In addition, the relatively recent introduction of winter glasshouse planting of specialist low-chill cultivars, where supplementary light and heat is used to force early cropping, has led to fruit availability from as early as mid-March in the UK.

Polytunnels were introduced to British farming in the 1990s, adapted from tunnels used in Spain to protect winter salad crops (British Summer Fruits 2012). Before the introduction of polytunnels, strawberry production was risky as the yield could be severely reduced by unpredictable weather damaging developing fruit or by increasing the spread of diseases such as grey mould and powdery mildew. Imported fruit from Europe therefore dominated the fresh market and much of the home produced fruit went into processing for jams and other fruit based products (Tunnel Facts 2004; British Summer Fruits 2012).

Prior to the introduction of polytunnels, 50-70% of the yield of field grown strawberries was Class 1, but the use of polytunnels have increased this to over 90% (Tunnel Facts 2004; British Summer Fruits 2012). Polytunnels not only reduce fruit loss due to disease, but accelerate ripening and improve fruit quality (Kadir et al. 2006). Under polytunnels there is a more uniform distribution of light and the natural greenhouse effect of the structure increases temperatures, enhancing the rate of photosynthesis and plant productivity (Kadir et al. 2006).

Polytunnels give the grower more control over the microclimate surrounding the plants (Lamont 2005). Temperatures are not only enhanced but fluctuations are reduced in tunnels compared to field conditions (Kadir et al. 2006). Plants under tunnels are also protected from frost damage which is particularly important for survival of the crown and the first flowers emerging in early spring. Fruit is also protected from rain, not only preventing water damage to the berries and the spread of disease, but also allowing picking to continue in adverse weather conditions (Armstrong 2004). Another advantage is earliness, as plants under polytunnels accumulate growing degree hours more quickly than un-covered plants, allowing dormancy to break earlier and promoting early growth and flowering. Fruit ripens up to four weeks earlier in polytunnels compared to the open field, giving growers who use them a competitive edge when it comes to early fruit production which is highly valuable (Kadir et al. 2006).

The greater adoption of Everbearer cultivars by commercial growers has also facilitated the extension of the British growing season; the use of Everbearer cultivars was previously limited as fruit was of poor quality and inferior to fruit imported from Europe. However, the release of new cultivars with improved quality has led to greater uptake in recent years. Whilst polytunnels have increased earliness, Everbearers have allowed for the extension primarily from August to October. This is because Everbearers initiate flowers over two periods with the second crop produced later than that of a typical Junebearer.

Not only has season extension and yield of strawberries increased rapidly over the last decade, but demand for home grown produce has also increased by 130% in the last four years (British Summer Fruits 2012). In 2014, imported fruit contributed 32% to the of total supply of strawberries in the UK which was mainly to satisfy the demand for out-of-season fresh fruit (DEFRA 2016). The main challenge for the UK strawberry industry is to further extend the growing season and increase production on the fringes of the main season to satisfy this demand and reduce reliance on imports. Production outside of the main season (June-July) needs to be profitable and the fruit of sufficient quality to compete with imported fruit. Interest currently lies in increasing strawberry production during what are known at the "shoulder periods" of April-May and October-November; these are the periods around the main strawberry season before the un-economic period between December and March where the high cost of heating and lighting has made large-scale growing un-profitable (Wilson 1997). Production during these shoulder periods is attractive for growers as supermarkets offer a price premium for home grown strawberries at this time (Wilson 1997).

1.4 Literature Review

1.4.1 The Importance of the Propagation Phase

Whilst there are many ways in which the agronomy and environment during fruiting can influence strawberry yield, the quality of the starting plant material also has an impact on cropping. This is particularly important in commercial plantings where strawberries, although perennial, are being increasingly cropped for a single season, with a new stock of transplants purchased from specialist nurseries each year (Kirschbaum et al. 2010a; Andriolo et al. 2014). High quality plant material is therefore essential for the success of commercial strawberry production and this has been highlighted by many researchers in the past (Fernadez et al. 2001; Johnson et al. 2005; Bartczak et al. 2010; Cocco et al. 2010; Kirschbaum et al. 2010a; Andriolo et al. 2014).

Many factors affect the quality of strawberry transplants, from the position of the daughter plant on the stolon and its initial size and date of rooting. The influence of the subsequent growing conditions including the photoperiod, temperature, nutritional status and level of winter chill accumulated also cannot be overestimated as they play a key role in determining the final quality of strawberry transplants. Responses to such conditions are cultivar dependent and so there can be no universal guidelines for the production of high quality strawberry transplants. To maximise yield potential, cultivar-specific conditions during plant propagation are therefore required. However, the exact requirements for optimal production of many new and existing cultivars are unknown and many plants are propagated in conditions optimised for the most widely grown cultivar 'Elsanta.'

1.4.2 Factors Affecting Yield Potential

1.4.2.1 *Initial Plant Selection and Condition*

Daughter Plant Position

Strawberry plants can produce multiple stolons (runners) and each runner can bear more than one daughter plant. Although genetically identical, daughter plants formed in later positions along the runner are physiologically younger, and often comparably smaller than those produced in earlier positions. There has been some research on the effect of daughter position on yield potential but with mixed results; Takeda et al. (2004) compared the fruiting response of daughter plants of the cultivar 'Chandler' originating from three positions on the runner (2nd, 4th and 6th) and

found no effect on early or total season yield. Larson (1994) also found no difference in yield between daughter positions in 'Chandler' whilst in 'Selva' fruit yield was greater in primary daughter plants. Similarly, Hamann & Poling (1997) found secondary daughters of 'Selva' flowered on average 14 days earlier that tertiary daughters, and also had a greater early and total fruit yield which was attributed to the meristem of the secondary daughters transitioning into a reproductive state earlier than the tertiary daughters.

Tipping and Rooting Date

Tipping date refers to the date in which daughter plants (referred to as tips) are harvested from the mother plant and rooting date refers to the date at which these have been successfully rooted in the cells (usually three to four weeks later). Late tipping and rooting could have a negative effect on yield performance as the plants have less time to establish and in flower inducing conditions before the onset of dormancy (Jahn & Dana 1970b). Webb et al. (1973) compared the effect of four rooting periods (April-May; June-July; August-September and October-November) on fruit production in three Junebearer cultivars and found the structure of inflorescences was less branched in the later rooted plants, average berry weight was greater as there was a higher proportion of larger, higher order berries but the total yield was still higher in the earlier rooted plants as a greater number of berries were produced.

Takeda & Newell (2006) found that later tipping led to reduced branch crown formation in strawberry as well as delayed flowering and reduced spring yield. In agreement, when Yoshida & Motomura (2011) compared the flowering response of daughter plants tipped on 24th June, 8th July, 22nd July and 5th August they found daughters harvested on the 24th June had earlier and more uniform flowering compared to those from the later tipping dates. Similarly, as part of a study with the cultivar 'Aráza' Cocco et al. (2010) compared four tipping dates (11th February, 26th February, 13th March and 28th March 2009) and found the earlier tipped daughters had a greater number of leaves and root and shoot mass at planting time, flowered and fruited earlier, and had a greater number of berries per plant at the end of fruiting. Jahn & Dana (1970b) found leaf emergence to be more rapid in the earlier rooted daughters and leaf area also remained consistently greater in earlier rooted daughters. However, results of the experiment differed to those found by Takeda & Newell (2006) and Yoshida & Motomura (2011) since there was no effect of rooting date on flowering time found.

Initial Crown Diameter

Initial crown diameter is linked to the physiological age of the daughter plant as earlier formed daughters have a greater crown diameter. Cocco et al. (2010) graded daughter plants by crown size into Class 1 (2.0-3.9 mm) Class 2 (4.0-5.5 mm) and Class 3 (5.6-7.0 mm); at planting time, crown diameter, shoot and root dry mass was greater in Class 3 daughters which also flowered earlier and had a greater early yield than the Class 1 or Class 2 daughters. However, there was no significant difference in total yield, berry number, or average berry weight between classes at the end of fruit production. Since Class 3 daughters were more vigorous they had a greater capacity to produce and store assimilates in the previous autumn, positively influencing early season yield, but as the season progressed and vegetative growth continued this effect was diluted meaning there was no effect of on the total season yield. A further study by Cocco et al. (2011) showed that the physical restraints of the rooting cell play a role in determining crown size. Daughters divided into the same classes as described above were rooted for 48 days on a rooting bed rather than in individual cells. By the end of rooting, differences in crown diameter had disappeared and all plants achieved crown diameter of 8.6 mm. Consequently, there were no differences in early or total fruit yield found. The authors explained that root growth was not restricted by the size of the cell allowing all plants to reach the same crown size, eliminating the differences in yield observed in previous studies.

Initial Daughter Weight

The initial weight of a daughter plant is attributed to the time in which it was formed. Takeda et al. (2004) found crown number and total yield was greater in heavier daughter plants. Results of a study by Takeda & Newell (2006) were in agreement; the fruiting response of daughter plants of 'Carmine' sorted into two plant sizes: average (3.0-6.0 g) and small (0.6-1.2 g) were compared. The results showed that formation of branch crowns was greater in the heavier daughters, particularly when coupled with an earlier harvest from the mother plant; subsequent spring yield was also greater in the heavier daughter plants which was attributed to the greater number of crowns produced.

1.4.2.2 *Final Transplant Condition*

Yield potential of strawberry is closely related to the condition of the transplant at planting time, particularly the number and size of various plant parts including crown number, crown diameter, leaf number, leaf area and plant weight.

Crown Size

Increased crown number and diameter at planting are positively associated with yield performance of strawberry as larger crowns offer more sites for floral initiation and so improve yield by increasing the number of flowers and fruit per plant. Perez de Camacaro et al. (2004) graded transplants of 'Elsanta' and 'Bolero' based on crown diameter and found a significant increase in the number of flower initials in the crown of the large grade plants. Le Miere et al. (1998) found total yield and berry number was positively correlated with crown diameter at planting, and one of the conclusions drawn from the 6th International Strawberry Symposium (2008) was that crown diameter is a good indicator of 60 day fruiting performance (Johnson et al. 2008).

Human (1999) compared the yield of three cultivars graded by crown diameter as small (<5 mm), standard (5-10 mm) or large (>10 mm) and a significantly higher yield was obtained in large grade plants compared to standard and small grade plants for the cultivar 'Tioga'; for 'Tiobelle' both large and standard plants yielded higher than the small plants whereas in 'Selekta' no significant difference in yield between plant grades were found.

Johnson et al. (2005) evaluated the effect of crown size on early and total marketable yield of 'Chandler' and 'Camarosa.' As crown size increased there was a linear increase in fruit number and yield per plant. Similarly, Bussell et al. (2003) compared the yield of two cultivars 'Pajaro' and 'Camarosa' after transplants were graded into three groups based on crown diameter: 4-8 mm, 8-12 mm, 12-16 mm and 16-20 mm. In both cultivars, a positive linear relationship between crown size and yield was found, and for every 1 mm increase in crown size there was a 27 g increase in total yield and a 15 g increase in marketable yield per plant.

In terms of early yield, Johnson et al. (2005) also found a positive relationship between initial crown diameter and early berry number, size and yield in 'Chandler' whilst in 'Camarosa' there was only a relationship with average berry weight found. It was suggested that since the cultivar 'Chandler' tends to produce an earlier crop than 'Camarosa' the early yield was more affected by initial crown size.

Canopy Size

The number of leaves and leaf area of strawberry transplants has been positively correlated with yield performance (Lacey 1973). Leaf number is important as buds in the leaf axils have the potential to become floral under the right environmental conditions, and so in general the more leaves per plant during the autumn, the more flower trusses and fruit produced in the following season (Darrow 1966). Leaf area is also important as a healthy canopy during the autumn is important for energy provision both during flower initiation, and in the following spring to support flower and fruit development as much of the resources utilised in early spring growth are from reserves accumulated and stored over the previous season.

Plant Weight

Lacey (1973) found that plant weight was positively correlated with fruit number and even more so with fruit size. Hughes (1967) graded plants 'Cambridge Favourite' and 'Cambridge Rival' as small (5.06 and 6.17 g / plant respectively) and large (17.7 g and 19.5 g / plant respectively) and found the larger transplants had a greater number of inflorescences per plant and total yield. In agreement, Bartczak et al. (2010) found a positive correlation between the initial fresh and dry weight of transplants and early and total marketable yield of cultivars 'Honeoye' and 'Elsanta.'

1.4.2.3 *Transplant Raising Conditions*

Photoperiod and Temperature

The first stage of strawberry fruit development is the initiation of flowers; for Junebearers this occurs entirely in the autumn proceeding the fruiting season and in Everbearers the first flush of fruit also originates from autumn initiated flowers. During the period of flower initiation, photoperiod and temperature are regarded as the most important environmental condition as temperature plays a modifying role on the required photoperiod for flower initiation in both plant types (Ito & Saito 1962).

In general, Junebearers are termed quantitative short-day plants, requiring a photoperiod of <15-hrs for floral initiation at an intermediate temperature range with flowering intensified at shorter day-lengths. In early studies Darrow (1936) showed that Junebearers form flower buds when the photoperiod is < 14-hrs and identified an optimum range of 9.5 to 12.5-hrs. Subsequent research has shown flower initiation occurs at a relatively wide range of photoperiods (8 to 15-hrs) at an intermediate temperature range of 15-24°C (Ito & Saito 1962; Verheul et al. 2006),

whilst at low temperature (<9°C) flower initiation occurs independent of photoperiod and at high temperature (>26°C) flower initiation is inhibited even under short-day conditions (Ito & Saito 1962; Manakasem & Goodwin 2001; Sønsteby & Heide 2006; Verheul et al. 2006). Sønsteby & Heide (2006) showed that some cultivars such as 'Korona' and 'Elsanta' are obligatory short-day plants as they require short days even at low temperatures.

Everbearers were identified shortly after the introduction of Junebearers and the development of "everbearer trait" is thought to have arisen due to a spontaneous mutation of a single gene occurring independently in both North America and Europe (Stewart & Folta 2010). Everbearers can be termed obligatory long-day plants at high temperatures (>25°C) and quantitative long-day plants at intermediate temperatures (15-21°C) (Nishiyama et al. 2003; 2006). As with Junebearers, flowers initiation occurs irrespective of day-length at low temperatures (Sønsteby & Heide 2007) whilst inhibition occurs when temperatures exceed 25°C (Smeets 1980; Wagstaffe & Battey 2006; Karapatzak et al. 2012).

The classification of strawberry plants into a third category "Day Neutral" is debated and the terms Day Neutral and Everbearer are used interchangeably in the literature resulting in confusion. Stewart & Folta (2010) distinguished the two stating that Day Neutrals, unlike Everbearers, are truly insensitive to day-length and fruit at the same rate over a broad range of photoperiods. However, Bradford et al. (2010) found the Day Neutral cultivar 'Tribute' initiated flowers irrespective of day-length at 26°C but at 29°C flower initiation only occurred under long-days, showing that this cultivar is an obligate long-day plant at high temperature. The effect of high temperature has been found to be cultivar dependent with plants divided into "weak" Day Neutrals and "strong" Day Neutrals where flower initiation remains insensitive to photoperiod even at high temperatures (Manakasem & Goodwin 2001).

Although flower initiation has been shown to occur at a range of photoperiods, the optimal combination of conditions for complete flower initiation are cultivar specific each having their own temperature response curve. Sønsteby & Nes (1998) found for 'Korona' the number of plants which had initiated flowers decreased at temperatures outside of the range of 15-18°C whilst 'Elsanta' was less sensitive with a range of 15-27°C. Sønsteby & Heide (2008) subsequently identified the optimum temperatures for floral initiation for 'Korona' (18°C) as well as 'Frida' (18°C) and 'Florence' (15°C) and suggested that lower than optimal temperatures during the flower

initiation period in commercial plantings prevented the yield potential of these cultivars from being realised.

A minimum number of short-day cycles are required for flower initiation, and the exact number of cycles is likely to vary between cultivars. Zhang et al. (2000) reported only 7 short-day cycles were required for floral induction whilst Verheul et al. (2006) found that 14 days of short-day treatment did not induce flowering in the cultivar 'Korona' whereas flowering was induced with 21 days and 28 days treatment. Konsin (2001) also studying 'Korona' found greater flower numbers in plants treated with 49 short days compared to 21 or 35 short days which was due to the branch crowns having time to initiate flowers. Both Verheul et al. (2006) and Konsin (2001) also found whilst increasing the number of cycles increased the total number of inflorescences and flowers per plant, the number of flowers per truss was reduced. Durner & Poling (1987) also found that short days increased flower induction in strawberry but delayed differentiation.

Photoperiod and temperature not only impact upon yield through their effect on flower initiation but also on vegetative growth. Day-length controls the differentiation of axillary buds, with short days promoting crown branching and long days promoting runner production (Hytönen et al. 2004; Kurokura et al. 2005). Low temperatures, particularly when coupled with short days, reduce vegetative plant growth which could have a negative impact on fruit yield (Konsin et al. 2001; Sønsteby & Heide 2006). Overall, the photoperiod and temperature conditions in which the plants are propagated are very important in determining subsequent fruit production due to the impact on both vegetative and reproductive plant growth, it is therefore important to establish the response curve for each cultivar in order to maximise flower number.

Nitrogen Concentration

Nitrogen (N) is one of three main macronutrients required by plants, and is the element absorbed in the greatest quantities accounting for 1.5-5% of total dry matter (Novoa & Loomis 1981; Torres-Olivar et al. 2014). Nitrogen is taken up through plant roots in the form of either nitrate (N03-) or ammonium (NH4+) (Marschner 1995; Torres-Olivar et al. 2014). For strawberries grown in soilless substrate, nutrients essential for plant growth must be supplied; nutrients are usually supplied via drip irrigation after dissolving them in the irrigation water, a process called fertigation.

Nitrogen is important for plant growth and development, but levels need to be carefully balanced at different stages of the plant life cycle. In general, lack of N supply leads to weak stems and limited leaf growth (Abbott 1968; Marschner 1995; Torres-Olivar et al. 2014) and plants with a severe nitrogen deficiency have small pale yellow-green coloured leaves due to reduction in chlorophyll leading to negative effects on photosynthesis and further biomass formation. Increased N supply stimulates plant growth with increases in leaf area and delayed leaf senescence. However, excessive N can also cause reduced leaf thickness causing leaves to droop which affects light interception and photosynthetic performance. Excessive N supply during early growth can also lead to an increase in the shoot:root ratio resulting in rapid shoot elongation to the point where the plant is unable to support itself (Marschner 1995; Torres-Olivar et al. 2014). Excessive leaf growth can also increase the humidity around the plant, increasing the susceptibility of diseases such as grey mould and powdery mildew. There is therefore an optimum curve of N supply as both limited and excessive supply can lead to growth inhibition (Ingestad 1977).

The level of N supplied during the propagation phase can impact on the growth and development of the strawberry transplants influencing subsequent cropping performance. Low levels of N during propagation can have a negative impact on subsequent fruit yield; Abbott (1968) showed that although the initiation of flowers itself remained unaffected in N deficient plants, there was a reduction in the potential flowering sites due to reduced branch crown formation. Consequently, branch crown formation was identified a prerequisite for achieving a high yield potential in strawberry. Similarly, Deng & Woodward (1998) found low levels of N in the autumn reduced subsequent fruit production in 'Elsanta' by 43% primarily due to a reduction in the number of flowers and berries per plant, but also a reduction in individual berry weight.

Increased N during plant propagation has been shown to improve yield performance by increasing transplant size, particularly stimulating branch crown formation. Motamedi et al. (2013) found increasing N from 200 mg / L to 240 mg / L led to an increase in crown diameter, flower number, fruit number and total yield in strawberry. Miner et al. (1997) also found total fruit yield of 'Chandler' increased as a result of increased flower production despite crown number not being affected. Rogers et al. (1985) concluded that N applied in the nursery was more important than later field applied N; N was applied at three rates in a nursery (80, 320 and 640 kg / ha) followed by three rates of N in the field (150, 300 and 450 kg / ha) and results showed that plant

biomass, N content and yield was greatest in plants where N was applied at 320 kg / ha in the nursery at all three levels supplied in the field.

Studies have shown a positive effect of increased N during plant propagation on yield performance of strawberry, but others have shown that that excessive application can have a negative effect. Guttridge (1960) explained that due to an antagonism between vegetative development and flower initiation, yield reduced when plants were grown on highly fertile soils. In agreement, Papadopoulos (1987) highlighted the need to carefully balance N application as too high N supply during the autumn can lead to reduced fruit set, berry number and average berry weight in the following season whilst too low N supply can negatively impacted yield performance due to limited plant growth. Choi et al. (2010) grew plants of the cultivar 'Seolhyang' in five concentrations of N (0, 35, 70, 140 and 210 ppm N). At 0 ppm and 35 ppm new leaves were small and pale-yellow indicative of N deficiency; plant weight did not differ between the 35 ppm, 70 ppm and 140 ppm treatments, but was significantly greater compared to the 0 ppm or 210 ppm treatments showing that both low and high N levels above an optimum had a negative effect on plant growth. Similarly, Himelrick & Dozier (1994) grew 'Chandler' at six concentrations of N (35, 70, 140, 280 and 350 ppm) but results differed to those of Choi et al. (2010) since fewer crowns per plant were recorded in the 35 ppm treatment and more in the 210 ppm treatment although supra-optimal yield responses to increased N inputs were shown as plants in the 70 ppm treatment had the greatest berry weight and yield whilst plants in the 350 ppm treatment the lowest.

The timing of fertiliser application during the autumn has also been identified as an important factor. Increased N during the first part of the autumn can benefit fruit yield by promoting branch crown formation and providing additional flowering sites (Abbott 1968) whereas there can be negative effects of high N levels toward the end of the autumn. Lieten (2002) found a positive effect of early N application on flowering and fruiting of 'Elsanta' when fertilisation was carried out in early-September at the start of floral initiation compared to when applied in mid-September and Sønsteby et al. (2009) were in agreement, finding a positive effect of additional nitrogen applied during the early stages of floral initiation compared to a negative effect at the end. Subsequently, Sønsteby et al. (2013) concluded that additional fertilisation, particularly with nitrogen, at the start of the flower initiation period increases flowering and yield.

Winter Chill Accumulation

The short-day and low temperature conditions of winter are un-favourable for plant growth; dormancy is a survival mechanism evolved in temperate and cold climates to allow perennial plants to survive the winter when there is a risk of low temperature damage (Luedeling et al. 2011; Atkinson et al. 2013). Satisfaction of the chilling requirement is important for many fruit crops as lack of chilling can have negative effects on bud development, flowering (time and synchronicity), flower quality, fruit set and yield (Sunley et al. 2006; Atkinson et al. 2013).

Strawberry plants start to become dormant during the first part of the autumn when the days are shortening and temperatures falling, with deepest dormancy attained by mid-November (Sønsteby & Heide 2006). Vegetative growth is restricted, and dormant plants have a low compact growth habit due to short petioles and small leaves (Kronenberg et al. 1976; Sønsteby & Heide 2006). For vigorous growth and normal inflorescence development when favourable conditions return in the spring, the chilling requirement must be satisfied in order to break dormancy (Lieten & Waite 2006; Sønsteby & Heide 2006). Post chilling, vegetative growth of strawberry plants is rapid and vigorous with long petiole growth and production of large leaves (Kronenberg et al. 1976; Pipattanawong et al. 1995; Lieten & Waite 2006; Sønsteby & Heide 2006). Starch reserves are important for spring growth and Lopez et al. (2002) found a positive correlation between the level of starch accumulated in the plant and the number of hours below 7°C leading to greater vegetative growth in chilled plants compared to un-chilled plants. Due to this increased vegetative vigour, chilling has been found to delay flower production leading to a concentration of the fruiting period and suppression of early yield (Smeets 1982; Albregts & Chandler 1994; Luedeling et al. 2011). It is important to establish the optimum range of chilling for each cultivar as outside of this range there can be a negative impact on yield. Higher than optimum levels of chilling can lead to rapid vegetative growth at the expense of reproductive activity leading to reduced yield and increased disease risk (Albregts & Chandler 1994; Tehranifar 1997; Lieten 2009). Lieten (2009) found excessive chilling in the cultivar 'Figaro' increased vegetative growth, decreased and delayed fruit production and increased runner formation. Reduction in resources such as starch and soluble sugars stored in the crown can also occur with prolonged chilling leading to a reduction in yield (Lieten et al. 1995). On the other hand insufficient chilling can lead to inadequate vegetative growth, poor anther and pollen quality, reduced fruit weight and increased malformation of fruit (Kronenberg et al. 1976; Lieten & Waite 2006).

1.5 Research Objective

The cultivated strawberry (*Fragaria x ananassa* Duch.) is a perennial plant, but in commercial production systems it is being increasingly cropped as an annual with growers purchasing a new stock of transplants from specialist propagators each year. Production of high quality transplants is therefore essential for maximising the yield of strawberry. From this literature review, it is clear that conditions during the propagation phase affect the growth, development and yield potential of strawberry transplants and so it is important to understand how crop management during the propagation phase impacts upon the quality and subsequent cropping performance of strawberry transplants.

There has been little to no research conducted on the appropriate conditions in which to propagate the relatively new cultivars cropped in the UK today which are typically produced in conditions best suited to the most widely grown cultivar 'Elsanta.' The aim of the research is therefore to examine the impact of crop management during plant propagation on transplant growth, yield potential and subsequent cropping performance of a range of new Junebearer and Everbearer strawberry cultivars currently cropped in the UK.

Chapter 2

General Materials and Methods

2.1 Plant Material

A total of eight cultivars were supplied for the five experiments conducted between September 2013 and October 2016 at the University of Reading (Table 2.1). The specific cultivars and plant types used for each experiment are outlined in Table 2.2. All plant material was supplied by commercial propagators except those for the experiment described in Chapter 3 where daughter plants were harvested from mother plants previously established at the University of Reading.

Table 2.1 Summary of the eight strawberry cultivars used in the five experiments conducted between September 2013 and October 2016 at the University of Reading. The table shows the plant type, breeder, registered name as well as the short name and code used throughout this thesis.

Type	Breeder	Registered Name	Short Name	Code
Junebearer	Driscoll's	Driscoll's® Lusa™	Lusa	L
Junebearer	Driscoll's	Driscoll's® Diamond™	Diamond	D
Junebearer	Driscoll's	Driscoll's® Elizabeth™	Elizabeth	E
Junebearer	Driscoll's	Driscoll's® Rosalie™	Rosalie	R
Junebearer	East Malling Research	Malling™ Centenary	Malling Centenary	MC
Everbearer	Driscoll's	Driscoll Jubilee	Jubilee	J
Everbearer	Driscoll's	Driscoll's® Scarlet™	Scarlet	SC
Everbearer	Driscoll's	Driscoll's® Serena™	Serena	SE

Table 2.2 Summary of the five experiments conducted between September 2013 and October 2016 at the University of Reading. The table shows the cultivars, plant types, experimental period, and the propagation and production locations for each experiment. UoR= University of Reading.

Chapter	Experimental Period	Research Topic	Plant Type	Cultivars	Propagation Location	Production Location
3	July 2014 to October 2015	Tipping Date	Fresh Tips	Jubilee, Scarlet, Serena	UoR, Glasshouse Compartments 21-22	UoR, Sonning Farm (All)
4	August 2015 to August 2016	Daughter Plant Position	Fresh Tips	Jubilee, Scarlet, Serena	UoR, Glasshouse Compartments 21-23	UoR, Sonning Farm (All)
5	September 2013 to October 2014	Nitrogen and Winter Chill Accumulation	Misted Tips	Lusa, Diamond, Jubilee, Scarlet, Serena	UoR, Glasshouse Compartments 20-25	UoR, Glasshouse 18 (Lusa) UoR, Shinfield Farm (Remaining)
6	August 2014 to October 2015	Supplementary Lighting and Temperature	Fresh Tips	Diamond, Elizabeth, Rosalie, Jubilee Scarlet, Serena	UoR, Glasshouse Compartments 23-25	UoR, Sonning Farm (All)
7	August 2015 to August 2016	Supplementary Lighting	Misted Tips	Lusa, Malling Centenary, Elizabeth, Rosalie	UoR, Glasshouse Compartments 20-25	UoR, Glasshouse 18 (Lusa) UoR, Sonning Farm (Remaining)

2.2 Propagation Phase

2.2.1 Misted Tip Production

In the experiments where fresh tips (daughter plants) were supplied (see Table 2.2), misting was carried out in a purpose built misting house situated at the Soft Fruit Technology Group's Field Site at the University of Reading's Sonning Farm (Figure 2.1). Fresh tips were supplied with a section of the stolon intact; tips were struck into 56-cell trays (Desch Plantpak BV, Waalwijk, The Netherlands) with an individual cell volume of 104 ml using the section of stolon as an anchor (Figure 2.2). Trays were filled with a 50:50 mix of peat (Fine Grade Irish Peat Moss, Clover Peat, Dungannon, Northern Ireland) and coir (Coir Growing Medium, William Sinclair Horticulture Ltd, Lincoln, UK). For root establishment, the tips were overhead misted with mains water for four weeks. A wet leaf sensor (MWL, Access Irrigation Ltd, Northampton, UK) was used to schedule misting; when the surface of the sensor dried out misting was automatically triggered. A control box (LT1, Access Irrigation Ltd, Northampton, UK) was used to set the sensitivity of the electronic leaf, the duration of the misting event and the delay in minutes before another misting event could be triggered. For all misted tip production, misting was carried out at a rate of 25 L / hr (Ultra-fine mist nozzles, Access irrigation, Ltd, Northampton, UK), wet leaf sensitivity was set to medium, the delay to off, and the duration of misting to 15 seconds.

Plants were also given a daily foliar feed which consisted of 5 ml / L starter nutrient solution (Table 2.3), 5 ml / L Maxicrop (Maxicrop UK Ltd, Corby, UK) and 5 ml / L Hortiphyte (Hortifeeds, Lincoln, UK). The foliar feed was applied in the morning using a knapsack sprayer and the misters were switched off for one hour to prevent the foliar feed from being washed off the leaves. Once misting was complete, uniform plants were selected and re-potted into 0.37 L terracotta coloured plastic pots (9 cm diameter x 8.7 cm deep) filled with coir (Coir Growing Medium, William Sinclair Horticulture Ltd, Lincoln, UK).

In the experiments where misted tips and tray plants were supplied directly from commercial propagators uniform plants were selected upon arrival and potted as previously described.

Figure 2.1 The misting house situated at the Soft Fruit Technology Group's Field Site at the University of Reading's Sonning Farm. Photographs show prepared trays of fresh tips (daughter plants) with the overhead misters off (left) and on (right).

Figure 2.2 An example tray prepared for misted tip production. Fresh tips (daughter plants) were struck into 56-cell trays with an individual cell volume of 104 ml using a section of stolon as an anchor. Trays were filled with a 50:50 mix of peat and coir.

2.2.2 Glasshouse Facilities

Plant propagation was conducted in a multi-compartmented glasshouse situated at the Crops and Environment Laboratory, School of Agriculture, Policy and Development, University of Reading. The middle six in a linear array of eight individually temperature-controlled glasshouse compartments (3.7 m x 7.0 m) were used during the propagation phase for the experiments (Figure 2.3). Lighting in each compartment was provided (where required) by high pressure sodium lamps (400 W, Philips SON/T). The average photon flux density at plant height was 220 μmols m^{-2} s^{-1} photosynthetic active radiation (PAR) measured at mid-day using a light meter (Skye Instruments, Llandrindod Wells, Powys). Black plastic was placed on the wall of adjacent compartments to prevent light spill between treatments in the experiments described in Chapter 6 and 7.

The compartments were individually temperature controlled through heating and venting set points which were, unless otherwise stated, 12 / 18˚C respectively from the transfer of the plants to the compartments until chilling commenced where the set points were reduced to 2 / 5˚C. Data loggers were used to record the average hourly temperature in each compartment (TinyTag Gemini Data Loggers Ltd, Chichester, UK).

2.2.3 Fertigation

One dripper stake with a 2.0 L / hr emitter (Netafim, Tel Aviv, Israel) was inserted into the substrate beside the crown of each individual plant; each emitter supplied the plant with water and nutrients through an automatic irrigation system. Irrigation events were scheduled using a timer (Heron Electric, Ford, UK) set to irrigate the plants for two minutes twice daily at 10:00 and 14:00 from the start of the propagation phase until chilling commenced when this was reduced to one minute twice weekly at 13:00. This irrigation programme was the standard set at the start of each experiment, but the number and duration of irrigation events was adjusted as and when required to ensure coir volumetric moisture content (VMC) was maintained between 50% and 60%. To determine the substrate moisture, plants were selected at random from each compartment and the coir VMC checked using a soil moisture meter connected with a sensor previously calibrated for coir substrate (HH2 Soil Moisture Meter and WET-2 Sensor, Delta-T Devices Ltd, Cambridge, UK). To take a reading, each plant was removed from the pot and the sensor inserted in the middle of the substrate.

Nutrients were also supplied to the plants through the irrigation system. The nutrient solution consisted of concentrate from two stock tanks added in equal quantities to a separate tank containing mains water using a dosing pump (BL-2, Blackstone Chemical Pump, Hanna Instruments Ltd, Leighton Buzzard, UK) which automatically triggered if the electrical conductivity (EC) of the nutrient solution fell below a set level. The dosing pump had a maximum output of 15 L / hr but was set at a 10% flow rate. Nutrients were then added from the stock tanks until the desired EC was reached. For all experiments, the EC set point was 1.80 mS / cm.

A dilute nitric acid solution was prepared by adding 2.5 L of 70% laboratory grade nitric acid (Fisher Scientific, Loughborough, UK) to 80 L of mains water in a third stock tank. The dilute acid was then added to the water tank using a separate dosing pump which was automatically triggered when the pH of the nutrient solution was greater than the set point of 5.50. Figure 2.4 shows the irrigation system including the two nutrient stock tanks, the acid stock tank, water tank, pH and EC meters, dosing pumps and the irrigation controller.

Irrigation input (drip) and output (run off) was collected regularly from each compartment and a handheld electrical conductivity meter (HI-9033, Hanna Instruments Ltd, Leighton Buzzard, UK) and pH meter (HI-9124, Hanna Instruments Ltd, Leighton Buzzard, UK) were used to check the EC and pH levels. Plants were flushed periodically with mains water to reduce EC build up in the substrate.

Figure 2.3 The linear array of eight individual temperature-controlled compartments (numbered 19 to 26) within a multi-compartmented glasshouse situated at the Crops and Environment Laboratory, School of Agriculture, Policy and Development, University of Reading. The middle six compartments (Compartments 20 to 25) were used for plant propagation in all experiments.

Figure 2.4 The irrigation system used during the propagation phase for each experiment. The photograph shows the two nutrient stock tanks (A and B), the acid stock tank (C), water tank (D), pH and EC meters (E), the three dosing pumps (F) and the irrigation controller (G).

2.2.4 Propagation Phase Measurements

To analyse treatments effects on transplant growth and yield potential, several measurements were carried out during the propagation phase.

Flower and Runner Number

Open flowers and runners (if present) were removed from all plants on a routine basis throughout the propagation phase. Upon transfer to the glasshouse compartments 10 plants of each cultivar in each treatment were selected at random and tagged; the numbers of open flowers and runners were counted as removed on these tagged plants.

Non-Destructive Measurements

In the experiments described in Chapters 3 and 4, the following measurements were carried out on the ten tagged plants:

- **Leaf Number (per plant):** The total number of trifoliate leaves was counted. Counts included leaves not yet fully expanded but excluded those that were senescing.
- **Crown Diameter (cm):** A digital micrometre was used to take a non-destructive measurement of crown diameter to the nearest 0.1 mm. The micrometre had a range of 0 to 150 mm and was accurate to ±0.1 mm.
- **Root Score:** Plants were removed from their pots and the extent of root development was scored on a scale of 1 to 10. Figure 2.5 shows example plants with root scores representing 1, 3, 5, 7 and 9 on the scale which was used as a reference to score from.

Figure 2.5 Example plants with root scores representing 1, 3, 5, 7 and 9 on the 1-10 scale used to score root development during the propagation phase.

Destructive Harvest (DH1)

In all experiments, a destructive harvest was carried out at the end of the propagation phase on the ten tagged plants in each cultivar and treatment combination. The following is a total list of measurements used across all experiments. All measurements were made on a per plant basis:

- **Crown Number (per plant):** The total number of crowns, including branch crowns, was counted.
- **Crown Diameter (cm):** Each plant was cut at the base just above the first primary root using a sharp knife; the diameter across the widest cross section of the base of the crown was measured to the nearest 10 mm using a 15 cm ruler.
- **Leaf Number (per plant):** The total number of trifoliate leaves was counted. Counts included leaves not yet fully expanded but excluded those that were senescing.
- **Leaf Area (cm^2 / plant):** The area of the fully expanded leaves was measured to the nearest 0.01 cm^2 using a Leaf Area Machine (WinDIAS Leaf Image Analysis System, Delta-T Devices, Cambridge, UK) calibrated using a 15 cm ruler.
- **Root Score:** Plants were removed from their pots and the extent of root development was scored on a scale of 1 to 10 (Figure 2.5).
- **Dry Weights (g / plant):** The leaves and crowns were weighed after drying in an oven at 70°C for 72-hrs. A total plant dry weight was also derived as a sum of these individual plants including the petioles and removed flowers but excluding the roots.

2.3 Production Phase

2.3.1 Glasshouse Production

The cultivar Lusa was cropped in the multi-compartmented glasshouse in a larger temperature-controlled compartment separate to those used for plant propagation (Glasshouse 18, Figure 2.6). Trolleys, 78 cm high with a wire mesh top for drainage, were arranged in four rows to simulate a commercial table top system. A one metre length bag containing coir substrate (Legro, Helmond, The Netherlands) was placed on each trolley and four dripper stakes with 2.0 L / hr emitters (Netafim, Tel Aviv, Israel) were inserted into each bag.

2.3.2 Polytunnel Production

The remaining cultivars in each experiment were cropped in a twin-span tunnel at the Soft Fruit Technology Group's Field Site at the University of Reading's Shinfield Farm (2014) and Sonning Farm (2015 and 2016). In both locations, the tunnels were covered in a single layer of polythene (EVA/UVI, British Polythene Industries, Greenock, UK) and the ends covered with a net to allow free air flow through the tunnel but prevent damage and loss of fruit from birds and other wildlife.

Inside each tunnel, four single rows (27 m) of a gutter system (Single Row Substrate System, Haygrove Ltd, Ledbury, UK) raised approximately 1 m from the ground were installed (Figure 2.7). On each bench 1 m coir substrate bags (Legro, Helmond, The Netherlands) were placed end to end and four dripper stakes with 2.2 L / hr emitters (Netafim, Tel Aviv, Israel) were inserted into each bag.

2.3.3 Temperature Control

In the glasshouse, heating and venting set points throughout the production phase were 14°C and 20°C respectively. In the polytunnel, temperature control was more limited, the sides of the tunnel were kept at ground level for the first few weeks after planting to retain heat within the tunnel and then the sides of the tunnel were raised up approximately 1 m for venting. The sides of the tunnel were then dropped back down to ground level when the weather turned colder in the autumn. Data loggers recorded the average hourly temperature in both the glasshouse and the polytunnel for each experiment (TinyTag, Gemini Data Loggers Ltd, Chichester, UK).

Figure 2.6 Set up of the large temperature-controlled compartment (Compartment 18 of the multi-compartmented glasshouse) used the production phase of the cultivar Lusa. The glasshouse is situated at the Crops and Environment Laboratory, School of Agriculture, Policy and Development, University of Reading.

Figure 2.7 Set up of the polytunnel for production phase of all cultivars except Lusa. The polytunnels were located at the Soft Fruit Technology Group's Field Site at the University of Reading's Shinfield Farm (2014) and Sonning Farm (2015 and 2016).

2.3.4 Fertigation

For cropping in both the glasshouse and the polytunnel, nutrient solutions were delivered to each bag to provide the plants with water and nutrients. Prior to planting the bags were flushed with calcium nitrate using pre-acidified water (5.5 pH at the drip) and this continued after planting until transplants showed signs of root extension. At this point they were also supplied with a commercial strawberry starter mix (Solufeed Strawberry Starter, Solufeed Ltd, Barnham, UK) to encourage vegetative growth. At flowering, the feed was switched to a commercial strawberry fruiting mix for the remainder of cropping. The feed was designed for use in conjunction with the supply of calcium nitrate and use of nitric acid (Solufeed Strawberry Special, Solufeed Ltd, Barnham, UK). Table 2.3 gives details on each nutrient solution.

In the glasshouse production, the nutrient solutions were delivered using the same type of system as used for the propagation phase (shown in Figure 2.4). Equal parts of concentrate from two stock tanks added via dosing pumps (BL-2, Blackstone Chemical Pump, Hanna Instruments Ltd, Leighton Buzzard, UK) to a third tank containing 227 L of mains water until the desired EC was reached. The EC after planting was of 2.2 mS / cm which was dropped to 1.8 mS / cm once the plants had established. Dilute nitric acid, prepared in the same way as previously described, was added to the tank using a third dosing pump to correct the pH in the tank to 5.5.

In the polytunnel pH and EC was controlled via dosatron injectors (D3GL2 Greenline, Dosatron International, Tresses, France). One dosatron injector was used to acidify the mains water as it was pumped to a 5000 L storage tank. During each irrigation event, the pre-acidified water was then pumped from the storage tank to the tunnels where it passed through a further two dosatron injectors which added nutrients in equal parts from the two stock tanks. The set-up of the irrigation system is shown in Figure 2.8.

In both the glasshouse and the polytunnels the frequency and duration of the irrigation events were controlled via automatic controllers. As a standard, the programme was set to irrigate for 2 minutes one hour after sunrise and then every two hours until two hours before sunset. However, the duration and number of irrigation events was adjusted through the season depending on the weather conditions with the overall aim to ensure daily run-off to prevent EC build up in the substrate. Coir VMC, pH and EC levels were measured and monitored in the same way as described for the propagation phase.

2.3.5 Production Phase Measurements

2.3.5.1 *Fruit Production*

Ripe fruit was picked once a week increasing to twice weekly during peak production, with an interval of three and four days. When fruit was picked twice weekly the results were combined to give a total for the week. Fruit was considered ripe when the surface was dark red and considered marketable (Class 1) if free from disease, uniform in shape and colour and over 22 mm in diameter at the shoulder. The diameter of small berries was checked using a 22 mm sizing ring. Figure 2.9 shows photographs of example berries classed as marketable and un-marketable.

After fruit was picked the following data was collected:

- **Marketable Yield (g / plant):** The total weight of the marketable fruit.
- **Marketable Berry Number (per plant):** Total number of marketable berries.
- **Un-Marketable Yield (g / plant):** The total weight of the un-marketable berries.
- **Un-Marketable Berry Number (per plant):** Total number of un-marketable berries.
- **Total Yield (g / plant):** The total weight of all the harvested fruit.
- **Total Berry Number (per plant):** The total number of berries harvested.
- **Average Marketable Berry Weight (g / berry):** Calculated at the end of cropping as (marketable yield / marketable berry number).
- **Percentage Class 1 (%):** Calculated at the end of cropping as the proportion of the total yield that was categorised as marketable (marketable yield / total yield)*100

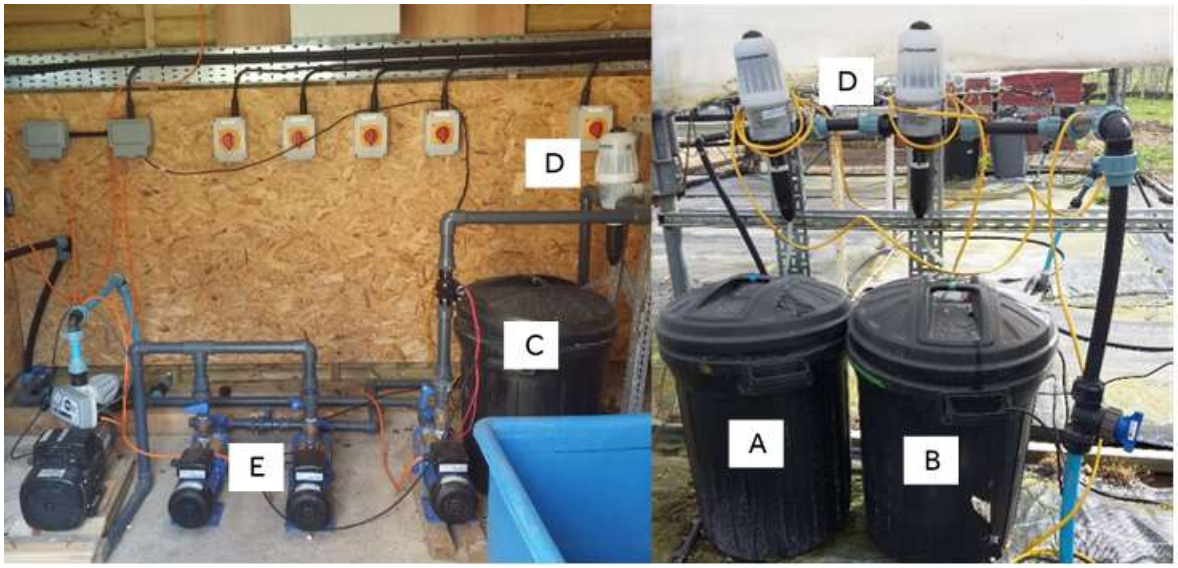

Figure 2.8 Set-up of the irrigation system for fruit production in the polytunnel. The photograph shows the two nutrient stock tanks (A and B), the acid stock tank (C), dosatron injectors (D) and irrigation pumps (E). The 5000 L storage tank and automatic controller are not shown.

Table 2.3 Composition of the starter and fruiting nutrient solutions; nutrients were diluted in a tank containing 80 L of mains water for a 10% stock solution.

	Starter Mix (% Content)	**Fruiting Mix (% Content)**
Total nitrogen (N)	14.9	2.2
NO_3-N	11.1	1.6
NH_4-N	3.8	0.6
Phosphorus pentoxide	6.9	9.2
Potassium oxide	29.9	29.0
Magnesium oxide	2.8	8.9
Boron	0.01	0.03
Copper (as EDTA)	0.002	0.03
Iron (as EDTA)	0.10	0.30
Manganese (as EDTA)	0.10	0.17
Molybdenum	0.001	0.008
Zinc	0.002	0.14

2.3.5.2 *Final Destructive Harvest (DH2)*

At the end of the production phase a second destructive harvest was carried out. The following measurements were made on a per plant basis:

- **Crown Number (per plant):** The total number of crowns including branch crowns.
- **Leaf Number (per plant):** The total number of trifoliate leaves. Counts included those not yet expanded but excluding those senescing.
- **Inflorescence Number (per plant):** The total number of inflorescences.
- **Dry Weights (g / plant):** Leaves, crowns, petioles and inflorescences were weighed after drying in a ventilated oven at 70°C for 72-hrs. A total plant dry weight was then derived as the sum of these individual components. Total plant dry weight excluded runners and roots.

Figure 2.9 Example berries categorised as marketable (left) and un-marketable (right). Marketable fruits are classified as being free from disease, uniform in shape and colour and over 22 mm in diameter at the shoulder.

2.4 Plant Husbandry

Dead leaves were removed routinely throughout both the propagation and production phase to help minimise disease risk. Weeds and runners were also routinely removed by hand. Spraying for the control of grey mould (*Botrytis cinerea*) and powdery mildew was conducted frequently and biological control for glasshouse white fly (*Trialeurodes vaporariorum*), two-spotted spider mite (*Tetranychus urticae*) and a range of thrip and aphid species were also introduced regularly (Syngenta Bioline, Little Clacton, UK). Application of chemicals and biological controls were carried as per the instruction of a certified agronomist.

In the glasshouse, hives containing 80-100 bees (*Bombus terrestis*, standard soft fruit hive, Syngenta Bioline, Little Clacton, UK) were introduced every six weeks during the production phase to aid pollination. Introductions were not necessary in the polytunnels due to the abundance of natural pollinators in the surrounding area.

2.5 Data Analysis

Microsoft Excel 2013 (and subsequently 2016) was used to store and manage the data. Genstat 17th Edition (VSN International Ltd, Hemel Hempsted, UK) was the statistical software used to analyse the data and Graphpad Prism (Graphpad Prism 5, La Jolla, California, USA) to draw the graphs.

Data was analysed using two or three-way ANOVA with differences between treatments separated using the least significant difference (LSD, 5% level). Three-way ANOVA was used in the experiments where two treatments were applied to more than one cultivar. For the two- way and three-way ANOVA results, main effects of the treatments are only discussed and presented where no significant interactions were found.

The glasshouse and polytunnels were blocked to minimise the effect of light and temperature gradients across the experimental areas. Blocking was also incorporated in the statistical analysis.

Chapter 3

Effect of tipping date on cropping performance of three Everbearer strawberry cultivars.

3.1 Introduction

The cultivated strawberry (*Fragaria x ananassa* Duch.) is a hybrid and so plants propagated from seed do not come true to type; generation of new plant material is therefore carried out via vegetative means using stolons (runners) upon which numerous genetically identical daughter plants are formed. In Northern Europe, commercial tray plant production begins in late-summer when daughter plants are cut (tipped) from mother plants previously established in specialist nurseries. Tips are then rooted into multi-celled trays and grown on until the following spring when they are dispatched to the fruit growers. Often propagators will delay tipping until August or September to ensure adequate numbers of tips are produced to meet grower demand, especially in the case of Everbearer cultivars which typically produce fewer runners than Junebearers.

Typically, tray plants are produced in cold glasshouses or polytunnels under natural light conditions. Early establishment of tips is therefore important to ensure adequate vegetative growth is established before dormancy is induced. Earlier tipping gives the propagator a greater opportunity and more suitable environmental conditions to build a transplant with a large crown, healthy canopy and well-established root system, all of which are important for establishing a high-quality transplant with a high yield potential. Later tipping could have a negative impact on subsequent yield performance as the plants have less time in more favourable light and temperature conditions for growth and flower initiation prior to the onset of dormancy. Reduced vegetative growth could also have a negative impact on potential fruit yield due to a reduction in crown size and the number of flowering sites, thereby capping yield potential (Abbott 1968). Reduced canopy size may also lead to a reduction in stored reserves which are accumulated in the autumn and winter and relied upon heavily in the spring when there is a period of rapid growth just after dormancy-breaking (Acuna-Maldonado & Pritts 2008; Kirschbaum et al. 2010a).

Previous work on the effect of tipping date is limited and mostly restricted to Junebearer cultivars, of which few are commercially cropped in the UK today. There has also been some research conducted on the effect of rooting date, which is linked to tipping date as it takes approximately four weeks after severance from the mother plant for a daughter to successfully root and form a plug. Jahn & Dana (1970b) found branch crown formation and leaf production was greater in earlier rooted plants which also had a greater leaf area and plant weight. Takeda & Newell (2006) also found that earlier tipped plants had a greater number of crowns per plant, flowered earlier and had a higher spring yield. Similarly, Yoshida & Motomura (2011) found earlier and more uniform flowering in plants tipped in June compared to those in August and Cocco et al. (2010) showed that earlier tipped daughters flowered earlier and fruited earlier and heavier than later tipped daughters. Webb et al. (1973) compared yield, berry number and berry weight of strawberry daughters rooted in monthly intervals from April to October and found a greater yield in earlier rooted daughters due to an increased number of berries per plant, even though average berry weight declined. The authors found fewer tertiary, quaternary and quinary flowers in later rooted daughters, showing that the inflorescences were less branched, and so although there was a reduction in the total flower and berry number per plant, there was an increase in the proportion of larger grade berries and average berry weight (although not enough to counteract the yield loss due to reduced berry number).

Overall, the environmental conditions in which strawberry transplants are produced is important in determining their yield potential. However, simple methods, such as earlier tipping, to aid establishment of strong transplants with enough vegetative vigour to promote maximal flower initiation should not be underestimated in terms of their impact on subsequent fruiting. There have been some investigations into the effect of tipping date on cropping of Junebearer cultivars but little to none on that of Everbearers, especially those currently cropped by UK growers. An experiment was therefore carried out to examine the impact of tipping date on transplant growth, yield potential and subsequent cropping performance of three Everbearer strawberry cultivars currently cropped the in UK.

3.2 Materials and Methods

3.2.1 Propagation Phase

Plant Material and Experimental Treatments

Fresh daughter plants of Everbearer cultivars Jubilee, Scarlet and Serena were supplied by Driscolls' Plants BV (Helenaveen, The Netherlands). One hundred daughter plants were tipped from mother plants in the nursery on three dates: 1st, 15th and 30th July 2014 and delivered to the Crops and Environment Laboratory at the University of Reading on the following day. The three tipping dates were given the following codes: 1st July (T01), 15th July (T15) and 30th July (T30).

Misted tip production was carried out using the methods described in Chapter 2; briefly, the tips were struck into individual cells of 56-cell trays containing a 50:50 mix of peat and coir and overhead misted with mains water, plus a daily foliar feed, in a propagation house for root establishment. Once rooted, 45 uniform plants were selected and individually re-potted into 90 x 87 mm (diameter x depth) coir filled pots.

The plants were transferred to two temperature-controlled glasshouse compartments with half of the plants for each cultivar and treatment assigned to each compartment. Plants were propagated with 12-hrs of supplementary lighting (07:00 to 19:00) from 13th October and the heating/venting set points of each compartment were 10/20˚C respectively until 1st December 2014 when the lights were switched off and temperatures were reduced to 2/5°C for chilling. Temperatures were logged in each compartment every hour and the average 24-hr temperature calculated prior to chilling in the two compartments was 19.5°C and 19.9°C. The compartments, lights and fertigation system were as described in Chapter 2.

Propagation Phase Measurements

Treatments effects on transplant growth and yield potential were determined through a combination of weekly measurements and a destructive harvest at the end of the propagation phase. Ten randomly selected plants of each cultivar in each treatment were tagged upon transfer to glasshouse; runners and open flowers were removed on all plants on a routine basis and the number removed on the tagged plants recorded. Additionally, leaf number per plant, crown diameter and root scores were recorded routinely on the tagged plants.

At the end of the propagation phase, a destructive harvest was carried out on the ten tagged plants and the following measurements were made on each plant: crown number, crown diameter, leaf number, leaf area, root score and dry weight of the leaves, crowns and petioles along with a total plant dry weight calculated as the sum of the individual components. All measurements were made using the methods described in Chapter 2.

3.2.2 Production Phase

Experimental Design

At the end of the propagation phase, remaining plants were transferred to a twin span tunnel at the Soft Fruit Technology Group's Field Site at The University of Reading's Sonning Farm. The tunnel was set up as described in Chapter 2. Four bags containing six plants, were planted for each cultivar and treatment giving a total of 24 plants. Bags were planted on 31st March 2015.

The experimental area was divided into four blocks with one replicate (bag) assigned to each block in a randomised design. Guard bags were placed at each end of each row to minimise edge effects. Figure 3.1 shows the layout of the blocks, cultivars and treatments.

Temperature control, plant husbandry and fertigation were set up and carried out during the production phase as described in Chapter 2. Figure 3.2 shows the average 24 hr temperature logged throughout the production phase.

Production Phase Measurements

To determine treatment effects on cropping performance, data on total, marketable and un-marketable yield and berry number were recorded on a weekly basis. Average marketable berry weight and percentage Class 1 were also calculated at the end of cropping. Data was collected at the bag level and converted to a per plant basis for analysis.

A final destructive harvest was carried out at the end of the production phase; two plants were harvested from each bag and the following measurements were made on a per plant basis: crown number, leaf number, inflorescence number and dry weight of the leaves, crowns, petioles and inflorescences with a total plant dry weight was calculated as the sum of the individual components. All data was collected using the methods described in Chapter 2.

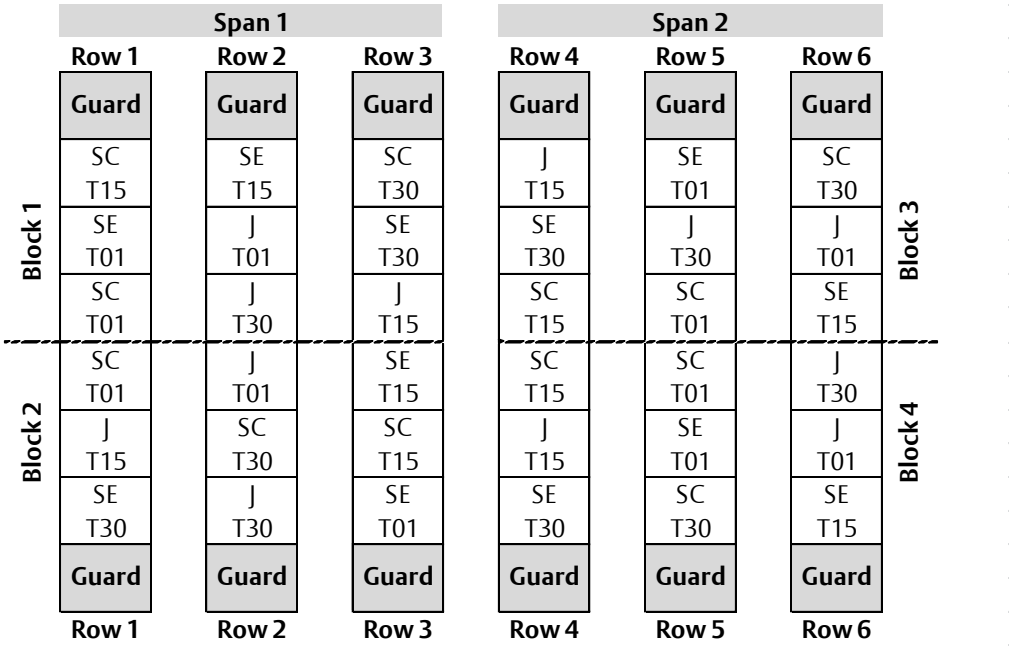

Figure 3.1 Arrangement of blocks, cultivars and treatments (tipping date) for the production phase of strawberry cultivars Jubilee (J), Scarlet (SC) and Serena (SE) in a twin span polytunnel situated at the Soft Fruit Technology Group's Field Site at the University of Reading's Sonning Farm. Each box represents a 1 m substrate bag each with six plants. Tipping dates were: 1st July 2014 (T01), 15th July 2014 (T15) and 30th July 2014 (T30).

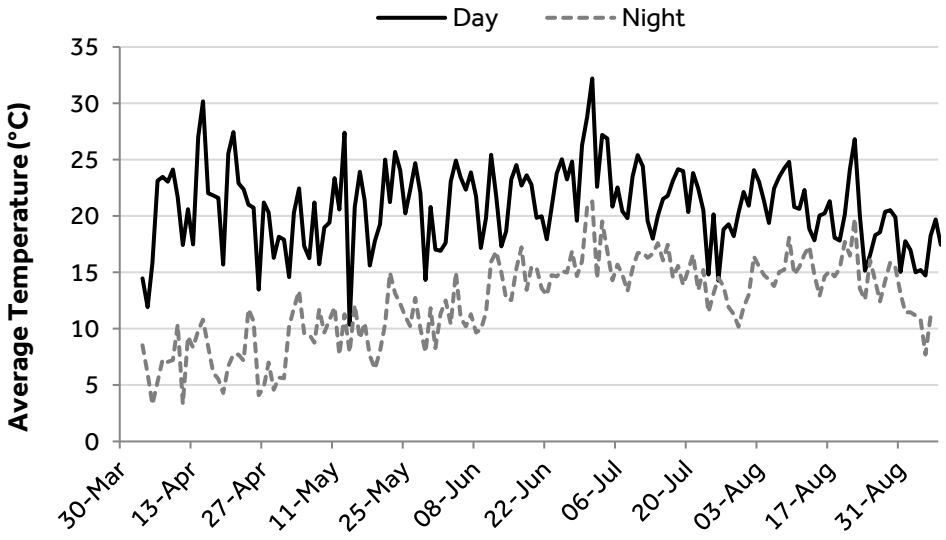

Figure 3.2 Mean day and night temperature logged throughout the production phase for cultivars Jubilee, Scarlet and Serena. Day = 07:00-19.00.

3.3 Results

3.3.1 Propagation Phase

3.3.1.1 *Open Flower Number*

The number of open flowers expressed during the propagation phase significantly differed between cultivars (P<0.001); all differences between cultivars were significant with flower number greatest in Serena (32.5±1.5 flowers / plant), followed by Scarlet (21.3±1.0) and Jubilee (16.2±1.5).

The interaction between cultivar and tipping date was also significant (P=0.018, Figure 3.3); for Jubilee and Serena, flower number was significantly higher in T01 compared to T30 (by 121% and 26% respectively), and there were no other significant differences between treatments. Whereas, for Scarlet, there were no significant differences in flower number between any treatments.

3.3.1.2 *Runner Number*

Overall, the number of runners produced per plant did not differ significantly between cultivars. However, the interaction between cultivar and tipping date was significant (P=0.031,Table 3.1) such that for Scarlet and Serena, significantly more runners were produced in T01 compared to T15 and T30 whilst in Jubilee, there were no significant differences in the number of runners between treatments.

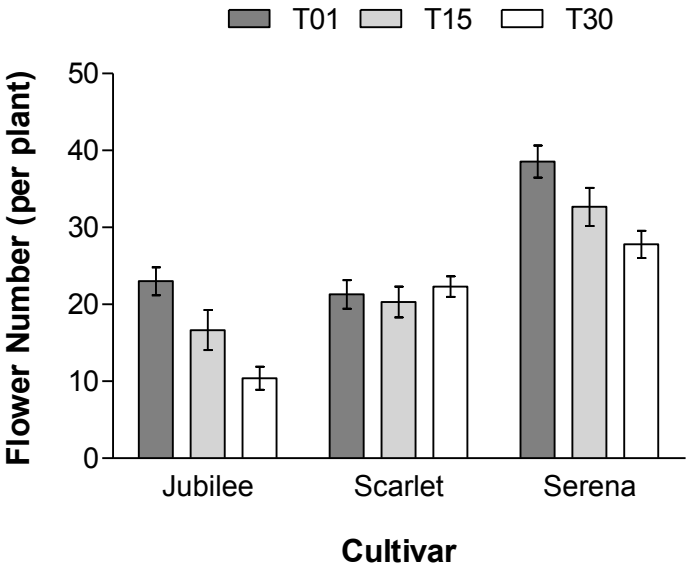

Figure 3.3 Effect of tipping date on the number of open flowers during the propagation phase for cultivars Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. Tipping dates were: 1st July (T01), 15th July (T15) and 30th July (T30) 2014.

Table 3.1 Effect of tipping date on the number of runners produced per plant during the propagation phase for cultivars Jubilee, Scarlet and Serena (n=10). The P. Value and LSD for the interaction is shown. Tipping dates were: 1st July (T01), 15th July (T15) and 30th July (T30) 2014.

	T01	T15	T30	LSD	P. Value
Jubilee	0.1	0.1	0.1	0.66	0.031
Scarlet	1.3	0.3	0.0		
Serena	1.2	0.0	0.1		

3.3.1.3 *Non-Destructive Measurements*

Leaf Number

Figure 3.4 shows the number of leaves per plant for each cultivar and treatment counted every week during the propagation phase. In all three cultivars, there was a significant effect of tipping date on leaf number ($P<0.001$). Leaf number was significantly higher in T01 compared to T15 and T30 every week for Scarlet and from 20th October for Jubilee and Serena. There was no significant difference in leaf number between T15 and T30 at any point for any cultivar. The total number of new leaves that emerged in T01, T15 and T30 was 8.2, 3.6 and 3.9 per plant for Jubilee; 11.8, 6.3 and 7.6 for Scarlet and 10.2, 7.2 and 7.7 for Serena. Leaf number was therefore increased the most in T01 for all three cultivars.

Crown Diameter

Figure 3.5 shows crown diameter for each cultivar and treatment measured every two weeks during the propagation phase. There was a significant effect of tipping date on crown diameter for all three cultivars ($P<0.001$). Crown diameter was significantly higher in T01 compared to T15 and T30 in all weeks for Scarlet and Serena and from 20th October for Jubilee. There was no significant difference in crown diameter between T15 and T30 at any time for any cultivar. Overall, mean crown diameter in T01, T15 and T30 increased by 1.78 cm, 0.60 cm and 0.71 cm for Jubilee; 0.94 cm, 0.89 cm and 1.13 cm for Scarlet and 0.95 cm, 0.81 cm and 1.02 cm for Serena. Crown diameter therefore increased the most in T01 for Jubilee and in T30 for Scarlet and Serena.

Root Score

Figure 3.6 shows the root score recorded for each cultivar and treatment every two weeks during the propagation phase. There was a significant effect of tipping date on root score for all three cultivars ($P<0.001$). Root score was significantly higher in T01 compared to T30 in all weeks for all three cultivars. Root score was also generally higher in T15 compared to T30 in all three cultivars, but this was only significant on 20th October for Jubilee, 3rd November for Scarlet and 3rd November and 17th November for Serena.

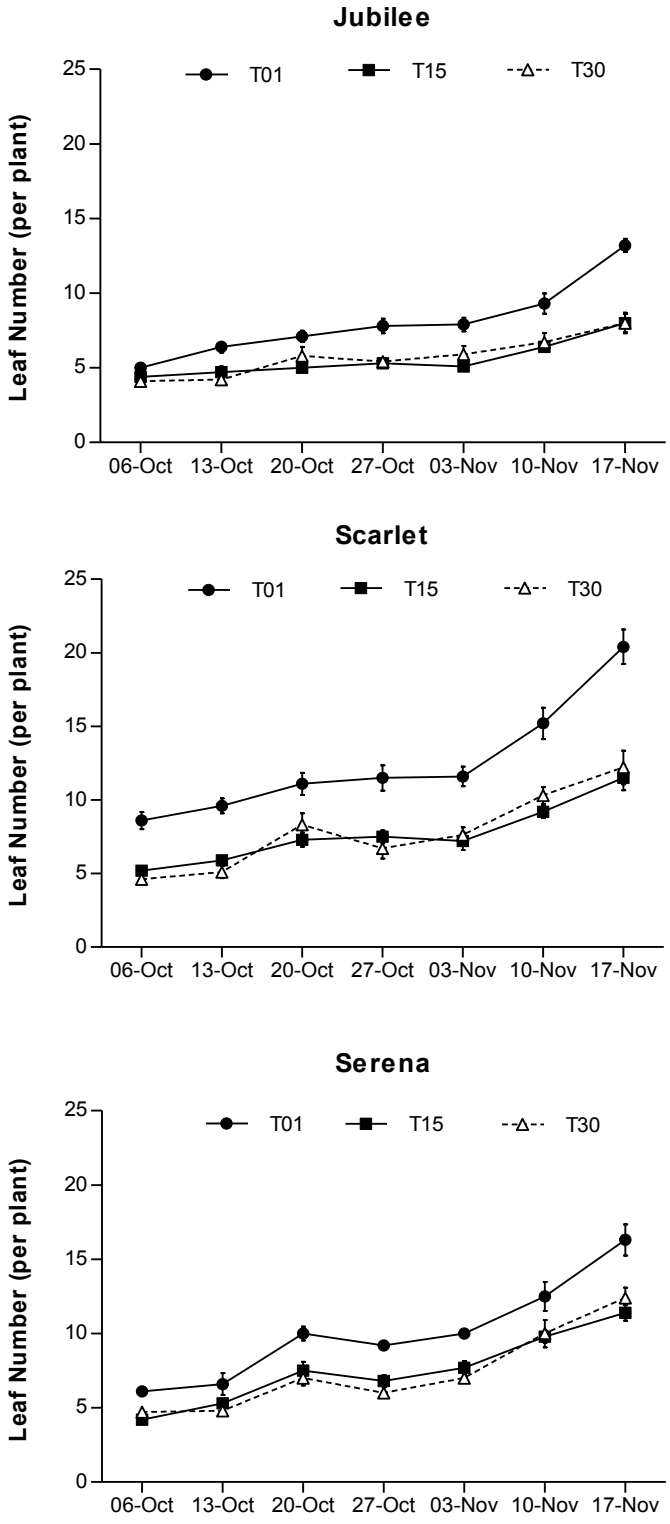

Figure 3.4 Effect of tipping date on leaf number per plant recorded every week during the propagation phase for cultivars Jubilee, Scarlet and Serena (n=10). The vertical line on each data point shows ±S.E.M. Tipping dates were: 1st July (T01), 15th July (T15) and 30th July (T30) 2014.

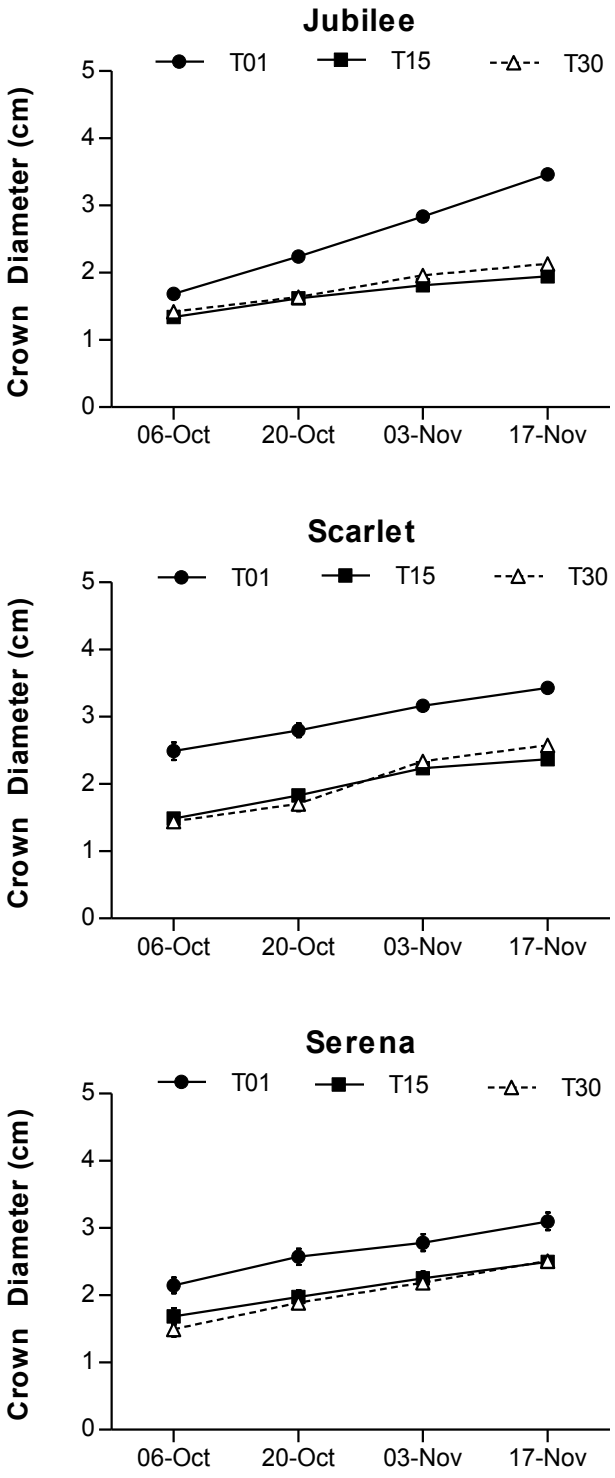

Figure 3.5 Effect of tipping date on crown diameter recorded every two weeks during the propagation phase for cultivars Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. Tipping dates were: 1st July (T01), 15th July (T15) and 30th July (T30) 2014.

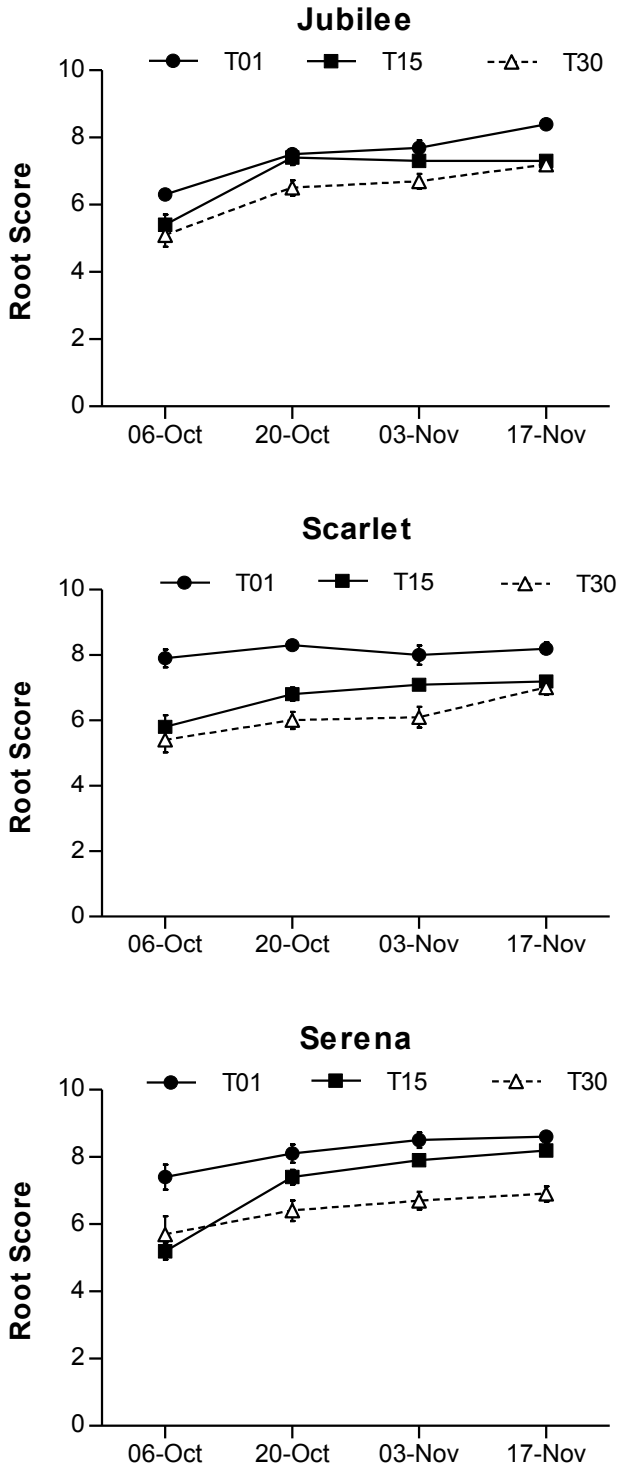

Figure 3.6 Effect of tipping date on root score recorded every two weeks during the propagation phase for cultivars Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. Tipping dates were: 1st July (T01), 15th July (T15) and 30th July (T30) 2014.

3.3.1.4 *Destructive Harvest (DH1)*

Crown Number

Overall, crown number was significantly (P<0.001) higher in Scarlet (3.9±0.2 crowns / plant) and Serena (4.3±0.2) compared to Jubilee (2.9±0.2), and there was no significant difference between Scarlet and Serena. Figure 3.7 shows the effect of tipping date on crown number for each cultivar; only the main effect of tipping date was significant (P<0.001) with crown number greater in T01 (4.5±0.2) compared to T15 (3.5±0.2) and T30 (3.0±0.2), and in T15 compared to T30.

Crown Diameter

Overall, crown diameter was significantly (P<0.001) greater in Scarlet (2.3±0.1 cm) and Serena (2.2±0.1) than Jubilee (1.6±0.1), and in Scarlet compared to Serena. There was also a significant interaction between the cultivars and tipping date (P<0.001, Figure 3.7); for Jubilee, crown diameter was significantly higher in T01 compared to T15 and T30 (by 23% and 30% respectively), with no significant difference between T15 and T30; whilst in Scarlet, all differences between treatments were significant, with crown diameter greater in T01 compared to T15 and T30 (by 29% and 67% respectively) and 29% greater in T15 compared to T30. In Serena, crown diameter was 16% higher in T01 than T15 and no other differences between treatments were significant.

Crown Dry Weight

Crown dry weight was significantly (P<0.001) higher in Scarlet (1.58±0.12 g / plant) and Serena (1.78±0.13) compared to Jubilee (1.35±0.14), and there was no significant difference between Scarlet and Serena. Figure 3.7 shows the effect of tipping date on crown dry weight for each cultivar; only the main effect of tipping date was significant (P<0.001) with crown dry weight greater in T01 (2.33±0.09) compared to both T15 (1.42±0.09) and T30 (0.96±0.06), and in T15 compared to T30.

Leaf Number

Leaf number of Scarlet (16.6±1.0 leaves / plant) was significantly (P<0.001) greater than Serena (14.2±0.5) and Jubilee (9.8±0.7), and in Serena compared to Jubilee. Figure 3.7 shows the effect of tipping date on leaf number for each cultivar; overall only the main effect of tipping date was significant (P<0.001) with leaf number greater in T01 (17.6±0.8) than both T15 (11.9±0.8) and T30 (11.1±0.6), and no significant difference between T15 and T30.

Leaf Area

Leaf area was significantly (P<0.001) greater in Scarlet (540.1±30.2 cm^2 / plant) compared to Serena (375.7±15.9) and Jubilee (254.6±14.2), and in Serena compared to Jubilee. There was a significant interaction between cultivar and tipping date (P<0.001, Figure 3.7); for Jubilee and Serena, leaf area was significantly higher in T01 compared to T15 and T30 (by 41% and 47% for Jubilee, and 31% and 53% for Serena) and there was no significant difference between T15 and T30 for either cultivar. In Scarlet, all differences between treatments were significant, and leaf area was 43% and 83% greater in T01 compared to T15 and T30 respectively, and 28% greater in T15 compared to T30.

Leaf Dry Weight

Leaf dry weight was significantly (P<0.001) greater in Scarlet (4.88±0.32 g / plant) compared to Serena (3.68±0.17) and Jubilee (2.99±0.20), and in Serena compared to Jubilee. There was also a significant interaction between cultivar and tipping date (P=0.002, Figure 3.7) in all three cultivars, leaf dry weight was significantly greater in T01 compared to T15 and T30 (74% and 80% for Jubilee, 64% and 100% for Scarlet and 51% and 52% for Serena respectively) and there was no significant difference between T15 and T30 for any cultivar.

Root Score

Root score was significantly (P=0.014) greater in Serena (7.9±0.2) and Jubilee (7.8±0.2) compared to Scarlet (7.5±0.1), and there was no significant difference between Serena and Jubilee. There was also a significant interaction between cultivar and tipping date (P=0.004, Figure 3.7) such that for Jubilee and Scarlet root score was significantly higher in T01 than T15 and T30 (by 19% and 19% for Jubilee, and 14% and 17% for Scarlet) and there was no significant difference between T15 and T30 for either cultivar. Whereas, in Serena, root score was significantly higher in T01 and T15 than T30 (25% and 19% respectively) with no significant difference between T01 and T15.

Total Dry Weight

Total plant dry weight of Scarlet (7.19±0.38 g / plant) was significantly (P<0.001) greater than Serena (8.66±0.52) and Jubilee (5.32±0.40), and in Serena compared to Jubilee. There was no significant interaction between the cultivars and tipping date (Figure 3.7) but all differences between treatments were significant (P<0.001) with total dry weight greatest in T01 (9.89±0.38) followed by T15 (6.22±0.35) and T30 (5.06±0.27).

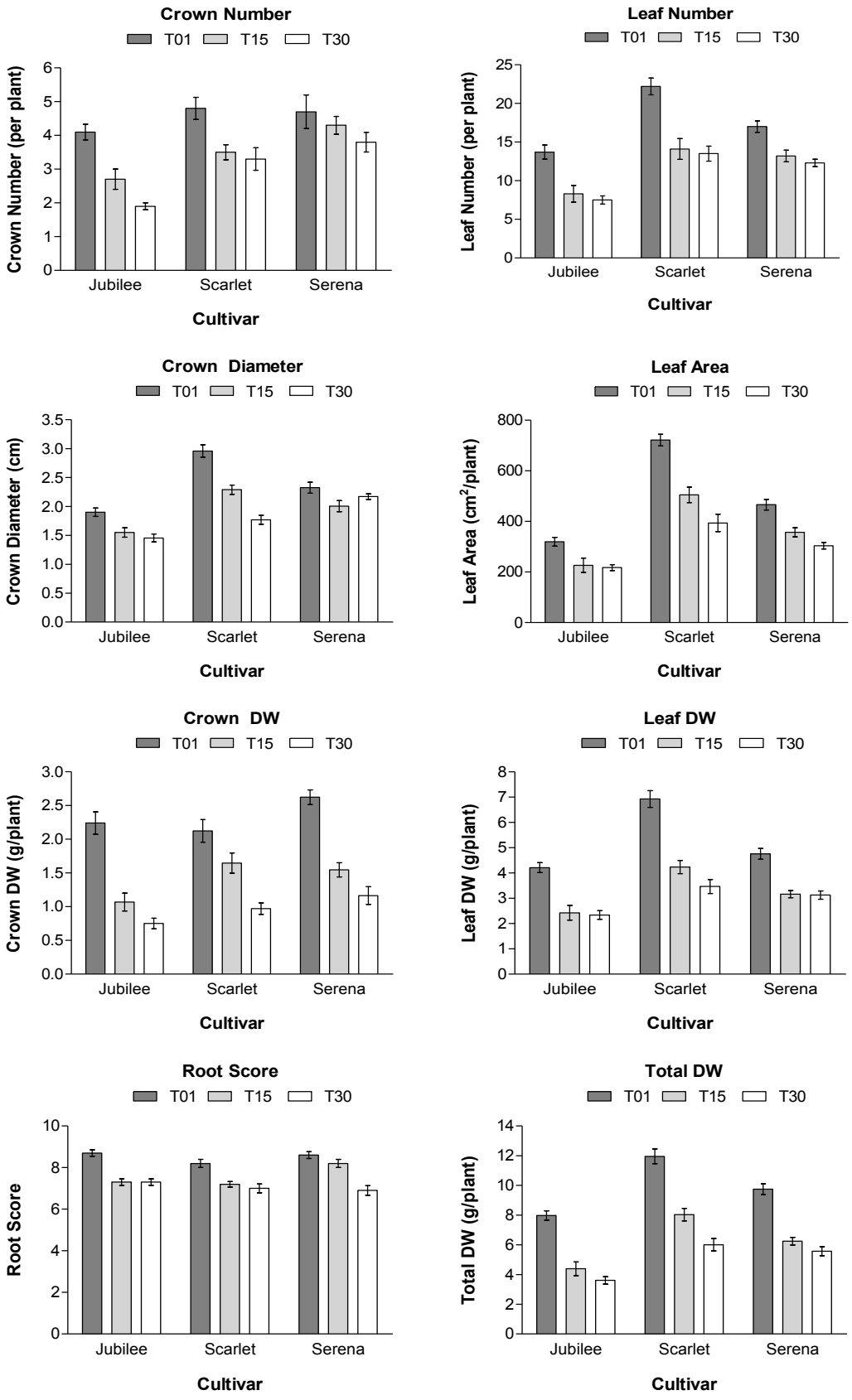

Figure 3.7 Effect of tipping date on DH1 results for cultivars Jubilee, Scarlet and Serena (n=10). DW= dry weight. The vertical line on each bar shows ±S.E.M. Tipping dates were: 1st July (T01), 15th July (T15) and 30th July (T30) 2014.

3.3.2 Production Phase

3.3.2.1 *Yield Results*

Marketable Yield

Marketable yield was significantly (P<0.001) higher in Serena (1215±41.1 g / plant) compared to Scarlet (1083±31.8) and Jubilee (755±34.4), and in Scarlet compared to Jubilee. The effect of tipping date on marketable yield for each cultivar is shown in Figure 3.8; overall only the main effect of tipping date was significant (P<0.001) with marketable yield greater in T01 (1084±61.0) and T15 (1055±56.1) than T30 (914±75.6), and no significant difference between T01 and T15.

Un-Marketable Yield

Un-marketable yield was significantly (P<0.001) higher in Jubilee (185±8.8 g / plant) compared to Scarlet (151±7.9) and Serena (124±10.7), and in Scarlet compared to Serena. The effect of tipping date on un-marketable yield for each cultivar is shown in Figure 3.8; overall only the main effect of tipping date was significant (P=0.020) with un-marketable yield higher in T01 (165±8.7) and T15 (161±14.0) compared to T30 (134±10.1), and no significant difference between T01 and T15.

Total Yield

Total yield was significantly (P<0.001) higher in Serena (1339±44.3 g / plant) compared to Scarlet (1234±34.2) and Jubilee (940±36.7), and in Scarlet compared to Jubilee. The effect of tipping date on total yield for each cultivar is shown in Figure 3.8; overall only the main effect of tipping date was significant (P<0.001) with total yield higher in T01 (1249±56.) and T15 (1216±46.8) compared to T30 (1047±69.1), and no significant difference between T01 and T15.

Percentage Class 1

Percentage Class 1 was significantly (P<0.001) higher in Serena (91±0.7 %) compared to Scarlet (88±0.6) and Jubilee (80±0.9), and in Scarlet compared to Jubilee. The effect of tipping date on the percentage Class 1 for each cultivar is shown in Figure 3.8; overall there was no significant interaction between cultivar and tipping date and the main effect of tipping date was also not significant.

3.3.2.2 *Berry Number*

Marketable Berry Number

Marketable berry number was significantly (P<0.001) greater in Serena (70.4±2.4 berries / plant) compared to Scarlet (58.2±1.8) and Jubilee (41.4±2.1), and in Scarlet than Jubilee. The interaction between cultivar and tipping date was significant (P=0.010, Figure 3.8) such that for Serena, marketable berry number was significantly higher in T01 compared to T15 and T30 (by 20% and 18% respectively), with no difference in between T15 and T30 whilst for Scarlet and Jubilee, there was no significant difference between T01 and T15 but berry number of both was significantly greater than T30 (by 21% and 18% for Scarlet respectively and 42% each for Jubilee).

Un-Marketable Berry Number

Un-marketable berry number was significantly (P<0.001) greater in Jubilee (21.5±1.1 berries / plant) compared to Scarlet (17.5±0.8) and Serena (13.7±1.2), and in Scarlet than Serena. The effect of tipping date on un-marketable berry number for each cultivar is shown in Figure 3.8; overall only the main effect of tipping date was significant (P=0.042) with un-marketable berry number higher in T01 (19.5±1.3) compared to T30 (16.2±1.1) but did not significantly differ from T15 (17.1±1.6), and there was no significant difference between T15 and T30.

Total Berry Number

Total berry number was significantly (P<0.001) greater in Serena (84.1±2.9 berries / plant) compared to Scarlet (75.7±1.9) and Jubilee (62.9±2.7), and in Scarlet than Jubilee. The interaction between cultivar and tipping date was also significant (P<0.001, Figure 3.8) such that for Serena, total berry number was significantly higher in T01 compared to T15 and T30 (by 25% and 21% higher respectively) with no significant difference between T15 and T30, whilst in Scarlet and Jubilee total berry number was significantly higher in T01 and T15 compared to T30 (by 19% and 17% respectively for Scarlet, and 35% and 31% for Jubilee) with no significant difference between T01 and T15 for either cultivar.

3.3.2.3 *Marketable Berry Weight*

Average marketable berry weight was significantly (P<0.001) greater in Scarlet (18.7±0.3 g / berry) and Jubilee (18.3±0.3) compared to Serena (17.3±0.3) with no significant difference between Scarlet and Jubilee. The interaction between cultivar and tipping date was also significant (P=0.002, Figure 3.8) such that in Jubilee, berry weight was significantly greater in T30 compared to T15 (by 8%) whilst in Scarlet, berry weight was greater in both T15 and T30 compared to T01 (by 8% and 11% respectively) and in Serena, berry weight was greater in T15 compared to T01 and T30 (by 11% and 9% respectively).

3.3.2.4 *Cropping Profiles*

Weekly Yield

Figure 3.9 shows marketable yield for Jubilee, Scarlet and Serena picked each week throughout the production phase. In Jubilee, there were no significant differences in marketable yield for the first seven harvests; in Week 8 (20th July) marketable yield was significantly greater in T01 compared to T30 (by 175%). Marketable yield was also significantly higher in T01 compared to T15 and T30 for Week 12 (17th August) by 43% and 44% respectively and in the following week (24th August) by 34% and 66%. All other differences between treatments were not significant.

In Scarlet, there were no significant differences in yield between treatments for the first two harvests, in Week 3 (15th June) marketable yield was significantly higher in T01 compared to T15 (by 28%). In the following week (22nd June) marketable yield was 116% and 85% greater in T01 and T30 compared to T15. However, for Week 6 (6th July) marketable yield was significantly higher in T15 compared to both T01 and T30 (by 119% and 220% respectively). Differences between treatments for the remaining harvests were not significant.

In Serena, there was no significant difference in marketable yield between treatments for the first four harvests, by Week 5 (29th June) marketable yield was 71% and 56% greater in T01 compared to T15 and T30 respectively. By Week 7 (13-July) marketable yield was 157% and 171% greater in both T01 and T15 compared to T30 respectively. However, in the following two weeks marketable yield was significantly greater in T15 compared to T01 and T30 by 243% and 652% respectively in Week 8 (20th July) and by 257% and 437% in Week 9 (27th July). For the remaining ten weeks, there were no significant differences in yield between treatments.

Monthly Yield

Figure 3.9 shows treatment effects on marketable yield for Jubilee, Scarlet and Serena each month throughout the production phase There was a significant difference in marketable yield between cultivars every month; in June, all differences in yield between cultivars were significant ($P<0.001$) with marketable yield 46% and 141% greater in Serena compared to both Scarlet and Jubilee, and 65% in Scarlet compared to Jubilee. In July, marketable yield was significantly ($P=0.010$) higher in Serena compared to Scarlet and Jubilee (by 22% each) whilst in August marketable yield was significantly ($P<0.001$) lower in Serena compared to both Jubilee and Scarlet (by 36% and 112% respectively). In the last two months of cropping (September and October) Serena once again had the greatest marketable yield, significantly higher than both Scarlet and Jubilee.

In June and July, only the main effect of tipping date was significant, in June, marketable yield was significantly ($P=0.003$) greater in T01 compared to both T15 and T30 (by 18% each), whereas in July marketable yield was significantly ($P<0.001$) higher in both T01 and T15 compared to T30 (by 33% and 49% respectively). In August, the interaction between the cultivars and treatments was just significant ($P=0.045$) and showed that whilst there were no significant differences in marketable yield between treatments for Scarlet and Serena, in Jubilee marketable yield was significantly higher in T01 compared to T15 and T30 (37% and 48% respectively). There were no significant treatment effects or interactions on marketable yield in September or October.

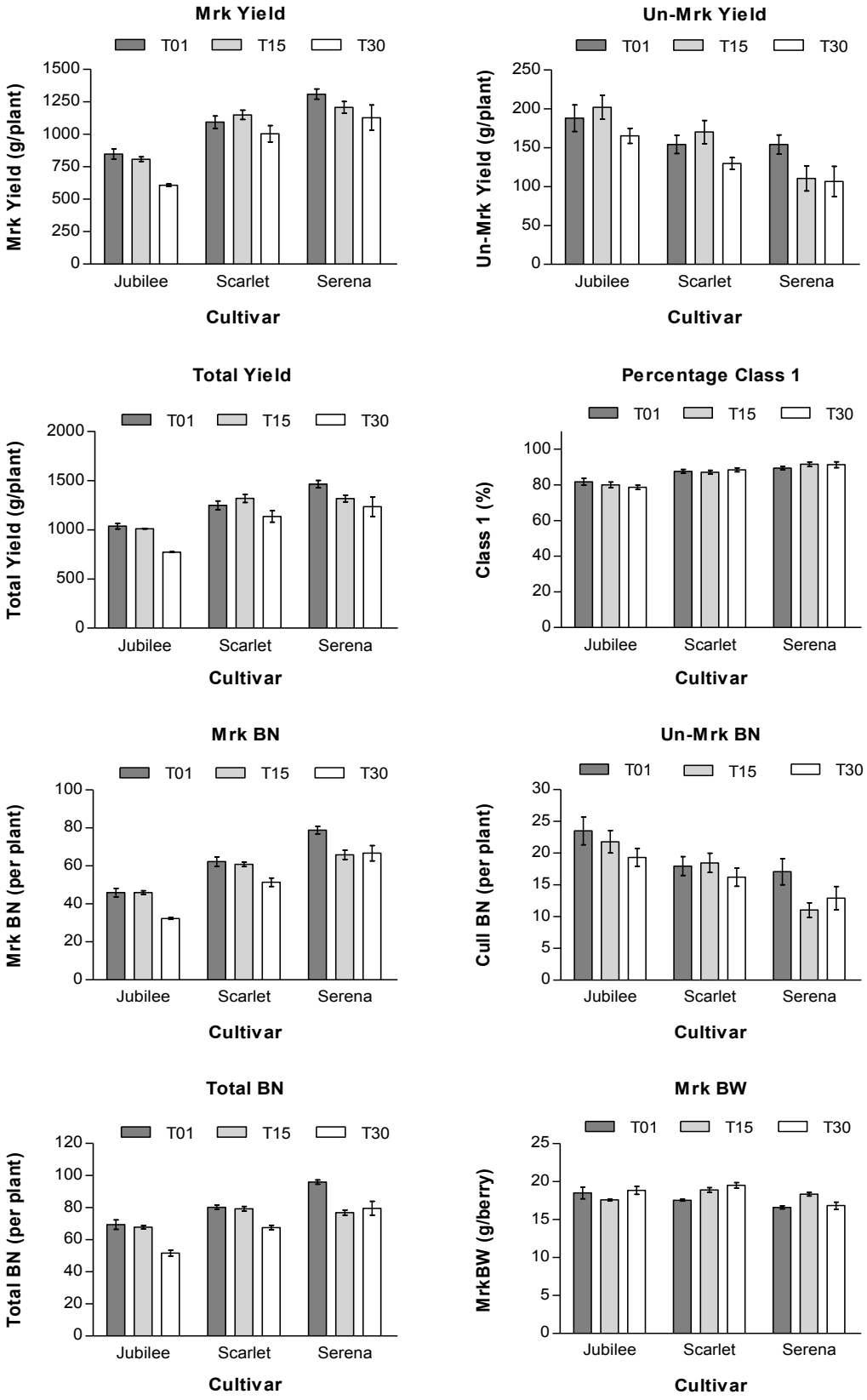

Figure 3.8 Effect of tipping date on cropping results for cultivars Jubilee, Scarlet and Serena (n=4). Mrk= marketable, Un-Mrk= un-marketable, BN= berry number, BW= berry weight. The vertical line on each bar shows ±S.E.M. Tipping dates were: 1st July (T01), 15th July (T15) and 30th July (T30) 2014.

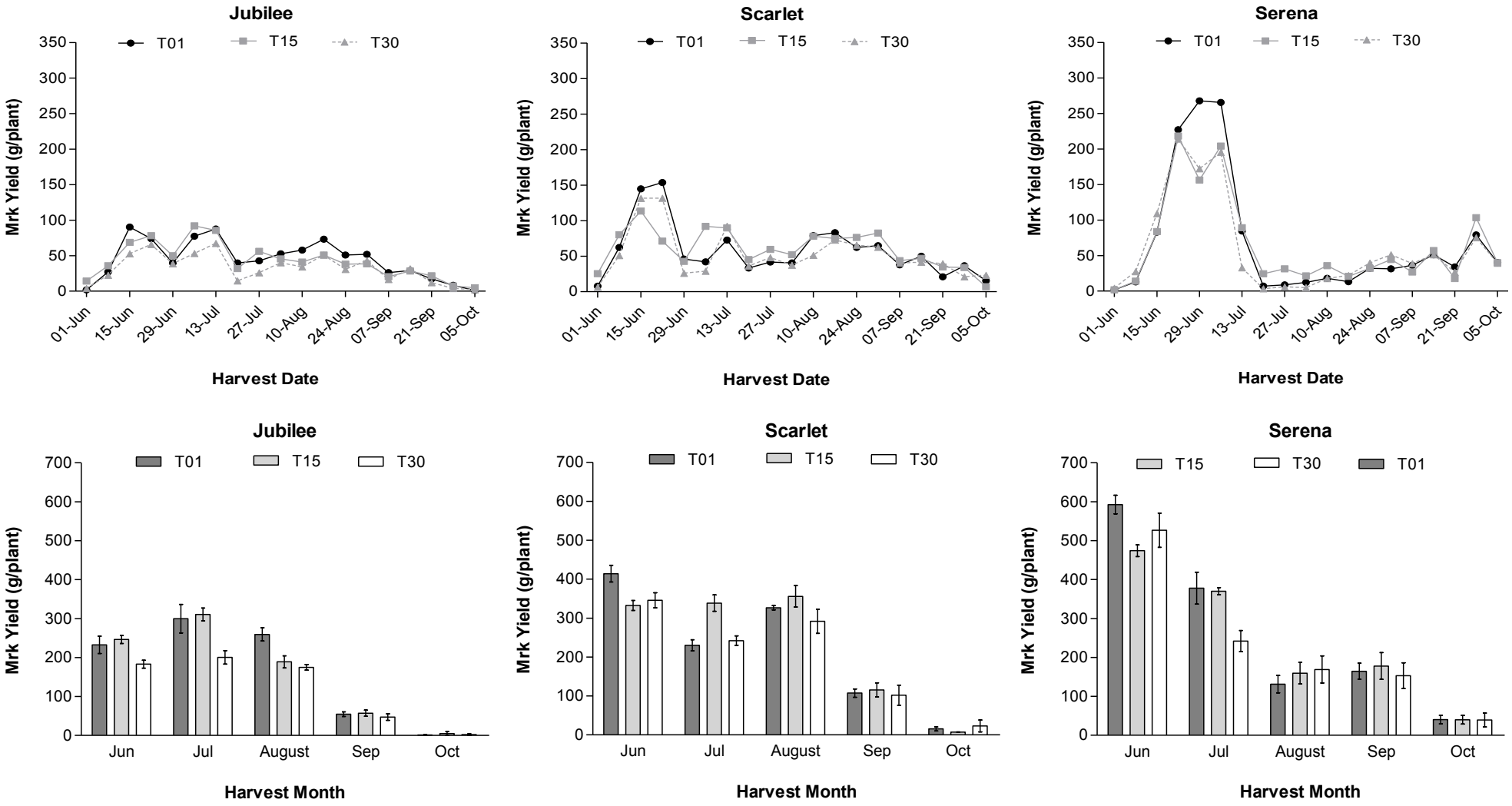

Figure 3.9 Effect of tipping date on weekly (above) and monthly (below) marketable yield for the cultivars Jubilee, Scarlet and Serena (n=4). Mrk= marketable. Tipping dates were 1st July (T01), 15th July (T15) and 30th July (T30) 2014.

3.3.2.5 *Final Destructive Harvest (DH2)*

Crown Number

Figure 3.10 shows the effect of tipping date on crown number for each cultivar; overall only the main effect of tipping date was significant (P=0.008) with crown number higher in T01 (8.3±0.2 crowns / plant) and T15 (8.5±0.5) compared to T30 (6.8±0.4), and there was no significant difference between T01 and T15.

Crown Dry Weight

There were no significant differences in crown dry weight between cultivars, but the interaction between cultivar and tipping date was significant (P=0.006, Figure 3.10) such that in Jubilee, crown dry weight was 42% and 55% higher in T01 compared to T15 and T30 respectively with no significant difference between T15 and T30, whilst in Scarlet and Serena there was no significant differences in crown dry weight between tipping dates.

Leaf Number

Leaf number did not differ significantly between Jubilee (49.9±2.2 g/plant) and Scarlet (55.4±2.5) but was significantly (P<0.001) greater in both compared to Serena (42.25±1.7). Figure 3.10 shows the effect of tipping date on leaf number for each cultivar; overall the main effect of tipping date was just significant (P=0.049) with leaf number higher in T01 (51.5±2.7 leaves / plant) and T15 (51.0±2.5) compared to T30 (45.0±1.8), with no significant difference between T01 and T15.

Leaf Dry Weight

Leaf dry weight was significantly (P<0.001) greater in Jubilee (28.5±1.5 g/plant) compared to Scarlet (24.1±1.2) and Serena (23.3±1.0), with no significant difference between Scarlet and Serena. The effect of tipping date on leaf dry weight for each cultivar is shown in Figure 3.10; overall there was no significant interaction between cultivar and tipping date and the main effect of tipping date was also not significant.

Inflorescence Number

Inflorescence number was significantly (P<0.001) higher in Scarlet (23.3±0.9 per plant) compared to Jubilee (20.3±1.0) and Serena (15.4±0.6), and in in Serena compared to Jubilee. The effect of tipping date on inflorescence number for each cultivar is shown in Figure 3.10; overall, only the main effect of tipping date was significant (P=0.007) with inflorescence number higher in T01 (21.7±1.7 per plant) and T15 (20.8±1.2) compared to T30 (17.8±1.1), and there was no significant difference between T01 and T15.

Total Dry Weight

There were no significant differences in crown dry weight between cultivars. Figure 3.10 shows the effect of tipping date on total plant dry weight for each cultivar; overall only the main effect of tipping date was significant (P=0.027) with total dry weight higher in T01 (68.0±3.7 g/plant) and T15 (67.2±2.4) compared to T30 (58.0±2.5), and there was no significant difference between T01 and T15.

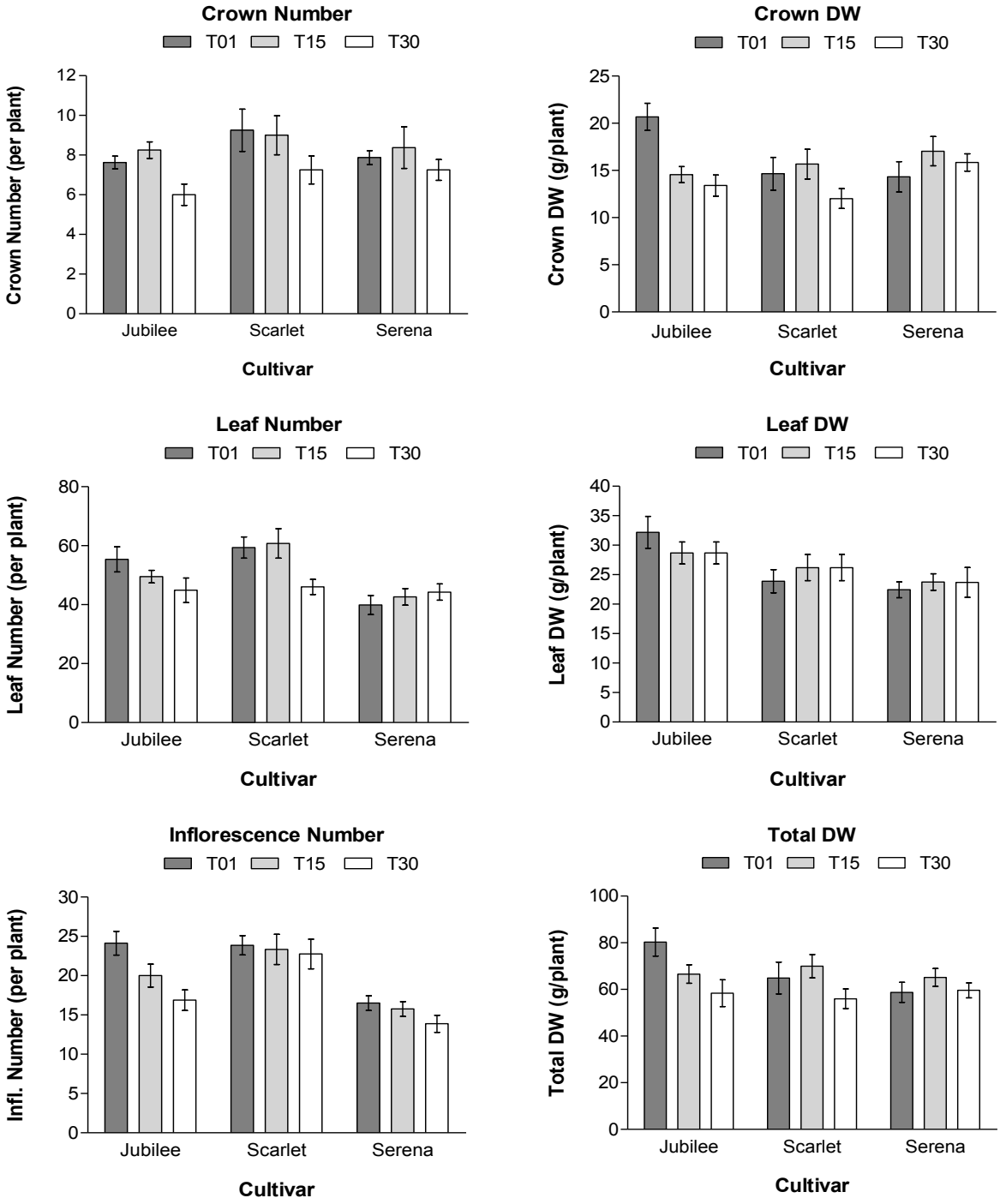

Figure 3.10 Effect of tipping date on DH2 results for cultivars Jubilee, Scarlet and Serena (n=8). DW= dry weight, Infl = inflorescence. The vertical line on each bar shows ±S.E.M. Tipping dates were 1st July (T01), 15th July (T15) and 30th July (T30) 2014.

3.4 Discussion

This experiment was designed to examine the impact of tipping date on transplant growth, yield potential and subsequent cropping performance of three Everbearer strawberry cultivars currently grown in the UK. Overall, tipping date had a significant effect on the cropping performance of the three cultivars; marketable yield was greatest in the daughters tipped on 1st and 15th July compared to those on 30th July (by 170 and 142 g / plant respectively), and this was due to a significant increase in the number of inflorescences and berries produced per plant. Despite there also being a significant increase in the number of un-marketable berries in the earlier tipped daughters, the percentage Class 1 did not significantly differ between treatments. Similarly, although average berry weight was generally higher in later tipped daughters, this did not compensate for the reduction in yield resulting from the reduced berry number.

The total yield of a strawberry plant is essentially the product of the number and individual weight of the berries produced. Berry weight is dependent on the position of the flower in the inflorescence, the number of achenes, pollination rate and plant vigour (Janick & Eggert 1968; Webb et al. 1974; Hansen 1989) whilst the maximum number of berries a plant can produce is determined by the total number of flowers per plant, a product of the number of inflorescences, the number of flowers per inflorescence and the number of flowers that set fruit. In this experiment, marketable yield was improved with earlier tipping due to a greater number of inflorescences and berries produced per plant with an additional 3.9 inflorescences and 12 berries per plant in plants tipped on 1st July compared to 30th July respectively. Webb et al. (1973) described how the period of development between rooting of strawberry daughters and the onset of flower initiation is critical in determining yield potential as this is the period of vegetative growth which ultimately determines the number of flowering sites available. Other researchers also recognised that early rooting allows plants to quickly overcome juvenility and reach an optimum vegetative state which is important for early fruit yield (D'Anna & Iapichino 2003; Cocco et al. 2010; Yoshida & Motomura 2011). Leshem & Koller (1966) identified a linear relationship between rooting date and the duration of vegetative growth, describing how the natural reduction in day-length and temperature through the autumn causes each day to become quantitatively more inductive for flowering, thus limiting further vegetative growth.

The promotion of vegetative growth in the early stages of the plant propagation process is essential to ensure the daughter plants can support maximal flower number. Correlations between the number and size of various plant parts and yield performance have been well-established in strawberry; crown size is regarded as one of the most important factors in determining yield potential, as this ultimately impacts upon the number of floral initiation sites available. The number of branch crowns in the autumn has therefore been positively associated with early and total fruit yield as has crown diameter (Abbott 1968; Lacey 1973; Faby 1997; Le Miere et al. 1998; Human 1999; Bussell et al. 2003; Johnson et al. 2005; Takeda & Newell 2006; Cocco et al. 2010; Fridiaa et al. 2016). Canopy size is also important as buds are formed in the leaf axils which, depending on the environmental conditions, can form a branch crown, stolon or an inflorescence. Leaves are also the main sight site of photosynthesis, and a healthy canopy is important for providing energy to the plant to promote growth. The number of leaves, leaf area and plant weight has also been found to have a positive impact on fruiting in strawberry (Darrow 1966; Hughes 1967; Lacey 1973; Bartczak et al. 2010). The reduction in yield with later tipping shown in this experiment may therefore be explained by the smaller plants produced at the end of the propagation phase. The earlier tipped daughters (1st July and 15th July) were rooted four and two weeks earlier than the daughters tipped on 30th July and so had a longer period for vegetative growth prior to the onset of flower initiation. Measurements made during the propagation phase tracked plant growth over time and, along with the destructive harvest carried out at the end of propagation, showed that plants from the earliest tipping date were larger in terms of crown size (crown number, diameter and dry weight), canopy size (leaf number, area, dry weight) and total plant dry weight. These results are in agreement with Jahn & Dana (1970b) who also found that crown size and canopy size were greater in earlier rooted plants.

The second destructive harvest, at the end of fruiting, revealed that plants originating from the earliest tipping date still had a greater number of crowns, leaves and plant dry weight compared to those originating from the later tipping dates indicating the effect of the tipping treatments was still detectable at the end of the fruiting phase, over a year later. Studies have also found that the vegetative status of the plant at harvest time was also linked to cropping performance, with crown diameter, leaf number and area and plant weight all positively correlated to berry number and yield (Lacey 1973).

Excessive emergence and removal of flowers during the propagation phase has also been found to reduce subsequent yield in strawberries (Professor Paul Hadley, *pers. comm*.). In this experiment, flower and runner number was greater in the earlier tipped daughters, but this did not appear to have a negative impact on fruiting, as the number of inflorescences, marketable berries and marketable fruit yield was also greater in the earlier tipped daughters. This may be linked to the increased transplant size, with larger crowns providing an increased number of sites for floral initiation, sufficient to mask any loss of yield potential due to the greater emergence of flowers and production of runners. Other researchers have also found yield increases in earlier tipped plants despite an increase in autumn flowering; Takeda & Newell (2006) compared the performance of the cultivar 'Carmine' originating from tips taken on 8th July and 4th August 2004 in an annual plasticulture system in Maryland, USA and showed that although autumn flowering was promoted in the July plugged plants, spring yield was significantly higher than the August plugged plants by approximately 23% or 162 g /plant. In the experiment described here, tray plants were produced for a substrate table top system in the UK, but despite the difference in plant type and production method, the results were remarkably similar as the marketable yield of daughters tipped on 1st July yielded 19% (170 g / plant) greater than those tipped on 30th July. Takeda & Newell (2006) attributed the increase in spring yield to the development of branch crowns in the autumn which was greater in July tipped plants (3.1 crowns / plant) than the August tipped plants (2.0) which was also found in this experiment where crown number was greater in the 1st July tipped plants (3.4 crowns / plant) compared to the 30th July (2.0).

Regardless of tipping date, in general there was a high number of flowers expressed during the autumn, particularly in the cultivar Serena. This may be due to the light and temperature conditions in which the plants were propagated, which were higher than ambient levels. In strawberry, flowers initiated in the autumn typically do not continue to develop once the plant has become dormant, flowering occurs in spring when conditions are more favourable. In this experiment, until 1st December all the plants were grown in a relatively warm temperature regime (10/20°C heating/venting) and with 12-hrs of high intensity supplementary lighting per; if this heating and lighting regime had continued it is likely there would have been a greater number of flowers produced in the autumn and a greater yield penalty may have been observed. However, since the plants were placed under natural light and cool conditions from 1st December they became dormant, preventing further flower emergence and loss of yield potential.

Analysis of the weekly and monthly harvest data showed that after the first month of cropping, marketable yield was greater in daughters tipped on 1st July compared to both 15th and 30th July, (by 22% each equating to 61 g / plant). However, by the end of cropping there was no significant difference in marketable yield between daughters tipped on 1st and 15th July, with the difference between these treatments reduced to 29 g / plant. Unlike Junebearers where flowers are initiated entirely within the autumn preceding fruiting, for Everbearer strawberries there is a second period of flower initiation in the spring which could have diluted the yield gained by the end of the season. This is supported by research by Fridiaa et al. (2016) who showed in Day Neutral cultivars, more vigorous transplants flowered earlier and had a greater yield early in the season but there was no difference in yield by the end of the season; the authors described a buffering effect of continued vegetative growth, flowering and fruiting leading to a dilution and eventual disappearance of the yield benefits found earlier in the season. Plants tipped on the 30th July in this experiment produced the smallest transplants and the lowest yield in both the first month of cropping and at the end of fruiting. At planting daughters tipped on 30th July were the smallest and least vigorous; transplants with a smaller leaf area have been shown to produce less photosynthate and have lower carbohydrate reserves stored in the roots and crowns, negatively impacting on flower production (Albregts 1968). Gautier (2001) also explained that less vigorous transplants also have a slower initial growth as new roots are not immediately able to take up nutrients in the spring and so plants are reliant on reserves stored over the previous season. These factors could explain why spring flower initiation was not substantial enough in the latest tipped daughters to dilute the yield benefit of earlier tipping gained early in the season.

Overall, the propagation process plays a key role in determining the yield potential of strawberry transplants. The results of the experiment conducted here clearly show the potential to improve fruit yield of Everbearer strawberries through earlier tipping. Vegetative plant growth was greater in the earliest tipped plants throughout the propagation phase and the earliest tipping date produced the largest transplants. Earlier tipping led to a significant increase in the number of inflorescences and berries produced per plant resulting in an increase in total yield at the end of cropping on average 19% or 170 g / plant compared to those tipped four weeks later. There was also a positive effect of tipping date on the cropping profile, which benefitted the economically important early yield, with marketable yield after the first month of cropping 22%, or 61 g / plant, greater in plants tipped on 1st and 15th July compared to 30th July.

Chapter 4

Effect of daughter plant position on cropping performance of three Everbearer strawberry cultivars.

4.1 Introduction

As the cultivated strawberry (*Fragaria x ananassa* Duch.) is a hybrid, vegetative propagation is carried out to ensure the next generation of plants are true to type. Vegetative propagation is achieved by harvesting genetically identical daughter plants which form on the runners (stolons) emerging from the crown of the mother plant in late summer. Each runner can bear numerous daughter plants in what is termed a runner string; and although genetically identical, daughter plants formed in later positions on the runner are physiologically younger, and comparably smaller, than those formed in earlier positions (closer to the mother plant). In current commercial practice, daughter plants ready to be rooted (those with two to three root nodules on the underside of the crown) are harvested regardless of their position on the runner string which could lead to great variability in the quality of the plant material produced.

Runners are typically produced under long photoperiods and high temperatures, with the daughter plants developing along the runner as the season progresses. This means that the daughter plants are formed under a range of photo-thermic conditions which alter their development. Leshem & Koller (1966) explained that daughters found in the middle of the runner are more balanced in terms of vegetative and reproductive growth, and this is due to the environmental conditions in which they are formed. The earliest daughter plants are typically produced when the days are still long and temperatures high which means vegetative growth is promoted but the flowering rate is low, whilst daughters at the end of the runner are produced later in the season when the flowering rate is high due to the shortening days and cooler temperatures, but the daughters have not achieved a great enough size to support maximal flower numbers. Research on the effect of daughter plant position on the cropping performance of strawberry is limited and has shown mixed results; Larson (1994) found no significant effect of daughter plant position on the yield of the Junebearer 'Chandler', also confirmed by Takeda et al. (2004), but in the Day Neutral cultivar 'Selva' secondary daughters yielded greater than tertiary daughters. D'Anna & Iapichino (2002) found no effect of daughter plant position on yield of the

Junebearer 'Cartuno' but in 'Tudlo' total yield was greater in primary daughters compared to secondary and tertiary daughters. In a subsequent study with the same cultivars, D'Anna & Iapichino (2003) found no effect of daughter position on total yield, but early season yield was greatest in tertiary daughter plants, supporting the results of Hamman & Poling (1997) where early yield was also found to be greater in earlier positioned daughters for the cultivar 'Selva.'

There has been little or no research conducted on the effect of daughter plant position on Everbearer strawberry cultivars, particularly on those currently cropped in the UK. The results of the previous experiments on Junebearer and Day Neutral strawberries suggest a potential to improve marketable yield using daughter plant position, and particularly to enhance early yield which would be beneficial to the industry where the current goal is to increase production outside of the main strawberry season. An experiment was therefore designed to examine the impact of daughter plant position on transplant growth, yield potential and subsequent cropping performance of three Everbearer strawberry cultivars currently cropped in UK.

4.2 Materials and Methods

4.2.1 Propagation Phase

Plant Material and Experimental Treatments

One-hundred runners were taken from mother plants of Everbearer strawberry cultivars Jubilee, Scarlet and Serena on 13th August 2015. Runners with at least three daughter plants with 2-3 visible root nodules, and at least one fully expanded leaf were selected and the daughter plants severed from the runners. The daughter plants were sorted into three treatments depending on their position on the runner. Treatments and codes were as follows: primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

Misted tip production was carried out using the methods described in Chapter 2; briefly, 56 uniform daughter plants for each cultivar and treatment were selected and struck into multi-celled trays containing a 50:50 mix of peat and coir and overhead misted with mains water, plus a daily foliar feed, for four weeks for root establishment. Once rooted, 30 uniform plants were selected and individually re-potted into 90 x 87 mm (diameter x depth) coir filled pots. The plants were then transferred to three temperature-controlled glasshouse compartments on 19th September, with ten plants per cultivar per treatment in each compartment.

The compartments were as described in Chapter 2; plants were propagated under ambient light levels and the heating and venting set points of each compartment was 12/18°C respectively until 3rd December 2015 when this was reduced to 2/5°C for chilling. Temperatures were logged in each compartment every hour and the average 24-hr temperature calculated prior to chilling was 15.1°C, 14.9°C and 15.8°C. Fertigation was set up and supplied as described in Chapter 2.

Propagation Phase Measurements

Treatments effects on transplant growth and yield potential were determined through a combination of non-destructive measurements and a destructive harvest at the end of the propagation phase. Ten randomly selected plants of each cultivar in each treatment were tagged upon transfer to glasshouse; on a weekly basis, open flower number, leaf number, crown diameter and root scores were recorded on the tagged plants.

At the end of the propagation phase a destructive harvest was carried out on six of the ten tagged plants and the following measurements were made on each plant: crown number, crown diameter, leaf number, leaf area, root score and dry weight of the leaves, crowns and petioles along with a total plant dry weight calculated as the sum of the individual components. All measurements were taken using the methods described in Chapter 2.

4.2.2 Production Phase

Experimental Design

At the end of the propagation phase, remaining plants were cropped in a twin span tunnel at the Soft Fruit Technology Group's Field Site at the University of Reading's Sonning Farm set up as described in Chapter 2. Four bags containing six plants, were planted for each cultivar and treatment giving a total of 24 plants. Bags were planted on 25th March 2016. The experimental area was divided into four blocks to account for variation in temperature and light levels across the experimental area and one replicate (bag) was assigned to each block in a randomised position. Guard bags were placed at the end of each row to minimise edge effects. Figure 4.1 shows the layout of the blocks, cultivars and treatments.

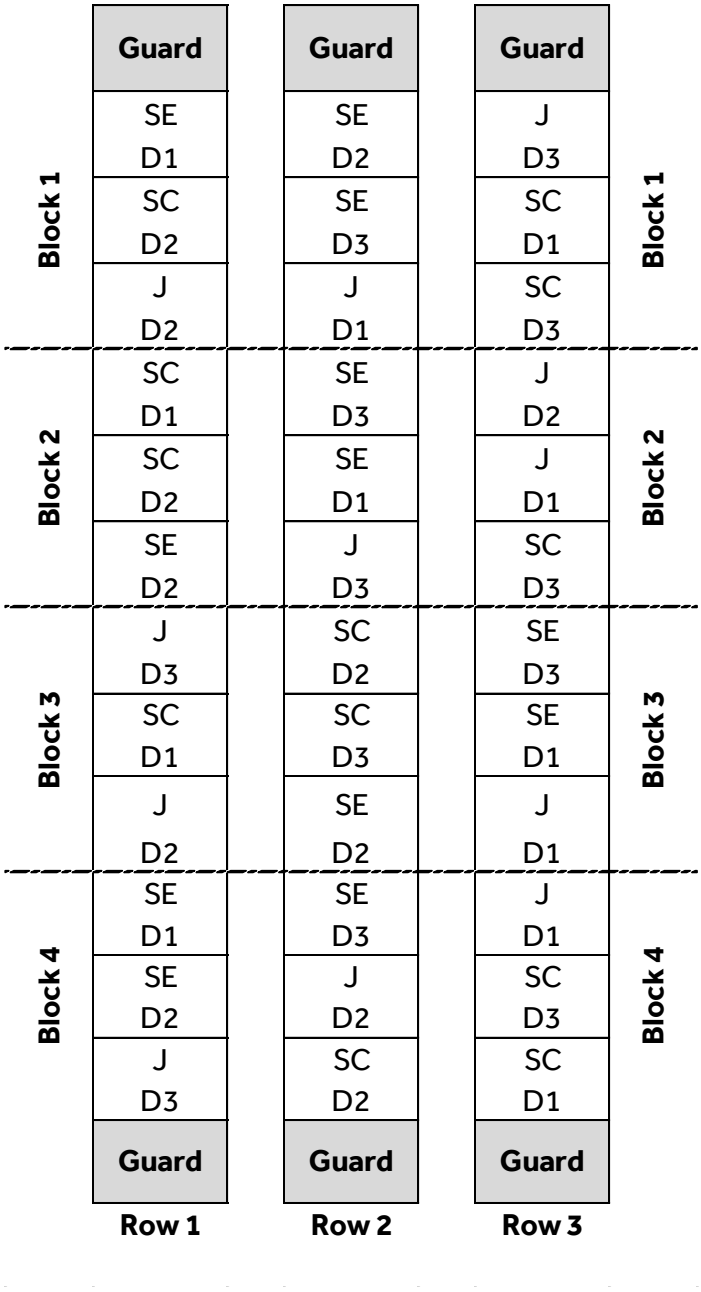

Figure 4.1 Arrangement of blocks, cultivars and treatments (daughter plant position) for the production phase of the strawberry cultivars Jubilee (J), Scarlet (SC) and Serena (SE) in one span of a twin span polytunnel situated at the Soft Fruit Technology Group's Field Site at the University of Reading's Sonning Farm. Each box represents a 1 m strawberry bag each with six plants. Treatments were: primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

Growing Conditions

Temperature control, plant husbandry and fertigation was set up and carried out as described in Chapter 2. Figure 4.2 shows the average 24 hr temperature logged throughout the production phase for the experiment.

Production Phase Measurements

To determine treatment effects on cropping performance, data on total, marketable and un-marketable yield and berry number were recorded on a weekly basis. Average marketable berry weight and percentage Class 1 were also calculated at the end of cropping. Data was collected at the bag level and converted to a per plant basis for analysis.

A final destructive harvest was carried out at the end of the production phase to determine treatment effects on final plant size; two plants were harvested from each bag for each cultivar and treatment combination and the following measurements were made on each plant: crown number, leaf number, inflorescence number and dry weight of the leaves, crowns, petioles and inflorescences with a total plant dry weight calculated as the sum of the individual components. All data was collected using the methods described in Chapter 2.

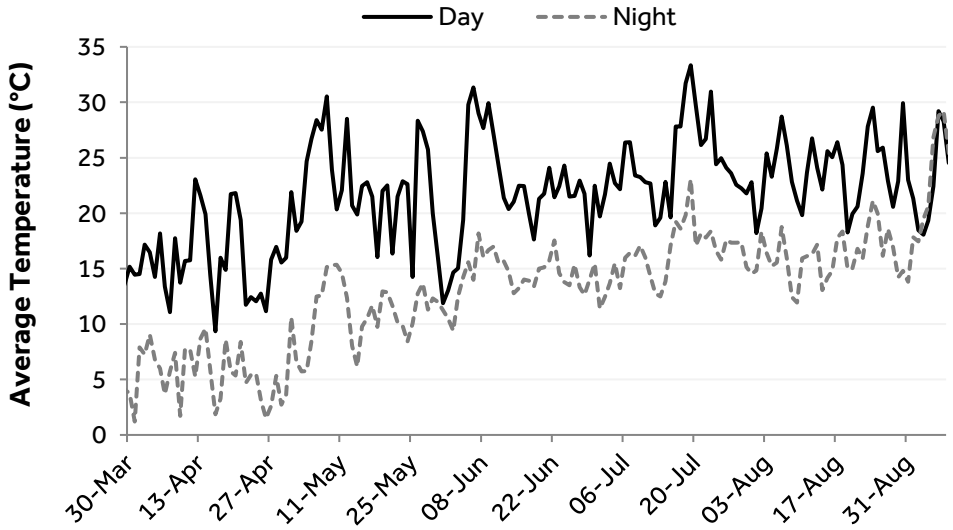

Figure 4.2 Mean day and night temperature logged throughout the production phase for Everbearer cultivars Jubilee, Scarlet and Serena. Day = 07:00 to 19:00.

4.3 Results

4.3.1 Propagation Phase

4.3.1.1 *Open Flower Number*

The number of flowers expressed during the propagation phase did not significantly differ between Scarlet (3.0±0.4 flowers / plant) and Serena (2.3±0.4) but was significantly (P<0.001) greater in both compared to Jubilee (1.3±0.3).

Treatment effects on open flower number for each cultivar are shown in Figure 4.3; overall only the main effect of daughter position was significant (P<0.001) with flower number greater in D1 (4.0±0.4 flowers / plant) compared to D2 (2.0±0.3) and D3 (0.6±0.1), and in D2 compared to D3.

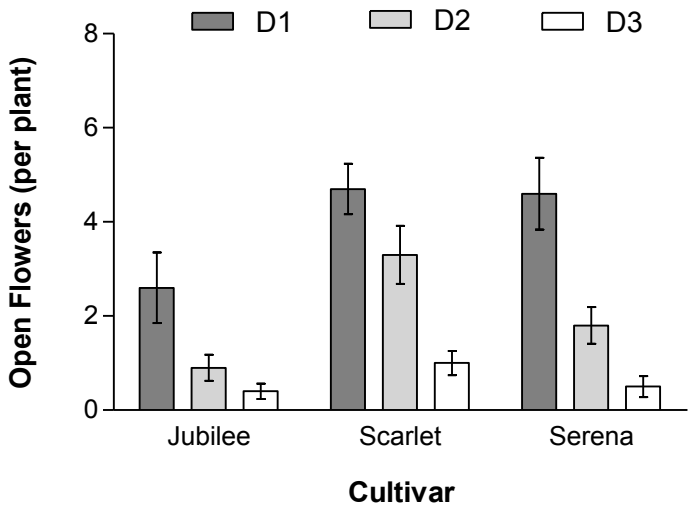

Figure 4.3 Effect of daughter plant position on the number of open flowers produced per plant during the propagation phase for cultivars Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. Treatments were primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

4.3.1.2 *Non-Destructive Measurements*

Leaf Number

Figure 4.4 shows leaf number per plant for each cultivar and treatment counted every week during the propagation phase. In Jubilee, there were no significant differences in leaf number between treatments in the first three weeks, but from 2nd November leaf number was significantly higher in D1 and D2 compared to D3, with no significant difference between D1 and D2 at any time. In Scarlet, there was only a significant effect of daughter position on leaf number in the first two weeks, where leaf number was significantly higher in D2 compared to D1 and D3. Leaf number was significantly higher in D1 compared to D2 and D3 every week for Serena, except on 19th October where there was no significant difference between D1 and D2. There was also no significant difference in leaf number between D2 and D3 at any time.

Crown Diameter

Figure 4.5 shows crown diameter for each cultivar and treatment measured every two weeks during the propagation phase. For Jubilee, crown diameter was significantly higher in D1 compared to D3 in all weeks, and all other differences between treatments were not significant. In Scarlet, crown diameter was significantly higher in D1 compared to D2 and D3 in all weeks, and there was no significant difference between D2 and D3 at any time. In Serena, crown diameter was significantly greater in D1 compared to D3 in all weeks, and greater than D2 in the first week (12th October) and from 9th to 23rd November. Crown diameter was also significantly higher in D2 compared to D3 from 19th October.

Root Score

Figure 4.6 shows the root score for each cultivar and treatment recorded every two weeks during the propagation phase. In Jubilee, there was only a significant difference in root score between treatments in the first two weeks, where root score was significantly greater in D2 compared to D1 and D3. In Scarlet, root score was significantly higher in D1 and D2 compared to D3 in all weeks, with no significant difference between D1 and D2 at any time. In Serena from 26th October root score was significantly higher in D1 compared to D2 and D3, and also in D2 compared to D3.

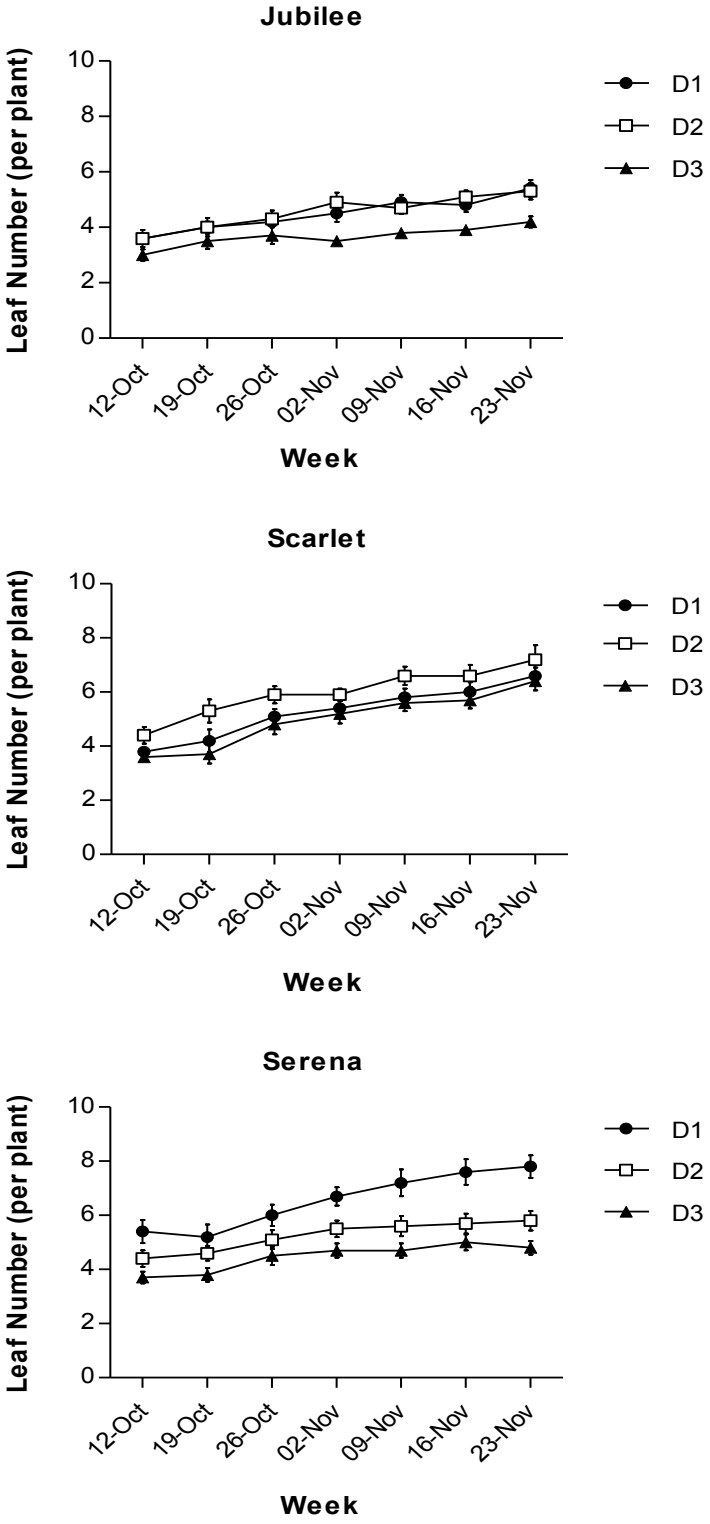

Figure 4.4 Effect of daughter plant position on leaf number every week during the propagation phase for cultivars Jubilee, Scarlet and Serena (n=10). The vertical line on each data point shows ±S.E.M. Treatments were primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

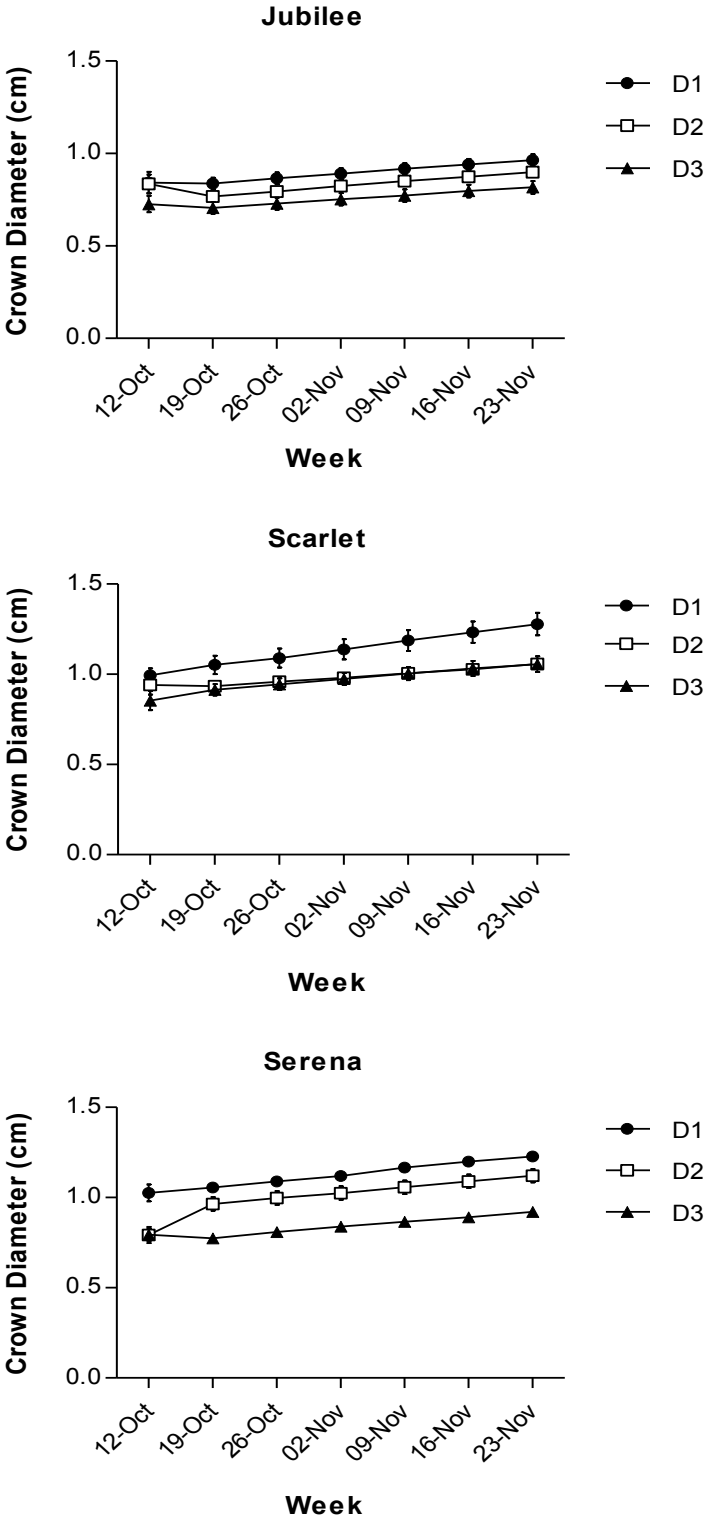

Figure 4.5 Effect of daughter plant position on crown diameter every week during the propagation phase for cultivars Jubilee, Scarlet and Serena (n=10). The vertical line on each data point shows ±S.E.M. Treatments were primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

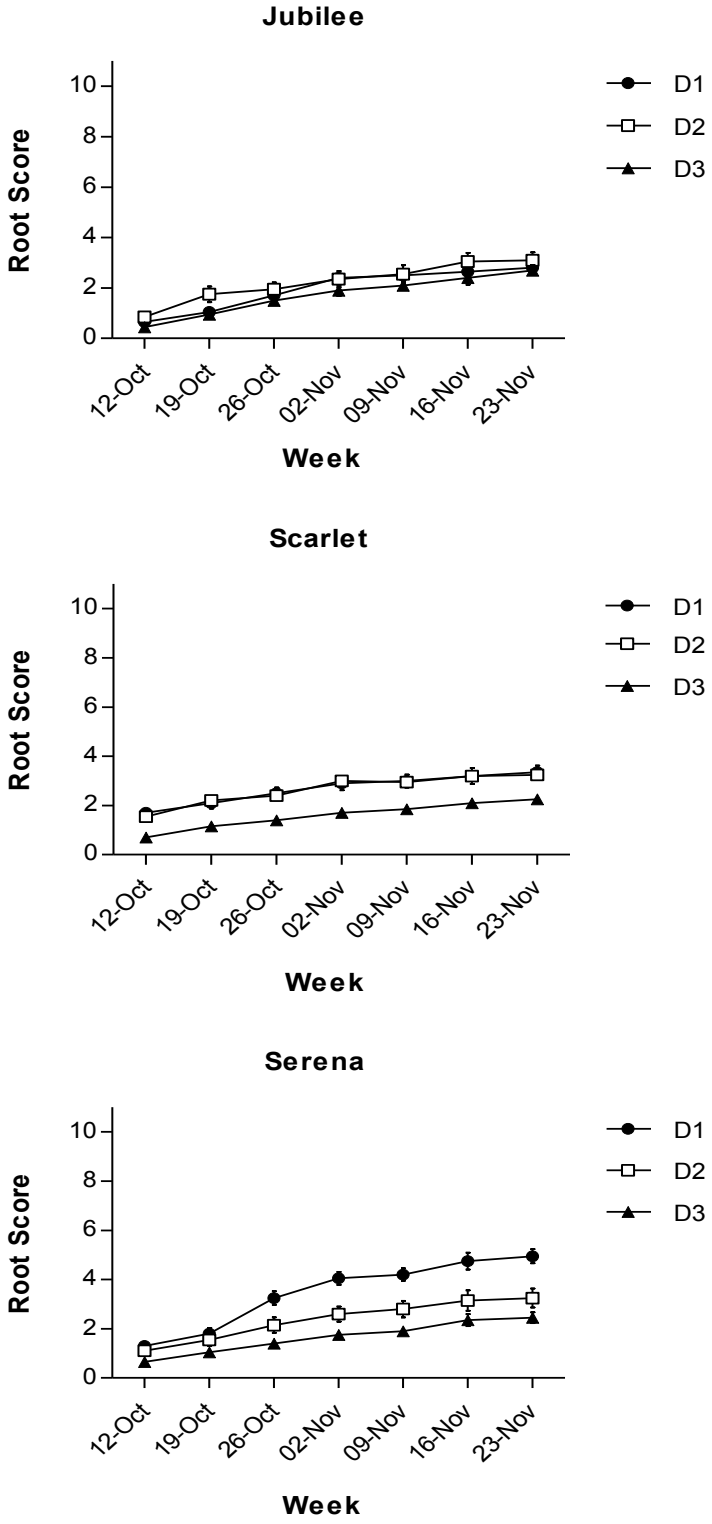

Figure 4.6 Effect of daughter plant position on root score every week during the propagation phase for cultivars Jubilee, Scarlet and Serena (n=10). The vertical line on each data point shows ±S.E.M. Treatments were primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

4.3.1.3 *Destructive Harvest (DH1)*

Crown Number

Treatment effects on crown number for each cultivar are shown in Figure 4.7; overall only the main effect of daughter position was significant (P=0.004) with crown number higher in D1 (2.0±0.1 crowns / plant) and D2 (1.9±0.1) compared to D3 (1.5±0.1), and there was no significant difference between D1 and D2.

Crown Diameter

Crown diameter was significantly (P<0.001) greater in Scarlet (1.2±0.05 cm) and Serena (1.1±0.06) compared to Jubilee (0.9±0.03), with no significant difference between Scarlet and Serena. Treatment effects on crown diameter for each cultivar are shown in Figure 4.7; overall only the main effect of daughter plant position was significant (P<0.001) with crown diameter greater in D1 (1.2±0.05 cm) compared to D2 (1.0±0.03) and D3 (0.9±0.04), and in D2 compared to D3.

Crown Dry Weight

Crown dry weight was significantly (P<0.001) greater in Scarlet (0.30±0.03 g / plant) and Serena (0.37±0.05) compared to Jubilee (0.17±0.04), and there was no significant difference between Scarlet and Serena. The interaction between the cultivars and treatments was also significant (P<0.001, Figure 4.7) such that for Jubilee, crown dry weight was 200% greater in D3 compared to D2, whilst in Serena crown dry weight was significantly higher in D1 compared to D2 and D3 (103% and 221% respectively) and there were no significant differences for Scarlet.

Leaf Number

Leaf number was significantly (P<0.001) greater in Scarlet (7.7±0.4 leaves / plant) compared to Serena (6.6±0.6) and Jubilee (5.4±0.3), and in Serena compared to Jubilee. The interaction between the cultivars and treatments was also significant (P<0.001, Figure 4.7) such that for Jubilee and Serena leaf number was significantly greater in D1 compared to D2 and D3 (by 19% and 36% for Jubilee, and 78% and 90% for Serena respectively) whereas in Scarlet, leaf number was significantly greater in D1 and D2 compared to D3 (23% and 31% respectively).

Leaf Area

Leaf area was significantly (P<0.001) higher in Scarlet (149.8±11.3 cm^2 / plant) compared to Serena (107.2±13.2) and Jubilee (60.9±4.4), and in Serena compared to Jubilee. The interaction between the cultivars and treatments was also significant (P<0.001, Figure 4.7); such that for Scarlet, leaf area was 82% and 83% greater in D1 and D2 compared to D3, whereas in Serena leaf area was 117% and 151% greater in D1 compared to both D2 and D3 and there were no significant differences for Jubilee.

Leaf Dry Weight

Leaf dry weight was significantly (P<0.001) greater in Scarlet (1.26±0.09 g / plant) compared to Serena (0.89±0.10) and Jubilee (0.44±0.04), and in Serena compared to Jubilee. The interaction between the cultivars and treatments was also significant (P<0.001, Figure 4.7) such that for Scarlet, leaf dry weight was 69% and 71% greater in D1 and D2 compared to D3, whereas in Serena leaf dry weight was 103% and 146% greater in D1 compared to both D2 and D3 and there were no significant differences for Jubilee.

Root Score

Root score was significantly (P=0.023) greater in Serena (3.4±0.3) compared to Scarlet (2.8±0.2) and Jubilee (2.9±0.2), with no significant difference between Scarlet and Jubilee. The interaction between the cultivars and treatments was also significant (P<0.001, Figure 4.7) such that for Scarlet, root score was significantly greater in D1 and D2 compared to D3, whereas in Serena root score was greater in D1 compared to both D2 and D3 and there were no significant differences for Jubilee.

Total Dry Weight

Total dry weight was significantly (P<0.001) greater in Scarlet (1.96±0.27 g / plant) compared to Serena (1.45±0.17) and Jubilee (0.68±0.06), and in Serena compared to Jubilee. The interaction between the cultivars and treatments was also significant (P=0.017, Figure 4.7) such that in Scarlet, total dry weight was 136% and 77% greater in D1 and D2 compared to D3, whereas in Serena total dry weight was 97% and 173% greater in D1 compared to both D2 and D3 and there were no significant differences for Jubilee.

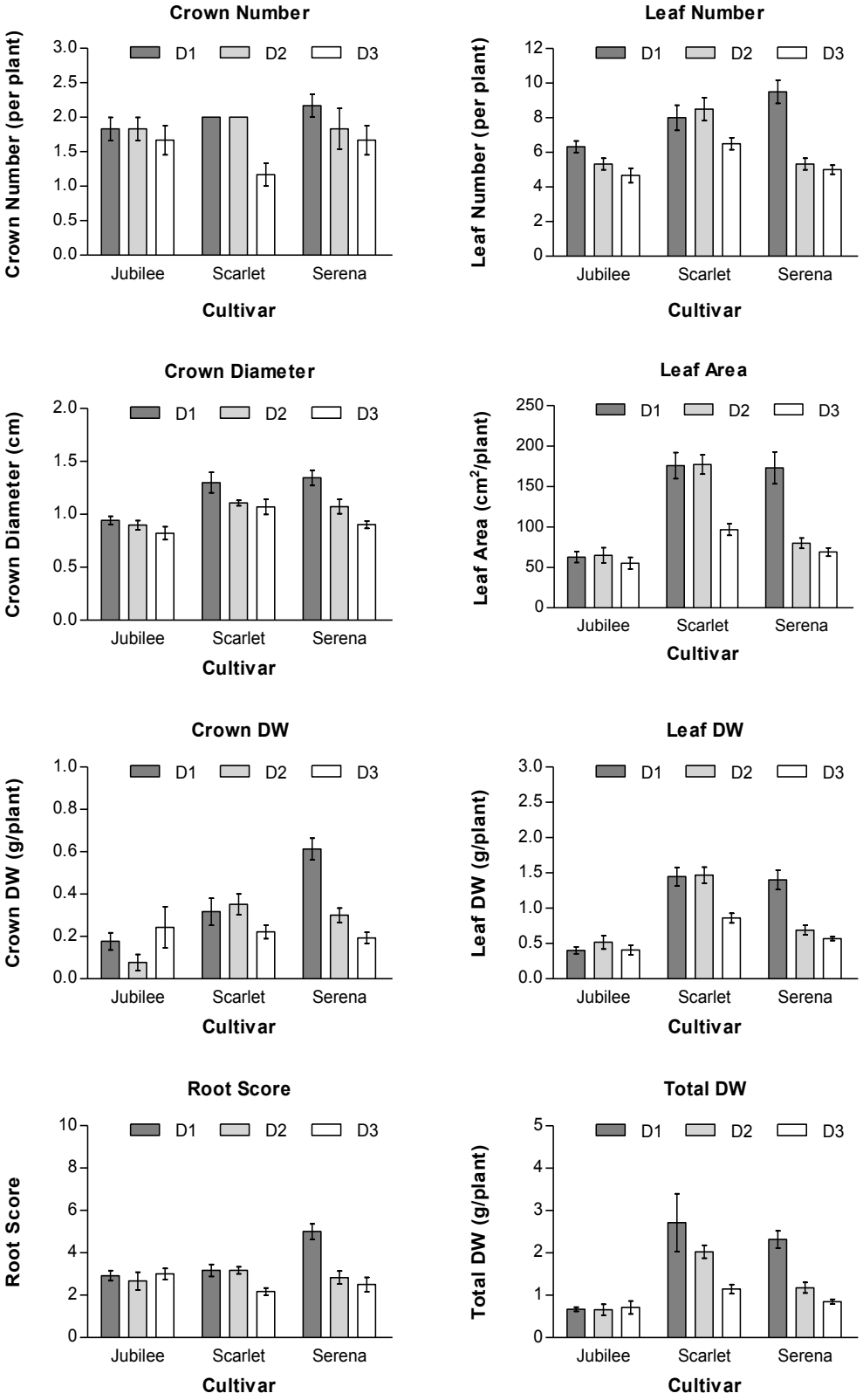

Figure 4.7 Effect of daughter plant position on DH1 results for cultivars Jubilee, Scarlet and Serena (n=6). DW= dry weight. The vertical line on each bar shows ±S.E.M. Treatments were primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

4.3.2 Production Phase

4.3.2.1 *Yield Results*

The effect of daughter plant position on cropping for each cultivar is shown in Figure 4.8. Although there was a reduction in marketable yield, total yield and marketable berry number with later tipping for Scarlet and Serena overall there was no significant differences between treatments found. There was also significant interaction between the cultivars and treatments for any yield data and the main effects of daughter plant position was also not significant. The following text therefore discusses the significant differences found between the cultivars.

Yield and Percentage Class 1

Total yield of Serena (637±15.4 g / plant) and Scarlet (665±22.1) did not significantly differ but were significantly ($P<0.001$) greater than Jubilee (505±17.6). Similarly, marketable yield was significantly ($P<0.001$) greater in Serena (587±17.2 g / plant) and Scarlet (587±23.2) compared to Jubilee (440±18.7), with no significant difference between Serena and Scarlet. The un-marketable yield was significantly ($P=0.005$) greater in Scarlet (78±8.2 g / plant) compared to Jubilee (65±5.6) and Serena (50±4.0), and in Jubilee compared to Serena. Serena therefore had the greatest percentage Class 1 (92±0.7%), significantly ($P<0.001$) higher than Scarlet (88±1.3%) and Jubilee (87±1.1%) which did not significantly differ.

Berry Number

Total berry number of Serena (42.6±0.7 berries / plant) and Scarlet (44.6±1.6) did not significantly differ but were significantly ($P<0.001$) greater than Jubilee (35.7±1.1). Similarly, marketable berry number of Serena (34.7±1.0 berries / plant) and Scarlet (32.5±1.6) were significantly ($P<0.001$) greater than Jubilee (24.9±1.1) with no significant difference between Serena and Scarlet. The un-marketable berry number was significantly ($P=0.005$) greater in Scarlet (12.2±1.4 berries / plant) and Jubilee (10.8±0.9) compared to Serena (7.9±0.6), with no significant difference between Scarlet and Jubilee.

Average Berry Weight

Average berry weight of Scarlet (18.2±0.2 g / plant) was significantly ($P=0.011$) higher than Serena (17.0±0.4) but did not significant differ from Jubilee (17.7±0.2). There was also no significant difference in average berry weight between Serena and Jubilee.

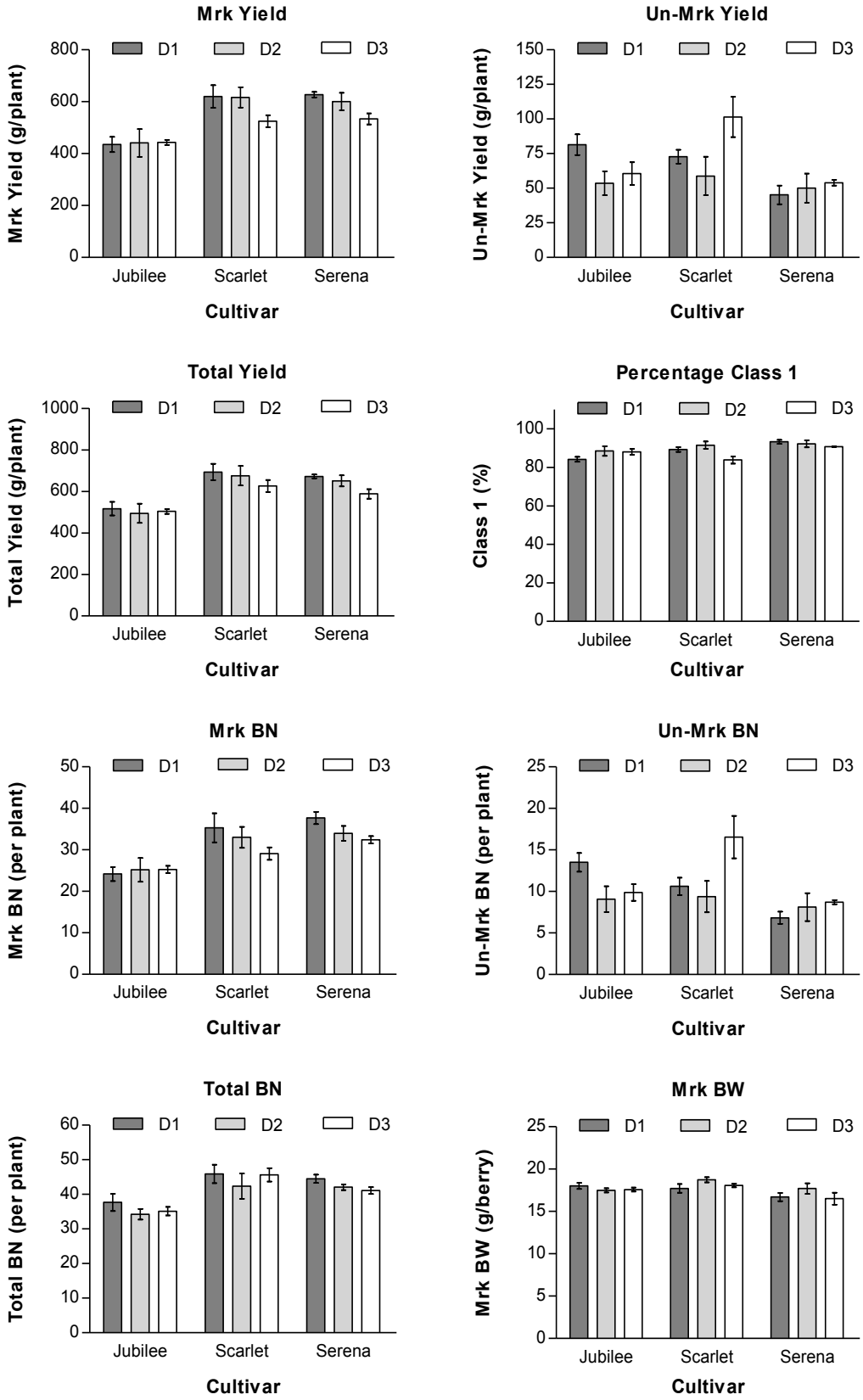

Figure 4.8 Effect of daughter plant position on cropping results for cultivars Jubilee, Scarlet and Serena (n=4). Mrk= marketable, Un-Mrk= Un-Marketable, BN= berry number, BW= berry weight. The vertical line on each bar shows ±S.E.M. Treatments were primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

4.3.2.2 *Cropping Profiles*

Weekly Yield

Figure 4.9A shows the effect of daughter plant position on marketable yield for Jubilee, Scarlet and Serena picked each week throughout the production phase. There was no significant interaction between the cultivars and treatments at any point. From Week 4 (14th June) to Week 7 (5th July) there was a significant difference in marketable yield between cultivars ($P<0.001$, Figure 4.10B), in Week 4 and 5 marketable yield was greater in Serena than both Scarlet and Jubilee (by 113% and 101% in Week 4, and 32% and 87% in Week 5 respectively). In Week 6 there was no significant difference between Serena and Scarlet but yield of both was significantly greater than Jubilee (by 179% and 138%), and by Week 7 marketable yield of Scarlet was significantly greater than both Serena and Jubilee (by 36% and 47% respectively).

The main effect of daughter plant position was also significant ($P=0.003$) in Week 2 (31st May, Figure 4.10B) where the marketable yield in D2 and D3 was 87% and 91% higher than D1 respectively and in Week 9 (19th July, Figure 4.10B) where marketable yield was 32% greater in D2 compared to D3.

Monthly Yield

Figure 4.9A shows the effect of daughter plant position on marketable yield for Jubilee, Scarlet and Serena picked each month throughout the production phase. Differences in monthly yield between cultivars were significant in June and July ($P<0.001$, Figure 4.9B). Marketable yield was significantly greater in both Serena and Scarlet compared to Jubilee in June by 94% and 44% respectively, and by 17% and 38% in July. Marketable yield of Serena was also 35% higher in Scarlet in June, whereas in July the marketable yield of Scarlet was 17% greater than Serena.

There was no significant interaction between the cultivars and treatments in any month. In May, the main effect of daughter plant position was just significant ($P=0.015$, Figure 4.9B); marketable yield was 111% and 102% greater in the D2 and D3 compared to the D1 respectively. For the remaining months, there was no significant effect of daughter plant position on marketable yield.

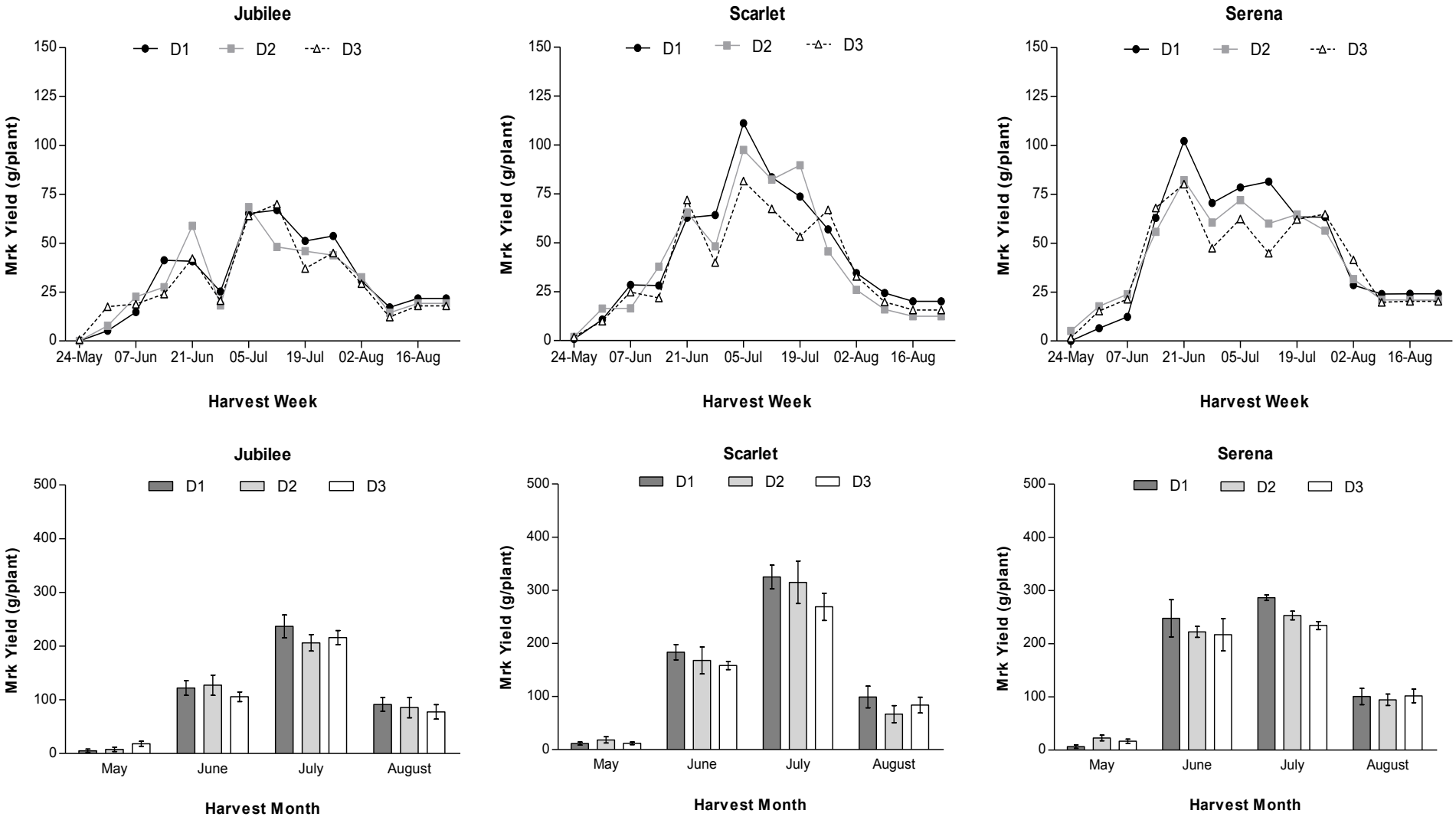

Figure 4.9A Effect of daughter plant position on weekly (above) and monthly (below) marketable yield for the cultivars Jubilee, Scarlet and Serena (n=4). Mrk= marketable. The vertical line on each bar shows ±S.E.M. Treatments were primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

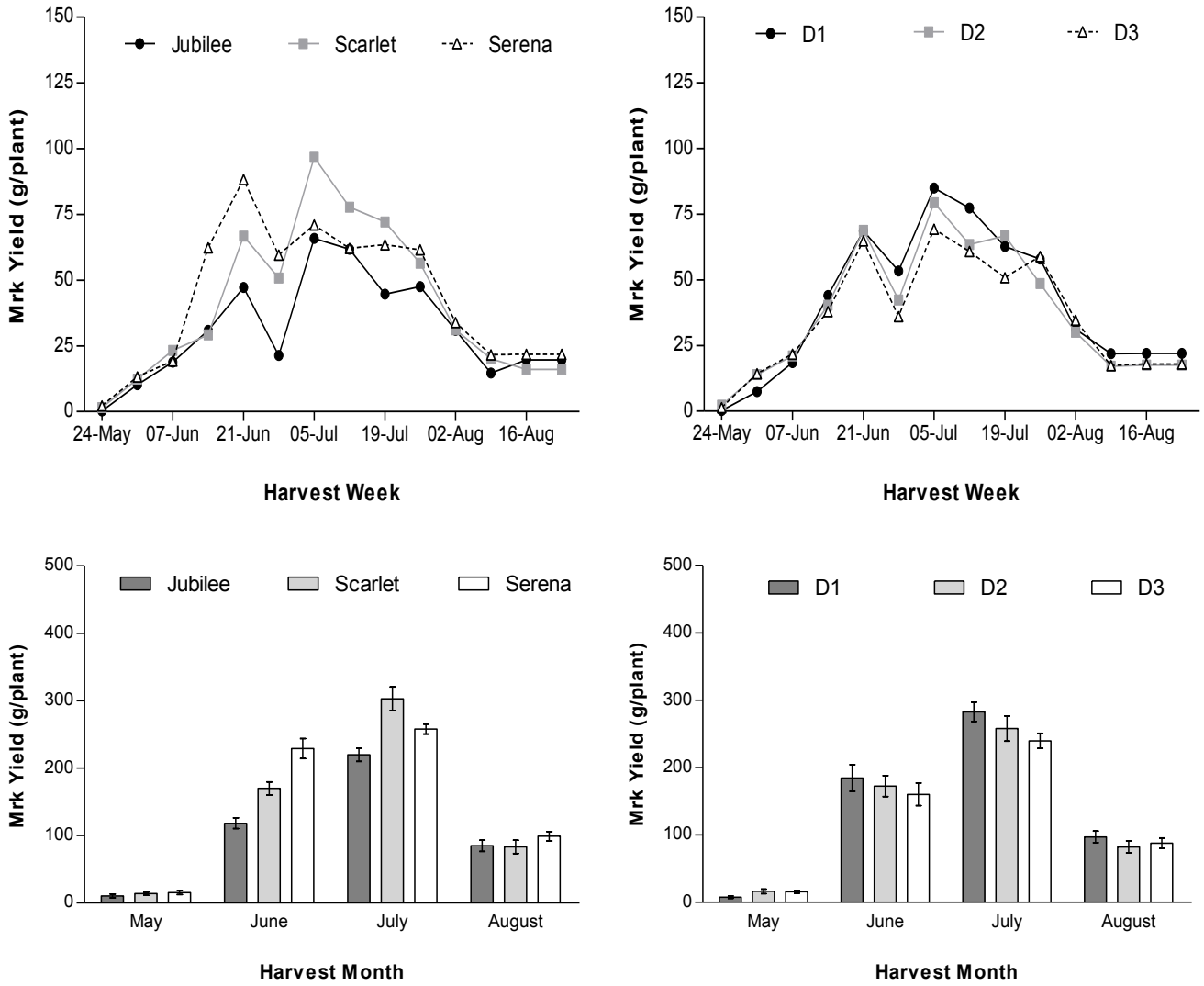

Figure 4.9B Effect of cultivar (n=12) and daughter plant position (n=12) on weekly (above) and monthly (below) marketable yield). Mrk= marketable. The vertical line on each bar shows ±S.E.M. Treatments were primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

4.3.2.3 *Final Destructive Harvest (DH2)*

Crown Number and Crown Dry Weight

Crown number was significantly (P<0.001) greater in Scarlet (7.3±0.4 crowns / plant) compared to Serena (4.6±0.3) and Jubilee (4.4±0.2), with no significant difference between Serena and Jubilee. Crown dry weight was significantly (P<0.001) greater in Jubilee (17.2±0.5 g / plant) compared to Serena (13.9±0.2) and Scarlet (9.6±0.6), and in Serena compared to Scarlet.

Treatment effects on crown number and crown dry weight for each cultivar is shown in Figure 4.10. Only the main effect of daughter position on crown number was significant (P=0.041) where crown number was greater in D3 (6.0±0.5 crowns / plant) compared to D2 (4.8±0.4) but did not significantly differ from D1 (5.5±0.4). There was also no significant difference between D2 and D1. The interaction between the cultivars and treatments for crown dry weight was significant (P=0.003) such that for Jubilee, crown dry weight was 24% and 28% greater in D1 and D2 compared to D3 (with no significant difference between D1 and D2) whilst for Scarlet and Serena there were no significant differences in crown dry weight between treatments.

Leaf Number and Leaf Dry Weight

Treatment effects on leaf number and dry weight for each cultivar is shown in Figure 4.10. Overall, only the differences between the cultivars were significant. Leaf number was significantly (P<0.001) greater in Scarlet (60.7±2.9 leaves / plant) compared to Serena (50.9±1.0) and Jubilee (30.4±1.3), and in Serena compared to Jubilee. Leaf dry weight was significantly (P<0.001) greater in Scarlet (35.4±2.5 g / plant) and Jubilee (33.3±1.4) compared to Serena (23.9±0.7), with no significant difference between Scarlet and Jubilee.

Inflorescence Number and Total Dry Weight

Treatment effects on inflorescence number and total dry weight for each cultivar is shown in Figure 4.10. Overall only the differences between the cultivars were significant. Inflorescence number was significantly (P<0.001) greater in Scarlet (10.2±0.4 inflorescences / plant) compared to Jubilee (6.8±0.3) and Serena (6.9±0.4), with no significant difference between Jubilee and Serena. Total dry weight was significantly (P<0.001) greater in Jubilee (85.2±2.9 g / plant) compared to Scarlet (63.8±4.1) and Serena (63.9±0.8), with no significant difference between Scarlet and Serena.

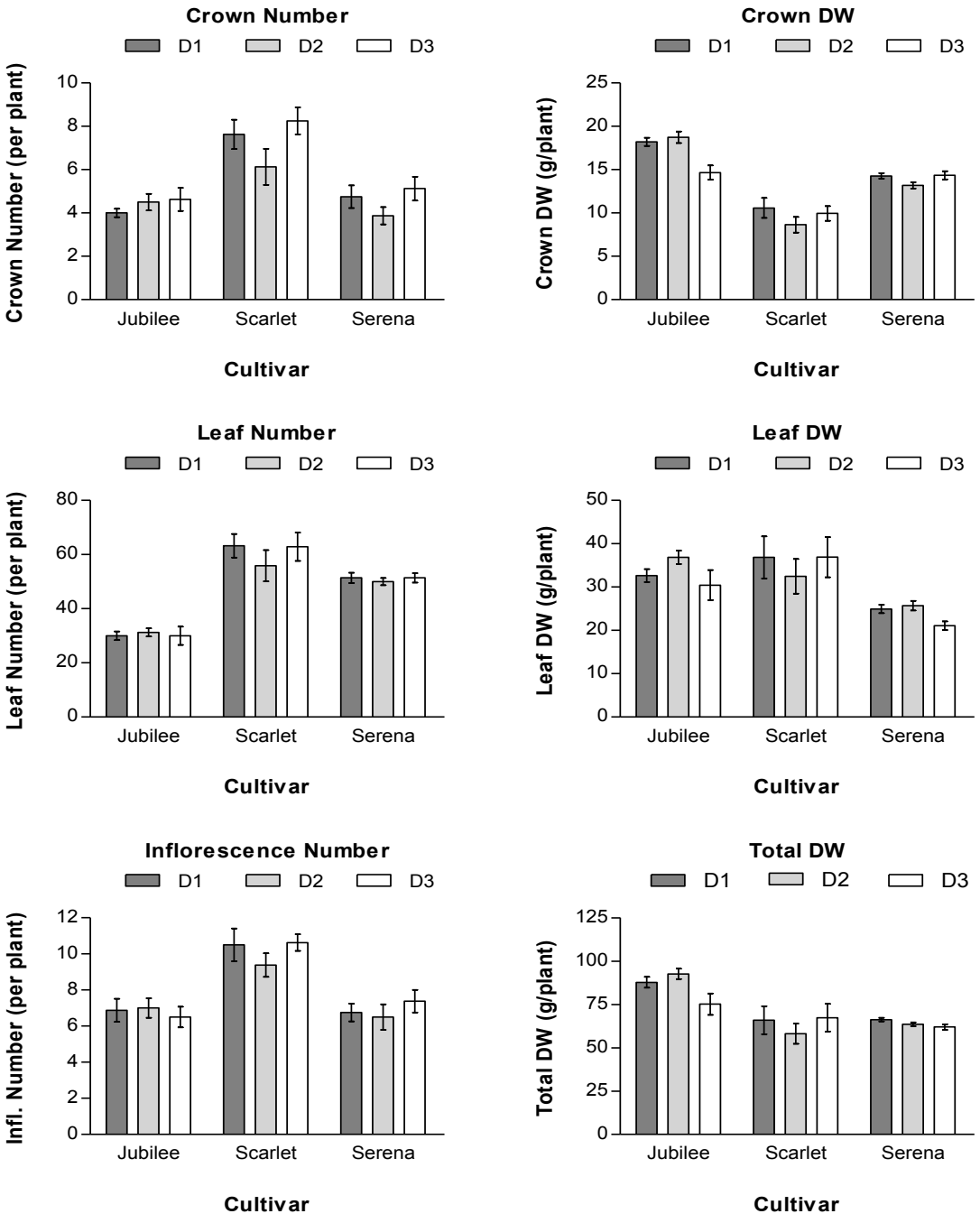

Figure 4.10 Effect of daughter plant position on DH2 results for cultivars Jubilee, Scarlet and Serena (n=8). Infl= inflorescence, DW= dry weight. The vertical line on each bar shows ±S.E.M. Treatments were primary daughter (D1), secondary daughter (D2) and tertiary daughter (D3).

4.4 Discussion

Grower preference and demand for strawberry plug plants has increased in recent years. Despite being costlier to purchase, plants produced using the plug plant method are more uniform, cleaner, and quicker to establish in the field and have a lower disease risk and increased survival rate compared to traditional bare-root transplants (Crawford et al. 2000; Durner et al. 2002; Bish et al. 2003; Takeda et al. 2004; Cocco et al. 2010; Husaini & Neri 2016). However, despite being genetically identical there can be considerable differences in the size, age and the developmental stage of daughter plants depending on their position on the runner as each daughter is formed under different photo-thermic conditions (Leshem & Koller 1966). This means that daughter plant position is likely to impact on the subsequent cropping performance of strawberry. The experiment described here was therefore designed to examine the impact of daughter plant position on cropping performance of three Everbearer strawberry cultivars currently grown in the UK.

Overall, no significant effect of daughter plant position on marketable yield, total yield or percentage Class 1 was found. These results are in agreement with the Takeda et al. (2004) who found no effect of daughter plant position on yield of the cultivar 'Chandler'. In strawberry, often a reduction in one yield component can be compensated for by an increase in another so that overall yield was not reduced. For example, a reduction in berry number can lead to an increase in average berry weight (Sønsteby et al. 2013). However, there was also no significant effect of daughter plant position on berry number or average berry weight found, which means that both the yield and the primary yield components were not affected by daughter plant position.

To assess treatment effects on transplant growth during the propagation phase, non-destructive measurements (leaf number, crown diameter and root score) were carried out on a weekly basis before a final destructive harvest was carried out. In the weekly measurements, plants originating from earlier positions on the runner were larger than those from later positions, but differences between the treatments were quite small. Similarly, in the destructive harvest, there were small but significant differences between the treatments for crown number, crown diameter and leaf number which were greater in the earlier positioned daughters and a positive effect on leaf area, leaf dry weight, root score and total plant dry weight for Scarlet and Serena.

Overall the transplants produced at the end of the propagation phase were small, with an average total dry weight of 1.9, 1.3 and 0.9 g / plant and crown size of 1.2, 1.0 and 0.9 cm for the primary, secondary and tertiary daughters respectively. The misted tips rooted successfully regardless of cultivar and treatment but after potting, the growth of the plants was relatively slow which can be seen in the weekly non-destructive measurements. The misted tips were potted in mid-September and propagated through the autumn under natural short days and ambient light levels. These conditions were not suitable for driving the vegetative growth of the plants, and so there was little development of branch crowns and leaf production leading to a lack of sites for floral initiation. Chabot (1978) also showed that the allocation of resources to reproductive development was reduced in low light and low temperature environments in the wild strawberry species *Fragaria vesca*. These factors together may explain why the yield was also low for these cultivars. Commercially, the cultivar Jubilee will yield approximately 750 g / plant whilst Scarlet and Serena typically produce over 1 kg / plant. In this experiment maximal yields were 440, 587 and 587 g / plant for Jubilee, Scarlet and Serena respectively. Fruiting also finished earlier than usual with the last fruit picked at the end of August when cropping in these cultivars typically continues into mid-October. The poor growth of the plants during the propagation phase likely resulted in the poor yield performance in the following season, which may have limited any potential differences between treatments. There were only minor differences in size between daughter plant positions for each cultivar at planting time and these could have been nullified by subsequent spring growth.

By the end of fruiting, the final destructive harvest results showed there were no significant differences in total dry weight between treatments; the plants were of a comparable size to that achieved previously for these cultivars (see Chapter 3). This shows that although the plants were small at planting time, plant growth in the following spring compensated for this. However, the number of inflorescences and berries produced per plant was low for these cultivars perhaps due to a low rate of both autumn and spring flower initiation, explaining the low yield produced and early end to fruiting, as a second crop was not produced which is typical of Everbearer strawberries and of these cultivars.

Unlike Junebearers, Everbearers continue to flower and fruit from late Summer into the autumn and the daughter plants can produce flowers even whilst still attached to the mother plant. The numbers of flowers expressed during the propagation phase in this experiment was relatively low

(no more than 5 flowers / plant). However, the number expressed was significantly higher in the primary daughters than the secondary and tertiary daughters. Flowers were removed routinely during the propagation phase, meaning there was potentially a greater loss of yield potential in the earlier positioned daughters, which may also explain why there were no significant yield differences found between the treatments.

The marketable yield of the tertiary daughters was significantly higher than both the primary and secondary daughters in the first month of picking (May 2016) whilst there were no significant differences for the remainder of cropping. Although the yield increase was small it was significant; D'Anna & Iapichino (2002; 2003) also found later positioned daughters fruit more heavily early in the season, despite no significant differences in yield at the end of fruiting. On a large scale commercial farm, where there are 8-12 plants per running metre, even a small increase in yield could be valuable, which is important particularly in the early season where fruit prices are high. One of the current goals of the strawberry industry is increase production levels on the fringes of the main season and the results of this experiment suggest that later positioned daughters yield higher early in the season, and despite their smaller size there is no detrimental impact on total yield. It would however be beneficial to repeat this study with better quality transplants to fully quantify the effect of daughter plant position on early fruit yield.

Chapter 5

Effect of nitrogen concentration and winter chill accumulation during the propagation phase on cropping performance of five strawberry cultivars.

5.1 Introduction

Development of strawberry fruit begins with the initiation of flowers; for Junebearers this occurs entirely in the autumn preceding the fruiting season, whilst the first flush of fruit for Everbearers also originate from autumn initiated flowers. During the period of flower initiation, photoperiod and temperature are regarded as the most important environmental conditions (Ito & Saito 1962) but nutrition and winter chill accumulation can also have an impact upon subsequent cropping in strawberry.

The yield potential of strawberry has been closely linked to the vegetative status of the initial plant material, and positive correlations between early and total fruit yield and various components of strawberry transplants including crown number, crown diameter, leaf number, leaf area and plant weight have been previously established (Darrow 1966; Hughes 1967; Abbott 1968; Lacey 1973; Faby 1997; Le Miere et al. 1998; Human 1999; Bussell et al. 2003; Johnson et al. 2005; Takeda & Newell 2006; Bartczak et al. 2010; Cocco et al. 2010; Fridiaa et al. 2016). Increased N during the raising of transplants has the potential to positively impact upon fruit yield by stimulating greater vegetative growth, particularly by promoting branch crown formation and increasing the number of sites for floral initiation (Abbott 1968). Deng & Woodward (1998) found low levels of N in the autumn reduced subsequent flower number, berry number, berry weight and fruit yield in the Junebearer strawberry 'Elsanta.' Whilst, Motamedi et al. (2013) found increasing N from 200 mg / L to 240 mg / L had a positive impact on crown diameter, flower number, fruit number and total yield and Miner et al. (1997) also found flower number and fruit yield increased with greater N inputs. However, since vegetative and reproductive growth occur simultaneously in strawberry plants, N application needs to be carefully balanced to prevent excessive vegetative growth at the expense of reproductive activity. The timing of fertiliser application during the autumn has been identified as a particularly important factor with greater

fertilisation early in the autumn when conditions become favourable for floral initiation having a positive effect on flowering and fruiting in the following season whereas, N application toward the end of the propagation phase has a negative impact (Lieten 2002; Sønsteby et al. 2009; Opstad et al. 2013; 2013).

Stored resources are also very important for spring growth once dormancy has broken. Like many perennials, strawberries accumulate carbon and nitrogen throughout the autumn and winter which are stored in the form of proteins and carbohydrates in the crowns and roots (Archbold & MacKown 1995; Kirschbaum et al. 2010a). These stored reserves are an important source of energy early in spring when conditions are not optimal for photosynthesis and the growth of new leaves, which are initially strong sinks, require support (Chapin et al. 1990; Archbold & MacKown 1995). Kirschbaum et al. (2010b pp. 1005) identified the importance of stored nitrogen reserves, stating that: "Nitrogen reserves have largely been overlooked as having a major role in plant establishment and early fruit development." Demirsoy et al. (2010) found that nitrogen, which had built up in the crowns and roots during the autumn, decreased as it was utilised through flowering and fruiting and other studies have concluded that strawberries gain more nitrogen from stored sources in early spring than that newly absorbed through the roots (Archbold & MacKown 1995; Tagliavinia et al. 2005). Acuna-Maldonado & Pritts (2008) found that autumn applied N resulted in increased yield whereas spring N application had no effect, and concluded that not only is autumn assimilated N used for flower and fruit development, but reserves can be sufficient to sustain strawberry growth and fruiting when N is not available.

The level of winter chill accumulation is another factor which can impact upon strawberry yield performance. Strawberries become dormant during the first part of the autumn with plants reaching deepest dormancy by mid-November (Sønsteby & Heide 2006). During dormancy, vegetative growth is restricted and plants have a low compact growth habit, short petioles and small leaves (Kronenberg et al. 1976; Sønsteby & Heide 2006). For vigorous growth and normal inflorescence development in the spring, the plants must break dormancy by satisfying a chilling requirement (Lieten & Waite 2006; Sønsteby & Heide 2006). Post chilling, vegetative growth is rapid and vigorous with long petioles and the production of numerous large leaves which then support the crop (Kronenberg et al. 1976; Pipattanawong et al. 1995; Lieten & Waite 2006; Sønsteby & Heide 2006).

Lopez et al. (2002) found a positive correlation between the level of starch accumulated in the plant and the number of hours below 7°C which can have a positive on early spring growth (Nishizawa et al. 1998). However, due to increased vegetative vigour, excessive chilling has been shown to delay flower production in the early season leading to a concentration of the fruiting period due to the suppression of early yield (Smeets 1982; Albregts & Chandler 1994; Luedeling et al. 2011).

It is important to establish the optimum range of chilling for each new strawberry cultivar, as outside this range there can be a negative effect on yield (Tanino & Wang 2008). Higher than optimum levels of chilling can lead to rapid vegetative growth reducing yield due to soft fruit, greater disease risk and increased runner formation (Albregts & Chandler 1994; Tehranifar 1997; Lieten 2009). Whereas, insufficient chilling can lead to inadequate vegetative growth and the inability of plants to support a large crop as well as having negative impacts on flowering, anther and pollen quality, leading to reduced fruit weight and increased malformation of fruit (Kronenberg et al. 1976; Lieten 2009).

Increased N has the potential to improve transplant growth and increase the number of sites for floral initiation, whilst chilling may be used to improve plant growth in the spring giving plants a greater ability to support a large crop. There is likely to be an optimum level of both factors, and this cultivar-specific. Research into the separate effects of autumn nitrogen application and level of winter chilling on cropping in strawberry has been carried out, but no information is available on the new Junebearer and Everbearer cultivars currently cropped commercially in the UK or the combination of these two factors. An experiment was therefore designed to examine the impact of increased nitrogen concentration during the propagation phase, and the level winter chill accumulation, on transplant growth, yield potential and subsequent cropping of five strawberry cultivars currently cropped in the UK.

5.2 Materials and Methods

5.2.1 Propagation Phase

Plant Material and Experimental Treatments

Fresh plug plants of the Junebearer cultivars Lusa and Diamond, and Everbearer cultivars Jubilee, Scarlet and Serena were supplied by Driscoll's Plants BV (Helenaveen, Netherlands) on 16th August 2013. Upon arrival, 300 uniform plants of each cultivar were selected and re-potted into 90 x 87 mm (diameter x depth) coir filled pots and transferred to the middle six of a suite of eight temperature-controlled glasshouse compartments (50 plants per cultivar per compartment). The compartments were as described in Chapter 2 and set up to provide six experimental treatments, a combination of two nitrogen treatments (Low N and High N) and three chilling treatments (Low Chill, Medium Chill and High Chill). The two nitrogen treatments were 60 ppm N (Low N) and 120 ppm (High N) delivered via the fertigation system from 29th October 2013. Two nutrient solutions were created with the amount of nitrate adjusted to achieve the two N concentrations (Table 5.1). Heating and venting temperatures in the compartments were reduced from 12/18°C to 2/5°C on three dates to give the three chilling treatments: 4th December 2013 (High Chill), 8th January 2014 (Medium Chill), and 23rd January 2014 (Low Chill).

Lusa was removed for planting in a large temperature-controlled glasshouse compartment on 4th February 2014 whilst the remaining cultivars were planted in a polytunnel on 31st March 2014. Lusa therefore accumulated less chill than the remaining cultivars. The chill level for the glasshouse and polytunnel crops are summarised in Table 5.2

The dates for chilling were set with the aim of achieving 200 CU, 500 CU and 800 CU for the Low Chill, Medium Chill and High Chill treatments in Lusa but a broken roof vent caused over chilling in one treatment and so to keep the design factorial, Treatments C and E were excluded from the experiment leaving the 200 CU (Low Chill) and 800 CU (High Chill) treatments (see Table 5.2). For the polytunnel cultivars, the final chill levels achieved were: 600 CU (Low Chill), 1000 CU (Medium Chill) and 1200 CU (High Chill). Chill accumulation was calculated using a positive chill model developed for the strawberry cultivar 'Elsanta' at the University of Reading (Tehranifar 1997).

Table 5.1 Composition of the Low N (60 ppm N) and High N (120 ppm N) nutrient solution stock tanks. Nutrients in each tank were diluted in 80 L of mains water.

	Nutrient Solution 1 (Low N – 60 ppm N)	**Nutrient Solution 2 (High N – 120 ppm N)**
Tank A	**kg / 80 L**	**kg / 80 L**
Calcium Nitrate	2.40	2.40
Tank B	**kg / 80 L**	**kg / 80 L**
Potassium Nitrate	1.60	1.60
Potassium Sulphate	1.60	1.60
Magnesium Nitrate	0.00	3.56
Magnesium Sulphate	3.25	0.00
MonoPotassiumPhosphate	1.60	1.60
	g / 80 L	**g / 80 L**
Iron-EDTA	136.00	136.00
Manganese Sulphate	44.00	44.00
Zinc Sulphate	17.44	17.44
Copper Sulphate	1.60	1.60
Sodium Molybdate	0.96	0.96
Solubor	6.00	6.00

Table 5.2 Summary of the experiment treatments applied to Lusa and remaining cultivars: Diamond, Jubilee, Scarlet and Serena.

Code	**N Treatment (ppm N)**	**Chilling Treatment (CU)**	
	All Cultivars	Lusa	Remaining Cultivars
A	60	208	524
B	60	800	1072
C	60	~~957~~	1249
D	120	188	588
E	120	~~372~~	961
F	120	759	1147

Propagation Phase Measurements

Ten randomly selected plants of each cultivar in each treatment were tagged upon transfer to the glasshouse. Runners and open flowers were removed from all plants on a routine basis and the numbers removed on the tagged plants were recorded.

At the end of the propagation phase, a destructive harvest was carried out on the ten tagged plants and the following measurements were made on each plant: crown number, crown diameter, leaf number, leaf area, root score and dry weights of the leaves and crowns (including petioles) with a total plant dry weight calculated as the sum of the individual components. All measurements were carried out using the methods described in Chapter 2.

5.2.2 Production Phase

Experimental Design

The cultivar Lusa was planted on 4th February 2014 in a large, temperature-controlled glasshouse compartment set up as described in Chapter 2. Four bags, each containing eight plants, were planted for each treatment giving a total of 32 plants per treatment. The remaining cultivars were cropped in a single span polytunnel at the Soft Fruit Technology Group Field Site at the University of Reading's Shinfield Farm set up as described in Chapter 2. Three bags, each containing six plants, were planted on 31st March 2014 and for each cultivar and treatment giving a total of 18 plants per cultivar per treatment.

In both productions, the experimental area was divided into four (glasshouse) or three (polytunnel) blocks to account for variation in temperature and light levels across the experimental area. One replicate (bag) was assigned to each block in a randomised position and guard bags were placed at the ends of each row to minimise edge effects. Figure 5.1 and Figure 5.2 show the layout of the blocks, cultivars and treatments for the glasshouse and polytunnel respectively.

Growing Conditions

Temperature control, plant husbandry and fertigation were carried out as described in Chapter 2. Figure 5.3 and Figure 5.4 show the average 24 hr temperature logged throughout the production phase in the glasshouse and polytunnel respectively.

Production Phase Measurements

To determine treatment effects on cropping performance, data on the total, marketable and un-marketable yield and berry number were recorded on a weekly basis. Average marketable berry weight and percentage Class 1 was calculated at the end of cropping. Data was collected at the bag level and converted to a per plant basis for analysis. All cropping data was collected using the methods described in Chapter 2. A final destructive harvest was carried out at the end of the production phase; three plants were selected from each bag and the following measurements were made on each plant: crown number, leaf number and dry weight of the leaves, crowns and remaining plant parts (petioles and inflorescences) with a total plant dry weight calculated as the sum of the individual components. Data was collected using the methods described in Chapter 2.

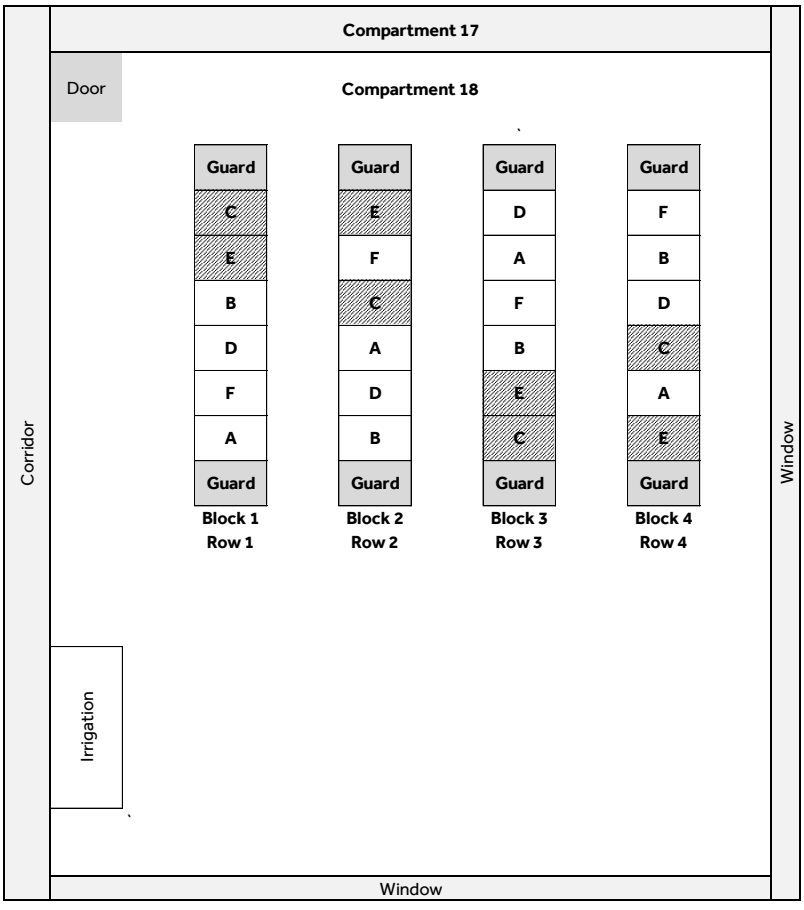

Figure 5.1 Arrangement of blocks and treatments for the production phase of the cultivar Lusa in Compartment 18 of a multi-compartmented glasshouse situated at the Crops and Environment Laboratory (School of Agriculture, Policy and Development, University of Reading). Treatments were: A = 60 ppm N / 200 CU, B = 60 ppm N / 800 CU, D = 120 ppm N / 200 CU and F = 120 ppm N/ 800 CU. Treatments C and E (hashed) were removed from the experiment.

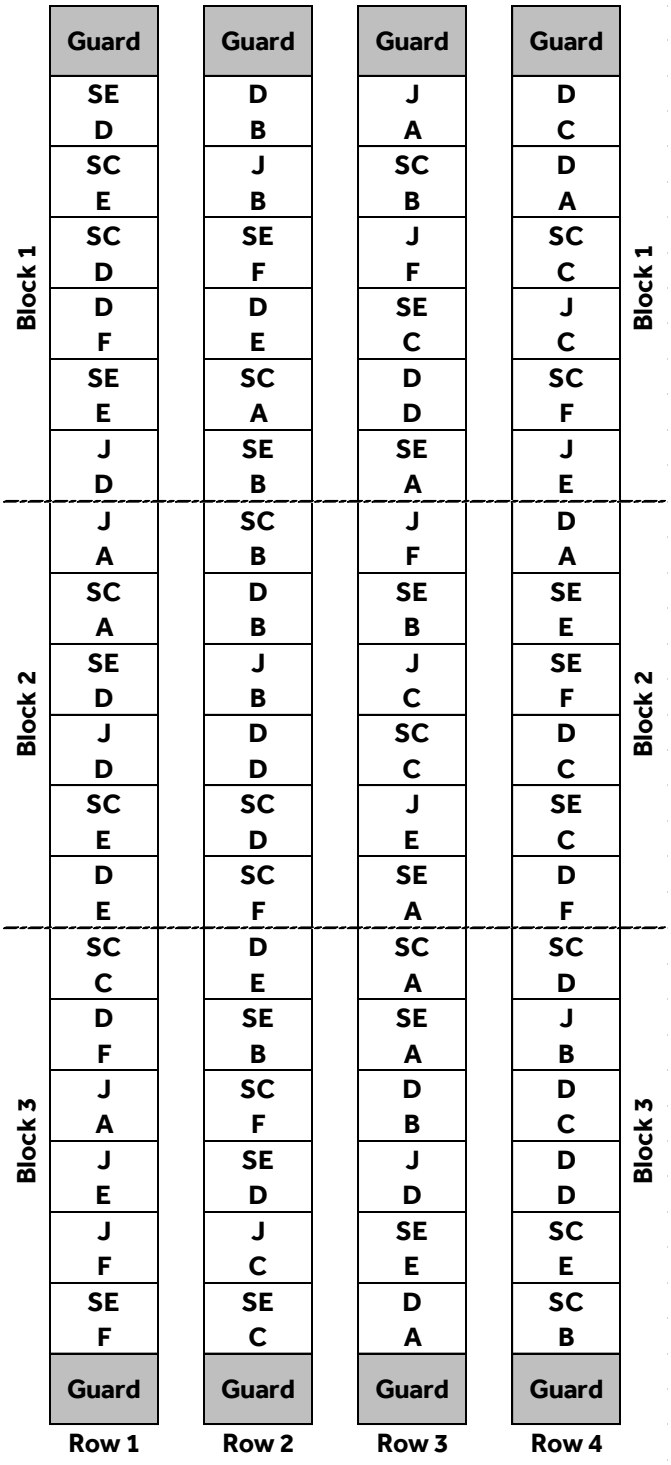

Figure 5.2 Arrangement of blocks, cultivars and treatments for the production phase of the cultivars Diamond (D), Jubilee (J), Scarlet (SC) and Serena (SE) in a single span polytunnel situated at the Soft Fruit Technology Group Field Site at the University of Reading's Sonning Farm. Each box represents a 1 m substrate bag each with six plants. Treatments were: A = 60 ppm N / 600 CU, B = 60 ppm N / 1000 CU, C = 60 ppm N / 1200 CU, D = 120 ppm N / 600 CU, E = 120 ppm N / 1000 CU and F = 120 ppm N / 1200 CU.

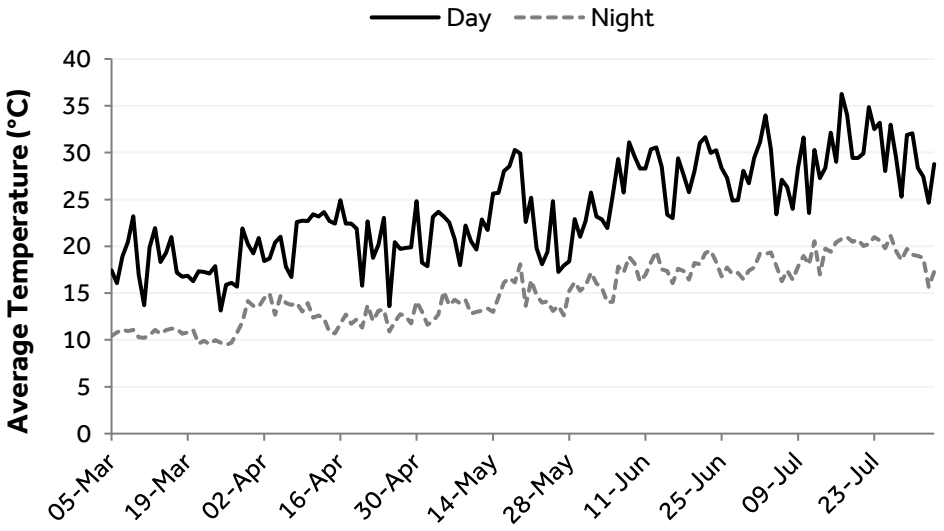

Figure 5.3 Mean day and night temperature logged throughout the production phase in the glasshouse production of the cultivar Lusa. Day = 07:00 to 19:00.

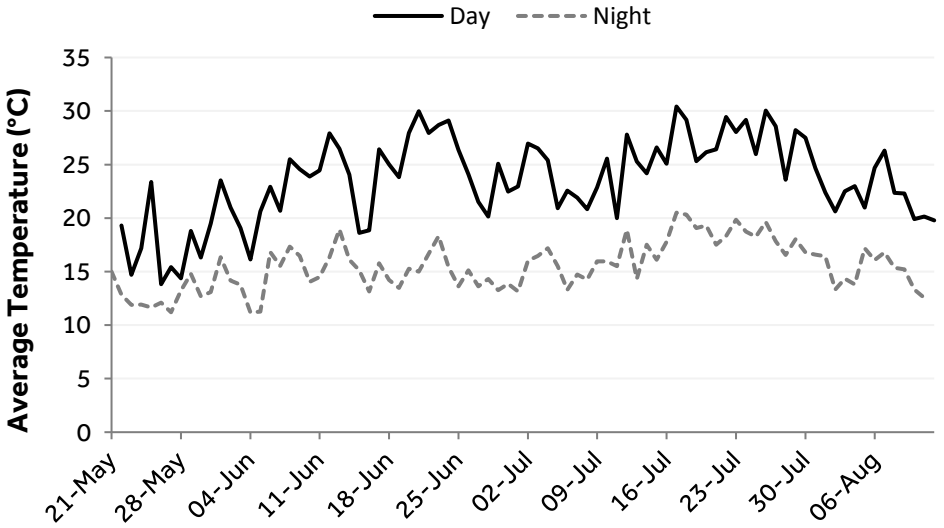

Figure 5.4 Mean day and night temperature logged throughout the production phase for polytunnel production of cultivars Diamond, Jubilee, Scarlet and Serena. Day = 07:00 to 19:00.

5.3 Results

5.3.1 Propagation Phase

5.3.1.1 *Open Flower Number*

For Lusa, there was a significant interaction between the nitrogen and chilling treatments for the number of open flowers expressed during the propagation phase (P=0.006, Figure 5.5). In the Low N treatment, the number of flowers declined by 56% when chilling increased from 200 CU to 800 CU; whereas in the High N treatment, chill level did not have a significant effect on flower number. The difference in flower number between N treatments was not significant at Low Chill, whereas at High Chill flower number was 148% greater in the High N treatment.

In the remaining cultivars, the number of open flowers expressed during the propagation phase significantly differed between cultivars (P<0.001). Overall, Serena had the greatest number of flowers per plant (19.0±1.1 flowers / plant), significantly greater than Scarlet (12.0±0.5), Jubilee (8.9±0.5) and Diamond (7.2±0.3) respectively.

Treatment effects on the number of flowers expressed for each cultivar are shown in Figure 5.5. There was a significant interaction between the nitrogen and chilling treatments (P=0.009); such that differences in flower number between chill treatments was only significant at High N, where flower number was significantly greater in the Low and Medium Chill treatments compared to the High Chill treatment by 34% and 18% respectively. Flower number was also greater in the High N treatment at the Low and Medium Chill levels (51% and 45% respectively) whereas there was no significant difference between N treatments in the High Chill level.

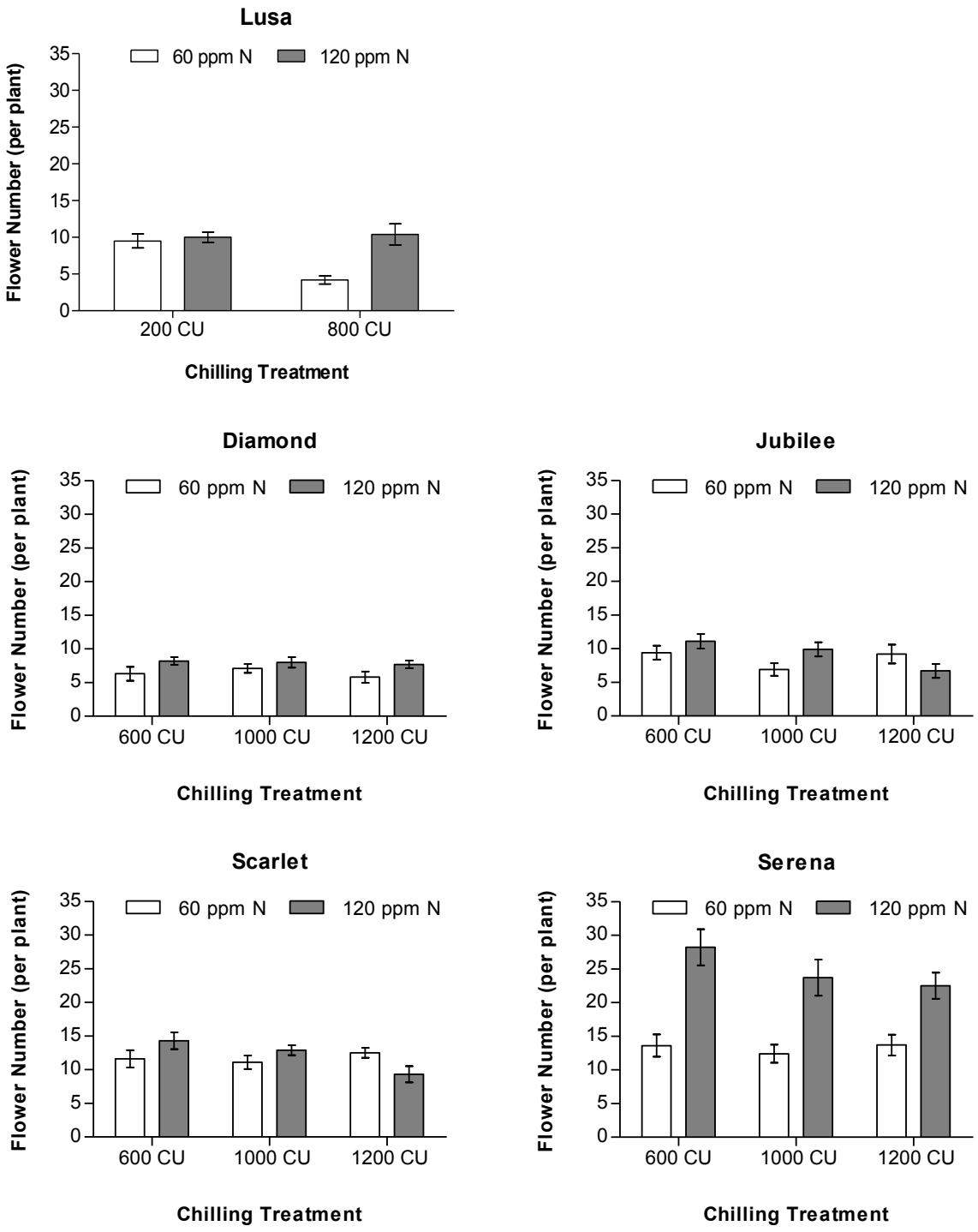

Figure 5.5 Effect of N treatment and chilling treatment on the total number of open flowers per plant during the propagation phase of cultivars Lusa, Diamond, Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) for all cultivars. Chilling treatments for Lusa were Low Chill (200 CU) and High Chill (800 CU) and chilling treatments for the remaining cultivars were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

5.3.1.2 *Destructive Harvest (DH1)*

Lusa

Crowns

Treatment effects on crown number, diameter and dry weight for the cultivar Lusa are shown in Figure 5.6. There was no significant interaction between the nitrogen and chilling treatments for any measurements of crown size, but the main effect of the N treatment was significant for crown number (P=0.024), crown diameter (P<0.001) and crown dry weight (P=0.006) which were significantly higher in the High N treatment compared to the Low N treatment by 27%, 17% and 35% respectively.

The main effect of the chilling treatment was also significant for crown diameter (P=0.008) and crown dry weight (P=0.009) which were significantly greater in the Low Chill treatment compared to the High Chill treatment (10% and 33% respectively) whereas there was no significant effect of chilling treatment on crown number.

Leaves

Treatment effects on leaf number, area and dry weight for the cultivar Lusa are shown in Figure 5.6. There was a significant interaction between the nitrogen and chilling treatments for leaf number (P=0.047) and leaf area (P=0.031); such that at Low Chill, leaf number and leaf area were significantly greater in the High N treatment compared to the Low N treatment (19% and 31% respectively) whereas there was no significant difference at High Chill. Leaf area was 46% greater in the Low Chill treatment compared to the High Chill treatment at the High N level whereas there was no significant difference at the Low N level.

There was no significant interaction between the nitrogen and chilling treatments for leaf dry weight but the main effect of both treatments was significant (P<0.001); leaf dry weight was 60% greater in the High N treatment compared to the Low N treatment, and 48% greater in the Low Chill treatment compared to the High Chill treatment.

Roots

There was a significant interaction between the nitrogen and chilling treatments on root score for Lusa (P=0.002, Figure 5.6) such that at High Chill, root score was 47% greater in the High N treatment compared to Low N treatment, whereas there was no significant difference at Low Chill.

Total Dry Weight

Treatment effects on total plant dry weight for Lusa are shown in Figure 5.6. The interaction between the nitrogen and chilling treatments was not significant but the main effects of the treatments were significant (P<0.001), total dry weight was 48% greater in the High N treatment compared to the Low N treatment and 41% greater in the Low Chill treatment compared to the High Chill treatment.

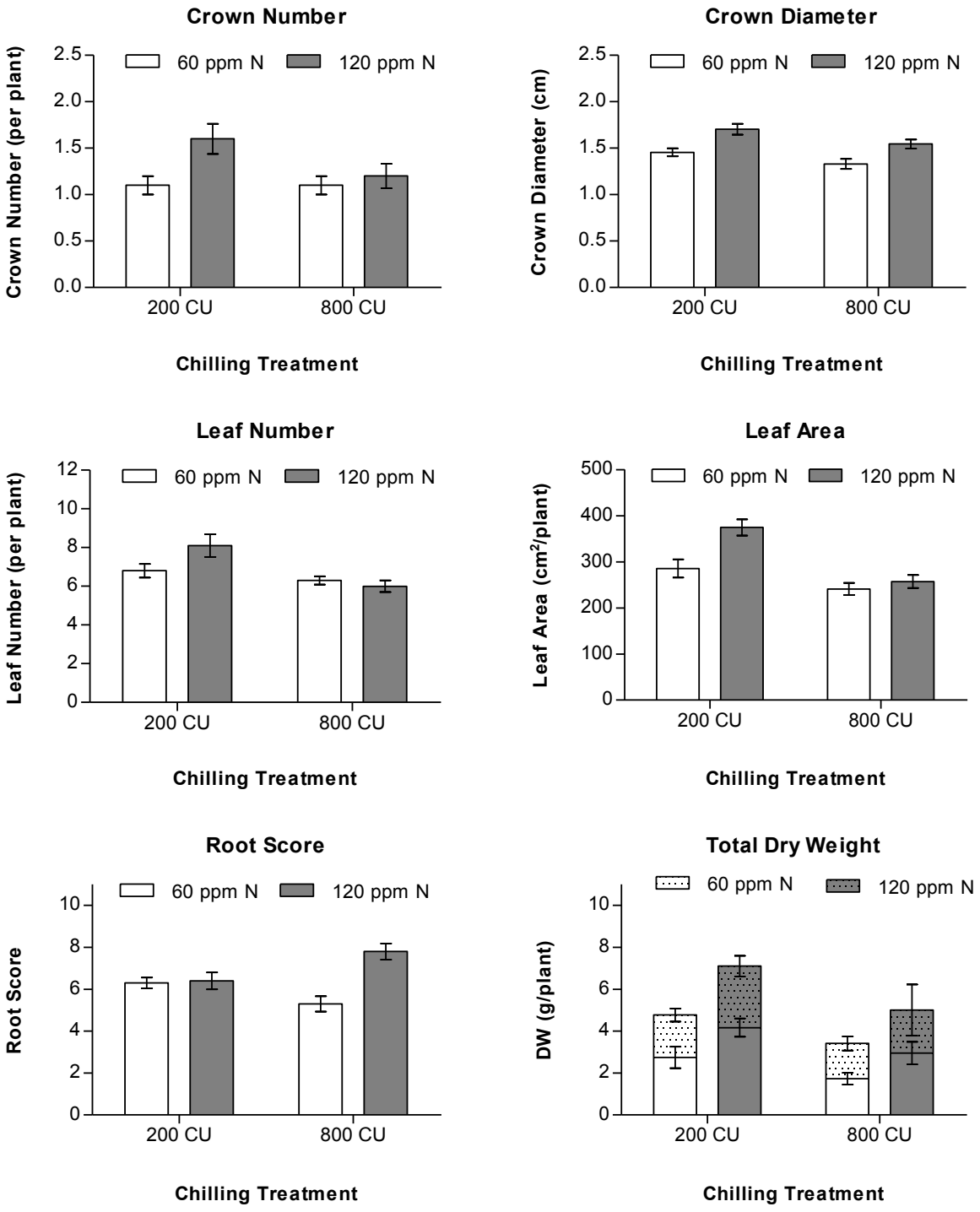

Figure 5.6 Effect of N treatment and chilling treatment on DH1 results for the cultivar Lusa (n=10). The bars on the graph for total plant dry weight are split into leaf dry weight (plain) and crown dry weight (spotted). DW = dry weight. The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (200 CU) and High Chill (800 CU).

Remaining Cultivars

Crown Number

Crown number of Serena (2.7±0.1 crowns / plant) was significantly (P<0.001) higher than Diamond (1.8±0.1), Jubilee (2.0±0.1) and Scarlet (2.0±0.1). Crown number of Jubilee and Scarlet did not differ significantly but were both also greater than Diamond.

Treatment effects on crown number for each cultivar are shown in Figure 5.7. Overall, crown number was significantly greater in the High N treatment (2.2±0.1 crowns / plant) compared to the Low N treatment (2.0±0.1) (P=0.002) and there was no significant interaction between the cultivars and N treatments. The effect of the chilling treatment did significantly differ between cultivars (P=0.003), for Diamond and Jubilee crown number was significantly greater in the High Chill treatment compared to the Medium and Low Chill treatments (by 30% and 37% for Diamond and by 20% and 24% for Jubilee respectively) whereas crown number was significantly higher in the Medium treatment compared to the High Chill treatment for Serena and there were no significant differences for Scarlet.

Crown Diameter

All differences in crown diameter between cultivars were significant (P<0.001); overall, Serena (2.1±0.06 cm) had the greatest crown diameter, followed by Scarlet (1.8±0.04), Jubilee (1.6±0.04) and Diamond (1.3±0.03).

There was a significant interaction between the nitrogen and chilling treatments (P<0.001, Figure 5.8) such that crown diameter was significantly greater in the High N treatment at the Low and Medium Chill levels by 15% and 21% respectively, but there was no significant difference at the High Chill level. In the Low N treatment, crown diameter was significantly greater at the High Chill level compared to the Medium and Low Chill levels (by 30% and 37% respectively) whereas in the High N treatment, crown diameter was significantly lower at the High Chill level compared to the Medium Chill level by 8% and there were no other significant differences between chilling treatments.

Crown Dry Weight

Crown dry weight of Serena (2.35±0.08 g / plant) was significantly ($P<0.001$) higher than Diamond (1.63±0.04), Jubilee (1.59±0.05) and Scarlet (2.03±0.06). Crown dry weight of Scarlet was also significantly greater than Jubilee and all other differences between cultivars were not significant.

There was a significant interaction between the nitrogen and chilling treatments ($P<0.001$, Figure 5.9) such that crown dry weight was 21% and 26% greater in the High N treatment compared to the Low N treatment at the Low and Medium Chill levels, but there was no significant difference at the High Chill level. In the Low N treatment, crown dry weight was significantly greater at the High Chill level compared to the Medium and Low Chill levels (by 10% and 4% respectively) whereas in the High N treatment, crown dry weight was 19% and 22% lower at the High Chill level compared to the Medium and Low Chill levels.

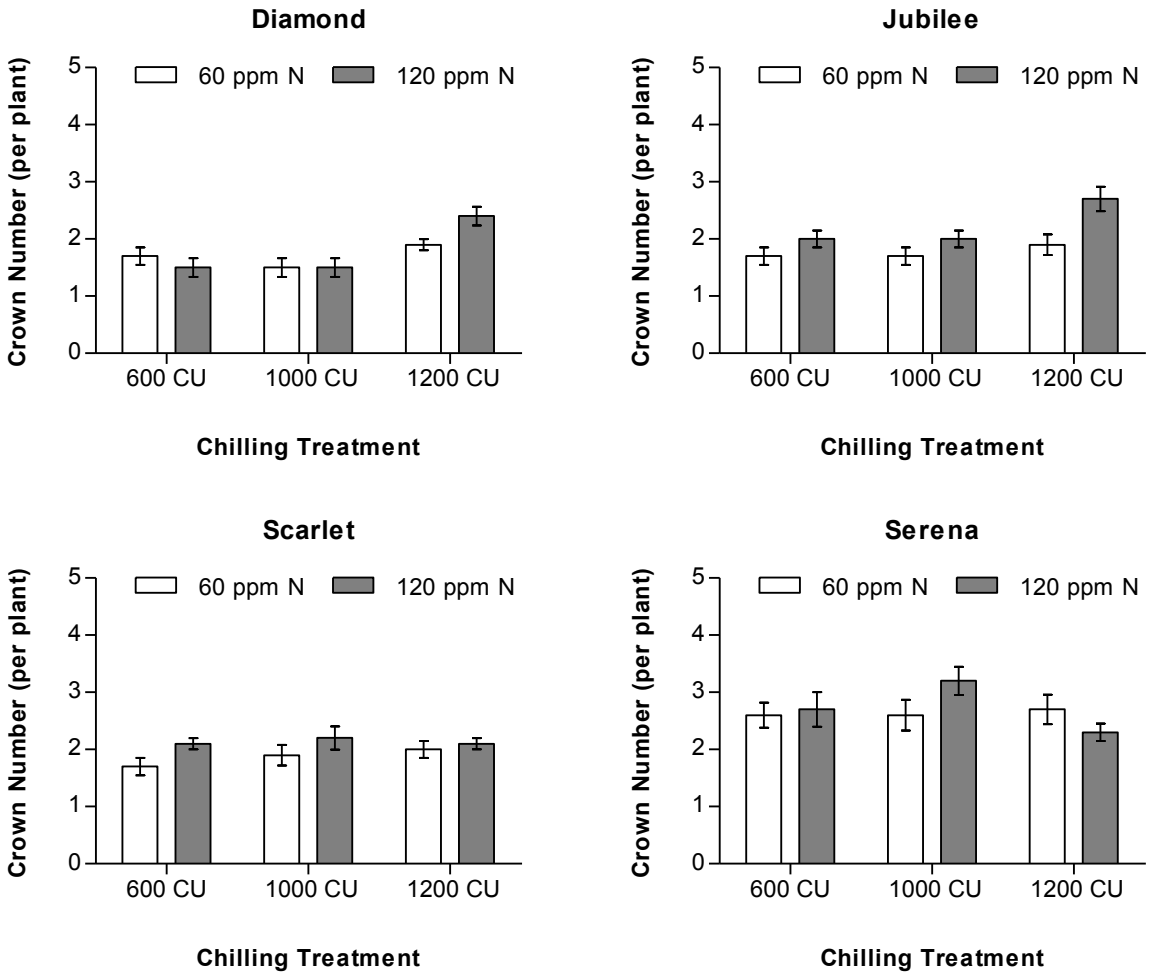

Figure 5.7 Effect of N treatment and chilling treatment on crown number at the end of the propagation phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=10). The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

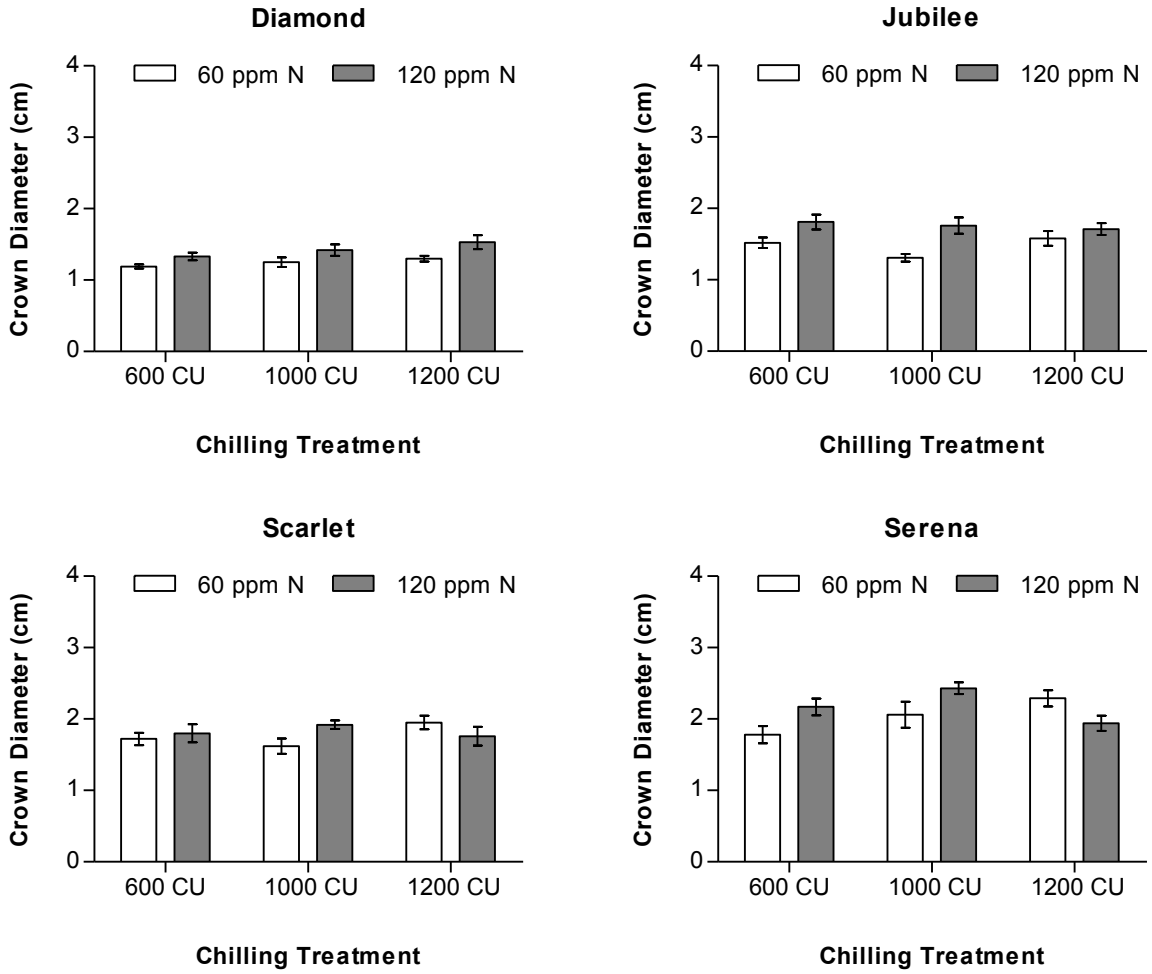

Figure 5.8 Effect of N treatment and chilling treatment on crown diameter at the end of the propagation phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=10). The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

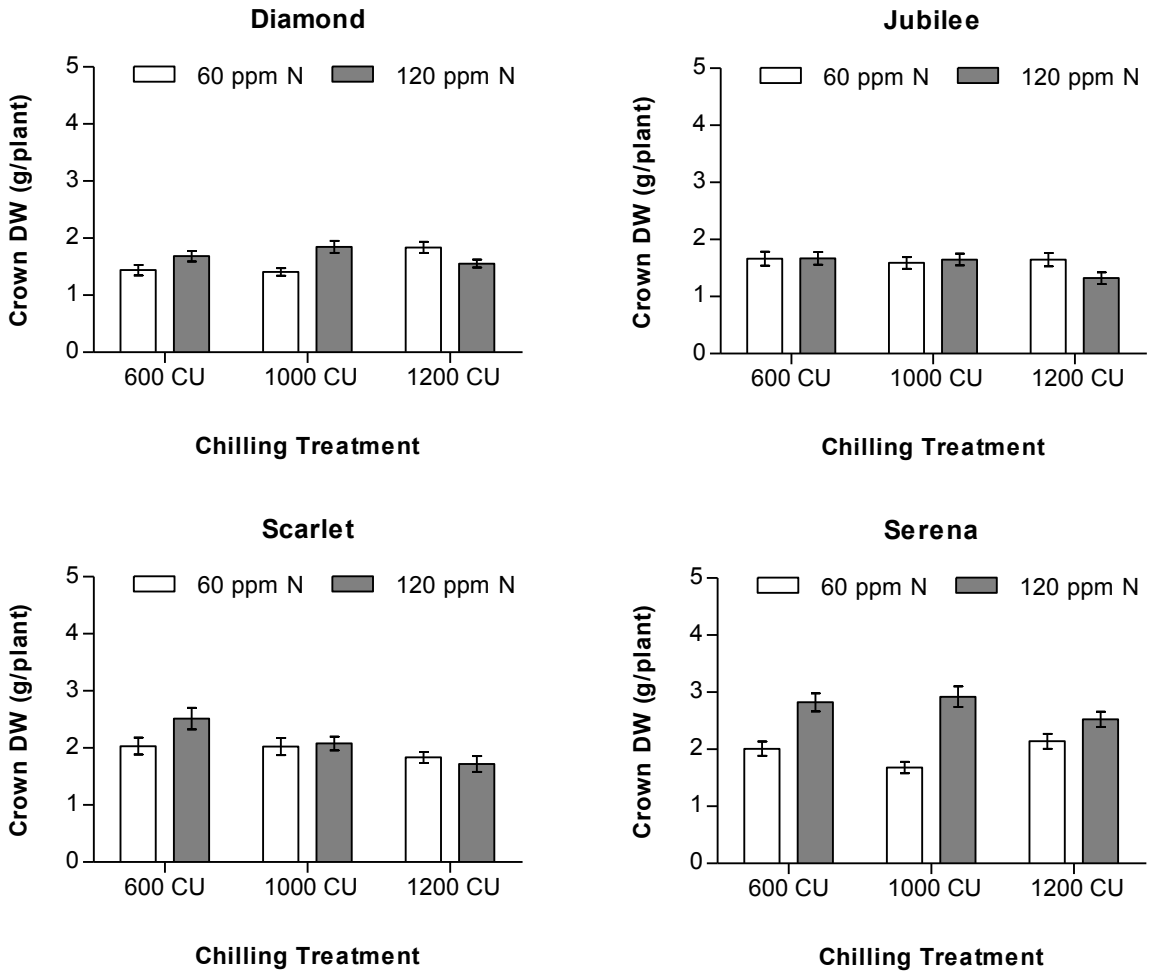

Figure 5.9 Effect of N treatment and chilling treatment on crown dry weight at the end of the propagation phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=10). DW = dry weight. The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

Leaf Number

Treatment effects on leaf number for each cultivar are shown in Figure 5.10. However, only the differences in leaf number between cultivars were significant (P<0.001); Scarlet had the greatest leaf number (13.1±0.4 leaves / plant) significantly higher than Serena (11.6±0.3), Jubilee (10.3±0.3) and Diamond (8.5±0.2).

Leaf Area

Leaf area of Scarlet (202.4±6.4 cm^2 / plant) was significantly (P<0.001) greater than Diamond (116.1±2.67), Jubilee (155.2±3.3) and Serena (152.2±4.9). There was no significant difference between Serena and Jubilee, but leaf area of both was also significantly greater than Diamond.

There was also a significant interaction between the nitrogen and chilling treatments (P<0.001, Figure 5.11) such that at the Low and Medium Chill level, leaf area was significantly greater in the High N treatment compared to the Low N treatment (by 23% and 13% respectively) whereas at the High Chill level this was reversed, with leaf area significantly higher in the Low N treatment (by 13%). At Low N, leaf area was significantly greater in the High Chill treatment compared to the Low and Medium Chill treatments (but this was only significant compared to Medium Chill by 10%); whereas, at High N leaf area was significantly greater in the Low Chill treatment compared to the Medium and High Chill treatments (11% and 29% respectively) and in the Medium Chill treatment compared to the High Chill treatment (by 16%)

Leaf Dry Weight

Leaf dry weight of Scarlet (2.8±0.07 g / plant) was significantly (P<0.001) higher than Diamond (1.87±0.04), Jubilee (2.29±0.05) and Serena (2.34±0.06). There was no significant difference between Serena and Jubilee but leaf dry weight of both was also greater than Diamond.

There was also a significant interaction between the nitrogen and chilling treatments (P<0.001, Figure 5.12) such that at the Low and Medium Chill levels, leaf dry weight was significantly greater in the High N treatment compared to the Low N treatment (11% and 20% respectively) whereas there was no significant difference at the High Chill level. At Low N, leaf dry weight was significantly greater in the High Chill treatment compared to the Medium Chill treatment (by 13%) whereas at High N, leaf dry weight was significantly higher in the Low and Medium Chill treatments compared to the High Chill treatment (by 9% each).

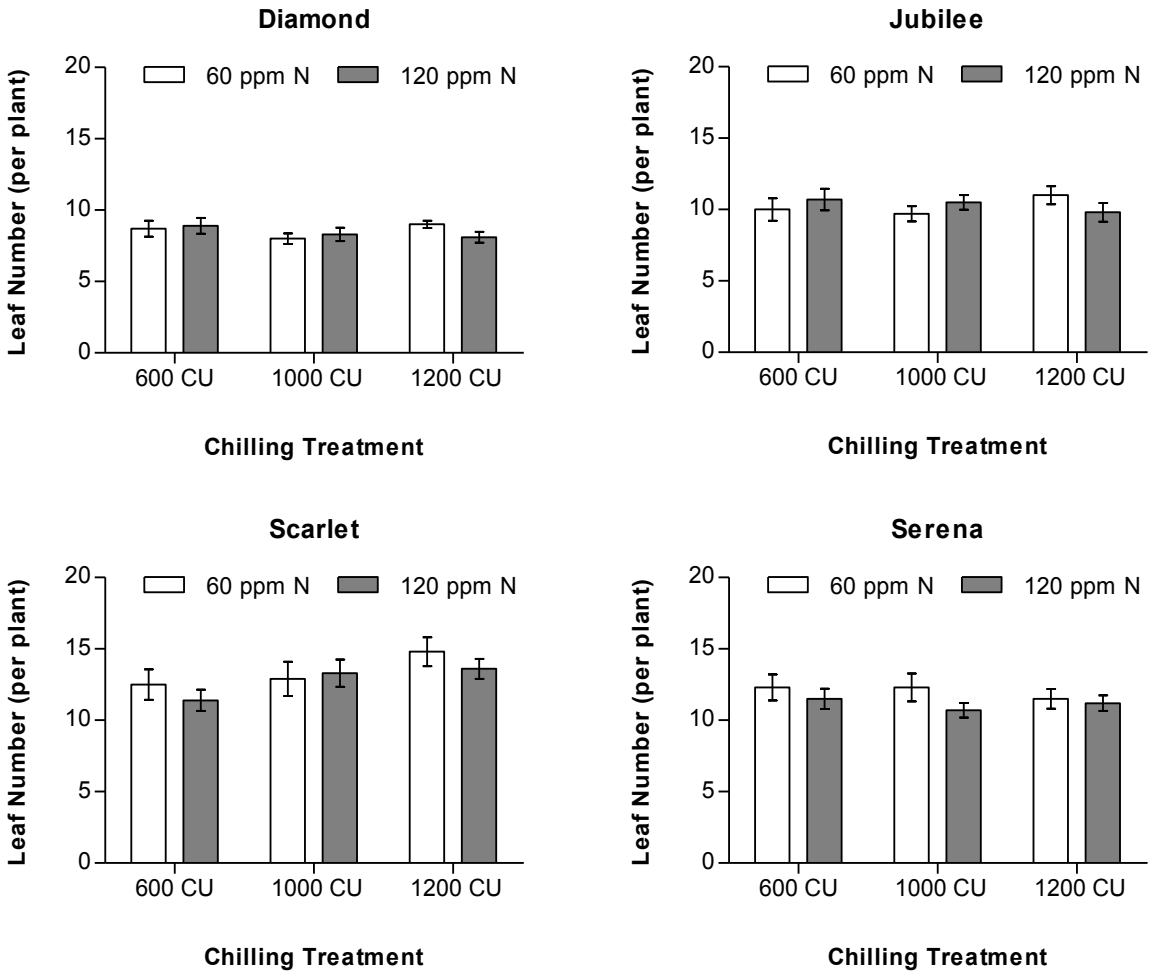

Figure 5.10 Effect of N treatment and chilling treatment on leaf number at the end of the propagation phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=10). The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

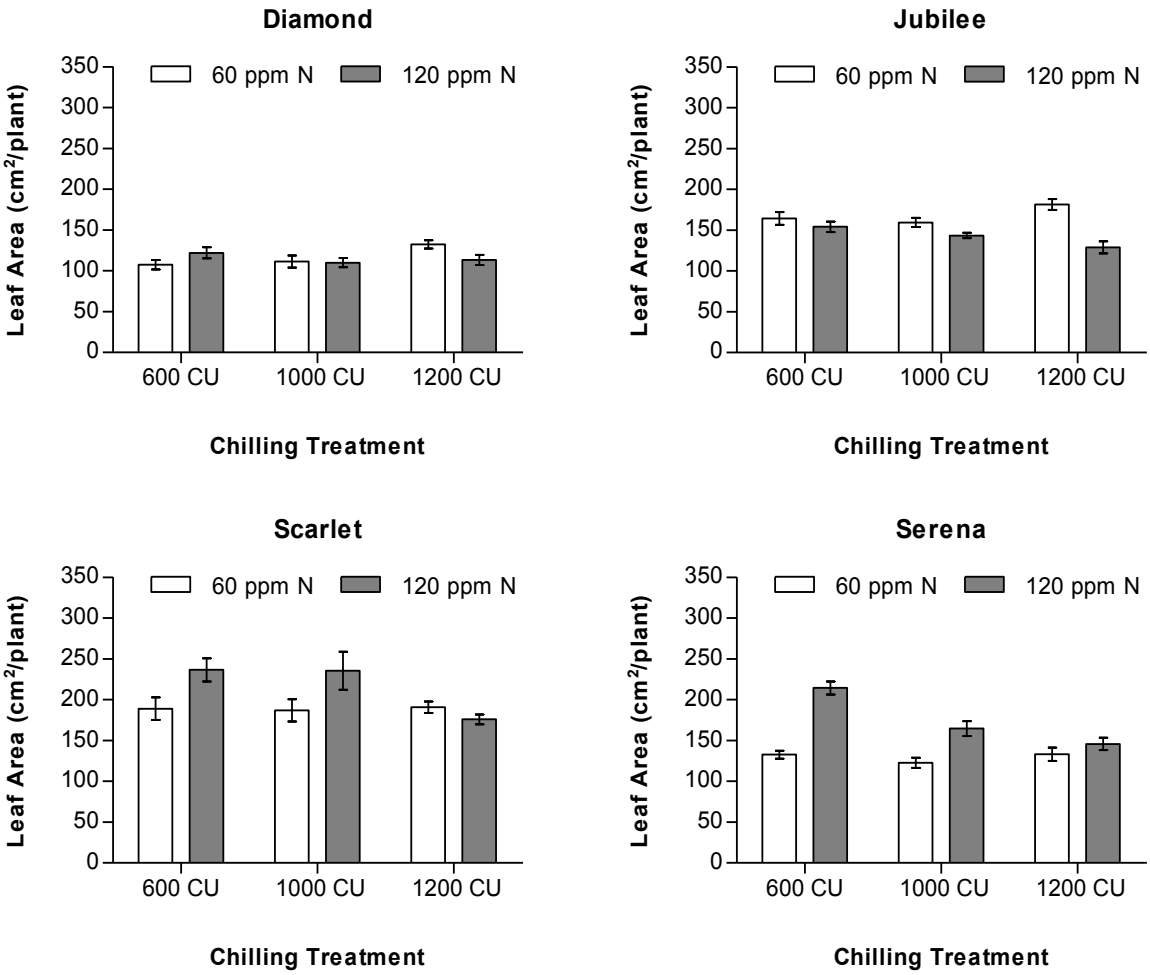

Figure 5.11 Effect of N treatment and chilling treatment on leaf area at the end of the propagation phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=10). The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

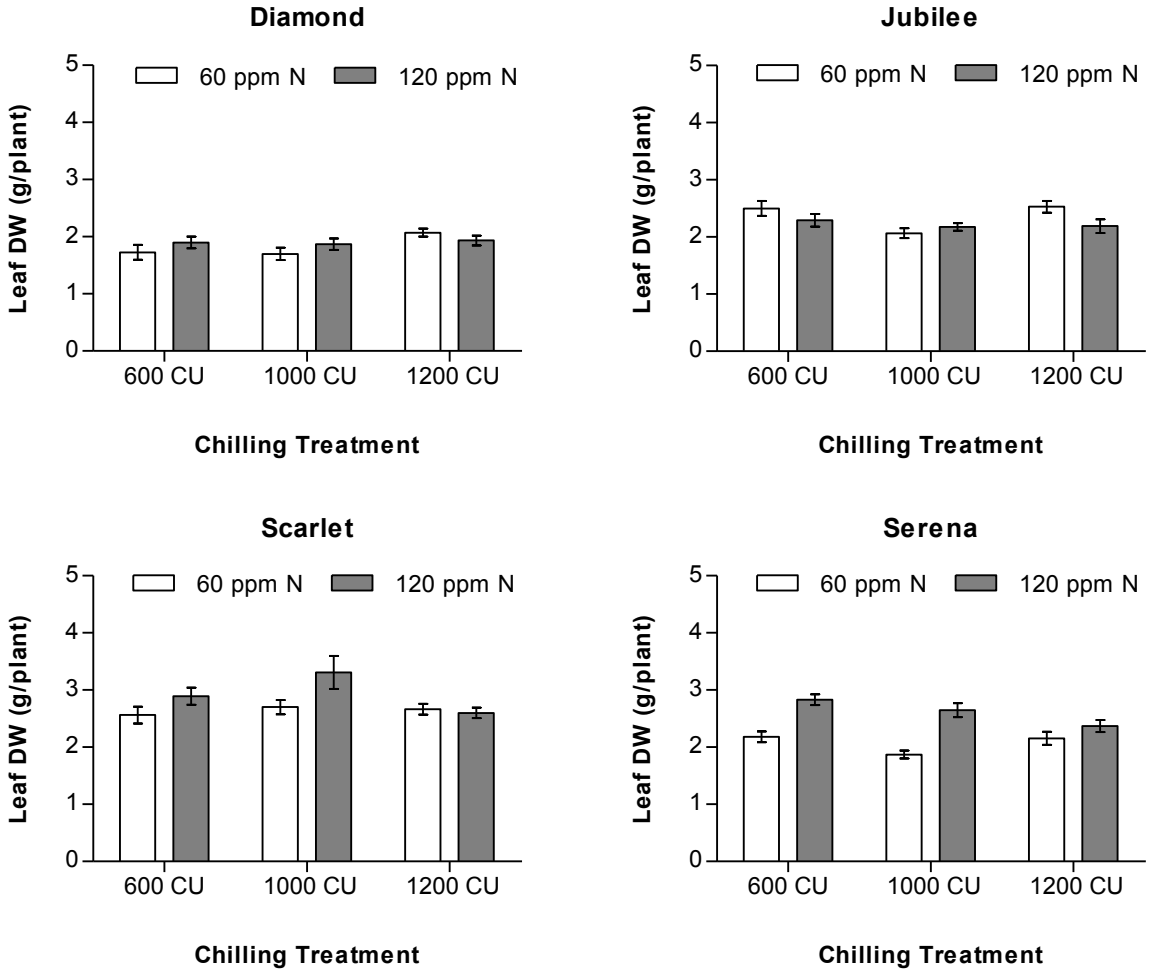

Figure 5.12 Effect of N treatment and chilling treatment on leaf dry weight at the end of the propagation phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=10). DW = dry weight. The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

Root Score

Root score of Scarlet (5.2±0.1) was significantly (P<0.001) higher than Jubilee (4.5±0.2), Diamond (4.5±0.1) and Serena (4.2±0.1). Root score of Diamond and Jubilee did not significantly differ but were also both greater than Serena.

There was a significant interaction between the nitrogen and chilling treatments (P=0.003, Figure 5.13) such that at the Medium Chill level, root score was 27% greater in the High N treatment compared to the Low N treatment; whereas, there was no significant difference at the Low and High Chill levels. At Low N, there was no significant differences in root score between chilling treatments whereas at High N root score was significantly greater in the Medium Chill treatment compared to the Low and High Chill treatments (by 22% each).

Total Dry Weight

Total dry weight of Scarlet (10.04±0.19 g / plant) was significantly (P<0.001) higher than Diamond (7.91±0.20), Jubilee (8.40±0.19) and Serena (8.84±0.23). Total dry weight of Serena and Jubilee did not significantly differ but were also greater than Diamond.

There was a significant interaction between the nitrogen and chilling treatments (P<0.001, Figure 5.14) such that at the Low and Medium Chill levels, total dry weight was significantly greater in the High N treatment compared to the Low N treatment (12% and 25% respectively) but there was no significant difference at the High Chill level. At Low N, total dry weight was significantly greater in the High Chill treatment compared to the Medium treatment (by 4%) whereas at High N, total dry weight was significantly higher in the Low and Medium Chill treatments compared to the High Chill treatment (7% and 18% respectively), and in the Medium compared to the Low Chill treatment (by 10%).

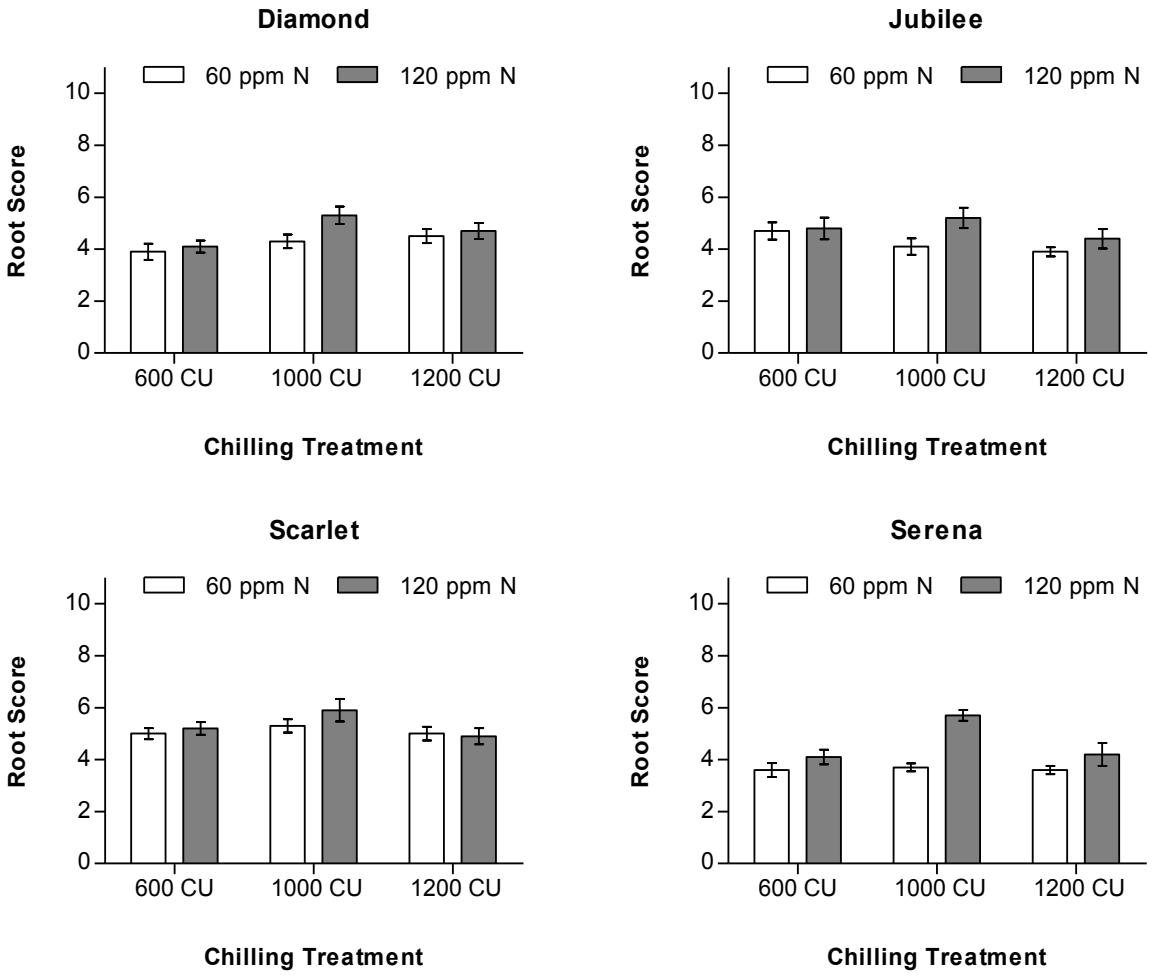

Figure 5.13 Effect of N treatment and chilling treatment on root score at the end of the propagation phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=10). The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

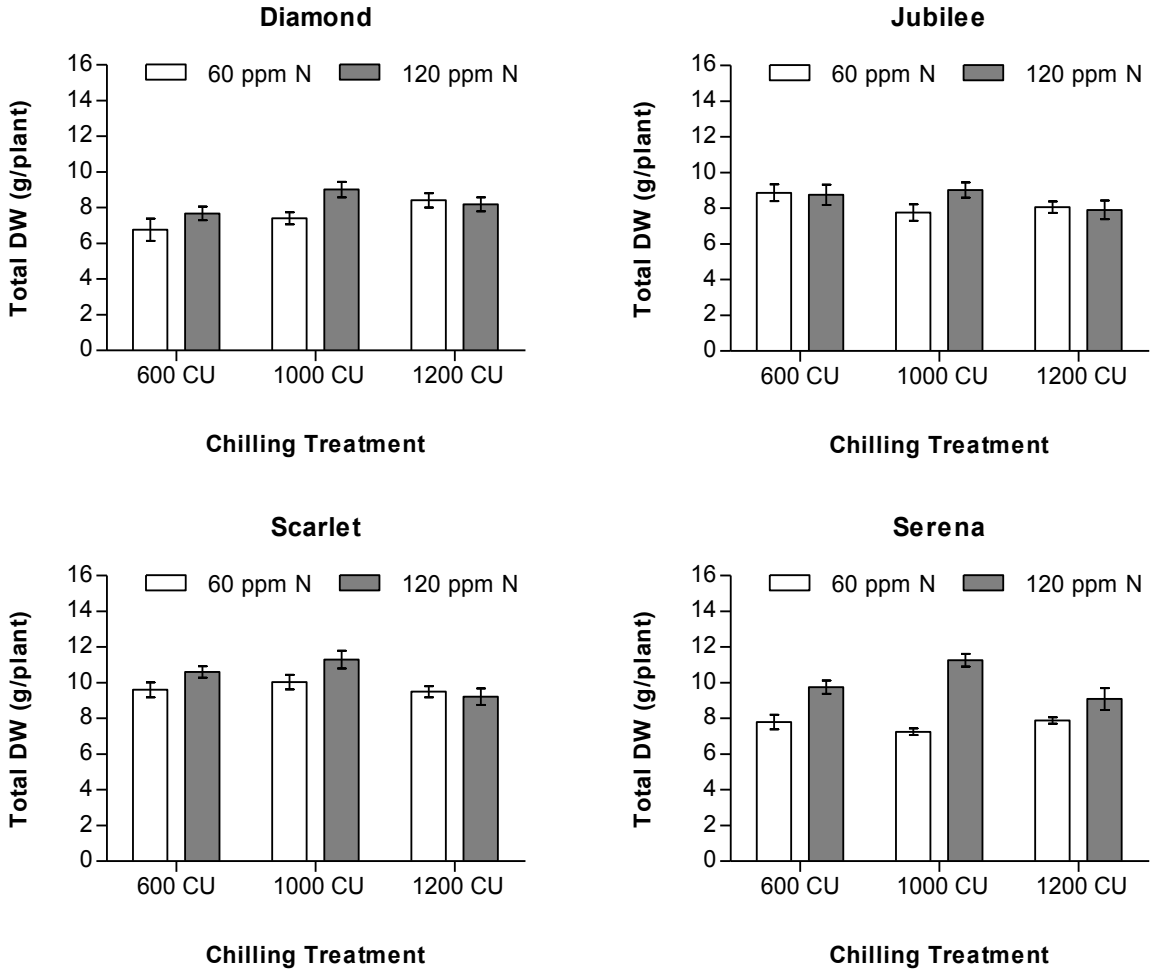

Figure 5.14 Effect of N treatment and chilling treatment on total plant dry weight at the end of the propagation phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=10). DW = dry weight. The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

5.3.2 Production Phase

5.3.2.1 *Glasshouse Production*

Yield

Treatment effects on total, marketable and un-marketable yield at the end of the production phase for Lusa are shown in Figure 5.15. Only the main effects of the treatments on the marketable and total yield were significant ($P<0.05$); marketable and total yield were 9% and 10% greater in the High N treatment compared to the Low N treatment respectively, and 12% and 13% greater respectively in the Low Chill treatment compared to the High Chill treatment respectively.

There was a significant interaction between the nitrogen and chilling treatments for the un-marketable yield ($P=0.022$) such that at Low N the un-marketable yield was 51% greater in the Low Chill treatment compared to the High Chill treatment, but there was no significant difference at High N. Un-marketable yield was 46%, greater in the High N treatment compared to the Low N treatment at the High Chill level but there was no significant difference at the Low Chill level.

Percentage Class 1

Treatment effects on percentage Class 1 for Lusa is shown in Figure 5.15; there were no significant treatment effects or interactions found. Overall the mean percentage Class 1 was 91±0.5 %.

Berry Number

Treatment effects on total, marketable and un-marketable berry number at the end of the production phase for Lusa are shown in Figure 5.16. Only the main effects of the treatments were significant ($P<0.05$). Marketable, un-marketable and total berry number were significantly greater in the High N treatment compared to the Low N treatment (15%, 13% and 27% respectively) and significantly greater in the Low Chill treatment compared to the High Chill treatment (15%, 12% and 28% respectively).

Berry Weight

Treatment effects on average marketable berry weight for Lusa is shown in Figure 5.16. There was no significant treatment effects or interactions found. Overall the mean marketable berry weight was 17.0±0.2 g / berry.

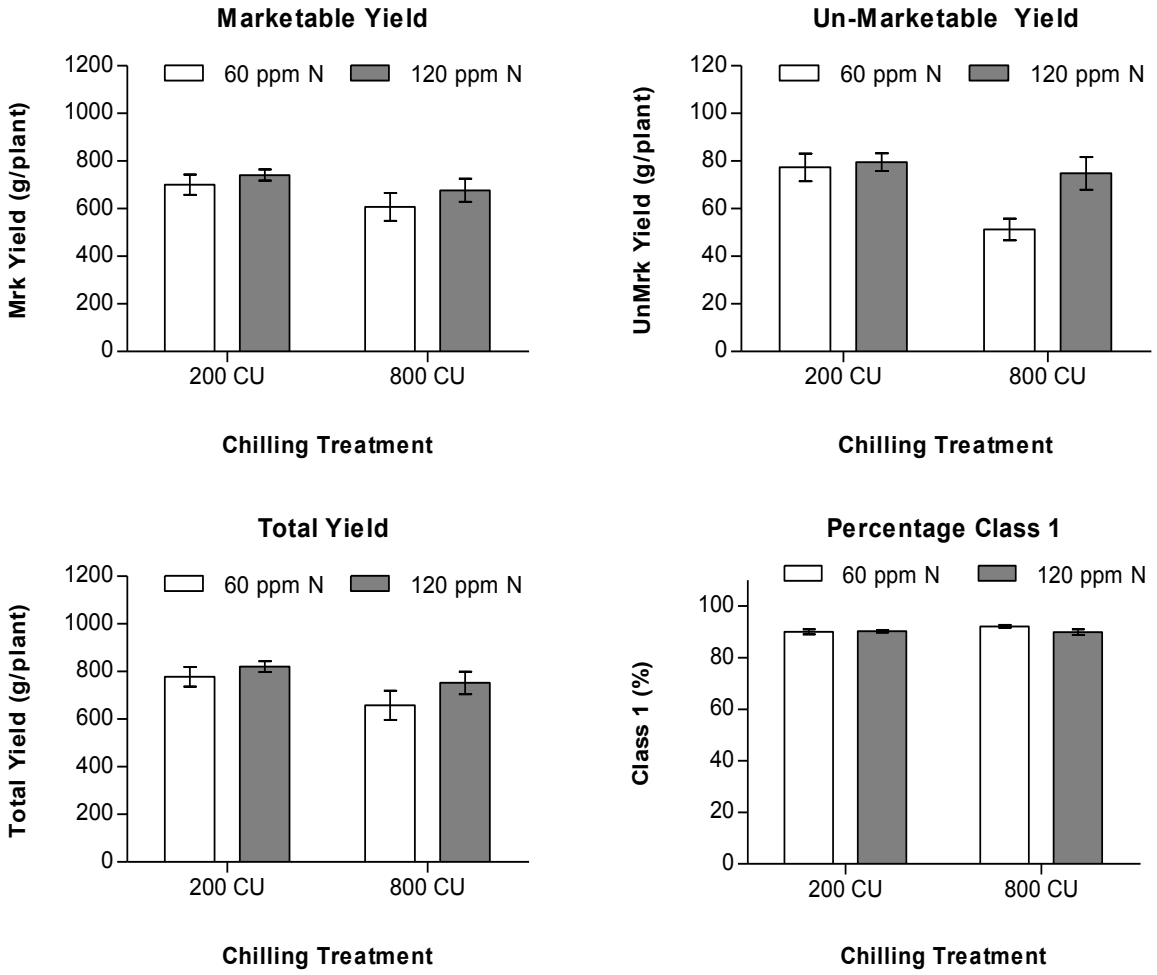

Figure 5.15 Effect of N treatment and chilling treatment on marketable, un-marketable and total yield and percentage marketable yield at the end of the production phase for the glasshouse crop of the cultivar Lusa (n=4). Mrk= marketable, Un-Mrk= Un-marketable. The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (200 CU) and High Chill (800 CU).

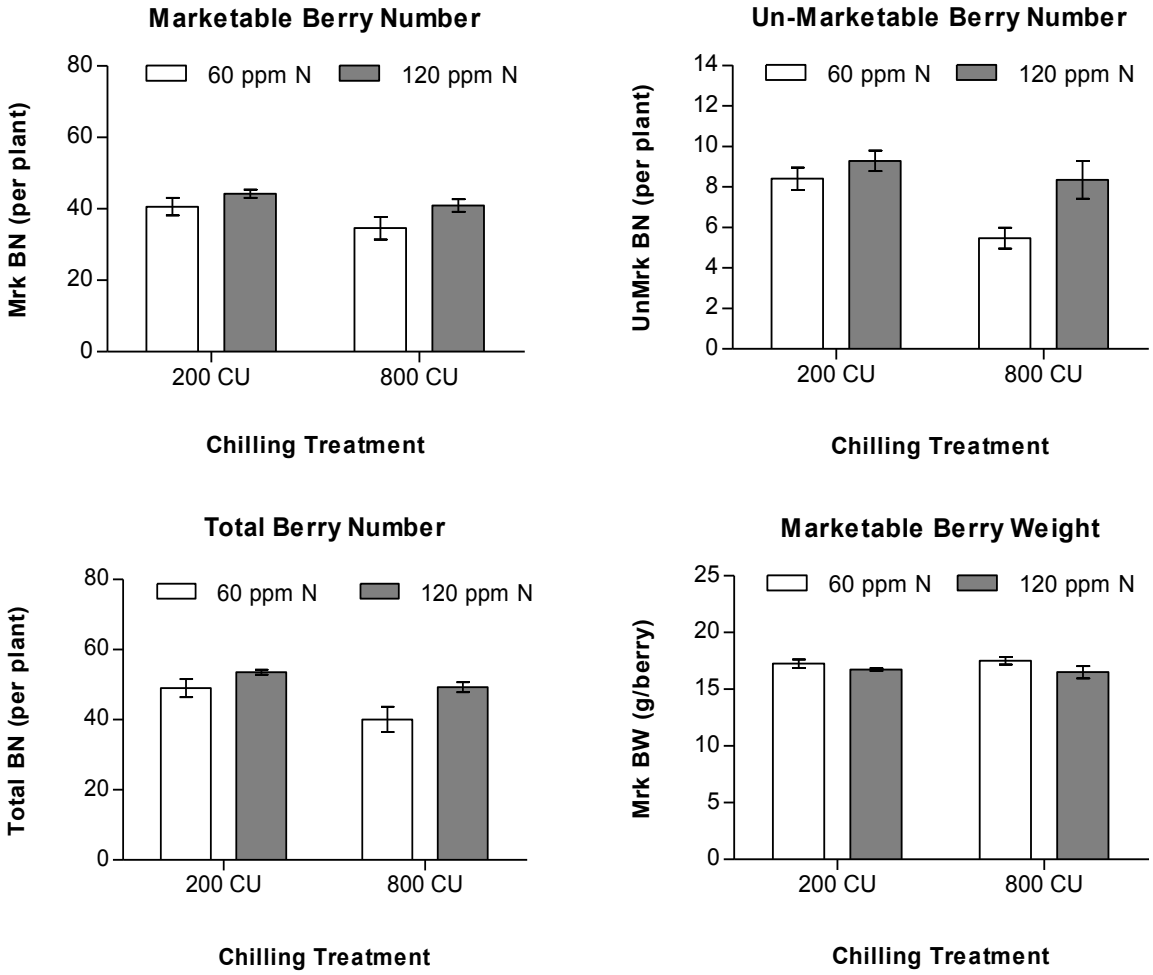

Figure 5.16 Effect of N treatment and chilling treatment on marketable, un-marketable and total berry number and marketable berry weight at the end of the production phase for the glasshouse cultivar Lusa (n=4). BN= berry number, BW= berry weight, Mrk= marketable, Un-Mrk= Un-marketable. The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (200 CU) and High Chill (800 CU).

5.3.2.2 *Polytunnel Production*

Marketable Yield

Marketable yield of Serena (1039±32.7 g / plant) and Scarlet (1019±21.3) was significantly greater (P<0.001) than both Jubilee (704±21.7) and Diamond (654±15.4). No other differences in marketable yield between cultivars were significant. Treatment effects on marketable yield for each cultivar are shown in Figure 5.17; overall, only the main effect of the nitrogen treatment was significant (P=0.013) where the marketable yield greater in the High N treatment (883±34.5 g / plant) compared to the Low N treatment (826±32.8).

Un-Marketable Yield

Treatment effects on un-marketable yield for each cultivar are shown in Figure 5.18. Overall, only the differences in un-marketable yield between cultivars were significant (P<0.001); Scarlet had the greatest un-marketable yield (205±11.8 g / plant), significantly greater than Diamond (66±5.2), Jubilee (156±8.0) and Serena (120±8.4).

Total Yield

All differences in total yield between cultivars were significant (P<0.001); Scarlet had the greatest total yield (1224±25.3 g / plant), followed by Serena (1159±32.8), Jubilee (860±21.9) and Diamond (721±16.3). Treatment effects on total yield for each cultivar are shown in Figure 5.19; overall, only the main effect of the nitrogen treatment was significant (P=0.003), where the total yield was greater in the High N treatment (1025±39.9) compared to the Low N treatment (957±37.6).

Percentage Class 1

Treatment effects on percentage Class 1 for each cultivar are shown in Figure 5.20; only the difference in percentage Class 1 between cultivars was significant (P<0.001). Percentage Class 1 of Diamond (91±0.7 %) and Serena (90±0.7) were significantly higher than Scarlet (83±0.8) and Jubilee (82±1.0). No other differences in percentage Class 1 between cultivars were significant.

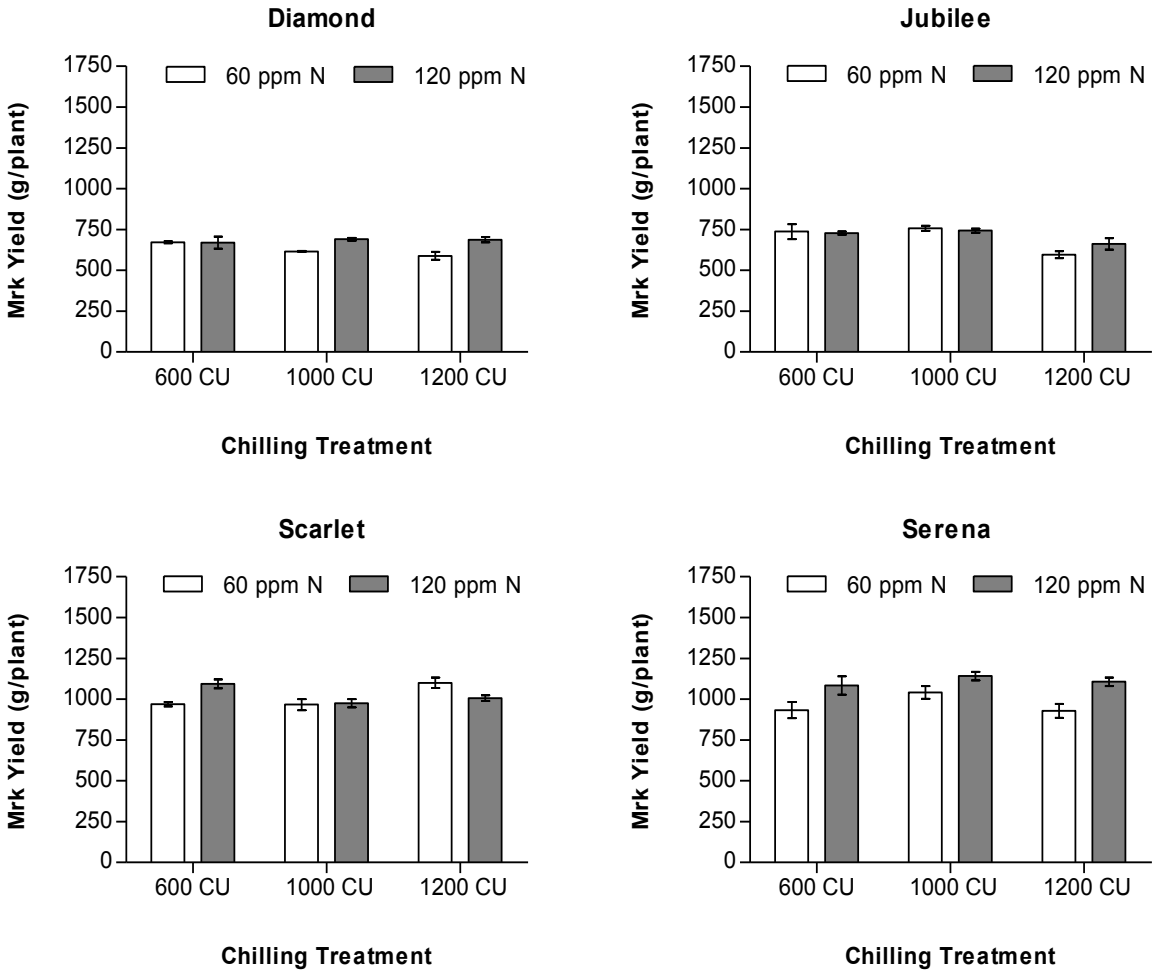

Figure 5.17 Effect of N treatment and chilling treatment on marketable yield at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=3). Mrk= marketable. The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

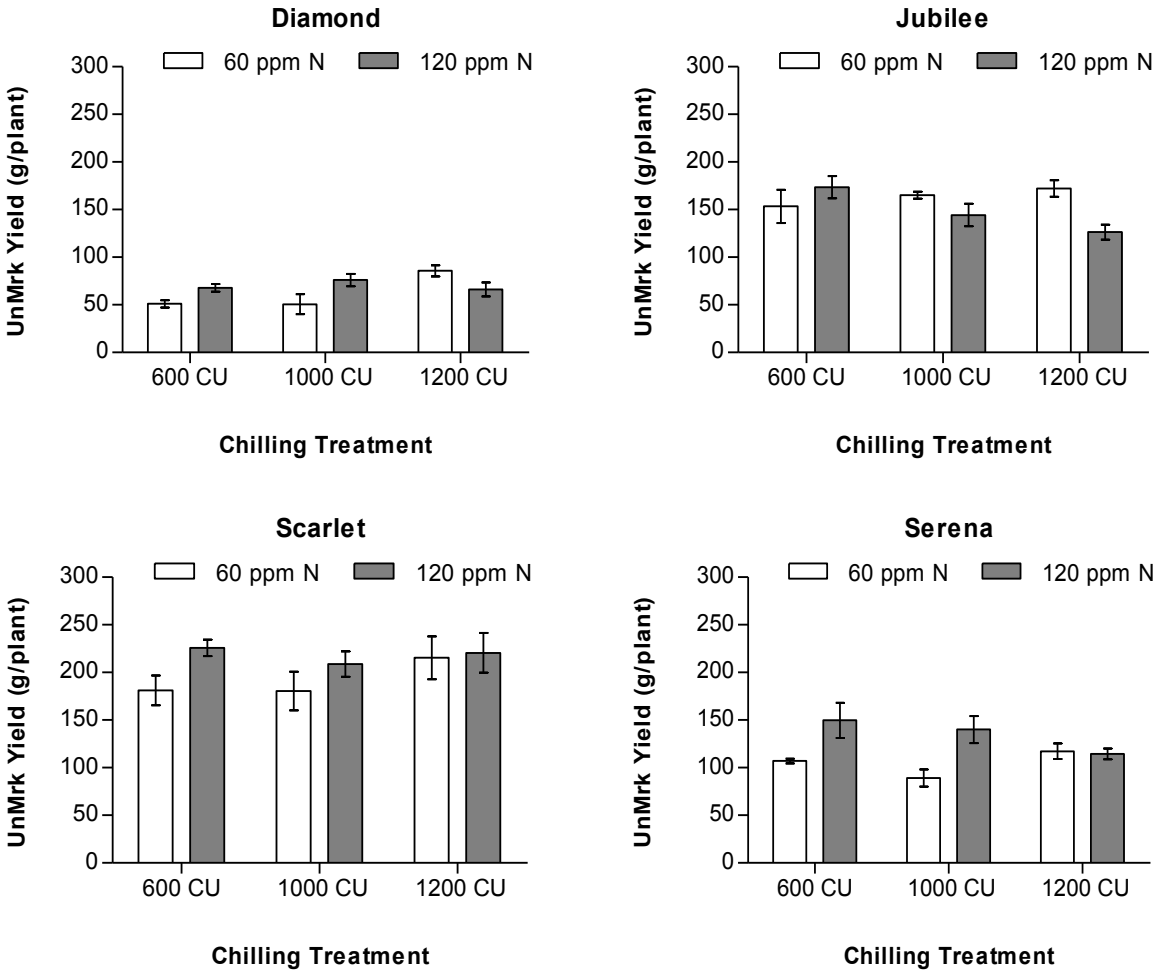

Figure 5.18 Effect of N treatment and chilling treatment on un-marketable yield at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=3). Un-Mrk= un-marketable. The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

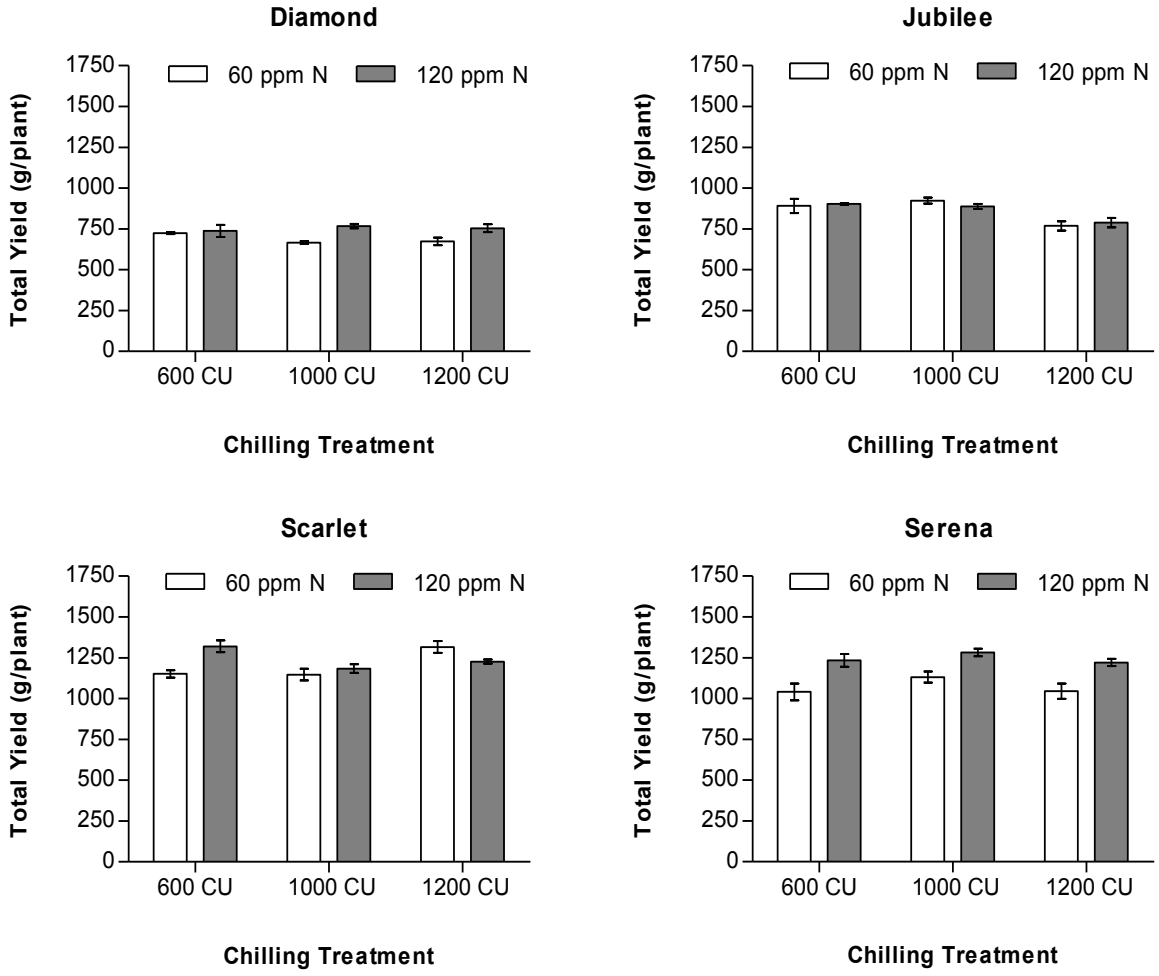

Figure 5.19 Effect of N treatment and chilling treatment on total yield at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=3). The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

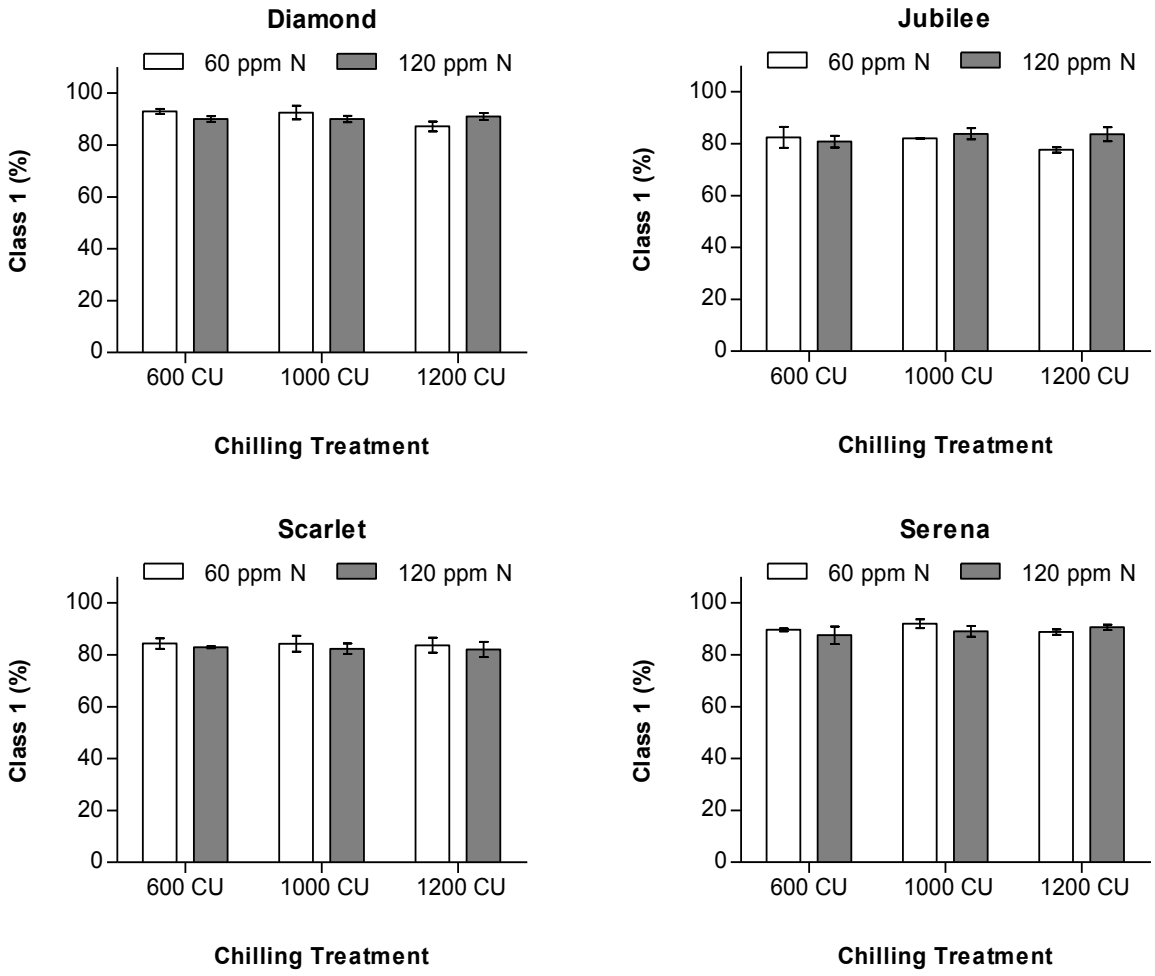

Figure 5.20 Effect of N treatment and chilling treatment on percentage Class 1 at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=3). The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

Marketable Berry Number

Scarlet had the greatest marketable berry number (60.4±1.5 berries / plant) significantly (P<0.001) higher than Diamond (28.3±0.7), Jubilee (39.1±1.0) and Serena (56.7±1.8). Marketable berry number of Serena was also significantly higher than Diamond and Jubilee, and in Jubilee compared to Diamond. Treatment effects on marketable berry number for each cultivar are shown in Figure 5.21; overall, only the main effect of the nitrogen treatment was significant (P=0.004), where marketable berry number was greater in the High N treatment (48.0±2.5) compared to the Low N treatment (44.3±2.2).

Un-Marketable Berry Number

Treatment effects on un-marketable berry number for each cultivar are shown in Figure 5.22. Only the differences in un-marketable berry number between cultivars were significant (P<0.001). Scarlet had the greatest un-marketable berry number (18.2±1.0 berries / plant), significantly higher than Jubilee (14.3±0.7), Serena (11.1±0.8) and Diamond (4.1±0.3).

Total Berry Number

All differences in total berry number between cultivars were significant (P<0.001); Scarlet had the greatest total berry number (78.5±1.9 berries / plant), followed by Serena (67.8±2.2), Jubilee (53.4±1.1) and Diamond (32.4±0.7). Treatment effects on total berry number are shown in Figure 5.23; overall, only the main effect of the nitrogen treatment was significant (P=0.002) where total berry number was 9% greater in the High N treatment (60.5±3.3) compared to the Low N treatment (55.6±2.9).

Average Berry Weight

Treatment effects on average berry weight for each cultivar is shown in Figure 5.24; only the difference in average marketable berry weight between cultivars was significant (P<0.001). Marketable berry weight was significantly higher in Diamond (23.2±0.4 g / berry) than Jubilee (18.0±0.3), Scarlet (17.0±0.3) and Serena (18.4±0.3). Marketable berry weight did not significantly differ between Serena and Jubilee but was also significantly greater in both compared to Scarlet.

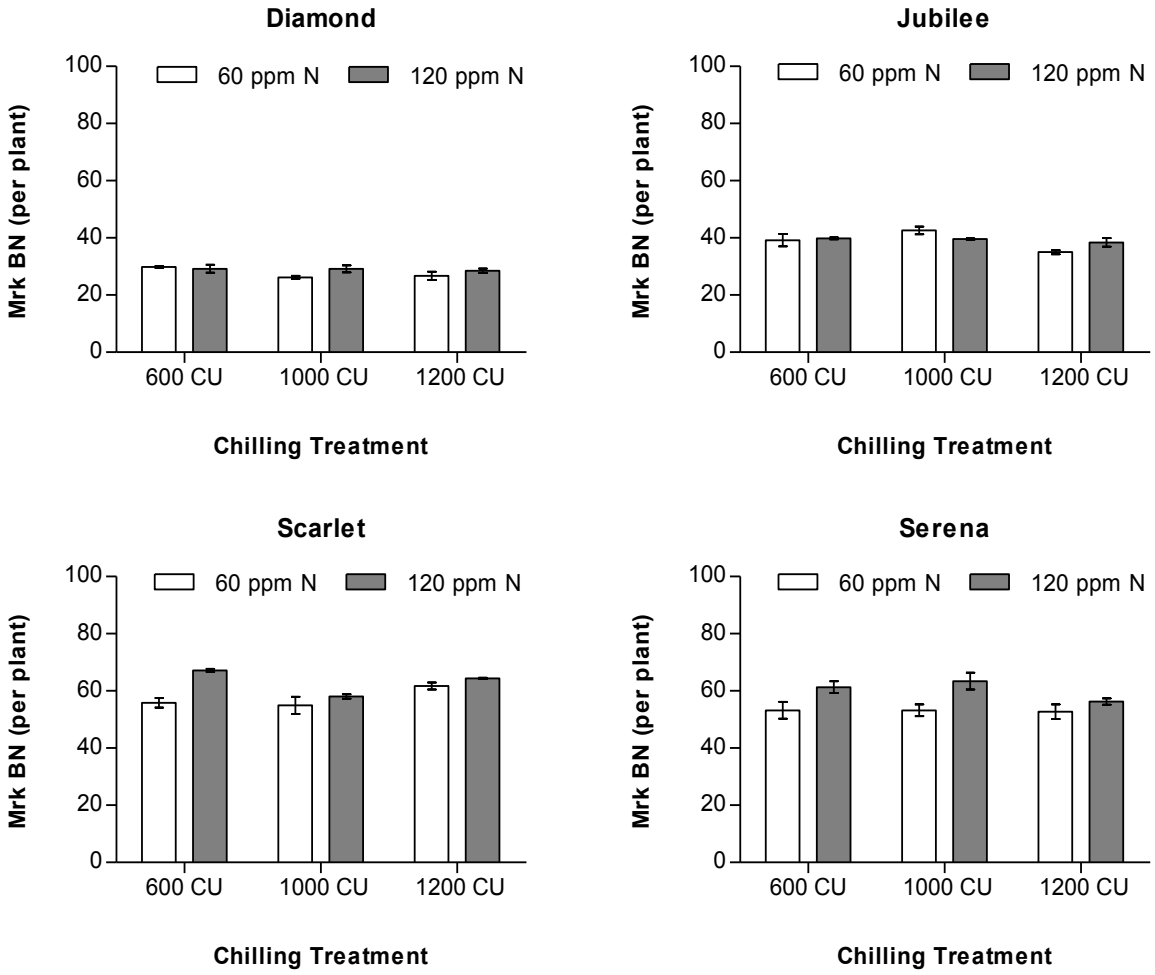

Figure 5.21 Effect of N treatment and chilling treatment on marketable berry number at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=3). BN= berry number, Mrk= marketable. The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

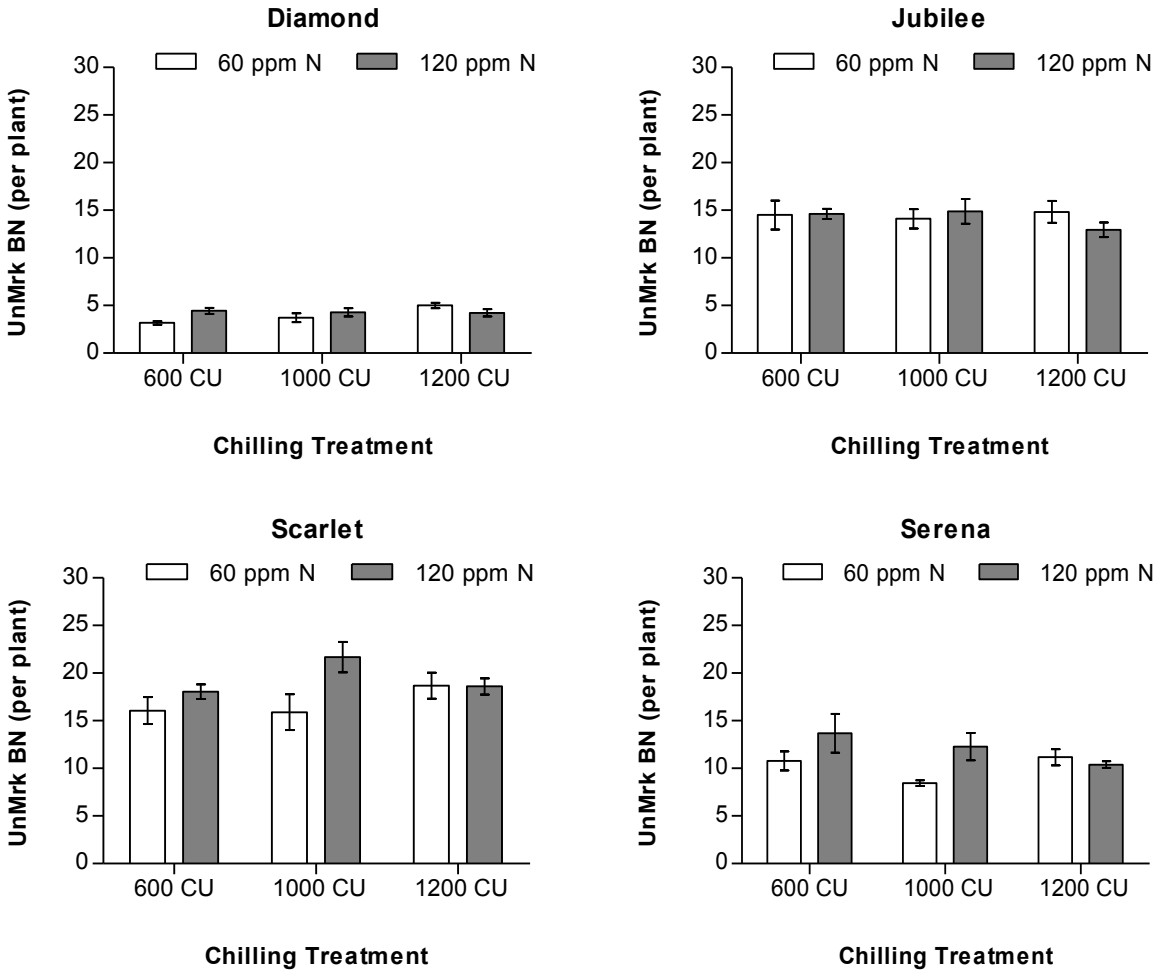

Figure 5.22 Effect of N treatment and chilling treatment on un-marketable berry number at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=3). BN= berry number, Un-Mrk= un-marketable. The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

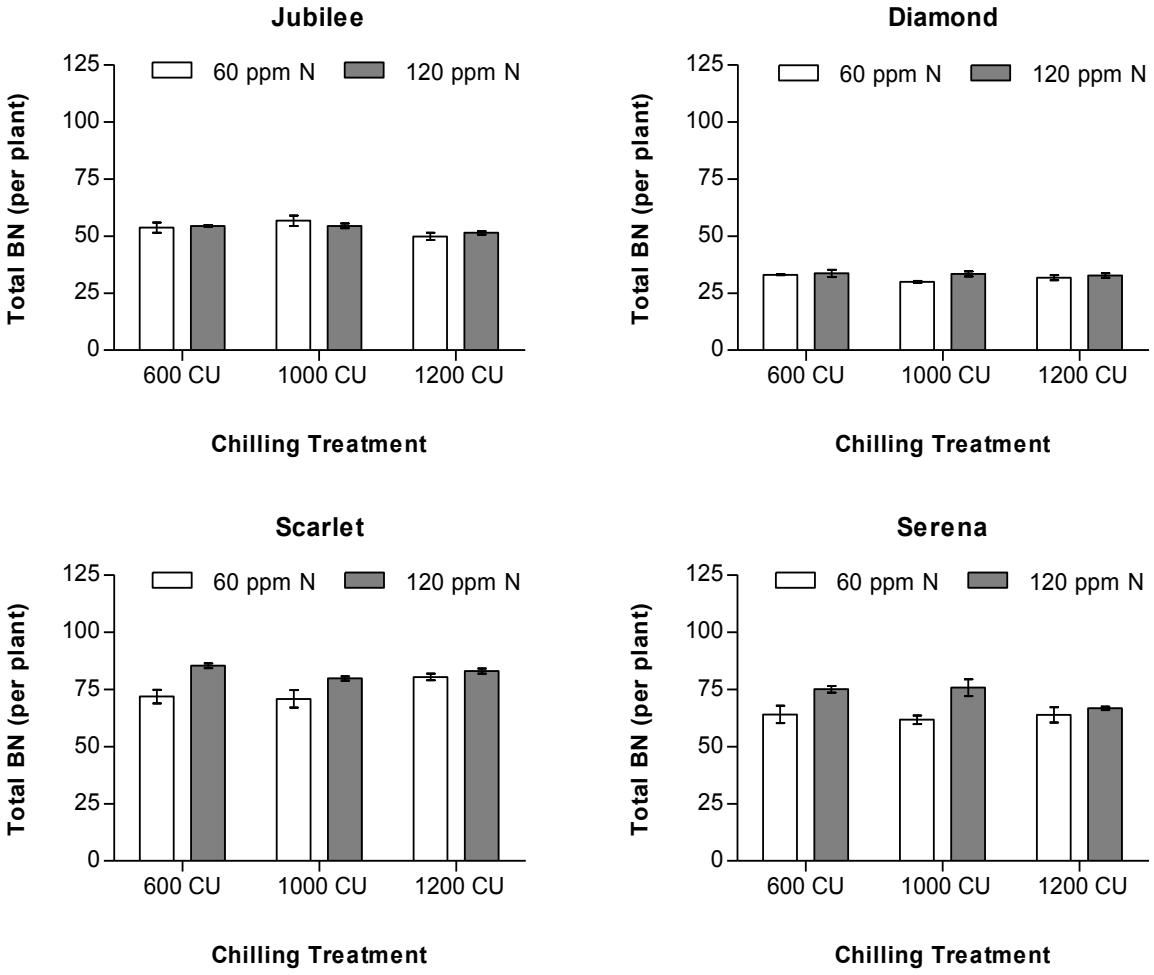

Figure 5.23 Effect of N treatment and chilling treatment on total berry number at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=3). BN= berry number. The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

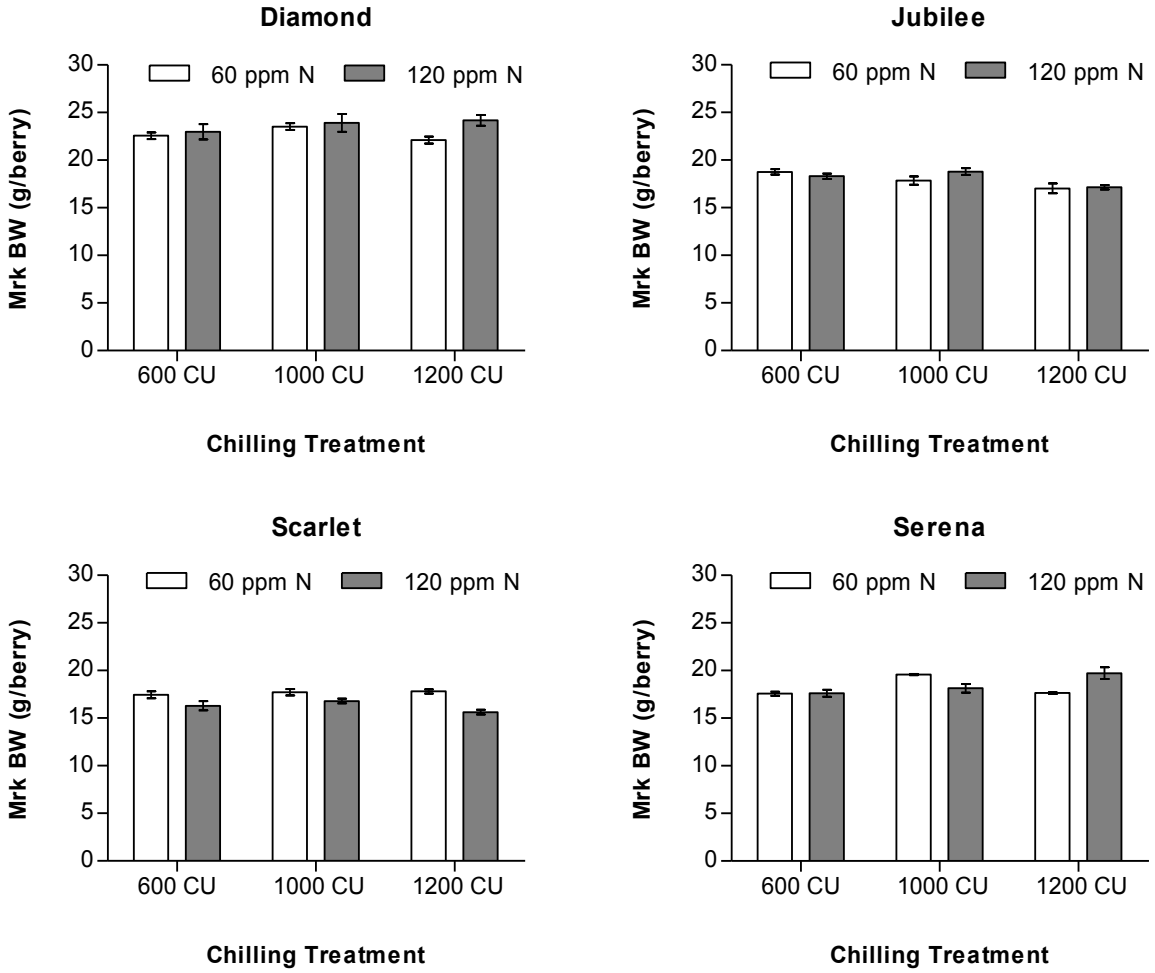

Figure 5.24 Effect of N treatment and chilling treatment on average marketable berry weight at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=3). BW= berry weight, Mrk= marketable. The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

5.3.2.3 *Cropping Profiles*

Glasshouse Production

Marketable yield was recorded for 18 weeks (24th March to 17th July) in the glasshouse crop of Lusa. There was no significant interaction between the nitrogen and chilling treatments at any point (Figure 5.25C) Main effects showed that marketable yield was significantly greater in the High N treatment compared to the Low N treatment on 24th May and 30th June (by 31% and 27% respectively) (Figure 5.25A) and in the High Chill treatment compared to the Low Chill treatment on 31st March, 14th April and 5th May by 322%, 65% and 50% respectively (Figure 5.25C). After eight weeks of cropping (23rd March to 12th May 2014) marketable yield was significantly greater in the High Chill treatment compared to the Low Chill treatment by 38% whereas there was no significant difference in marketable yield between N treatments.

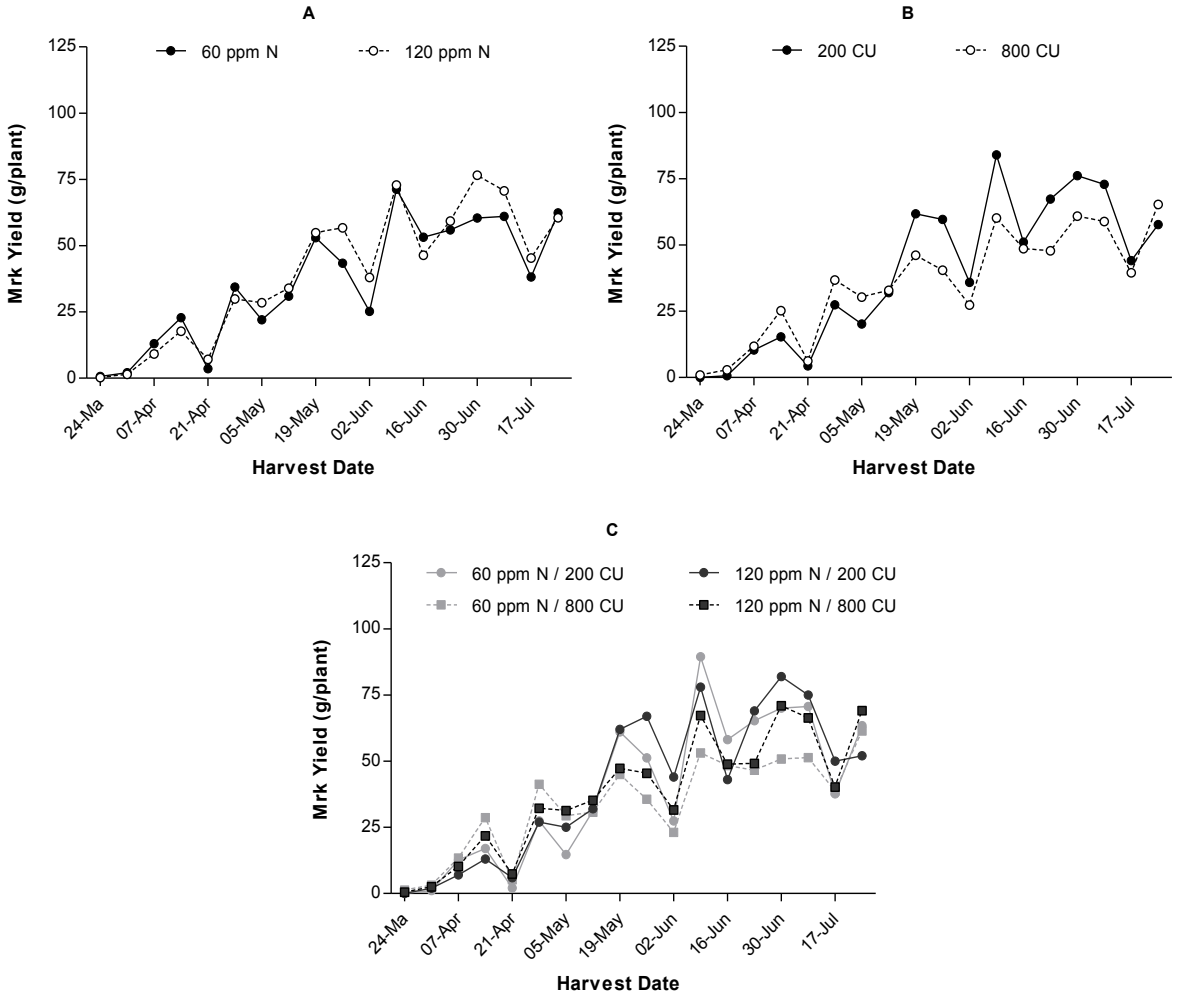

Figure 5.25 Effects on N treatment (A, n=8), chilling treatment (B, n=8) and the interaction between (C, n=4) on marketable yield each week in the glasshouse crop of Lusa. Mrk= marketable. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (200 CU) and High Chill (800 CU).

Polytunnel Production

In the polytunnel production, marketable yield for each cultivar and treatment was recorded for 21 weeks (29th May to 16th October 2014) (Figure 5.26). There was a significant ($P<0.05$) difference in marketable yield between cultivars for every harvest except the fifth (Figure 5.27A). At the start of cropping, marketable yield was generally greater in Diamond, and this was significant compared to all other cultivars in Week 3 (12th June) and Week 4 (17th June) where the marketable yield was, on average, 156%, 114% and 75% greater compared to Jubilee, Scarlet and Serena respectively. However, from Week 9 (24th July) Diamond had the lowest marketable yield of all four cultivars, and this was significantly lower compared to Jubilee between 21st August and 22nd September (on average 130%), and in Scarlet and Serena from 24th July to the end of cropping (on average 295% and 254% respectively). Marketable yield was also significantly lower in Jubilee compared to Scarlet from 22nd September and Serena from 21st August to the end of cropping (on average 154% and 98% respectively).

Overall, there was no significant interaction between the nitrogen and chilling treatments at any time, and the main effects of the treatments were also not significant (Figure 5.27B-D). When analysing treatment effects on individual cultivars, significant cultivar and N treatment interactions in Week 3, 4, 20 and 21 showed some significant differences between N treatments for Serena and Scarlet, such that marketable yield was greater in the High N treatment for Serena in Week 3 and 4 (by 118% and 111% respectively) and in the Low N treatment for Scarlet in Week 20 and 21 (by 42% and 40%). Similarly, there were significant cultivars and chilling treatment interactions in Week 7 and 13 which showed marketable yield was greater in Low chill treatment compared to High Chill treatment for Jubilee in Week 7 (by 52%) and in the Low Chill treatment compared to Medium Chill and High Chill treatments for Serena in Week 13 (by 47% and 51%).

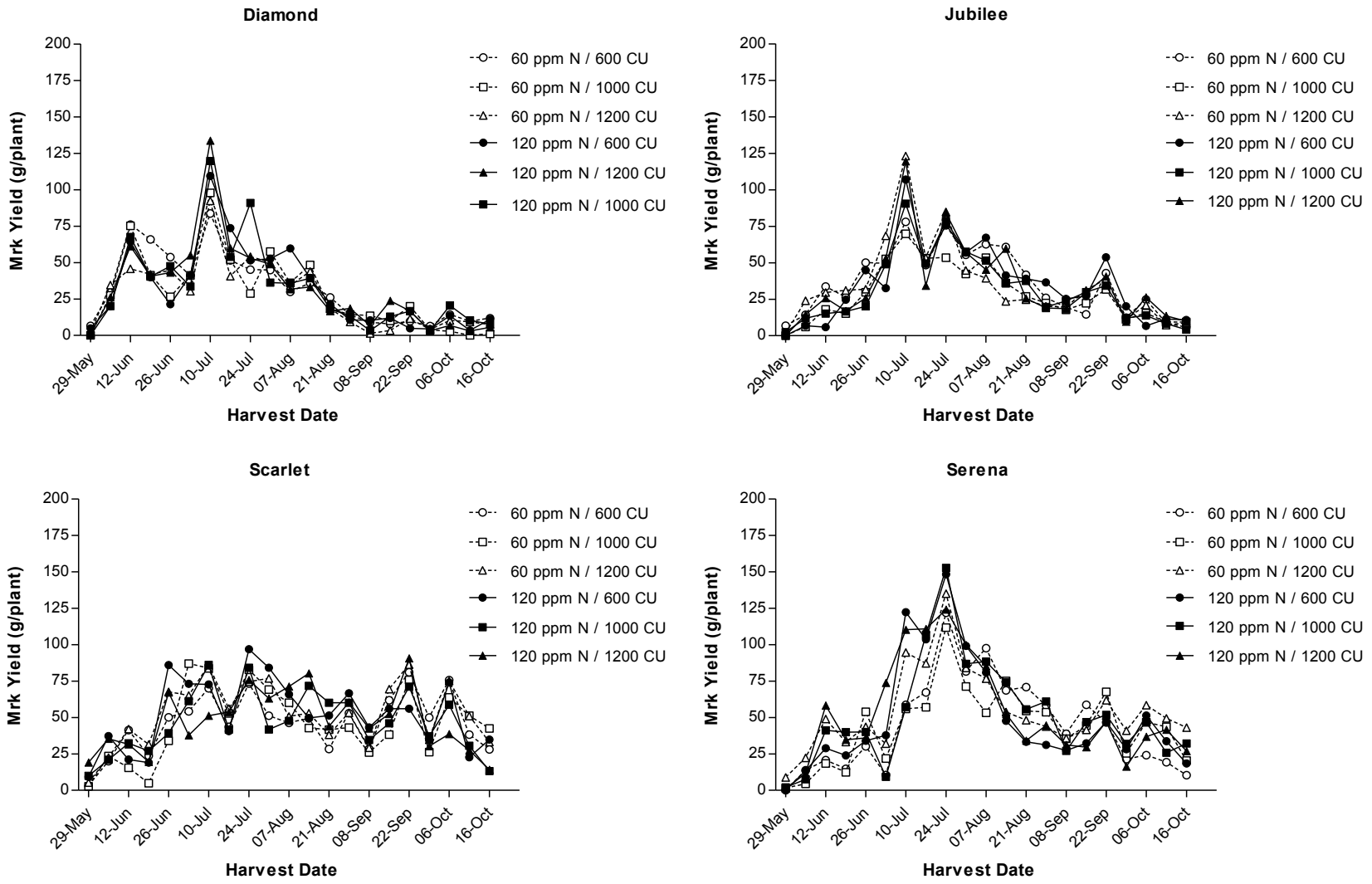

Figure 5.26 Treatment effects on marketable yield each week for the polytunnel production of cultivars Diamond, Jubilee, Scarlet and Serena (n=3). Mrk= marketable. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

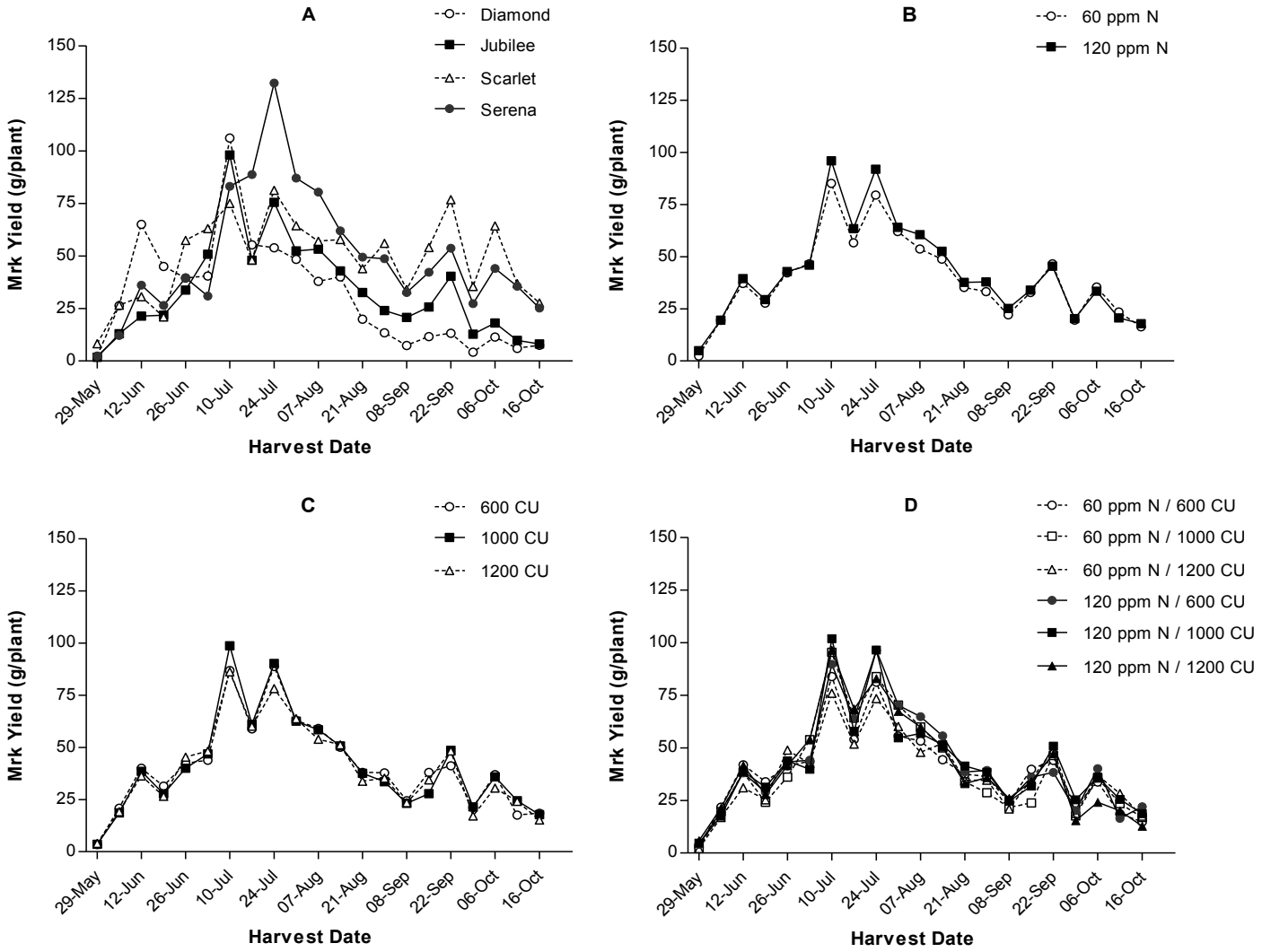

Figure 5.27 Effect of cultivar (A, n=18), N treatment (B, n=36), chilling treatment (C, n=24) and the interaction between the nitrogen and chilling treatments (D, n=12) on marketable yield each week for the polytunnel production of cultivars Diamond, Jubilee, Scarlet and Serena. Mrk= marketable. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

5.3.2.4 *Final Destructive Harvest (DH2)*

Lusa

Crowns

Treatment effects on crown number and crown dry weight for Lusa are shown in Figure 5.28. There was no significant interaction between the treatments for either measurement. The main effect of the chilling treatment on crown dry weight was just significant (P=0.046) with crown dry weight greater in the Low Chill treatment (8.1±0.6 g / plant) compared to the High Chill treatment (6.5±0.5). The main effect of the chilling treatment on crown number was not significant, and there was no significant effect of N treatment on either crown number or crown dry weight.

Leaves

Treatment effects on leaf number and leaf dry weight for Lusa are shown in Figure 5.28. There was no significant interaction between the treatments for either measurement. The main effect of the N treatment on leaf number was significant (P=0.028) with leaf number greater in the High N treatment (27.8±1.8 leaves / plant) compared to the Low N treatment (22.1±1.7). The main effect of the N treatment on leaf dry weight was also significant (P=0.034) with leaf dry weight greater in the High N treatment (21.7±1.3 g / plant) compared to the Low N treatment (17.2±1.7). There was no significant effect of chilling on either leaf number or leaf dry weight.

Total Dry Weight

Treatment effects on total plant dry weight for Lusa is shown in Figure 5.28. There was no significant interaction between the treatments. The main effect of the N treatment was significant (P=0.023) with total dry weight greater in the High N treatment (45.6±2.8 g / plant) compared to the Low N treatment (35.7±3.4). There was no significant effect of chilling treatment on plant dry weight.

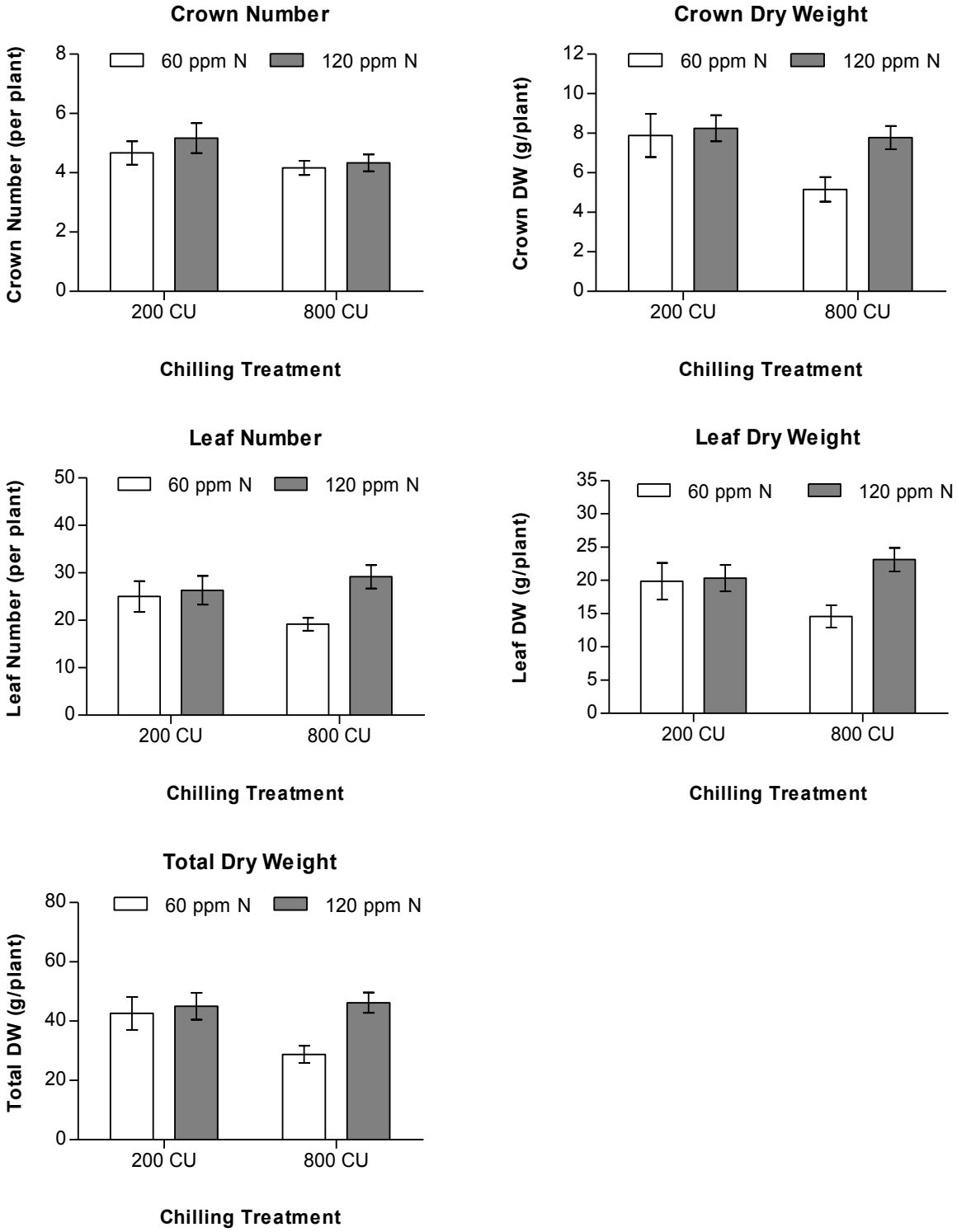

Figure 5.28 Effect of N and chilling treatments on DH2 results for the glasshouse cultivar Lusa (n=12). DW= dry weight. The vertical line on each bar shows ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (200 CU) and High Chill (800 CU).

Remaining Cultivars

Crown Number

Crown number of Diamond (9.0±0.5 crowns / plant) and Scarlet (8.9±0.4) did not significantly differ but were significantly (P<0.001) greater than both Jubilee (7.3±0.3) and Serena (7.4±0.3). Treatment effects on crown number for each cultivar are shown in Figure 5.29. Only the interaction between the cultivars and N treatments was significant (P<0.001) such that crown number was significantly greater in the High N treatment compared to the low N treatment for Diamond and Scarlet (49% and 23% respectively) and there were no significant differences for Jubilee and Serena.

Crown Dry Weight

Crown dry weight of Diamond (20.3±1.5 g / plant) was significantly (P<0.001) greater than Jubilee (13.3±0.6), Scarlet (16.6±0.9) and Serena (13.2±0.8). Crown dry weight of Scarlet was also significantly greater than Jubilee and Serena. Treatment effects on crown dry weight for each cultivar are shown in Figure 5.30. The interaction between the nitrogen and chilling treatments was not significant. The interaction between the cultivars and N treatments was significant (P<0.001) such that crown dry weight was significantly greater in the High N treatment compared to the Low N treatment for Diamond (by 47%) whereas there were no significant differences for Jubilee, Scarlet or Serena. The interaction between the cultivars and the chilling treatments was also significant (P<0.001) such that crown dry weight was significantly greater in the High Chill treatment compared to the Medium and Low Chill treatments for Diamond (94% and 73% respectively and Serena (38% and 25% respectively) whereas there were no significant differences for Jubilee or Scarlet.

Leaf Number

Leaf number of Diamond (67.1±3.3 leaves / plant) was significantly (P<0.001) greater than Jubilee (42.3±1.9), Scarlet (59.7±2.4) and Serena (47.6±2.1). Leaf number was also significantly higher in Scarlet compared to Jubilee and Serena. Treatment effects on leaf number for each cultivar are shown in Figure 5.31. The interaction between the nitrogen and chilling treatments was not significant. The interaction between the cultivars and N treatments was significant (P=0.024) such that leaf number was significantly higher in the High N treatment compared to the Low N treatment for Diamond by 34% whereas there were no significant differences for the remaining

cultivars. The interaction between the cultivars and the chilling treatments was also significant (P=0.003) such that leaf number was significantly greater in the High Chill treatment compared to the Medium and Low Chill treatments for Diamond (45% and 31% respectively) and Serena (30% and 26% respectively) whereas there were no significant differences for Jubilee or Scarlet.

Leaf Dry Weight

Leaf dry weight of Diamond (35.2±2.0 g / plant) was significantly (P<0.001) greater than Jubilee (18.0±1.1), Scarlet (23.9±1.3) and Serena (17.9±1.1). Leaf dry weight was also significantly higher in Scarlet compared to Jubilee and Serena. Treatment effects on leaf dry weight for each cultivar are shown in Figure 5.32. The interaction between the nitrogen and chilling treatments was not significant and neither was the interaction between the cultivars and N treatments. However, the main effect of the nitrogen treatment was (P=0.013) with leaf dry weight 15% greater in the High N treatment (25.4±1.3 g / plant) compared to the Low N treatment (22.1±1.3). The interaction between the cultivars and the chilling treatments was significant (P=0.009) such that leaf dry weight was significantly greater in the High Chill treatment compared to the Medium and Low Chill treatments for Diamond (45% and 26% respectively) and Serena (32% and 41% respectively) whereas there were no significant differences for Scarlet and Jubilee.

Total Dry Weight

Total dry weight of Diamond (70.1±4.0 g / plant) was significantly (P<0.001) higher than Jubilee (37.90±2.0), Scarlet (49.74±2.3) and Serena (37.2±2.1). Total dry weight of Scarlet was also significantly greater than Jubilee and Serena. Treatment effects on total dry weight for each cultivar are shown in Figure 5.33. The interaction between the nitrogen and chilling treatments was not significant and neither was the interaction between the cultivars and N treatments. However, the main effect of the nitrogen treatment was (P=0.003) with plant dry weight greater in the High N treatment (52.3±2.6 g / plant) compared to the Low N treatment (45.2±2.3). The interaction between the cultivars and the chilling treatments was significant (P<0.001) such that total dry weight was significantly higher in the High Chill treatment compared to the Medium and Low Chill treatments for Diamond (31% and 25% respectively) and Serena (36% and 34% respectively) and there were no significant differences for Scarlet or Jubilee.

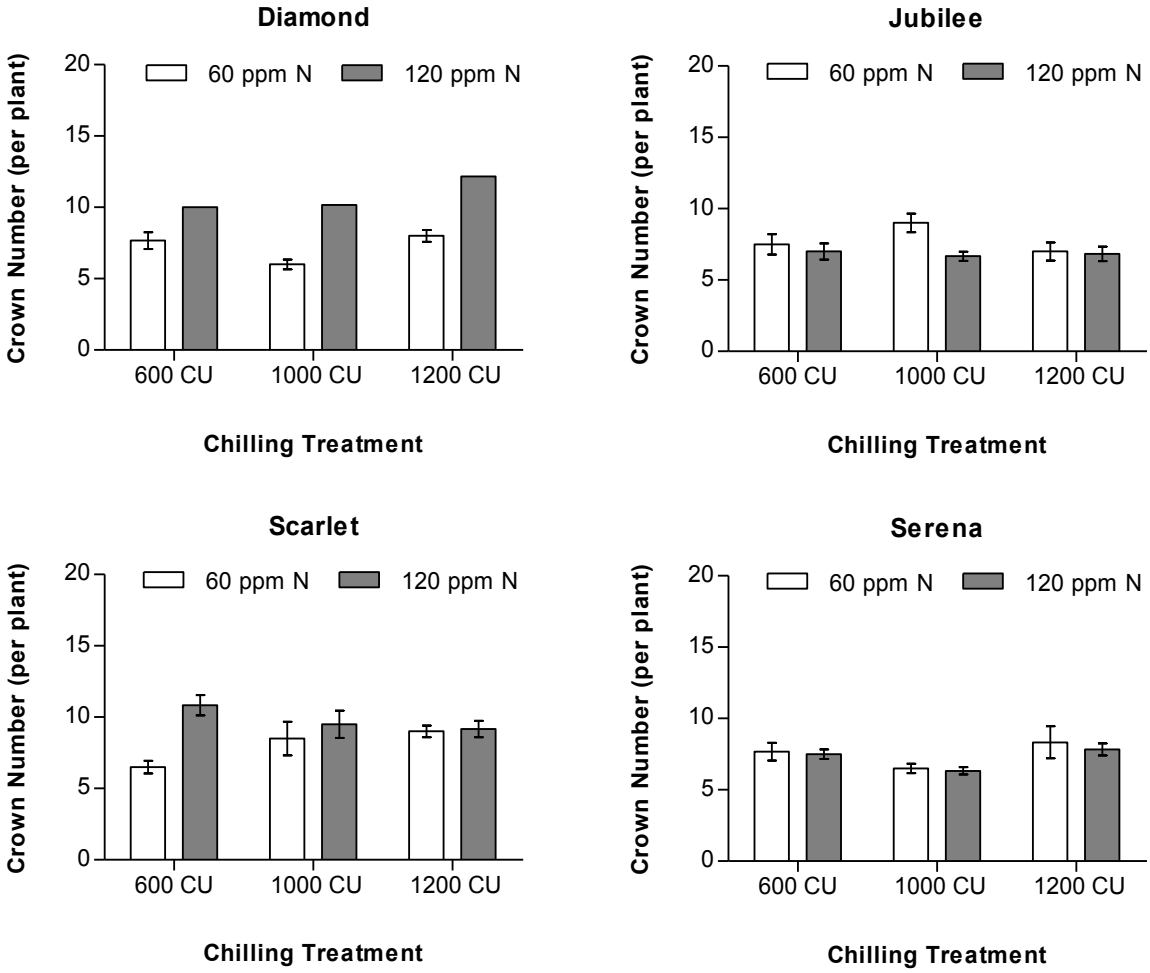

Figure 5.29 Effect of N treatment and chilling treatment on crown number at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=9). The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

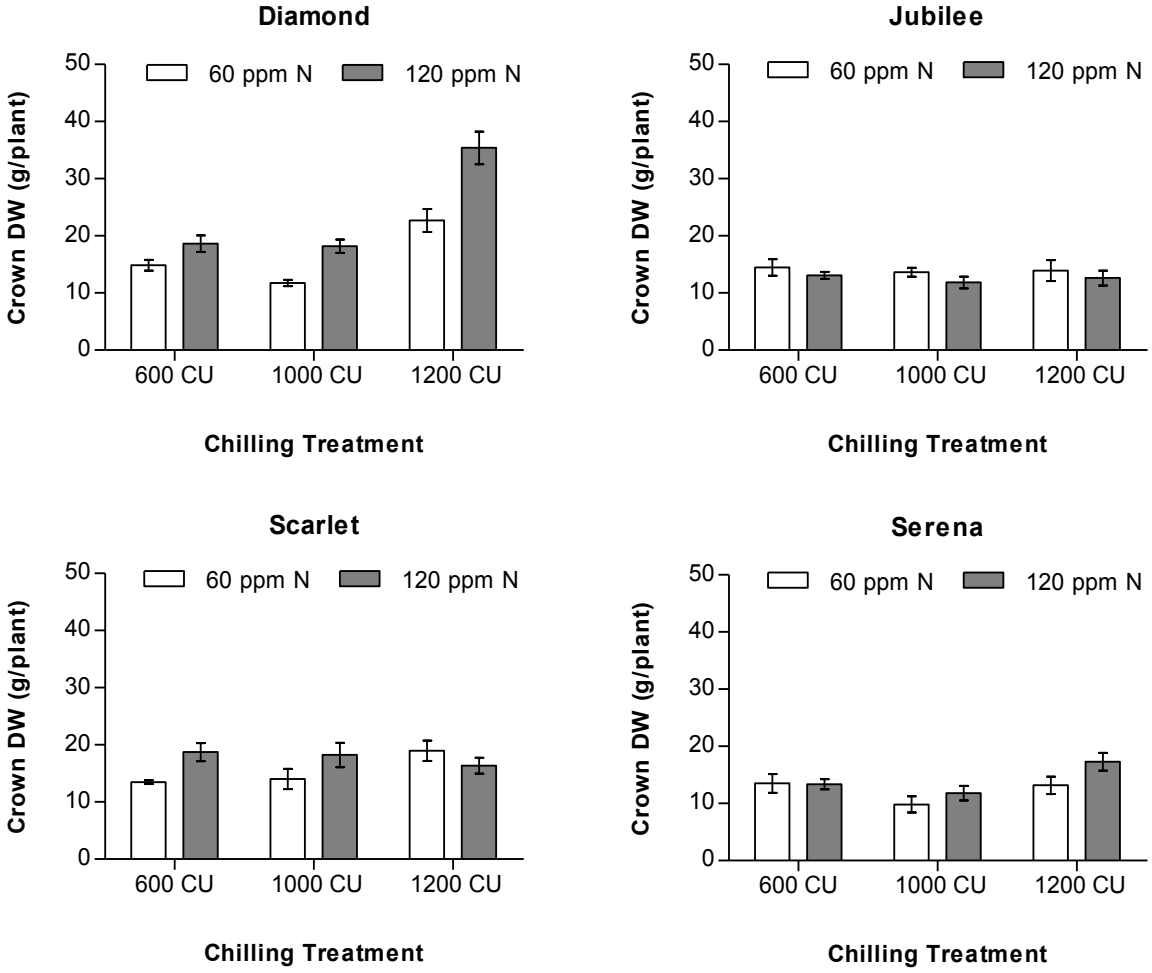

Figure 5.30 Effect of N treatment and chilling treatment on crown dry weight at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=9). DW= dry weight. The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

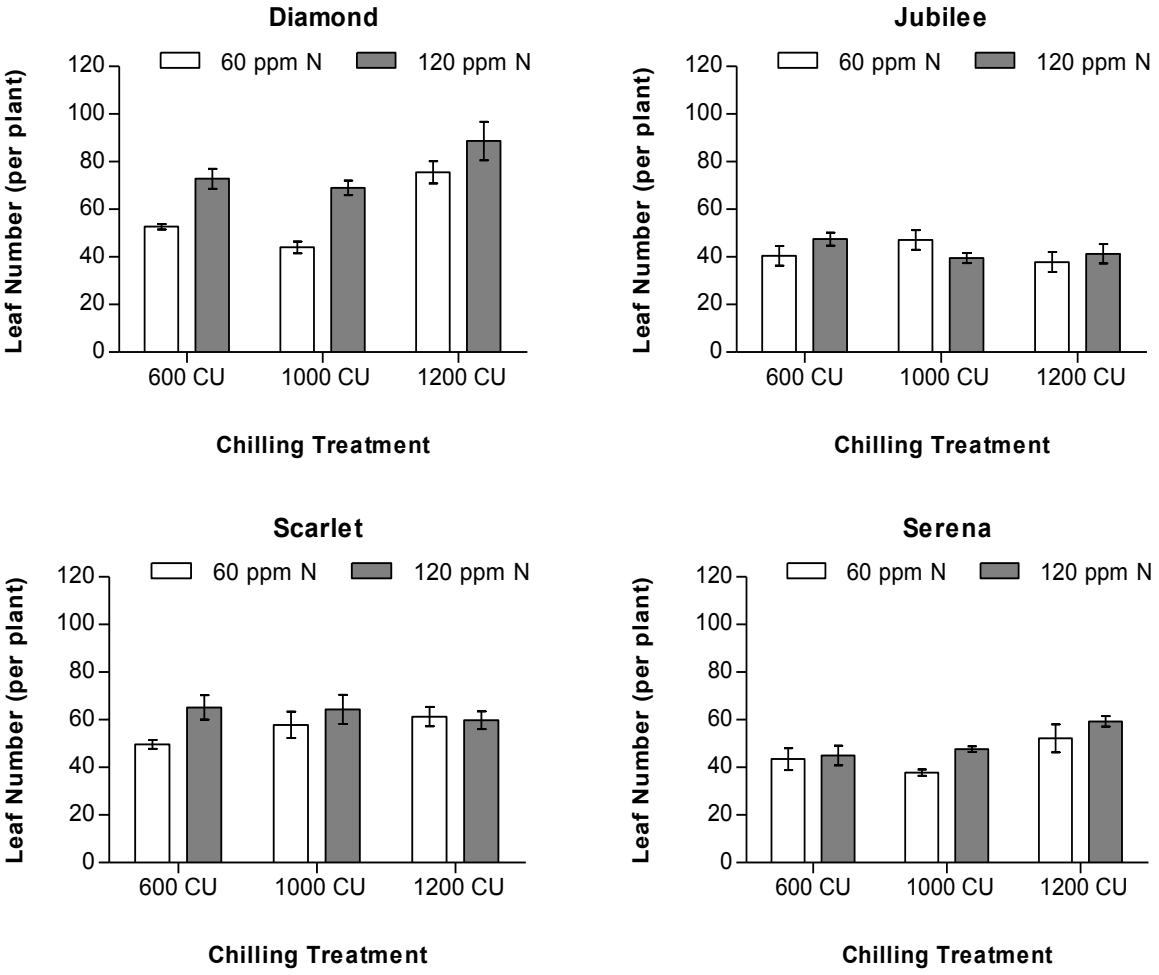

Figure 5.31 Effect of N treatment and chilling treatment on leaf number at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=9). The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

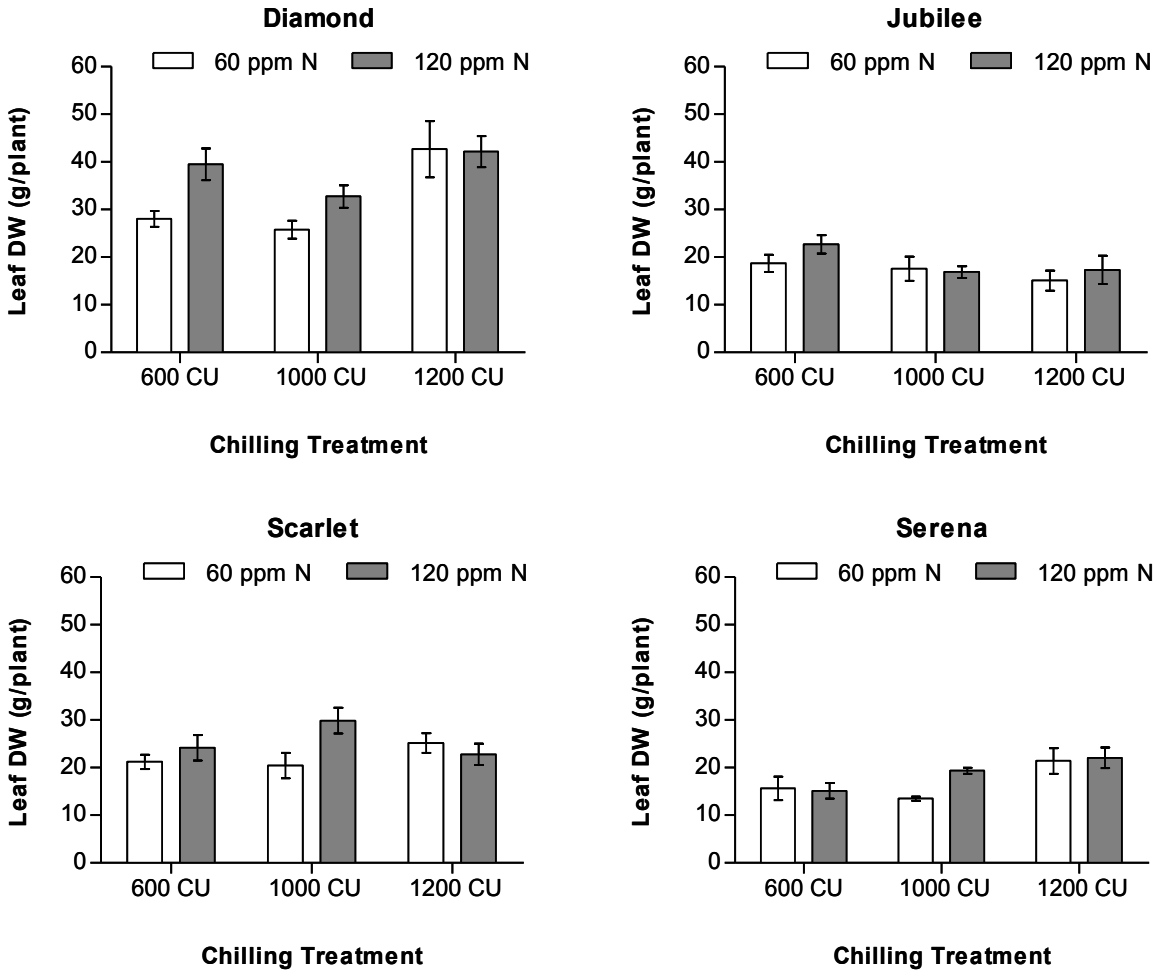

Figure 5.32 Effect of N treatment and chilling treatment on leaf dry weight at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=9). DW= dry weight. The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

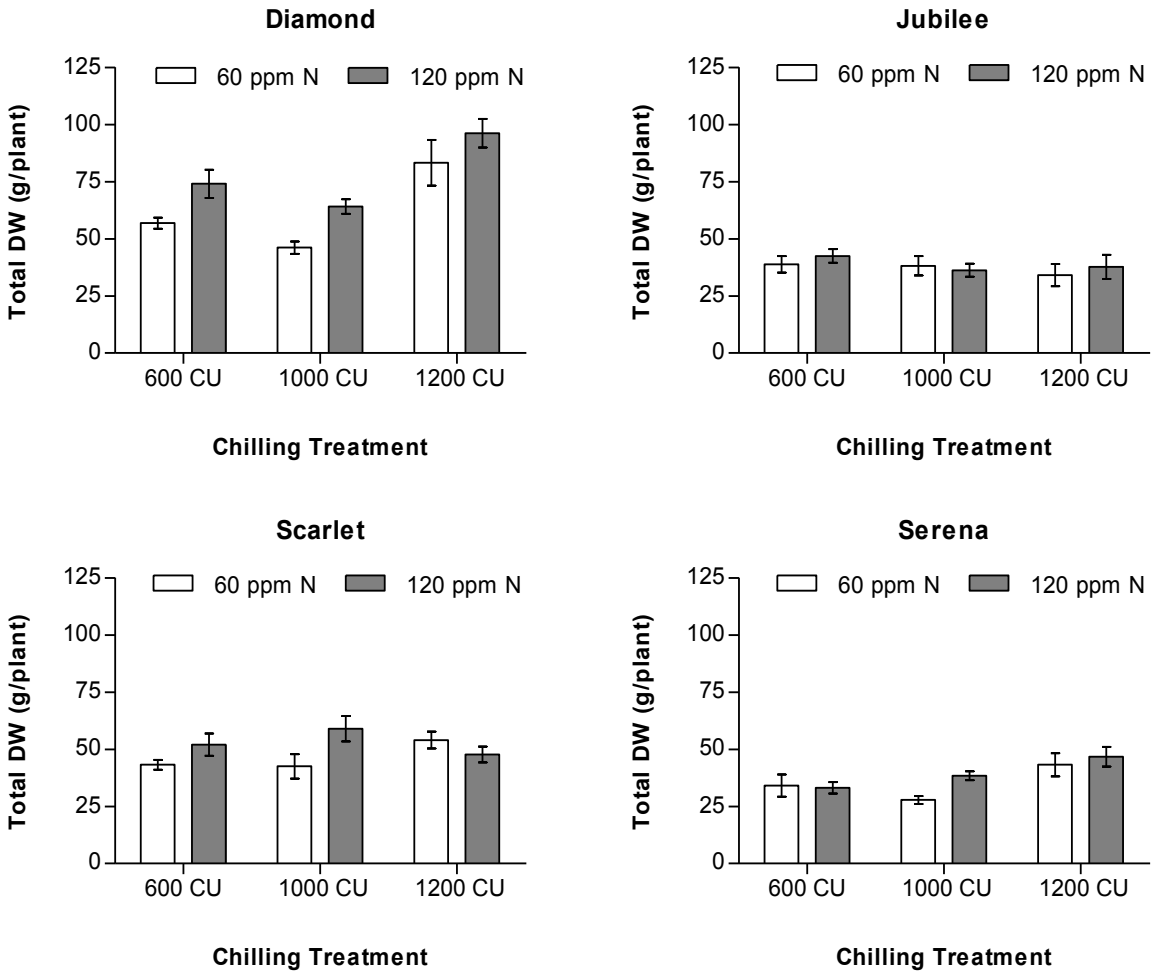

Figure 5.33 Effect of N treatment and chilling treatment on total plant dry weight at the end of the production phase for cultivars Diamond, Jubilee, Scarlet and Serena (n=9). DW= dry weight. The vertical lines on each bar represent ±S.E.M. N treatments were Low N (60 ppm N) and High N (120 ppm N) and chilling treatments were Low Chill (600 CU), Medium Chill (1000 CU) and High Chill (1200 CU).

5.4 Discussion

The experiment was designed to examine the impact of nitrogen concentration and level of winter chill accumulation during the propagation phase on transplant growth, yield potential and subsequent cropping performance of five strawberry cultivars currently cropped in the UK.

Previous research has found a positive effect of increased N supply during the autumn on subsequent flowering and fruiting in strawberry (Rogers et al. 1985; Miner et al. 1997; Deng & Woodward 1998; Lieten 2002; Sønsteby et al. 2009; Motamedi et al. 2013; Opstad et al. 2013; 2013). In this experiment, increasing N concentration from 60 ppm to 120 ppm had a positive effect on subsequent cropping performance; marketable yield in the glasshouse crop of Lusa increased by 8.5% (56 g / plant) and in the polytunnel production of cultivars Diamond, Jubilee, Scarlet and Serena there was a similar improvement of 7% (57 g / plant) on average. Marketable yield was improved due to an increase in marketable berry number of 13% and 8% respectively, whilst there was no significant effect on average berry weight. Percentage Class 1 did not differ significantly between treatments which means that although un-marketable yield increased in the High N treated plants, this was proportional to the increase in marketable fruit yield. No interaction between the cultivars and chilling treatments on cropping (yield, berry number, berry weight) were found but increased chilling from 200 to 800 CU reduced the marketable yield of Lusa by 11% (79 g / plant) due to a 12% reduction in berry number.

Berry weight is primarily influenced by the position of the flower within the inflorescence; when a strawberry flower is pollinated, achenes produce auxin which cause the receptacle to swell and form the berry, the primary flower produces the largest berry as it has the greatest number of achenes with secondary, tertiary and further flowers then producing fruit progressively reducing in size (Webb et al. 1974). When crop load on the plant is high, berry weight can decline due to greater competition for resources between the berries both on the same truss and between trusses on the same plant. In this experiment, plants propagated in the High N treatment produced a greater number of berries but average berry weight was maintained to the same level as those in the Low N treatment, meaning there was an overall increase in yield. The destructive harvests carried out at the end of the propagation phase and the production phase revealed that plants propagated in the High N treatment were significantly larger in terms of leaf dry weight and total plant dry weight compared to those in the Low N treatment. Berry weight may therefore

have been maintained due to the greater vegetative vigour of the High N plants giving them the ability to support a greater number of berries without a detrimental impact on berry size.

The effect of both increased N and chilling on berry number were likely due to in-direct effects of the treatments on transplant size. Positive correlations between crown size, canopy size and transplant weight at planting time with the number of inflorescences, flowers and fruit yield per plant has been previously reported in strawberry (Darrow 1966; Hughes 1967; Abbott 1968; Lacey 1973; Faby 1997; Le Miere et al. 1998; Bussell et al. 2003; Johnson et al. 2005; Takeda & Newell 2006; Bartczak et al. 2010). Overall, increased N had a positive effect on transplant size; for Lusa, an increase in N concentration led to a significant increase in crown size (number, diameter and dry weight) as well as leaf dry weight and total plant dry weight. Increased N also led to a significant increase in leaf number and leaf area but only at the Low Chill level (200 CU). Similarly, for Diamond, Jubilee, Scarlet and Serena crown diameter, crown dry weight, leaf dry weight and total plant dry weight were greater in the High N plants at the Low (600 CU) and Medium (1000 CU) Chill levels. In this experiment, to have three chill levels and keep the planting date the same for all treatments, the heating and venting temperature set points in the compartments were reduced on three dates: 4th December (High Chill), 8th January 2014 (Medium Chill) and 23rd January 2014 (Low Chill). The more chill units required before planting the earlier the date at which the compartment temperature was reduced; this means that chilling was delayed in the Low and Medium Chill treatments compared to the High Chill treatment where plants were exposed earlier to dormancy inducing conditions (2/5°C). The earlier cessation of growth in the High Chill treatment could explain why there was no significant effect of N treatment on plant growth, whilst greater N inputs improved plant growth in the Low and Medium Chill treatments.

When plants become dormant, the growth rate slows and eventually halts; any new leaves produced are small and have short petioles as the growth habit of the plant becomes small and compact (Kronenberg et al. 1976; Sønsteby & Heide 2006); this could also mean that any effects of the N treatment on plant growth were diminished by the chilling treatments at the point the first destructive harvest was carried out as this was just prior to planting for all cultivars. Since chilling alters the morphology of the plant, this may have masked any prior effects of the N treatment if present; it would have therefore been beneficial to have conducted an interim destructive harvest prior to the commencement of each chilling treatment to assess the effect

of the N treatment on the plant growth before the plants turned dormant. An alternative, would have been to take non-destructive measures of plant growth periodically throughout the propagation phase so that effects of N treatment on plant growth could be examined over time.

It is important to consider that although high chilling appeared to have a restraining effect on transplant growth, greater chilling has been found to lead to more rapid growth in the following spring due to increased levels of stored reserves (Kronenberg et al. 1976; López et al. 2002; Lieten 2009). During the autumn, carbon and nitrogen are accumulated in the crown and roots creating an important storage reserve for subsequent spring growth (Chapin et al. 1990; Archbold & MacKown 1995; Nishizawa et al. 1998; Acuna-Maldonado & Pritts 2008; Kirschbaum et al. 2010a). Several studies have found that strawberry plants rely more on their stored N reserves during cropping than on newly acquired N absorbed through the roots (Archbold & MacKown 1995; Tagliavinia et al. 2005; Acuna-Maldonado & Pritts 2008); this could mean that restraints on transplant growth due to the longer duration of chilling in the High Chill treatment may have been compensated for by increased in vigour and growth in the following spring. The results of the destructive harvest conducted at the end of cropping were highly cultivar specific; leaf number and dry weights of the crown, leaves and whole plant were greatest in the High Chill treatment for Serena and Diamond suggesting that greater chilling in these cultivars increased plant vigour, whilst in Lusa, Jubilee and Scarlet chilling had no significant effect on crown, canopy or plant size. Differences in plant growth between chilling treatments for these cultivars may have only been present at the beginning of the season and so were not noted in the destructive harvest conducted at the end of fruiting; this was found by Kronenberg et al. (1976) where differences in growth between chilled versus non-chilled plants of cultivars 'Glasa' and 'Tioga' declined over time and were not significant after 12 weeks.

Lusa is a specialist low chill cultivar bred exclusively for glasshouse production to produce high-value fruit early in the season (March to Mid-May) before field strawberry production begins. It is therefore important to understand treatment effects on early cropping performance in this cultivar. Overall, a positive effect of increased chilling on early yield of Lusa was found; although there were little significant differences between chilling treatments on a week to week basis. The accumulated marketable yield after eight weeks cropping was 38% (37 g / plant) greater in the High Chill treatment compared to the Low Chill treatment. Lieten (2009) found increased chilling in the cultivar 'Figaro' decreased and delayed fruit production as a result of excessive vegetative

growth, and results from other studies were in agreement, showing that increased chilling reduces early yield due to an imbalance of vegetative and reproductive growth causing delayed flowering and a concentration of the harvest period (Smeets 1982; Albregts & Chandler 1994; Luedeling et al. 2011). The results for Lusa in this experiment contradict these findings since increased chilling benefited early fruit yield in this cultivar; in previous studies, plants chilled above-optimum had excessive vegetative growth early in the growing season leading to a suppression of early yield, this suggests that the High Chill treatment applied to Lusa in this experiment was not above the optimum as negative effects on yield performance were not found. In 2012, in preliminary experiments conducted at the University of Reading, Lusa was cropped after receiving 0, 250, 500, 750, 1000, 1200 and 1400 CU and results indicated that the optimum chilling for this cultivar in terms of fruit production was between 250 CU and 750 CU, with early yield optimised at 750 CU (Professor Paul Hadley, *pers. comm.*). These results are in line with those found in the present study where early yield was greatest in the High Chill (800 CU) treatment. Delayed fruit production for early glasshouse cropping is not desirable as fruit produced after the middle of May competes with the start of the main strawberry season in the UK. At the Low N level, increased chilling reduced the number of flowers expressed in Lusa during the propagation phase by 56%; this could explain why early yield was greater in the High Chill treatment since the flowers would have been retained within the crown and not expressed before planting for fruit production.

In the polytunnel cultivars at the High N level, flower removal was reduced by 25% and 15% in the High Chill treatment compared to the Low and Medium Chill treatments respectively. However, there was no significant effect of chilling on fruit yield at any point during cropping. This means that the range of chilling treatments studied in this experiment (600-1200 CU) were within the optimum range for these cultivars, which is still a useful finding as it shows these cultivars can be chilled over a relatively wide range before there are any negative effects on yield. With year to year variation in winter temperatures it can be difficult for growers to reach a target level of chill accumulation; when plants are chilled in the field or cold glasshouses, warm winters make it difficult to reach a target chill level and cold winters can cause excessive chill to accumulate, both of which could have negative effects on cropping. These results suggest that, for the cultivars studied here, the target chill level is relatively broad and certainly within the 600-1200 CU examined. It would be worthwhile to repeat the study with an extended range of chilling levels to

estimate the true optimum chill level for these cultivars. It would also be beneficial to find out if to there is a level of chill that can be applied to these cultivars whereby valuable yield at the fringes of the main season could be enhanced, a current goal in the UK strawberry industry.

Overall, the results of this experiment showed that increased N concentration during the propagation phase improved transplant size and yield potential so that, in the subsequent cropping period, marketable fruit yield was significantly improved due an increase in the number of marketable berries produced per plant. The results also showed that there is the potential to use chilling to increase marketable yield and manipulate cropping profiles to enhance valuable early season yield of the specialist low-chill cultivar Lusa. These findings are important for commercial strawberry production where increased plant productivity, particularly in early glasshouse crops, to extend the British season is an important industry goal.

Chapter 6

Effect of supplementary lighting and temperature during the propagation phase on cropping performance of six strawberry cultivars.

6.1 Introduction

Propagation of strawberry plants begins in the summer months of June and July, continuing through to the following spring when transplants are dispatched from the nurseries to fruit growers. The environment in which strawberry transplants are produced plays a crucial role in both building up the vegetative status (size of the crown and accumulated carbohydrates) of the plants and in governing the process of flower initiation, ultimately determining the quality of the growers starting plant material.

During the period of flower initiation, photoperiod and temperature are regarded as the most important environmental conditions affecting floral development (Ito & Saito 1962). Critical photoperiods in both Junebearers and Everbearers are cultivar dependent and can be modified by temperature. Typically, at an intermediate temperature range (15-24°C) Junebearers are quantitative short-day plants, requiring a photoperiod of <15-hrs for floral initiation, with flowering intensified at shorter day-lengths, whilst Everbearers are quantitative long-day plants, with flowering intensified at longer day-lengths. At high temperatures (>25°C) flower initiation is inhibited regardless of photoperiod in both plant types, whilst at low temperatures (<9°C) flower initiation occurs regardless of photoperiod (Ito & Saito 1962; Sønsteby & Nes 1998; Nishiyama et al. 2003; Sønsteby & Heide 2006; Verheul et al. 2006; 2007; 2007; Durner 2015).

Previous research has shown that the optimal photoperiod and temperature combination for complete flower initiation in strawberry is highly cultivar-specific with each cultivar having its own temperature response curve. Sønsteby & Nes (1998) compared the number of short-days required to maximise flower initiation at a range of temperatures in four Junebearer cultivars and found strong interactions between the treatments which also varied markedly between cultivars; for 'Korona' the number of plants which had initiated flowers decreased at temperatures outside

of the range of 15-18°C whilst 'Elsanta' was less sensitive to temperature with a range of 15-27°C. Durner et al. (2015) also showed that the number of short-day cycles required is cultivar dependent; the flowering response of five Junebearer and three Everbearer cultivars were conditioned with short-days for 0, 1, 2 or 4 weeks at 15°C and all but one Junebearer and one Everbearer showed enhanced flower initiation and/or differentiation following conditioning when compared to long-day controls, but the optimal treatment varied between cultivars in both plant types. The results of the experiment highlighted the need for cultivar-specific evaluation to identify appropriate conditioning treatments to maximise flowering; subsequently, Durner (2016 pp 187) went on to state: "Conditioning protocols should be developed on a cultivar basis, since cultivars cannot be categorically lumped together into short-day and long-day types when examining flowering and fruiting."

Photoperiod and temperature also impact upon plant growth and play a key role in the building up the vegetative status of strawberry transplants. Short-days, for example, promote crown branching (Hytönen et al. 2004; Kurokura et al. 2005) which has been identified as a pre-requisite for satisfactory flowering in strawberry (Abbott 1968), with crown number and crown diameter positively correlated with yield performance (Lacey 1973; Faby 1997; Le Miere et al. 1998; Bussell et al. 2003; Johnson et al. 2005; Bartczak et al. 2010; Fridiaa et al. 2016). Low temperatures restrict vegetative plant growth particularly when coupled with short-days, which may have a negative impact on subsequent fruit yield due to reduced plant vigour during floral initiation; consequently, leaf number, leaf area and total plant weight have also been positively linked to cropping performance in strawberry (Hughes 1967; Lacey 1973; Bartczak et al. 2010).

Many studies have been conducted on a range of Junebearer and Everbearer cultivars to find the optimal photoperiod and temperature combination for complete flower initiation. In these studies, low intensity lighting has been used to extend the natural day-length to provide different photoperiod treatments whilst keeping the PAR level between treatments uniform (Sønsteby & Nes 1998; Manakasem & Goodwin 2001; Verheul et al. 2006; 2007; Durner 2015; 2016). However, supplementary lighting could also be used during the propagation phase to increase light intensity within the natural day-length when autumn light levels are naturally low stimulating greater vegetative and reproductive plant growth. This may be particularly important for Everbearers as although termed long-day plants, they are not "true" long-day plants since they are not regulated by the length of the dark period and short-days do not inhibit flower initiation

(Stewart & Folta 2010). Dennis et al. (1970) showed that Everbearers are regulated more by the total amount of light received than the duration of either the light or dark period, finding a marked increase in flowering when light intensity was increased from 220 to 430 μmol m^{-2} s^{-1} in both short and long photoperiods. Subsequently, within the natural short days of autumn flower initiation, berry number and yield of two Everbearer cultivars were greater in plants propagated under supplemented light levels compared to those under ambient light levels (Professor Paul Hadley, *pers. comm*.).

Temperature also plays an important role in optimising flower initiation; higher temperatures benefit floral initiation, but only up to an optimum level for a given photoperiod. Manakasem & Goodwin (2001) showed that the percentage of initiated apices in the cultivar 'Torrey' increased with temperature up to an optimum of 18/13°C (day/night), but was then reduced with a further increase in temperatures from 83% to 18% (30/25°C). Similarly, Verheul et al. (2006) found that 100% of plants of 'Korona' flowered when conditioned with short-days at 12°C, 15°C and 18°C whilst an increasing percentage of plants remained vegetative at 24°C and 30°C. Other studies have shown reduced flower initiation outside of a temperature of 18°C where the critical photoperiod shortens or a greater number of cycles are required for complete flower initiation (Sønsteby & Nes 1998; Verheul et al. 2007; Durner 2015).

Sønsteby & Heide (2008) showed that a relatively high night temperature is also required to further maximise flowering; cultivars 'Korona', 'Frida' and 'Florence' were conditioned with short-days and a day temperature of 18°C coupled with night temperatures of 9°C, 12°C, 15°C or 18°C. Flower number increased with increasing night temperature up to 18°C in 'Korona' and 'Florence' and up to 15°C in 'Frida'. The authors concluded that an increase in autumn temperatures would be beneficial to short-day induction in strawberry and this was supported by Le Miere et al. (1997) who found the rate of floral initiation in 'Elsanta' increased linearly with temperature, concluding that in the UK there was scope for increasing yield by increasing autumn temperatures, and that the poor flowering and yield performance some growers were experiencing was due to sub-optimal temperatures, especially autumn night temperatures. Sønsteby et al. (2008) went as far as to say that increases in autumn temperatures due to global warming should not be a concern for strawberry growers and could be beneficial especially in Nordic environments.

However, some caution is required when using temperature to promote flower initiation as a negative effect of increased autumn temperature on yield and berry number has been found due to high levels of flower emergence during the propagation phase, leading to a loss of yield potential (Professor Paul Hadley, *pers. comm.*). Early emergence of initiated flowers is undesirable in commercial practice, flowers are removed by propagators to keep the plants vegetative and can be damaged by frost or not set fruit due to lack of pollinator availability if they emerge too early.

Overall, the environmental conditions in which strawberries are propagated is important in determining the quality of the transplants supplied to the fruit grower. There is potential to improve the yield potential of strawberry transplants by providing supplementary lighting and heating during the autumn to stimulate greater vegetative growth and reproductive development. Little research has been conducted on the effect of using supplementary lighting during strawberry propagation and none on the new Junebearer and Everbearer cultivars which are widely cropped in the UK today. An experiment was therefore designed to examine the impact of supplementary lighting and increased temperature during the propagation phase on transplant growth, yield potential and subsequent cropping performance of three Junebearer and three Everbearer strawberry cultivars currently cropped in the UK.

6.2 Materials and Methods

6.2.1 Propagation Phase

Plant Material and Experimental Treatments

Fresh tips of the Junebearer cultivars Diamond, Elizabeth and Rosalie and Everbearer cultivars Jubilee, Scarlet and Serena were supplied by Driscoll's Plants BV (Helenaveen, The Netherlands) on 13th August 2014. Misted tip production was carried out using the methods described in Chapter 2; briefly, 300 uniform daughter plants for each cultivar and treatment were selected and struck into multi-celled trays containing a 50:50 mix of peat and coir and overhead misted with mains water, plus a daily foliar feed, for four weeks to encourage root establishment. Once rooted, 210 uniform plants were selected and individually re-potted into 90 x 87 mm (diameter x depth) coir filled pots before being transferred to three temperature-controlled glasshouse compartments on 20th September 2014 (35 plants per cultivar per treatment).

The compartments were as described in Chapter 2 and set up to provide six experimental treatments, a combination of two light treatments: ambient light levels (AMB) and 8-hrs (8:00-16:00) supplementary lighting (SUPP) and three temperature treatments: minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20) with venting set 3°C above this. Treatment combinations were coded A to F and these are summarised in Table 6.1. Treatments were initiated on 13th October once the natural day length that reduced to 8-hrs and were carried out for seven weeks, ceasing on 1st December 2014, when the lights were switched off and the temperature in the three compartments were reduced to 2/5°C for chilling (heating/venting). Lighting was provided as described in Chapter 2 and temperatures in each treatment were logged hourly. Mean temperatures calculated at the end of the treatment period were: 13.5°C, 13.3°C, 16.1°C,15.9°C, 21.0°C, and 20.9°C for treatments A to F respectively.

Propagation Phase Measurements

Ten randomly selected plants of each cultivar in each treatment were tagged upon transfer to the glasshouse compartments. Runners and open flowers were removed from all plants on a routine basis and the number removed on the tagged plants was recorded. A destructive harvest was carried out on the same ten tagged plants using the methods described in Chapter 2. The

following measurements made on each plant: crown number, crown diameter, leaf number, leaf area, root score and dry weights of leaves, crowns, petioles and the whole plant.

6.2.2 Production Phase

Experimental Design

At the end of the propagation phase, remaining plants of each cultivar and treatment were cropped in a twin span tunnel at the Soft Fruit Technology Group's Field Site at the University of Reading's Sonning Farm set up as described in Chapter 2.

Three bags, containing six plants, were planted for each cultivar and treatment on 31st March 2015 giving a total of 18 plants per cultivar per treatment. The experimental area was divided into three blocks, each with one replicate (bag) in a randomised position. Guard bags were placed at the ends of each row to minimise edge effects. Figure 6.2 shows the layout of the blocks, cultivars and treatments.

Temperature control, plant husbandry and fertigation were set up and carried out as described in Chapter 2. Figure 6.1 shows the average 24 hr temperature logged throughout the production phase.

Production Phase Measurements

To determine treatment effects on cropping performance, total, marketable and un-marketable yield and berry number were recorded on a weekly basis and the average marketable berry weight and percentage Class 1 were calculated at the end of cropping. Data was collected at the bag level and converted to a per plant basis for analysis.

A final destructive harvest was carried out at the end of the production phase; two plants were randomly selected from each bag for each cultivar and treatment combination and the following measurements were made on each plant: crown number, leaf number, inflorescence number and dry weights of leaves, crowns, petioles, inflorescences with the total plant dry weight calculated as the sum of the individual components. All measurements were taken using the methods described in Chapter 2.

Table 6.1 Summary of the six experimental treatments (A to F) applied during the propagation phase to six strawberry cultivars. Treatments were a combination of two light treatments: ambient light levels (AMB) and 8-hrs (8:00 to 16:00) supplementary lighting (SUPP) and three temperature treatments: minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

Treatment Code	Light Treatment	Temperature Treatment
A	SUPP	T10
B	AMB	T10
C	SUPP	T15
D	AMB	T15
E	SUPP	T20
F	AMB	T20

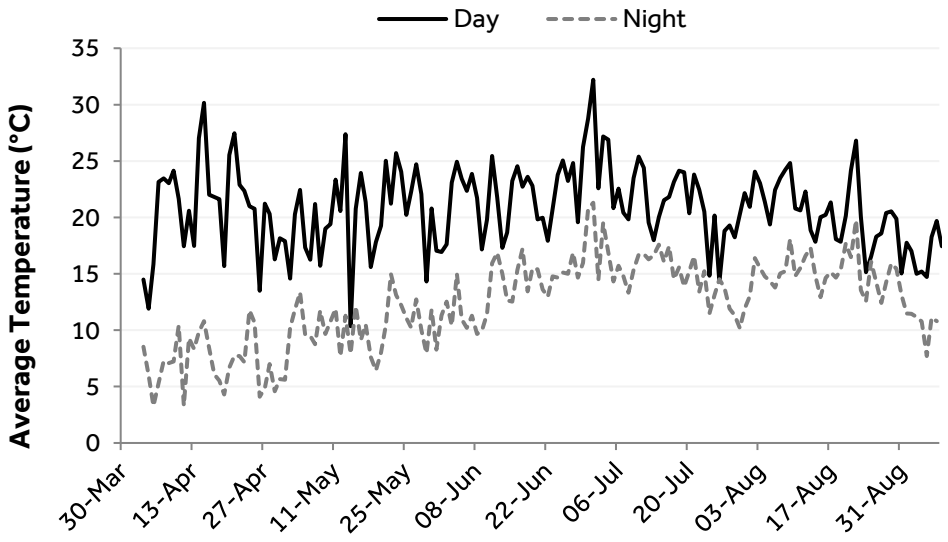

Figure 6.1 Mean day and night temperature logged throughout the production phase for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena. Day = 07:00 to 19:00.

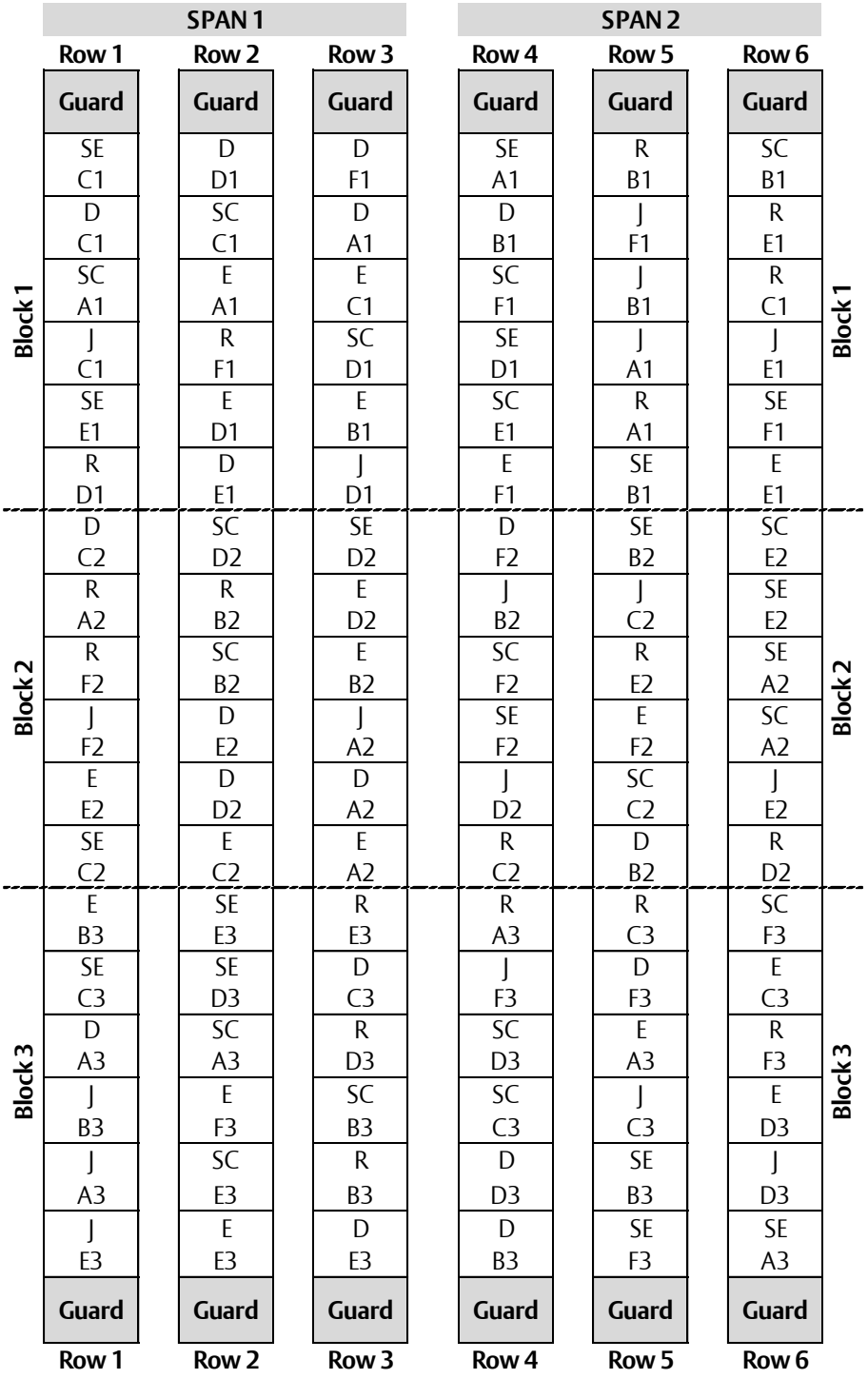

Figure 6.2 Arrangement of blocks, cultivars and treatments for the production phase of the cultivars Diamond (D), Elizabeth (E), Rosalie (R), Jubilee (J), Scarlet (SC) and Serena (SE) in a twin span polytunnel situated at the Soft Fruit Technology Group's Field Site at the University of Reading, Sonning Farm. Each box represents a 1 m substrate bag, each with six plants. Treatments were: SUPP / T10 (A), AMB / T10 (B), SUPP / T15 (C), AMB / T15 (D), SUPP / T20 (E) and AMB / T20 (F).

6.3 Results

6.3.1 Propagation Phase

6.3.1.1 *Open Flower Number*

There was a significant difference in the number of open flowers between cultivars (P<0.001). In the Everbearers, there was no significant difference between Serena (2.3±0.41 flowers / plant) and Scarlet (2.8±0.36), but flower number of both cultivars was significantly greater than Jubilee (1.2±0.27). There were no significant differences in the number of flowers expressed between the Junebearer cultivars Diamond (0.1±0.07), Elizabeth (0.1±0.04) or Rosalie (0.4±0.17), but flower number was significantly lower in all three Junebearers compared all three Everbearers.

Treatment effects on flower number for each cultivar are shown in Figure 6.3. There was no significant interaction between the light and temperature treatments. However, there was a significant interaction between the cultivars and light treatments (P<0.001) which showed that flower number was significantly greater in SUPP compared to AMB for Scarlet and Serena (by 49% and 166% respectively) whereas there was no significant difference for the remaining cultivars. The effect of temperature also significantly differed between cultivars (P<0.001) such that for the Everbearer cultivars flower number was 1475%, 140% and 309% greater in T20 compared to T10 for Jubilee, Scarlet and Serena respectively. In the Junebearer cultivars Diamond and Elizabeth flowers were only recorded in T20, whilst for Rosalie flowers were recorded in all temperature treatments. Overall, however, there were no significant differences between temperature treatments found.

6.3.1.2 *Runner Number*

There was a significant three-way interaction between the cultivars, light treatments and temperature treatments (P<0.001, Table 6.2). Runners were only produced in the Junebearer cultivars and more runners were produced in Diamond (0.6±0.16 runners / plant) compared to Elizabeth (0.4±0.14) and Rosalie (0.3±0.09). For all three Junebearers, runners were only produced in T20 but a greater number of runners were produced in SUPP T20 (1.2±0.20 runners / plant) compared to AMB T20 (0.1±0.04).

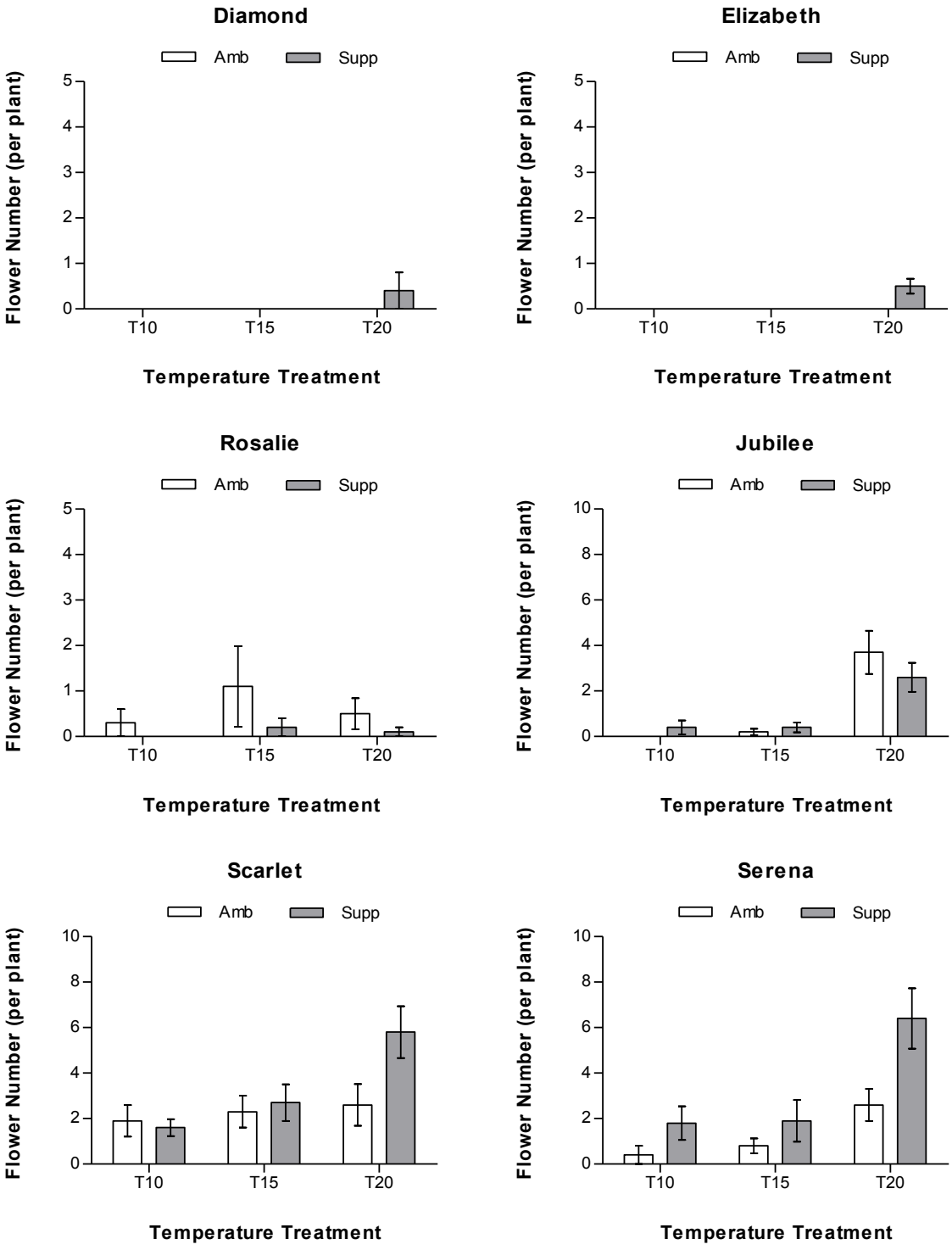

Figure 6.3 Effect of the light and temperature treatments on the total number of open flowers per plant at the end of propagation phase for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

Table 6.2 Effect of the light and temperature treatments on the total number of runners per plant at the end of propagation phase for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10). Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20). LSD (5% level) and P Values are shown.

	AMB			SUPP			LSD	P. Value
	T10	T15	T20	T10	T15	T20		
Diamond	-	-	0.3	-	-	3.1	0.32	<0.001
Elizabeth	-	-	-	-	-	2.5		
Rosalie	-	-	-	-	-	1.5		
Jubilee	-	-	-	-	-	-		
Scarlet	-	-	-	-	-	-		
Serena	-	-	-	-	-	-		

6.3.1.3 *Destructive Harvest (DH1)*

Crown Number

Overall, there was a significant difference in crown number between cultivars (P<0.001); crown number was significantly greater in Serena (2.5±0.2 crowns / plant) compared to Scarlet (2.1±0.1) and Jubilee (1.8±0.1), and in Scarlet compared to Jubilee. There was no significant difference in crown number between the Junebearer cultivars Diamond (1.2±0.1), Elizabeth (1.4±0.1) or Rosalie (1.2±0.1), but crown number of all three Junebearers was significantly lower compared to all three Everbearers.

For crown number, there were different responses to the treatments depending on the cultivar resulting in significant two and three-way interactions (Figure 6.4). There was a significant interaction between the light and temperature treatments (P<0.001); such that crown number was significantly higher in SUPP compared to AMB in all three temperature treatments but to a greater extent in T20 (61%) than T10 (36%) and T15 (31%). Crown number also significantly increased from T10 to T15 in both light treatments (by 21% and 17% for AMB and SUPP respectively) whereas from T15 to T20 crown number only significantly increased in SUPP (17%).

Difference between the treatments also depended on the cultivar, resulting in a significant three-way interaction (P=0.040). Crown number was significantly higher in SUPP compared to AMB for all cultivars except Rosalie, and there was also no significant difference in crown number between temperature treatments for Rosalie.

Crown Diameter

There was a significant difference in crown diameter between cultivars (P<0.001). In the Everbearers, crown diameter of Serena (1.3±0.03 cm) and Scarlet (1.2±0.04) did not significantly differ but were greater than Jubilee (1.0±0.05). In the Junebearers, crown diameter was significantly higher in Rosalie (1.1±0.03) than both Elizabeth (1.0±0.03) and Diamond (1.0±0.03) and crown diameter of Scarlet and Serena was significantly greater than all three Junebearers.

Treatment effects on crown diameter for each cultivar is shown in Figure 6.5. Only the main effect of the light and temperature treatments were significant (P<0.001) where crown diameter was greater in SUPP (1.3±0.02 cm) compared to AMB (1.0±0.02) and increased from T10 (1.0±0.02cm) to T15 (1.1±0.02) and from T15 to T20 (1.2±0.03).

Crown Dry Weight

There was a significant difference in crown dry weight between cultivars (P<0.001). Crown dry weight of each Everbearer cultivar was significantly higher than each Junebearer. Within the Junebearers, crown dry weight of Rosalie (0.44±0.05 g / plant) did not significantly differ from Elizabeth (0.41±0.04) but was greater than Diamond (0.34±0.04). In the Everbearers, crown dry weight was significantly higher in Serena (0.83±0.06) compared to Scarlet (0.59±0.05) and Jubilee (0.62±0.09), and no other differences between cultivars were significant.

Treatment effects on crown dry weight for each cultivar are shown in Figure 6.6. The interaction between the light and temperature treatments was significant (P<0.001) such that crown dry weight was significantly higher in SUPP in all three temperatures treatments, but to a greater extent in T10 (174%) than T15 (152%) and T20 (157%). Crown dry weight also significantly increased from T10 to T15 in both light treatments (by 53% and 40% for AMB and SUPP respectively) and from T15 to T20 (by 31% and 32% respectively).

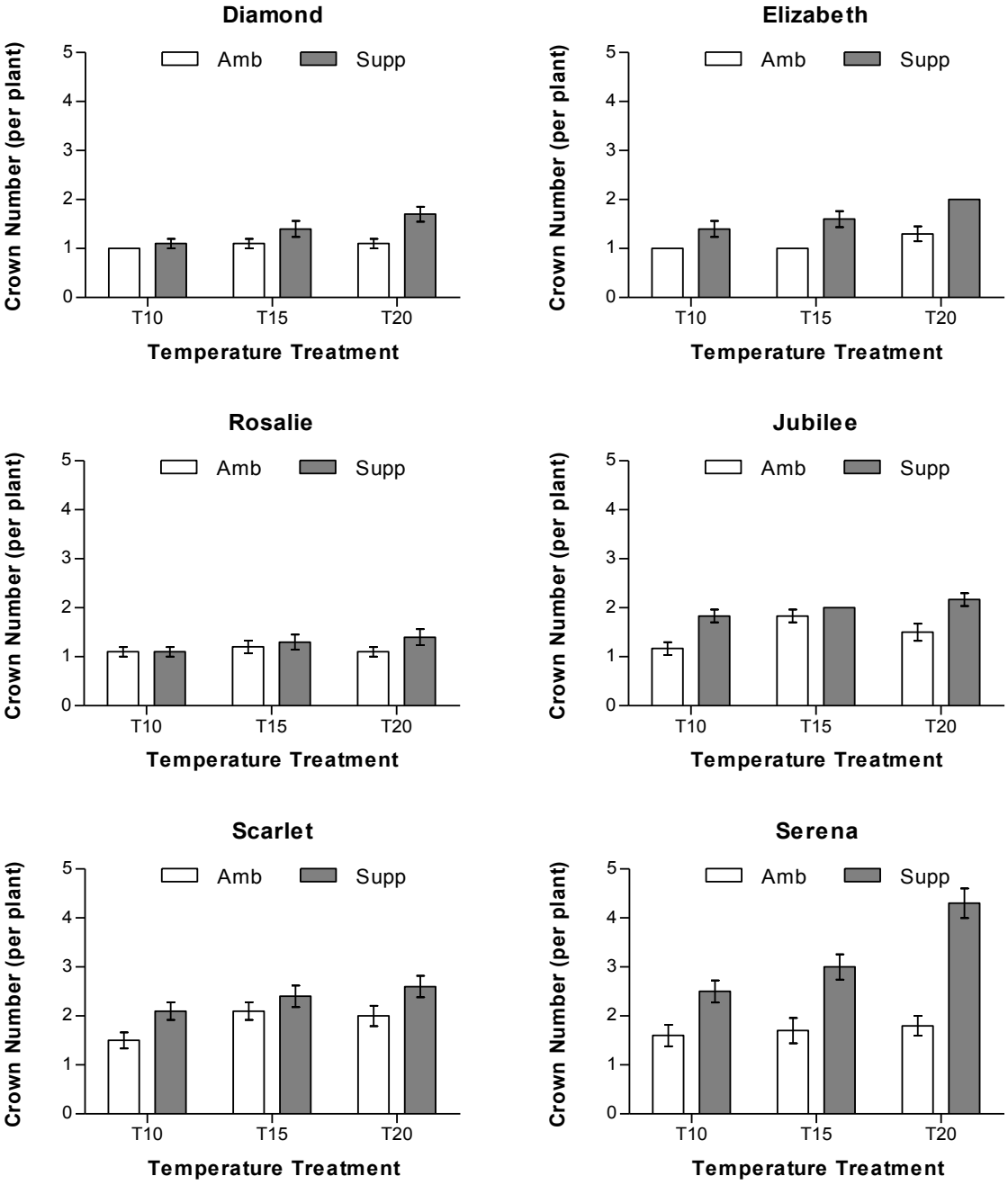

Figure 6.4 Effect of the light and temperature treatments on crown number for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

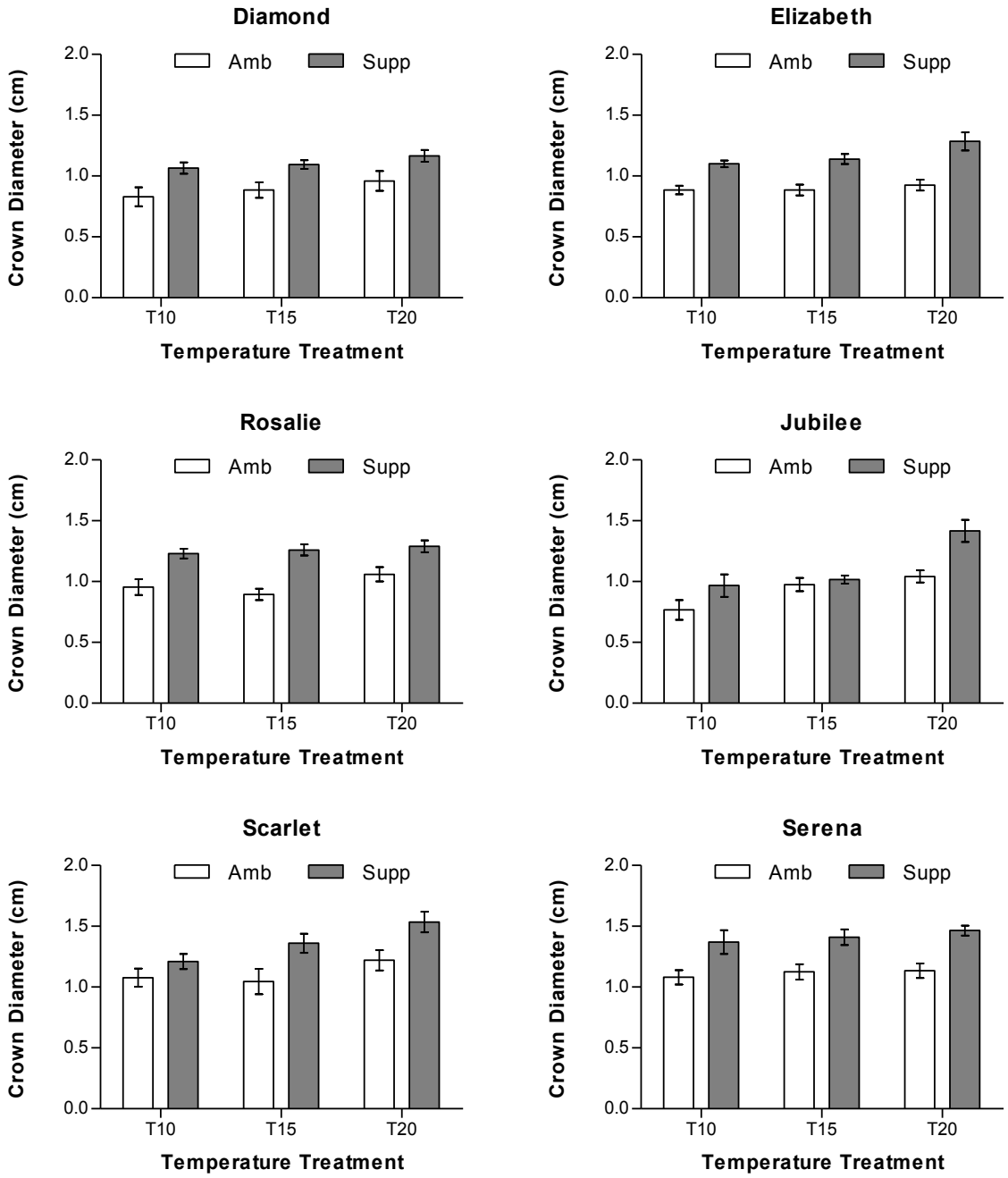

Figure 6.5 Effect of the light and temperature treatments on crown diameter for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10 The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

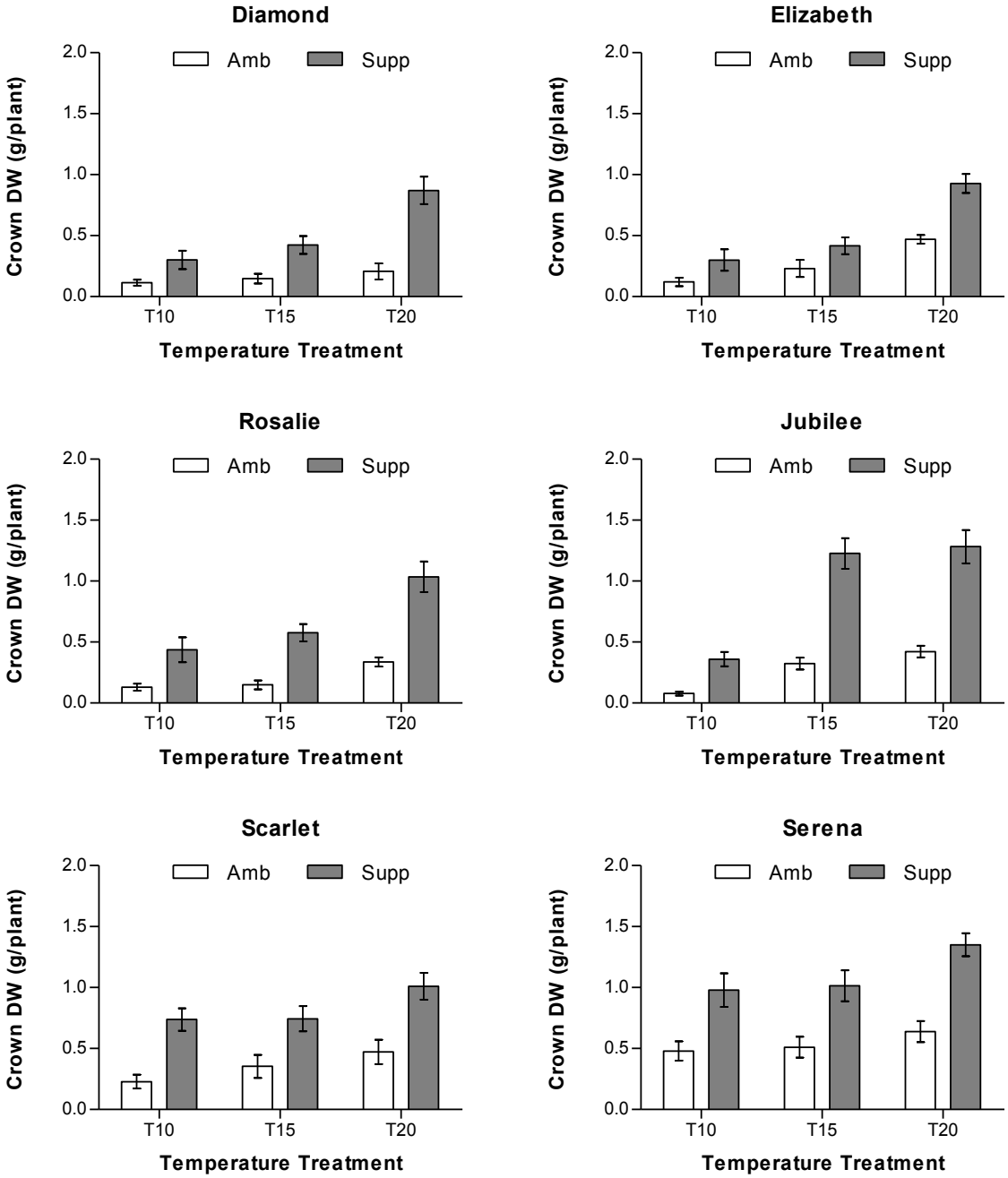

Figure 6.6 Effect of the light and temperature treatments on crown dry weight for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10). DW=dry weight. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

Leaf Number

There was a significant difference in leaf number between cultivars (P<0.001). Leaf number was significantly greater in Serena (8.2±0.3 leaves / plant) compared to Jubilee (5.4±0.4), Diamond (5.8±0.2), Elizabeth (5.9±0.2) and Rosalie (5.4±0.2) but did not significantly differ from Scarlet (8.8±0.5). Leaf number of Scarlet was also significantly greater than all cultivars except Serena.

Treatment effects on leaf number for each cultivar is shown in Figure 6.7. The interaction between the light and temperature treatments was not significant and there was no significant interaction between the cultivars and light treatments. However, the main effect of the light treatment was significant (P<0.001) with leaf number greater in SUPP (7.2±0.2 leaves / plant) compared to AMB (5.9±0.2).

The effect of temperature did significantly differ between cultivars (P<0.001); leaf number was significantly greater in T20 compared to T10 in all cultivars but the extent varied by cultivar (24%, 41% and 35% for Diamond, Elizabeth and Rosalie and 69%, 67% and 20% for Jubilee, Scarlet and Serena respectively). There were no significant differences in leaf number between T10 and T15 for any cultivar except Scarlet where leaf number was 21% greater in T15 compared to T10.

Leaf Area

Overall, there was a significant difference in leaf area between cultivars (P<0.001); Scarlet had the greatest leaf area (200.5±20.00 cm^2 / plant), significantly higher than Jubilee (116.7±22.15), Serena (142.2±10.55), Diamond (113.6±13.35), Elizabeth (169.1±18.08) and Rosalie (74.5±4.43). All other differences in leaf area between cultivars were also significant except between Jubilee and Diamond.

There were different responses to the treatments depending on the cultivar resulting in a significant two and three-way interactions (Figure 6.8). There was a significant interaction between the light and temperature treatments (P<0.001); such that leaf area was significantly higher in SUPP compared to AMB for all three temperature treatments but to a greater extent in T20 (145%) than T15 (47%) and T10 (71%). Leaf area between T10 and T15 did not significantly differ in either light treatment, but from T15 to T20 leaf area significantly increased (by 41% and 65% in AMB and SUPP respectively).

Differences in leaf area between treatments also depended on the cultivar, resulting in a significant three-way interaction (P<0.001). Leaf area was significantly higher in SUPP compared to AMB for all cultivars but to a greater extend in Diamond, Elizabeth, Rosalie and Jubilee (159%, 162%, 102% and 248% respectively) than Scarlet and Serena (47% and 31%). The differences in leaf area between T10 and T15 were not significant for any cultivar, but from T15 to T20 leaf area significantly increased in all cultivars except Rosalie.

Leaf Dry Weight

Overall, there was a significant difference in leaf dry weight between cultivars (P<0.001). Leaf dry weight was greatest in Scarlet (1.50±0.14 g / plant), significantly higher than Serena (1.18±0.07), Jubilee (1.10±0.22), Diamond (1.06±0.12), Elizabeth (1.20±0.15) and Rosalie (1.09±0.09). No other differences between cultivars were significant.

There were different responses to the treatments depending on the cultivar resulting in a significant two and three-way interactions (Figure 6.9). There was a significant interaction between the light and temperature treatments (P<0.001); such that leaf dry weight was significantly higher in SUPP compared to AMB for all three temperature treatments but to a greater extent in T20 (183%) than T15 (69%) and T10 (75%). Leaf dry weight between T10 and T15 significantly increased in SUPP (by 22%) but there was no significant difference in AMB. Whereas from T15 to T20 leaf dry weight significantly increased in both light treatments (by 34% and 60% in AMB and SUPP respectively).

Differences in leaf dry weight between treatments also depended on the cultivar, resulting in a significant three-way interaction (P<0.001). Leaf dry weight was significantly higher in SUPP compared to AMB for all cultivars but to a greater extend in Diamond, Elizabeth, Rosalie and Jubilee (179%, 137%, 268% and 152% respectively) than Scarlet and Serena (95% and 27%). There were no significant differences in leaf area between T10 and T15 for any cultivar except Jubilee where leaf dry weight was 85% greater in T15. From T15 to T20 leaf area significantly increased in all cultivars but to a greater extent in Jubilee and Elizabeth (462% and 326% respectively) compared to Diamond, Scarlet, Serena and Rosalie (143%, 128%, 85% and 66%).

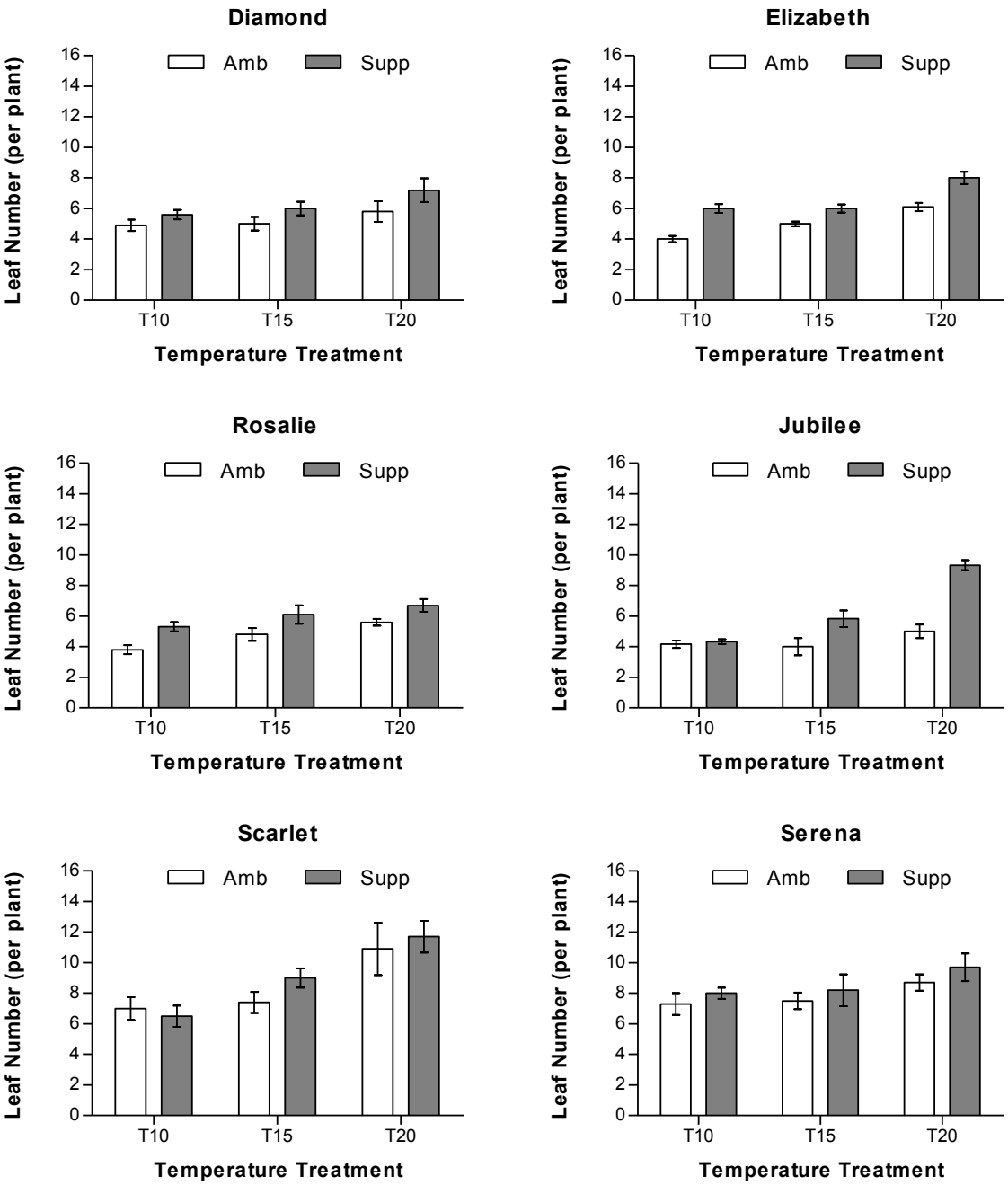

Figure 6.7 Effect of the light and temperature treatments on leaf number for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

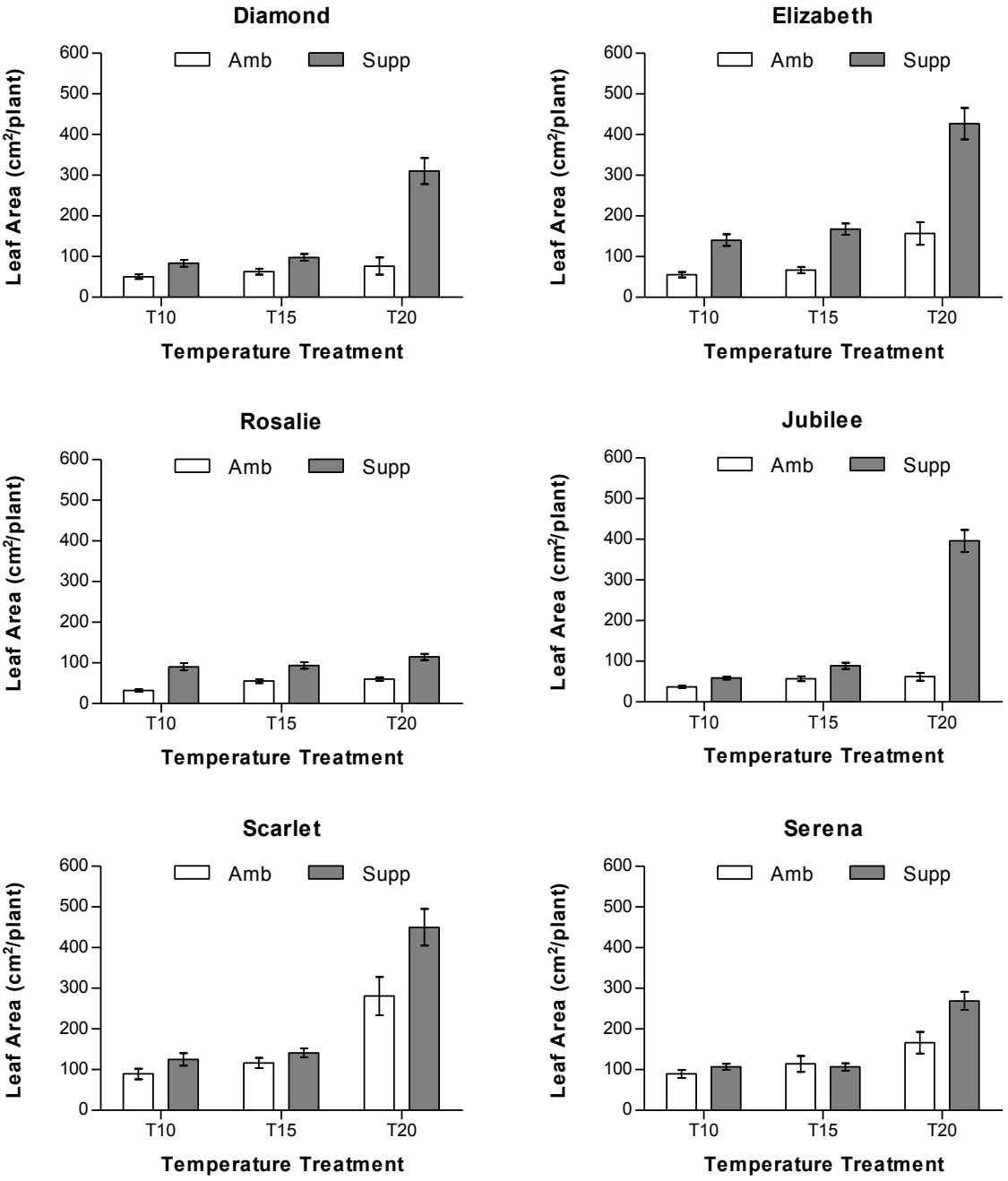

Figure 6.8 Effect of the light and temperature treatments on leaf area for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

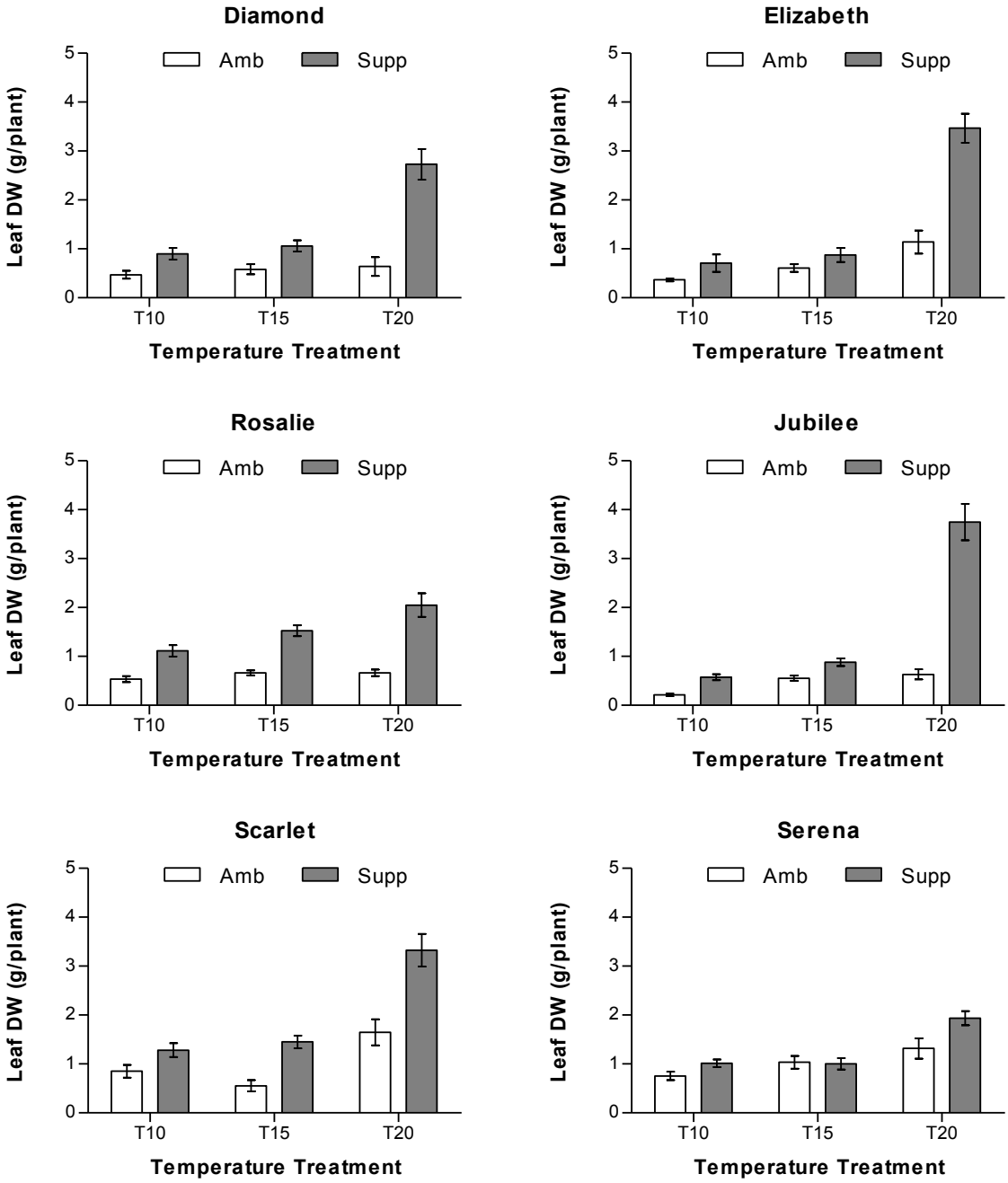

Figure 6.9 Effect of the light and temperature treatments on leaf dry weight for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10). DW=dry weight. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

Root Score

Overall, there was a significant difference in root score between cultivars ($P<0.001$). Root score of Elizabeth (6.2±0.1), Scarlet (5.9±0.1), Serena (6.1±0.1) and Rosalie (5.8±0.2) were significantly higher than Jubilee (4.3±0.3) and Diamond (4.0±0.2) and root score of Elizbeth was also significantly higher than Rosalie. No other differences between cultivars were significant.

Treatment effects on root score for each cultivar is shown in Figure 6.10. The interaction between the light and temperature treatments was not significant, but the effect of the light treatment did significantly differ between cultivars ($P<0.001$) such that root score was significantly greater in SUPP compared to AMB for all cultivars except Serena. The interaction between the cultivars and temperature treatments was not significant, but the main effect of the temperature treatment was ($P<0.001$) all differences between treatments were significant with root score greatest in T20 (6.1±0.1) followed by T15 (5.6±0.1) and T10 (4.7±0.1).

Total Dry Weight

There was a significant difference in total dry weight between cultivars ($P<0.001$). Total plant dry weight was significantly higher in Serena (2.73±0.16 g / plant) compared to Diamond (1.71±0.20), Rosalie (1.98±0.16), Jubilee (2.04±0.34) and Elizabeth (2.11±0.21) but did not significantly differ from Scarlet (2.63±0.21). Total dry weight of Scarlet was also greater than all other cultivars except Serena, and Elizabeth, Rosalie and Jubilee had a greater total dry weight than Diamond.

There were different responses to the treatments depending on the cultivar resulting in significant two and three-way interactions (Figure 6.11). There was a significant interaction between the light and temperature treatments ($P<0.001$); such that total dry weight was significantly higher in SUPP compared to AMB for all three temperature treatments but to a greater extent in T20 (184%) than T15 (98%) or T10 (123%). Total dry weight increased from T10 and T15 in both light treatments (by 42% and 26% for AMB and SUPP respectively) and from T15 to T20 (by 31% and 52% respectively).

Differences in total dry weight between treatments also depended on the cultivar, resulting in a significant three-way interaction ($P<0.001$). Total dry weight was significantly higher in SUPP for all cultivars (on average 162%) and significantly increased from T10 and T15 in Elizabeth, Jubilee and Rosalie whereas there was no significant difference for Diamond, Scarlet or Serena. From T15 to T20 total dry weight significantly increased in all cultivars on average 176%.

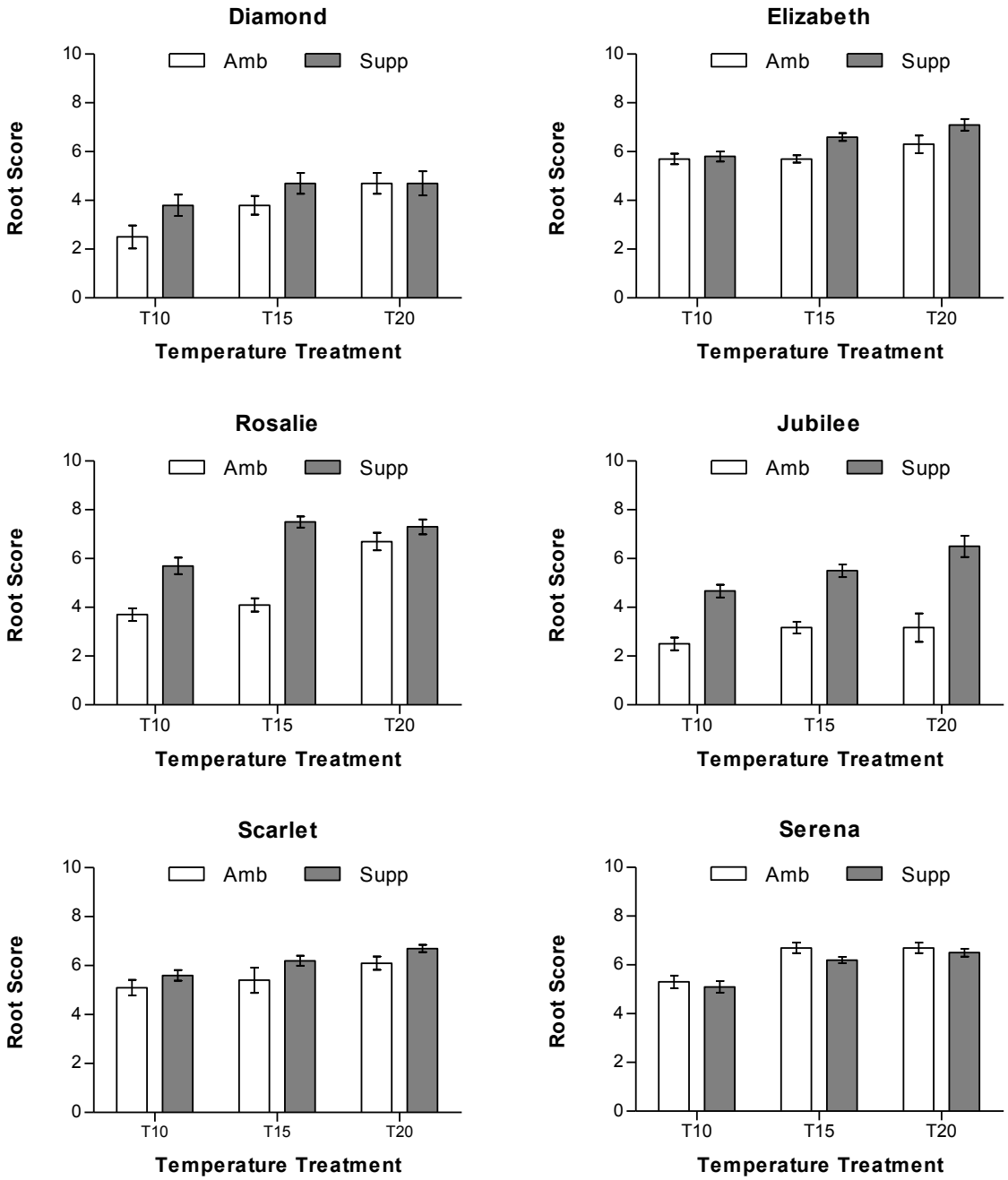

Figure 6.10 Effect of the light and temperature treatments root score for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10). The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

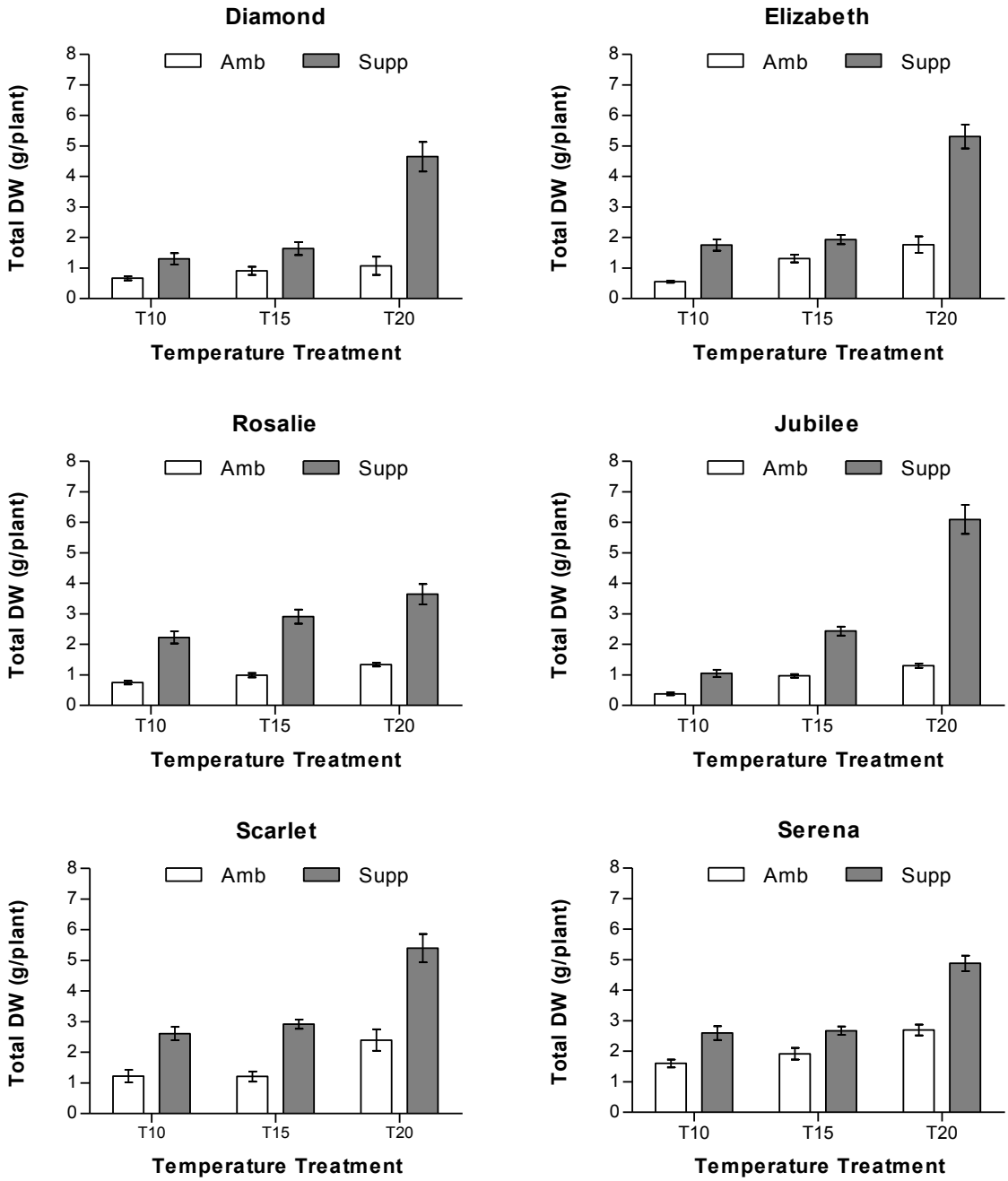

Figure 6.11 Effect of the light and temperature treatments on total plant dry weight for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=10). DW=dry weight. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

6.3.2 Production Phase

6.3.2.1 *Cropping Results*

Marketable Yield

There was a significant difference in marketable yield between cultivars (P<0.001). In the Junebearers, Rosalie had the greatest marketable yield (736±55.7 g / plant) significantly higher than Diamond (671±48.6) and Elizabeth (576±45.4). Jubilee had the lowest yield of the three Everbearer cultivars (574±29.7), significantly lower than Scarlet (949±29.3) and Serena (1067±28.7). Marketable yield of Jubilee was also significantly lower than Rosalie and Diamond.

Treatment effects on marketable yield for each cultivar are shown in Figure 6.12. The interaction between the light and temperature treatments was not significant, but there was a significant interaction between the cultivars and light treatments (P<0.001) such that the marketable yield of Diamond, Elizabeth, Rosalie and Jubilee was significantly greater in SUPP than AMB (29%, 65%, 51% and 23% respectively) whereas the differences for Scarlet or Serena were not significant. The effect of temperature also significantly differed between cultivars (P=0.001); marketable yield was 67%, 50%, 58%, 19% and 16% greater in T20 compared to T10 for Diamond, Elizabeth, Rosalie, Scarlet and Serena respectively whereas there was no significant difference for Jubilee.

Un-Marketable Yield

There was a significant difference in un-marketable yield between cultivars (P<0.001). In general, un-marketable yield was greater in the Everbearers than the Junebearers. Within the Everbearers, un-marketable yield of Scarlet (143±5.9 g / plant) was significantly greater than Jubilee (93±7.8) and Serena (70±4.8). In the Junebearers, un-marketable yield was significantly higher in Rosalie (42±8.0) and Elizabeth (35±4.8) compared to Diamond (21±4.4).

Treatment effects on un-marketable yield for each cultivar is shown in Figure 6.13. The interaction between the light and temperature treatments was not significant, but there was a significant interaction between the cultivars and light treatments (P=0.013) such that un-marketable yield was significantly greater in SUPP compared to AMB for Jubilee and Rosalie (64% and 87% respectively), but there was no significant difference in the remaining cultivars.

There was no significant interaction between the cultivar and temperature treatments, but the main effect of the temperature treatment was significant (P<0.001) with un-marketable yield significantly higher in T20 (79±7.2 g / plant) compared T15 (59±8.5) and T10 (64±8.4).

Total Yield

There was a significant difference in total yield between cultivars (P<0.001). In the Junebearer cultivars Rosalie had the greatest total yield (778±60.7 g / plant) significantly greater than Diamond (692±52.5) and Elizabeth (611±47.4). In the Everbearers, total yield did not significantly differ between Serena (1137±30.0) and Scarlet (1092±30.1) but was significantly greater than Jubilee (668±33.7). Total yield of Jubilee was also significantly lower than that of Rosalie.

Treatment effects on total yield for each cultivar is shown in Figure 6.14. The interaction between the light and temperature treatments was not significant, but there was a significant interaction between the cultivars and light treatments (P<0.001). Total yield of Diamond, Elizabeth, Rosalie and Jubilee was significantly greater in SUPP compared to AMB by 30%, 59%, 53% and 28% respectively but there was no significant difference for Scarlet or Serena. The effect of temperature also significantly differed between cultivars (P<0.001); total yield was significantly greater in T20 compared to T10 by 69%, 52%, 58%, 18% and 15% for Diamond, Elizabeth, Rosalie, Scarlet and Serena respectively whilst there was no significant difference for Jubilee.

Percentage Class 1

There was a significant difference in the percentage Class 1 between cultivars (P<0.001). Diamond had the greatest percentage Class 1 of the six cultivars (97±0.3 %) significantly higher than all other cultivars, and Jubilee and Scarlet had the lowest (86±0.9 and 87±0.6 respectively). There was no significant difference between Serena (94±0.4), Elizabeth (94±0.8) and Rosalie (95±0.8) the percentage Class 1 was significantly greater in all three cultivars compared to Jubilee and Scarlet.

Treatment effects on percentage Class 1 for each cultivar is shown in Figure 6.15. Only the main effect of the temperature treatment was significant (P=0.013). However, despite being statistically significant, differences between treatments were minimal with percentage Class 1 greater in T15 compared to T10 and T20 by 1%.

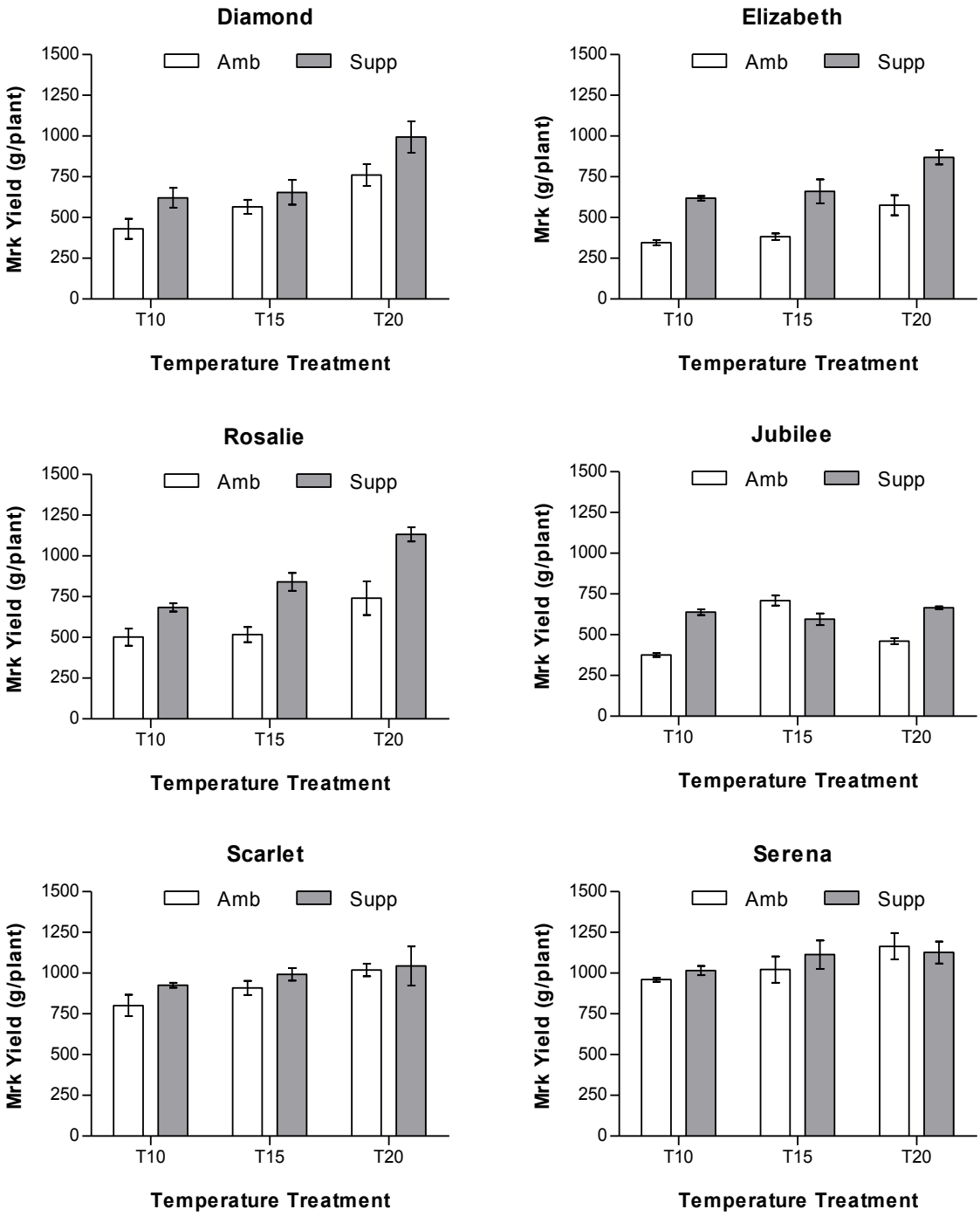

Figure 6.12. Effect of the light and temperature treatments on marketable yield of cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). Mrk= marketable. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20)

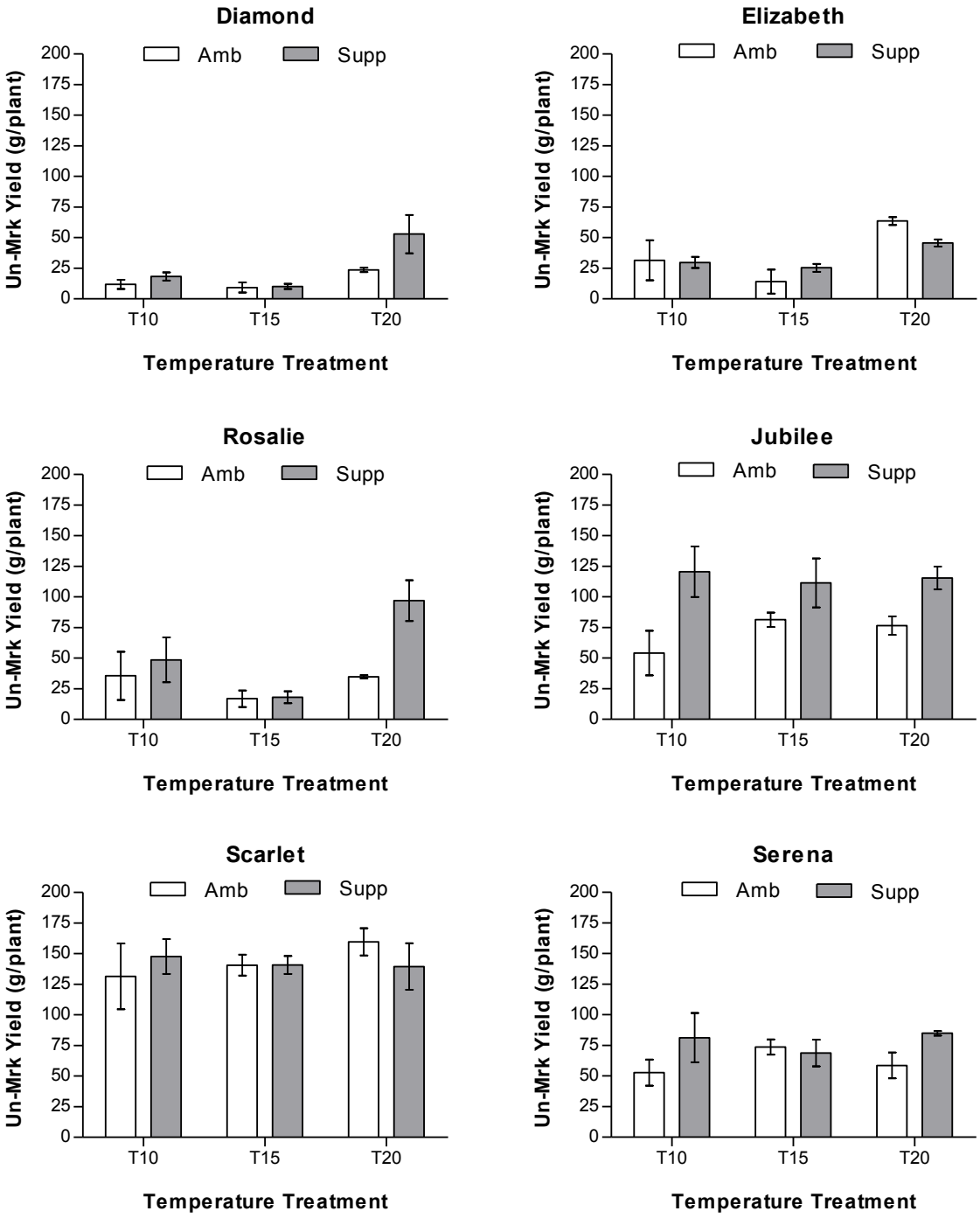

Figure 6.13 Effect of the light and temperature treatments on un-marketable yield of cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). Un-Mrk= un-marketable. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

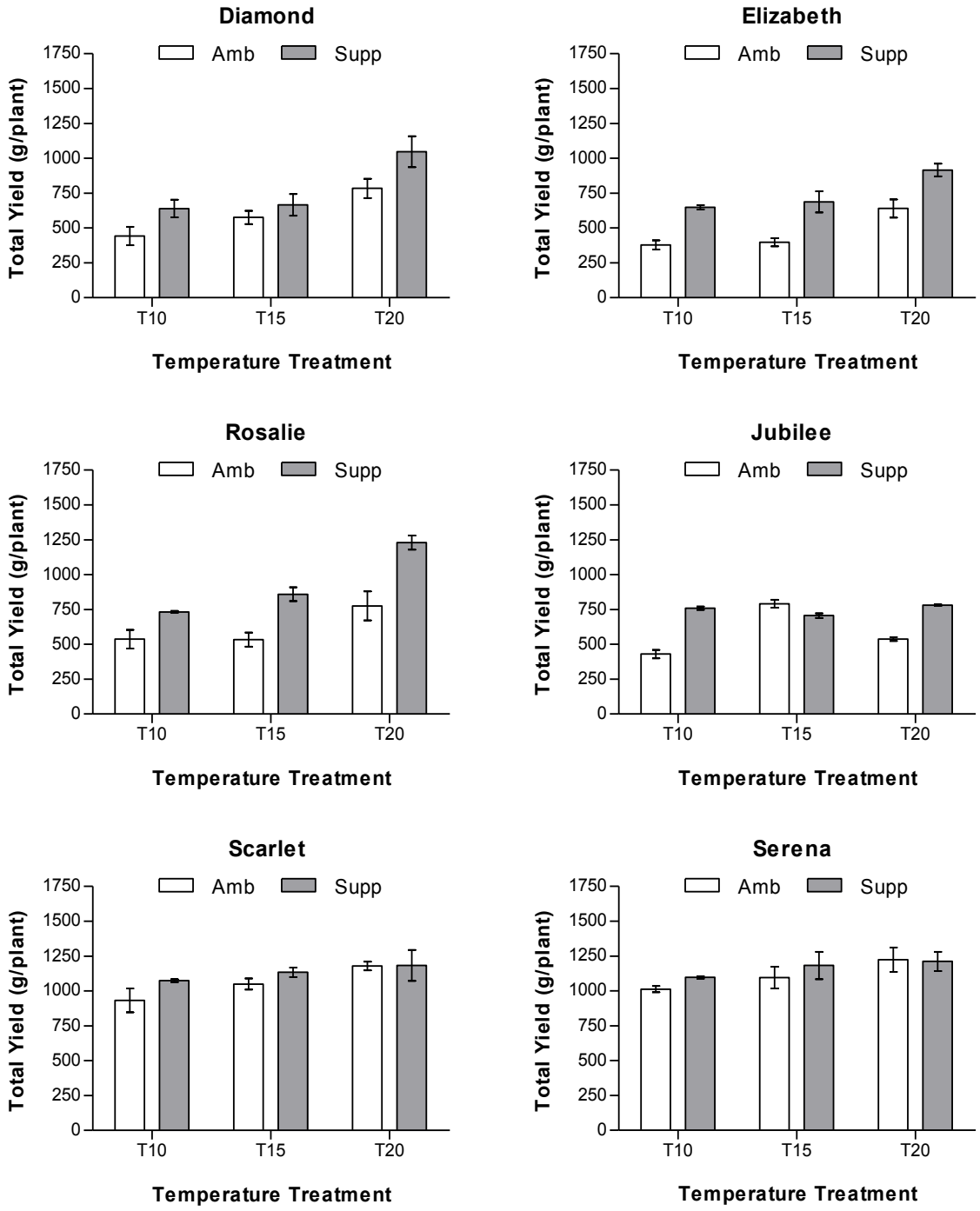

Figure 6.14 Effect of the light and temperature treatments on total yield of cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

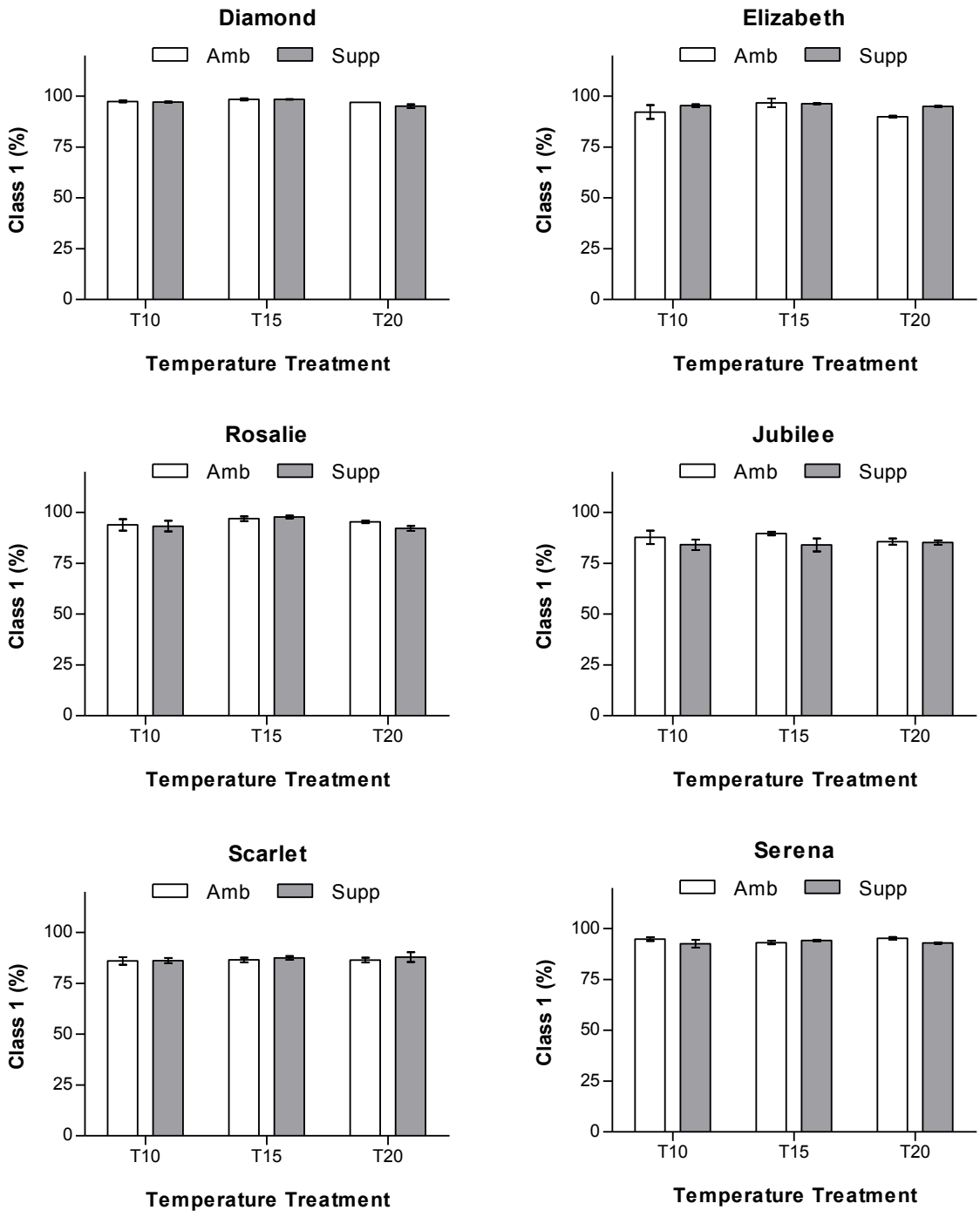

Figure 6.15 Effect of the light and temperature treatments on the percentage Class 1 for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

Marketable Berry Number

There was a significant difference in marketable berry number between cultivars (P<0.001). In general, marketable berry number was greater in the Everbearers than the Junebearers. Within the Everbearers, berry number of Serena (53.8±1.7 berries / plant) was significantly higher than Scarlet (48.7±1.7) and Jubilee (30.4±1.8). In the Junebearers there was no significant difference between Diamond (25.0±1.9) and Elizabeth (24.2±2.0) but marketable berry number of both was significantly lower than Rosalie (28.4±2.1).

Treatment effects on marketable berry number for each cultivar is shown in Figure 6.16. Only the main effects of the treatments were significant. Marketable berry number was significantly (P<0.001) greater in SUPP (39.5±1.7 berries / plant) compared to AMB (30.7±2.0) and there was also a positive effect of increased temperature on marketable berry number (P<0.001), which significantly increased from T10 (30.6±2.2 berries / plant) to T15 (33.7±2.3) and from T15 to T20 (40.9±2.3).

Un-marketable Berry Number

There was a significant difference in un-marketable berry number between cultivars (P<0.001). In general, un-marketable berry number was greater in the Everbearers than the Junebearers. All differences between cultivars were significant, Scarlet had the greatest number of un-marketable berries (16.0±0.6 berries / plant), followed by Jubilee (11.4±1.1), Serena (8.7±0.5), Rosalie (4.9±0.9), Elizabeth (3.6±0.5) and Diamond (2.1±0.5).

Treatment effects on un-marketable berry number for each cultivar is shown in Figure 6.17. The interaction between the light and temperature treatments was not significant. There was a significant interaction between the cultivars and light treatments (P=0.003); un-marketable berry number was significantly greater in SUPP compared to AMB for Jubilee and Rosalie by 58% and 80% respectively but there was no significant difference for the remaining cultivars. The interaction between the cultivars and temperature treatments was not significant, but the main effect of the temperature treatment was significant (P<0.001) with the un-marketable berry number significantly higher in T20 (9.3±0.9 berries / plant) compared to T15 (7.0±1.0) and T10 (7.1±0.9).

Total Berry Number

There was a significant difference in total berry number between cultivars (P<0.001). In general, total berry number was greater in the Everbearers compared to the Junebearers. Within the Everbearers, berry number did not significantly differ between Scarlet (64.7±1.7 berries / plant) and Serena (62.5±2.0) but was greater in both compared to Jubilee (41.8±2.5). In the Junebearers total berry number was significantly higher in Rosalie (33.3±2.8) compared Diamond (27.2±2.4) and Elizabeth (27.8±2.4) which had no significant difference between them.

Treatment effects on total berry number for each cultivar is shown in Figure 6.18. The interaction between the light and temperature treatments was not significant, but there was a significant interaction between the cultivars and light treatments (P=0.006). Total berry number was significantly greater in SUPP compared to AMB for all cultivars (by 43%, 57% and 61% for Diamond, Elizabeth, Rosalie and by 44%, 6% and 10% for Jubilee, Scarlet and Serena respectively). The effect of temperature also significantly differed between cultivars (P=0.010); total berry number significantly increased from T10 to T20 in all cultivars by 65%, 68%, 53% for Diamond, Elizabeth and Rosalie and 21% 21% and 17% for Jubilee, Scarlet and Serena.

Marketable Berry Weight

Average marketable berry weight did not significantly differ between the Everbearer cultivars Serena (19.9±0.3 g / berry), Scarlet (19.6±0.2) and Jubilee (19.2±0.5). Whereas, all differences in berry weight between the Junebearer cultivars were significant (P<0.001), with berry weight greatest in Diamond (27.0±0.5) followed by Rosalie (26.1±0.6) and Elizabeth (24.1±0.4).

The interaction between the light and temperature treatments was not significant; there was also no significant interaction between the cultivars and light treatments, but the main effect of the light treatment was significant (P=0.004) with berry weight greater in AMB (23.3±0.5 g / berry) compared to SUPP (22.0±0.5). The interaction between the cultivars and temperature treatments was significant (P=0.004); for Elizabeth and Jubilee average berry weight was significantly higher in T10 and T15 compared to T20 (by 8% and 11% for Elizabeth and 15% and 11% for Jubilee respectively) whilst in Rosalie marketable berry weight was significantly higher in T15 compared to both T10 and T20 (12% and 6% respectively). For the remaining cultivars Diamond, Scarlet and Serena there were no significant differences in average berry weight between treatments.

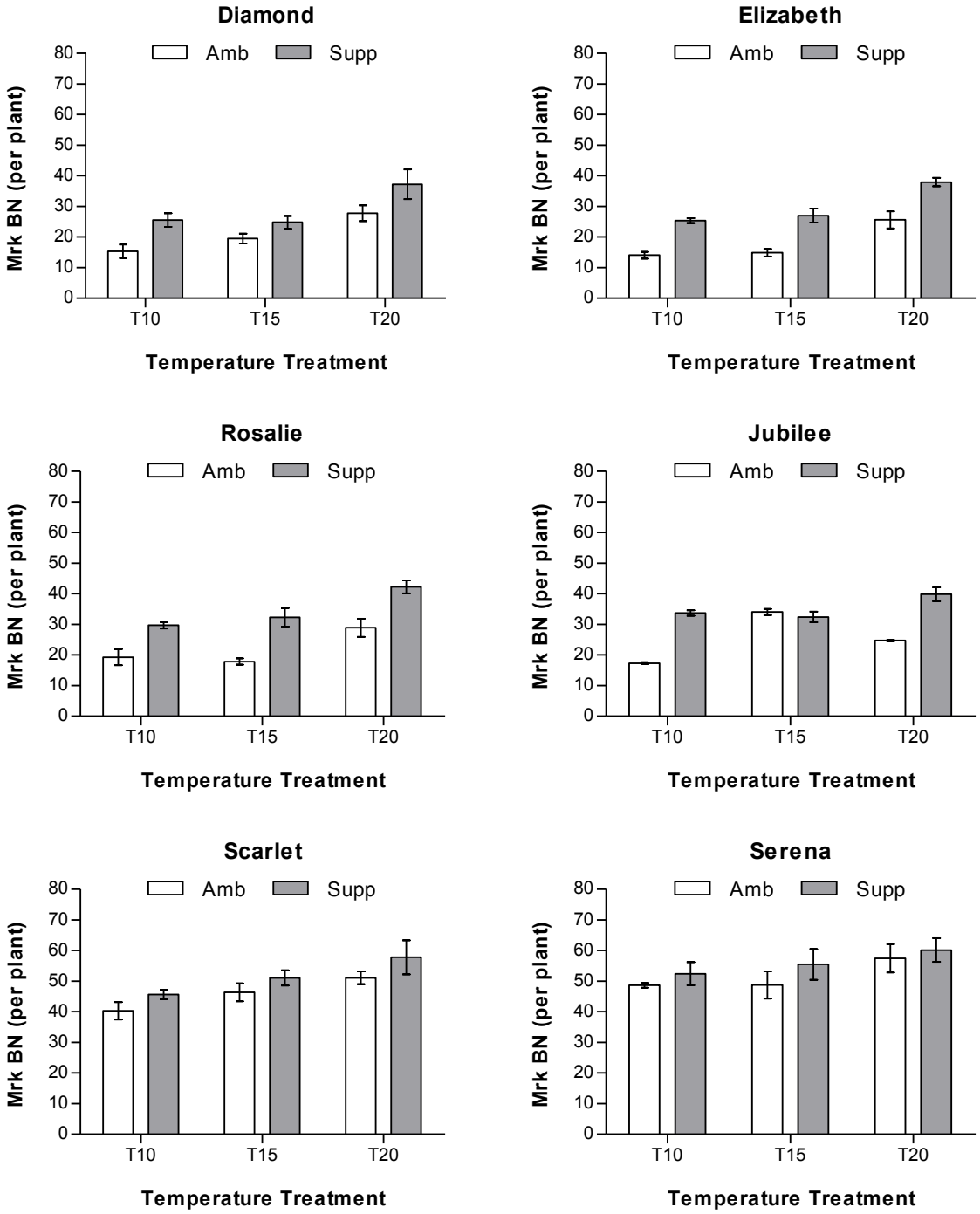

Figure 6.16 Effect of the light and temperature treatments on marketable berry number for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). BN= berry number, Mrk= marketable. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

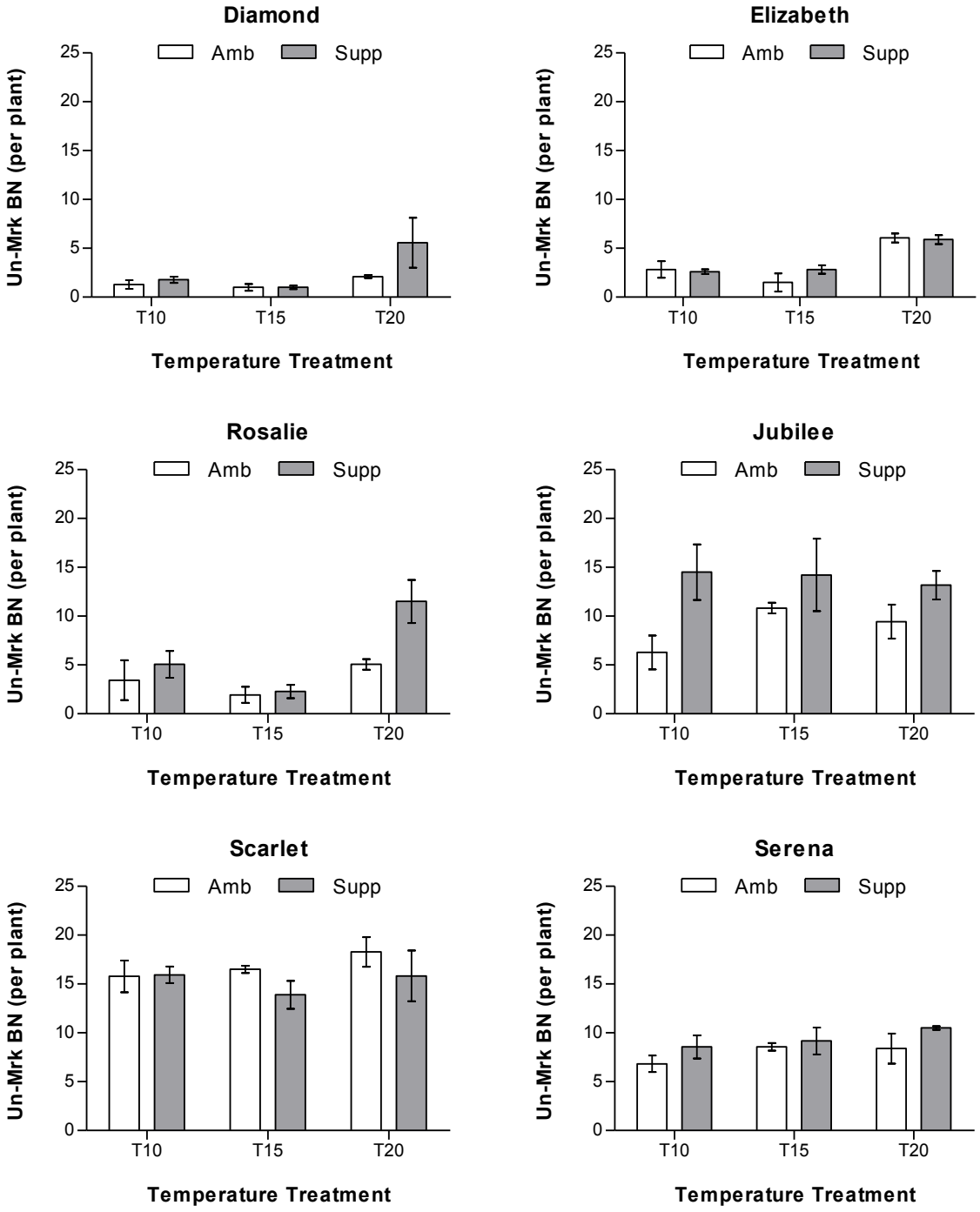

Figure 6.17 Effect of the light and temperature treatments on un-marketable berry number for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). BN= berry number, Un-Mrk= un-marketable. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

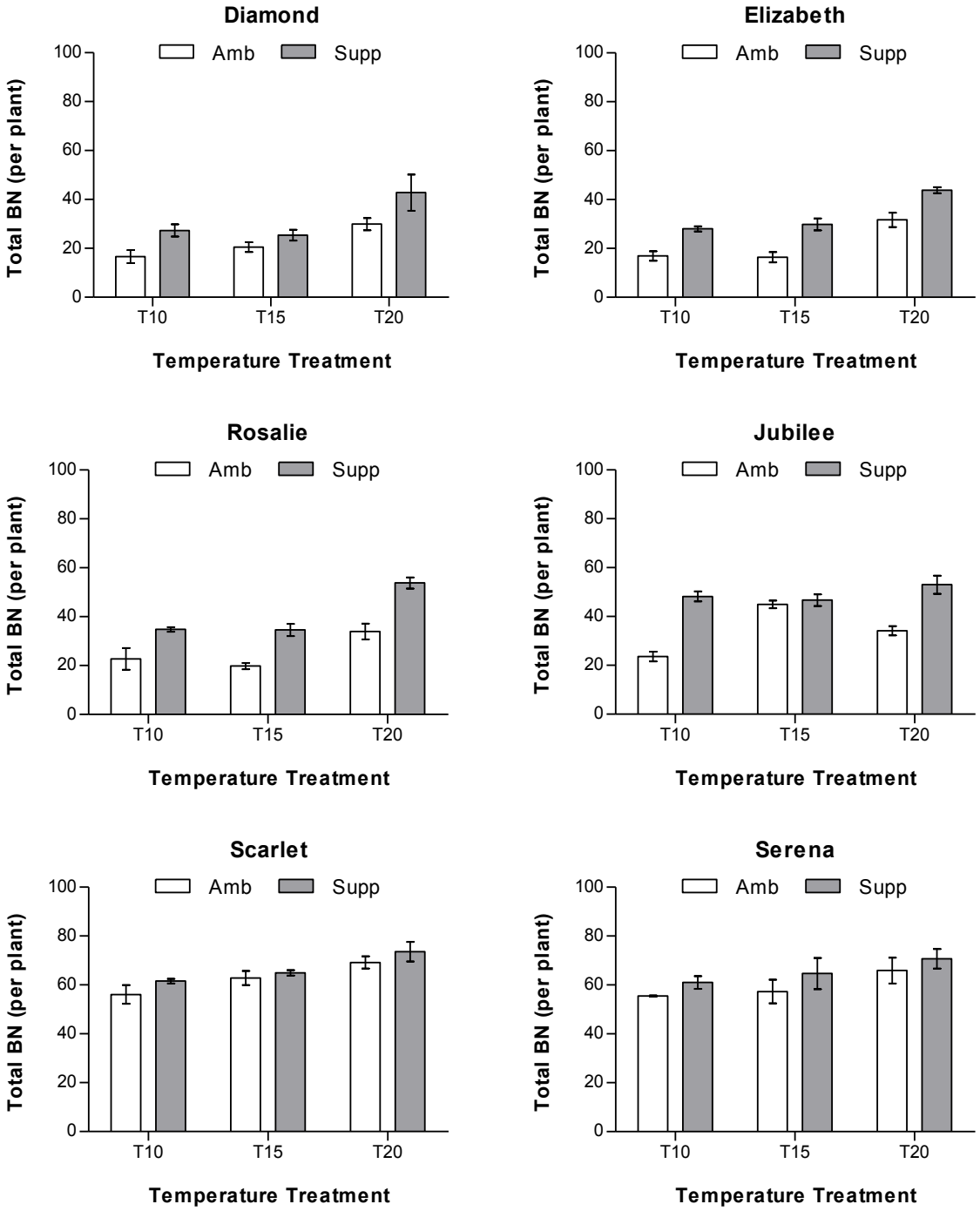

Figure 6.18 Effect of the light and temperature treatments on total berry number for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). BN= berry number. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

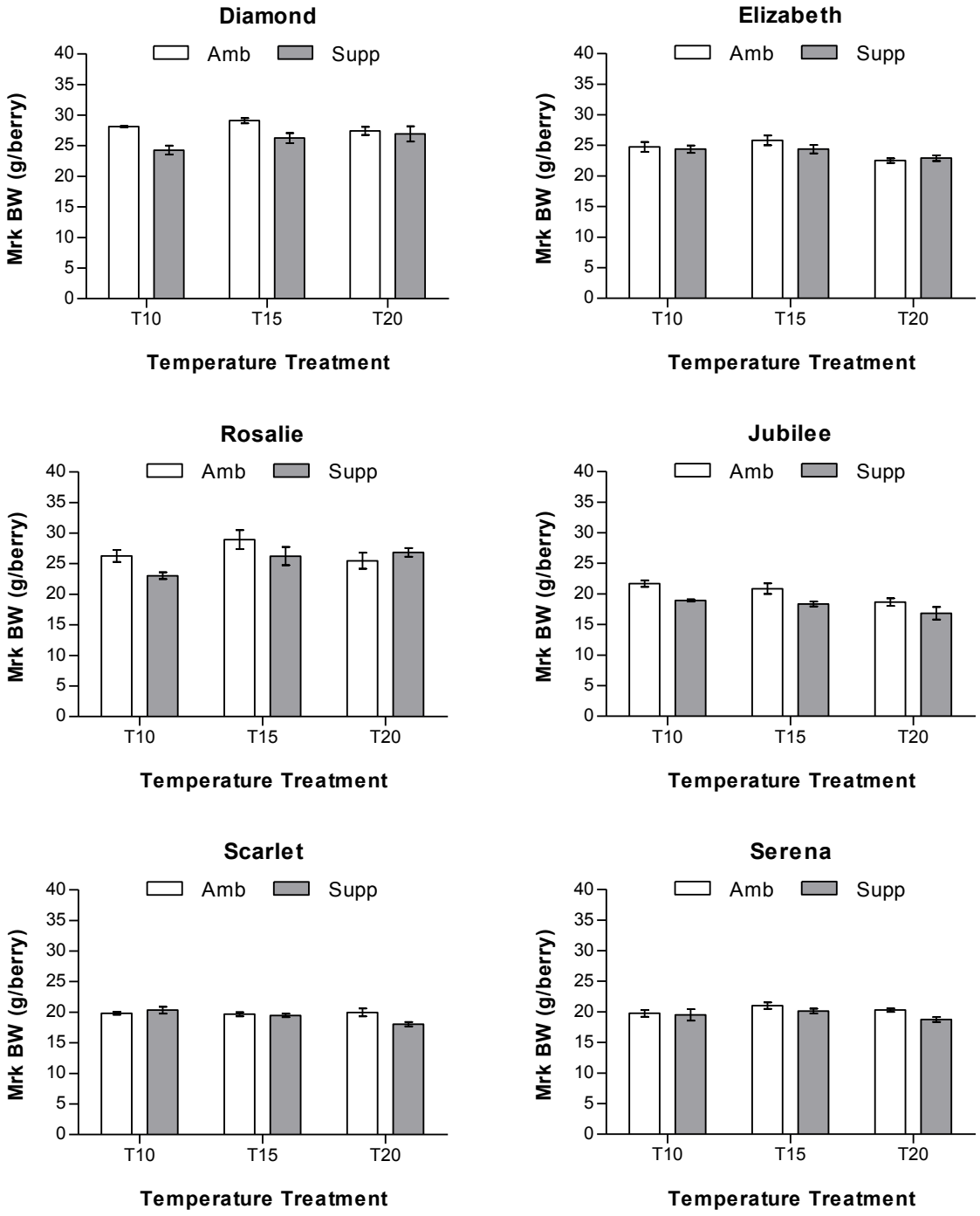

Figure 6.19 Effect of the light and temperature treatments on average marketable berry weight for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). BW= berry weight, Mrk= marketable. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

6.3.2.2 *Cropping Profiles*

Marketable yield for each cultivar and treatment was recorded for 19 weeks from 1st June 2015 (Week 23) to 12th October 2015 (Week 41) (Figure 6.20). There was a strong significant difference in marketable yield between cultivars every week ($P<0.001$, Figure 6.21A). In the Junebearers, for first nine weeks of cropping (Week 23-31) marketable yield was greater in Rosalie and Diamond compared to Elizabeth after this fruit production was virtually finished in the Junebearers and there were little differences between cultivars from this point. Marketable yield peaked for all three Junebearers in Week 26 and 29; in Week 26 marketable yield was significantly greater in Diamond compared to Rosalie and Elizabeth (by 34% and 33% respectively) and in Week 29 marketable yield was significantly greater in both Diamond and Rosalie compared to Elizabeth (by 35% each). In the Everbearers, for the first two weeks of cropping marketable yield was greater in Scarlet compared to Jubilee and Serena, but from Week 25 to 27 marketable yield was significantly higher in Serena compared to Scarlet by 83%, 188% and 112% respectively and by 171%, 232% and 112% compared to Jubilee. The first flush of fruit in the Everbearers had been picked by Week 30; in the second flush from Week 31 to 35, marketable yield was greater in Scarlet compared to both Serena and Jubilee. However, yield of Serena increased in the final two weeks cropping and was significantly greater than both Scarlet and Jubilee.

The main effect of light treatments is shown in Figure 6.21B; in general, marketable yield was greater in SUPP compared to AMB in the first eight weeks of cropping (Week 23 to Week 30), and this was significant for Week 24-27 and 30 where marketable yield was greater in SUPP by 16%, 21%, 90%, 69% and 28% compared to AMB respectively. For the remainder of cropping (Week 31-41) there were no significant differences between the light treatments.

The main effect of the temperature treatments is shown in Figure 6.21C. In the early stages of cropping (Week 26-30) marketable yield was generally greater in T20 compared to T15 and T10; whereas, for the remainder of cropping there was little difference between temperature treatments. Marketable yield was significantly greater in T20 compared to T15 and T10 from Week 28 to 32 by 31%, 58%, 85%, 123% and 75% compared to T15 and by 54%, 83%, 103%, 125% and 42% compared to T10 respectively. For the remainder of cropping, the only significant difference in marketable yield between temperature treatments were in Week 37 and 38 where marketable yield was also significantly higher in T20 compared to both T15 and T10.

Figure 6.21D shows the interaction between the light and temperature treatments. Marketable yield was generally greater in SUPP compared to AMB at the start of cropping for all three temperature treatments but more so in T20 than T15 or T10; whereas, there was little difference in marketable yield between treatments toward the end of cropping. There was only a significant interaction between the light and temperature treatments in Week 29 and 30 where marketable yield was significantly higher in SUPP compared to AMB in T20 (by 38% and 64% respectively) whereas there were no significant differences in T15 or T10.

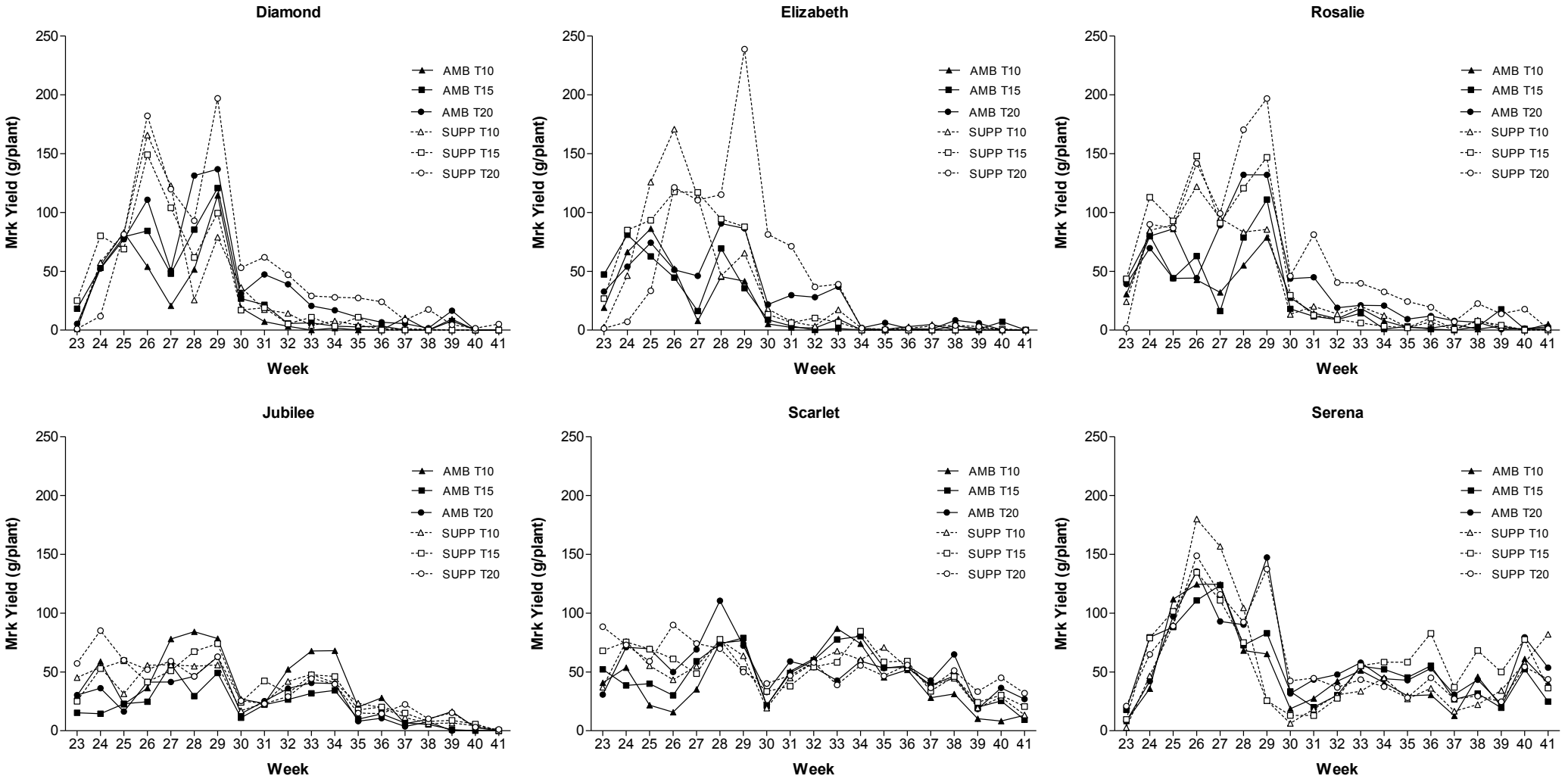

Figure 6.20 Effect of the light and temperature treatments on marketable yield each week during the production phase for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). Mrk= marketable. Light treatments were ambient light levels (AMB) and 8 hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

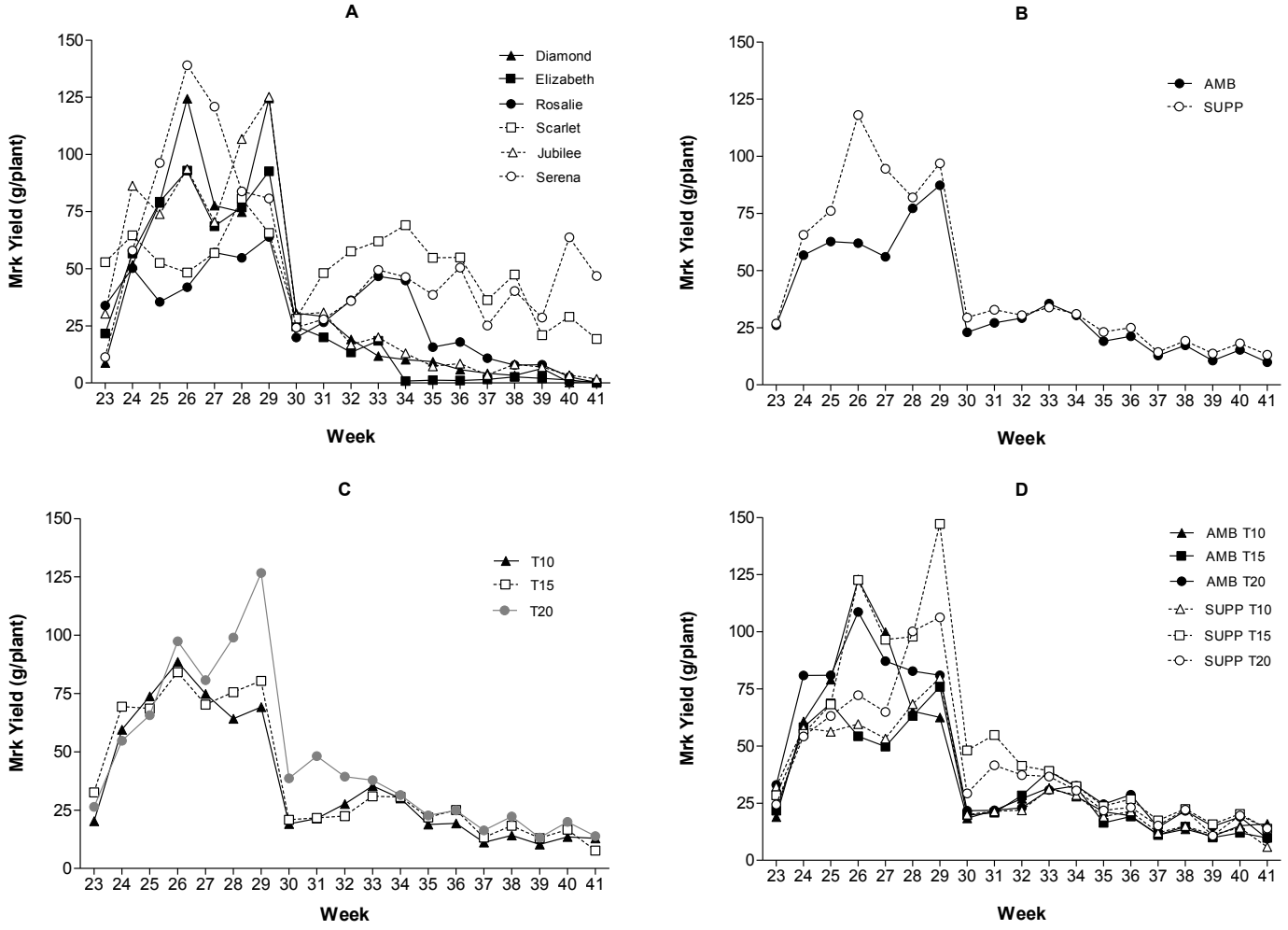

Figure 6.21 Effect of cultivar (A) (n=18), light treatment (B) (n=54), temperature treatment (C) (n=36) and the interaction between the light and temperature treatments (D) (n=18) on marketable yield each week during the production phase. Mrk= marketable. Light treatments were ambient light levels (AMB) and 8 hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

6.3.2.3 *Combined Treatment Effects*

Marketable Yield

Figure 6.22A shows the marketable yield for each cultivar in Treatment B (AMB T10) and Treatment E (SUPP T20). Marketable yield was significantly (P<0.001) greater in Treatment E (972±46.9 g / plant) compared to Treatment B (569±57.8) by 71%, or 403 g / plant. However, there was also a signficant interaction between the cultivars and treatments (P=0.003) such that marketable yield was 131%, 151%, 126%, 77%, 30% and 17% greater in Treatment E for Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena respectively with the difference between treatments significant for all cultivars except Serena.

Marketable Berry Number

Figure 6.22B shows the marketable berry number for each cultivar in Treatment B (AMB T10) and Treatment E (SUPP T20). Marketable berry number was significantly greater in Treatment E (45.9±2.6 berries / plant) compared to Treatment B (25.8±3.3) by 78%, or 20 berries / plant (P<0.001). The interaction between the cultivars and treatments was not signficant, marketable berry number was significantly greater in Treatment E compared to Treatment B for all cultivars by 143%, 170% and 119% for Diamond, Elizabeth and Rosalie and by 130%, 43% and 24% for Jubilee, Scarlet and Serena respectively.

Marketable Berry Weight

Figure 6.22C shows the average marketable berry weight for each cultivar in Treatment B (AMB T10) and Treatment E (SUPP T20). Average marketable berry weight was significantly lower in Treatment E (21.7±1.0 g / berry) compared to Treatment B (23.4±0.8) by 8%, or 1.7 g / berry, (P<0.001). However, there was also a signficant interaction between the cultivars and treatments (P=0.034) which showed average berry weight was only significantly reduced in SUPP compared to AMB for Jubilee (by 29%).

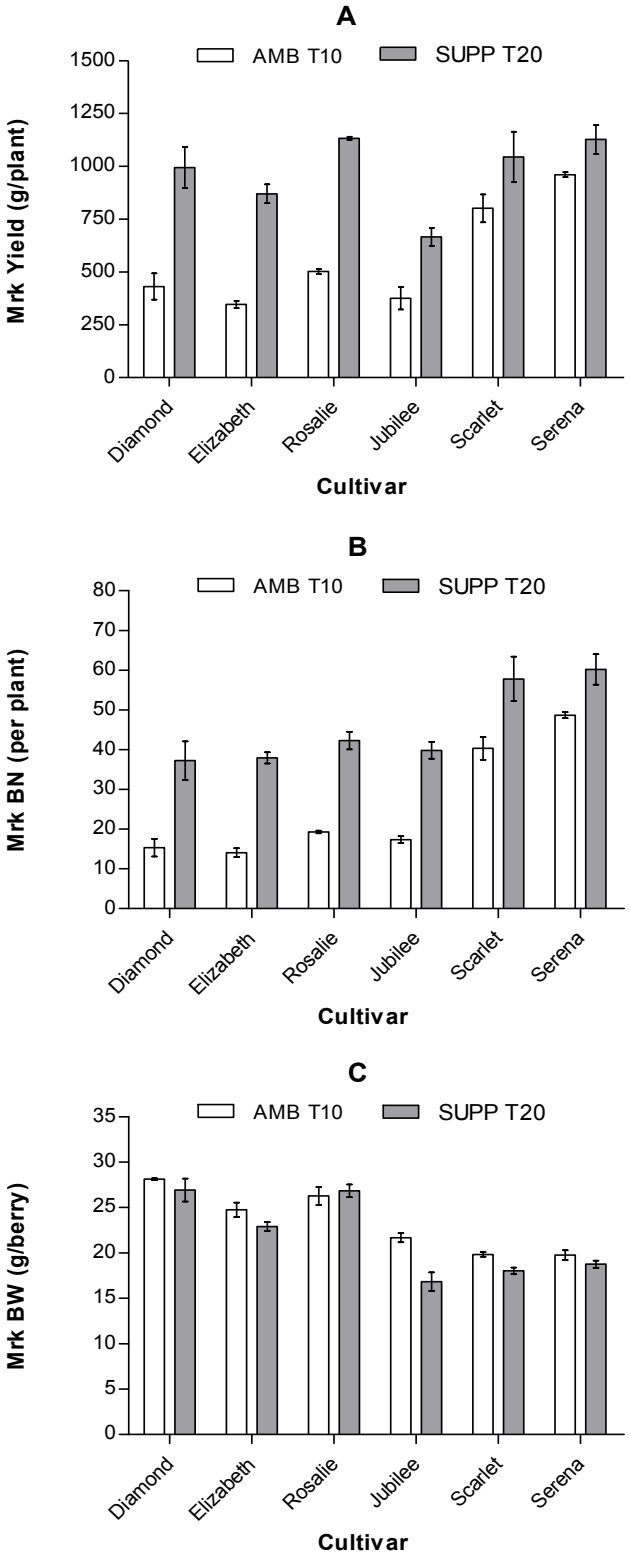

Figure 6.22 Effect of treatments on marketable yield (A), berry number (B) and average berry weight (C) of cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=3). Mrk= marketable, BN= berry number, BW= berry weight. The vertical line on each bar shows ±S.E.M. Treatments were ambient light level, minimum 10°C (AMB T10) and 8-hrs supplementary lighting, minimum 20°C (SUPP T20).

6.3.2.4 *Final Destructive Harvest (DH2)*

Crown Number

There was a significant difference in crown number between cultivars (P<0.001); crown number of Rosalie (8.3±0.6 crowns / plant) and Scarlet (7.8±0.3) did not significantly differ but were both significantly greater than Diamond (6.3±0.4), Serena (5.8±0.3), Jubilee (6.5±0.2) and Elizabeth (6.5±0.4). Serena had the lowest number of crowns per plant, significantly lower than all cultivars except Diamond.

The interaction between the light and temperature treatments was just significant (P=0.049, Figure 6.23) such that crown number was significantly higher in SUPP compared to AMB but to a greater extent in T20 (38%) than T15 (29%) and T10 (23%). Crown number also increased from T10 to T20 in both light treatments but to a greater extend in SUPP (32%) compared to AMB (18%).

Crown Dry Weight

There was a significant difference in crown dry weight between cultivars (P<0.001). Overall, crown dry weight was greater in the Junebearers than the Everbearers. Within the Junebearers, Rosalie had the greatest crown dry weight (19.62±1.09 g / plant), significantly greater than Elizabeth (15.16±0.73) and Diamond (14.99±0.64). In the Everbearers, crown dry weight was greatest in Scarlet (13.15±0.48) followed by Jubilee (11.90±0.42) and Serena (10.81±0.48) but was only significantly higher in Scarlet compared to Serena.

Treatment effects on crown dry weight for each cultivar are shown in Figure 6.24. There was no significant interaction between the light and temperature treatments but there was a significant interaction between the cultivars and light treatments (P<0.001); crown dry weight was significantly greater in SUPP compared to AMB for the Junebearer cultivars (by 34%, 51% and 26% for Diamond, Elizabeth and Rosalie respectively) and there were no significant differences for the Everbearer cultivars.

The effect of the temperature treatment also differed significantly between cultivars (P<0.001) such that from T15 to T20 there was a significant reduction in crown dry weight for Jubilee and Serena (by 27% and 31% respectively), a significant increase for Elizabeth and Rosalie (13% and 45% respectively) and no significant differences for Diamond or Scarlet.

Leaf Number

There was a significant difference in leaf number between cultivars (P<0.001); for the Junebearers, Rosalie had the greatest leaf number (72.1±4.5 leaves / plant), significantly higher than Elizabeth (61.7±3.6) and Diamond (57.2±2.3), and in Elizabeth compared to Diamond. In Everbearers, leaf number significantly higher in Scarlet (59.6±2.1) compared to Jubilee (42.3±1.2) and Serena (36.4±1.2), and in Jubilee compared to Serena.

The interaction between the light and temperature treatments was significant (P=0.027, Figure 6.25) such that leaf number was significantly higher in SUPP compared to AMB but to a greater extent in T20 (30%) than T15 (18%) and T10 (21%). Leaf number also increased from T10 to T20 in both light treatments but to a greater extend in SUPP (20%) compared to AMB (12%).

Leaf Dry Weight

There was a significant difference in leaf dry weight between cultivars (P<0.001); overall, leaf dry weight was greater in the Junebearers than the Everbearers. Elizabeth had the greatest leaf dry weight of the Junebearer cultivars (73.50±2.96 g / plant), significantly greater than Diamond (55.74±2.25) and Rosalie (51.86±2.30). In the Everbearers, leaf dry weight was significantly higher in Scarlet (33.1±0.0) compared to Jubilee (28.86±1.11) and Serena (21.26±0.90), and in Jubilee compared to Serena.

Treatment effects on leaf dry weight for each cultivar are shown in Figure 6.26. The interaction between the light and temperature treatments was not significant but there was a significant interaction between the cultivars and light treatments (P<0.001) which showed leaf dry weight was significantly greater in SUPP compared to AMB for Diamond and Elizabeth (by 28% and 33% respectively) whilst there were no significant differences for the remaining cultivars.

The effect of the temperature treatment also differed significantly between cultivars (P<0.001) such that from T10 to T20 there was a significant increase in leaf dry weight of Jubilee and Rosalie (by 33% and 54% respectively) but there were no significant differences for the remaining cultivars.

Inflorescence Number

There was significant difference the number of inflorescences between cultivars (P<0.001). Overall the number of inflorescences per plant was greater in the Everbearers compared to the Junebearers. Within the Junebearers, inflorescence number was significantly higher in Diamond (4.6±0.3) and Rosalie (4.1±0.3) compared to Elizabeth (3.5±0.2). In the Everbearers, Scarlet had the greatest number of inflorescences (9.1±0.3 per plant), significantly greater than Serena (6.4±0.2) and Jubilee (5.5±0.3), and in Serena compared to Jubilee.

Treatment effects on inflorescence number for each cultivar is shown in Figure 6.27. The interaction between the light and temperature treatments was not significant but there was a significant interaction between the cultivars and light treatments (P<0.001), inflorescence number was significantly greater in SUPP compared to AMB for the Junebearers (by 58%, 49% and 45% for Diamond, Elizabeth and Rosalie respectively) but there was no significant difference for the Everbearer cultivars.

The effect of the temperature treatment also differed significantly between cultivars (P=0.008) such that inflorescence number significantly increased from T10 to T20 in Diamond, Elizabeth, Rosalie and Scarlet (by 43%, 38%, 61% and 15% respectively) whereas there was no significant difference in inflorescence number between temperature treatments for Jubilee or Serena.

Total Dry Weight

There was a significant difference in total plant dry weight between cultivars (P<0.001). Overall, total plant dry weight was greater in the Junebearers than the Everbearers. Elizabeth had the greatest total plant dry weight of the Junebearer cultivars (120.66±5.15 g / plant), significantly greater than Diamond (102.73±4.21) and Rosalie (104.39±4.83). In the Everbearers, total dry weight was greatest in Scarlet (72.14±2.79), significantly higher than Jubilee (60.11±2.02) and Serena (49.75±1.84), and in Jubilee compared to Serena.

The interaction between the light and temperature treatments was just significant (P=0.045, Figure 6.28) such that total dry weight was significantly higher in SUPP compared to AMB but to a greater extent in T20 (28%) than T15 (17%) and T10 (14%). Total dry weight also increased from T10 to T20 in both light treatments but to a greater extent in SUPP (23%) compared to AMB (9%).

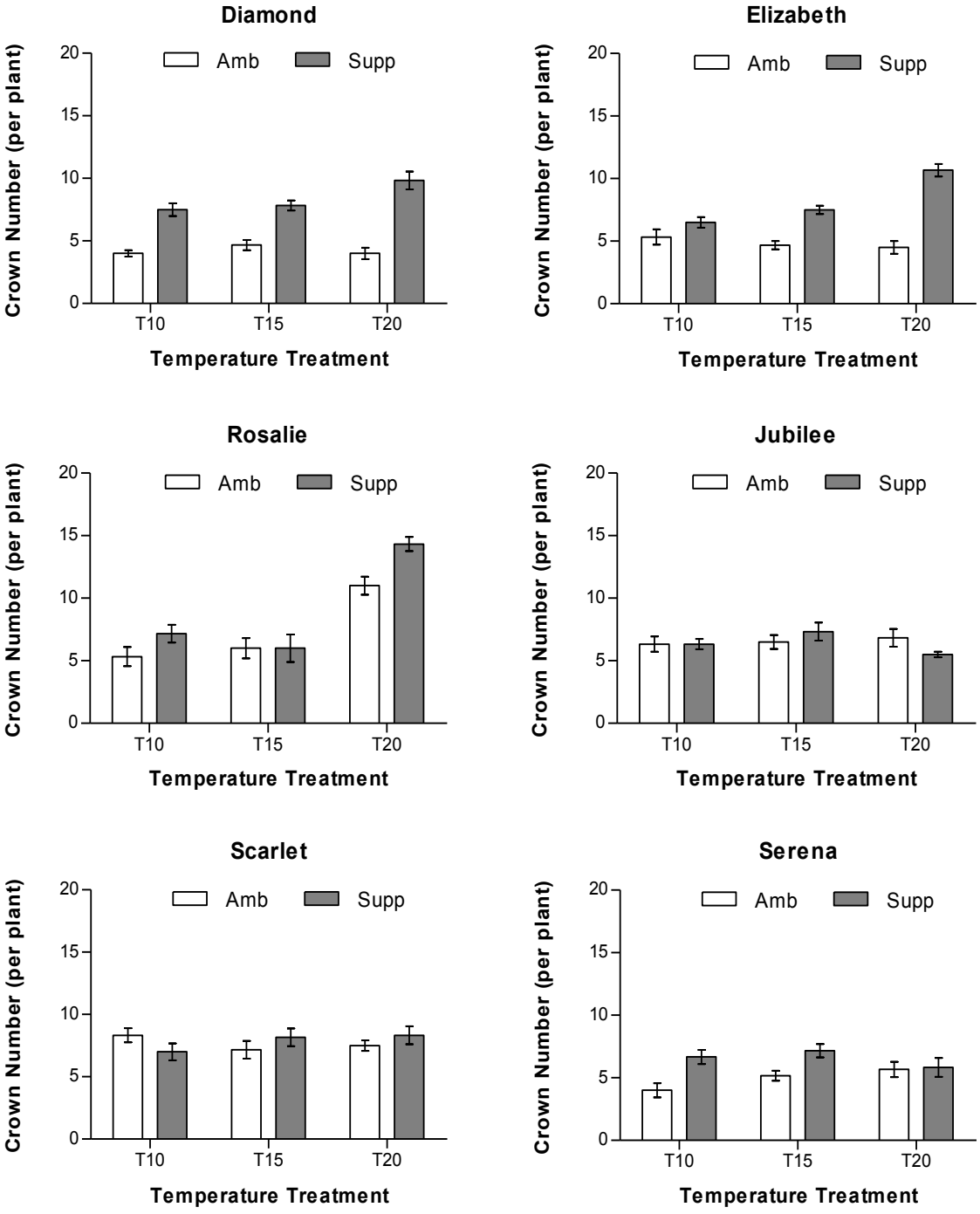

Figure 6.23 Effect of the light and temperature treatments on crown number for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=6). The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

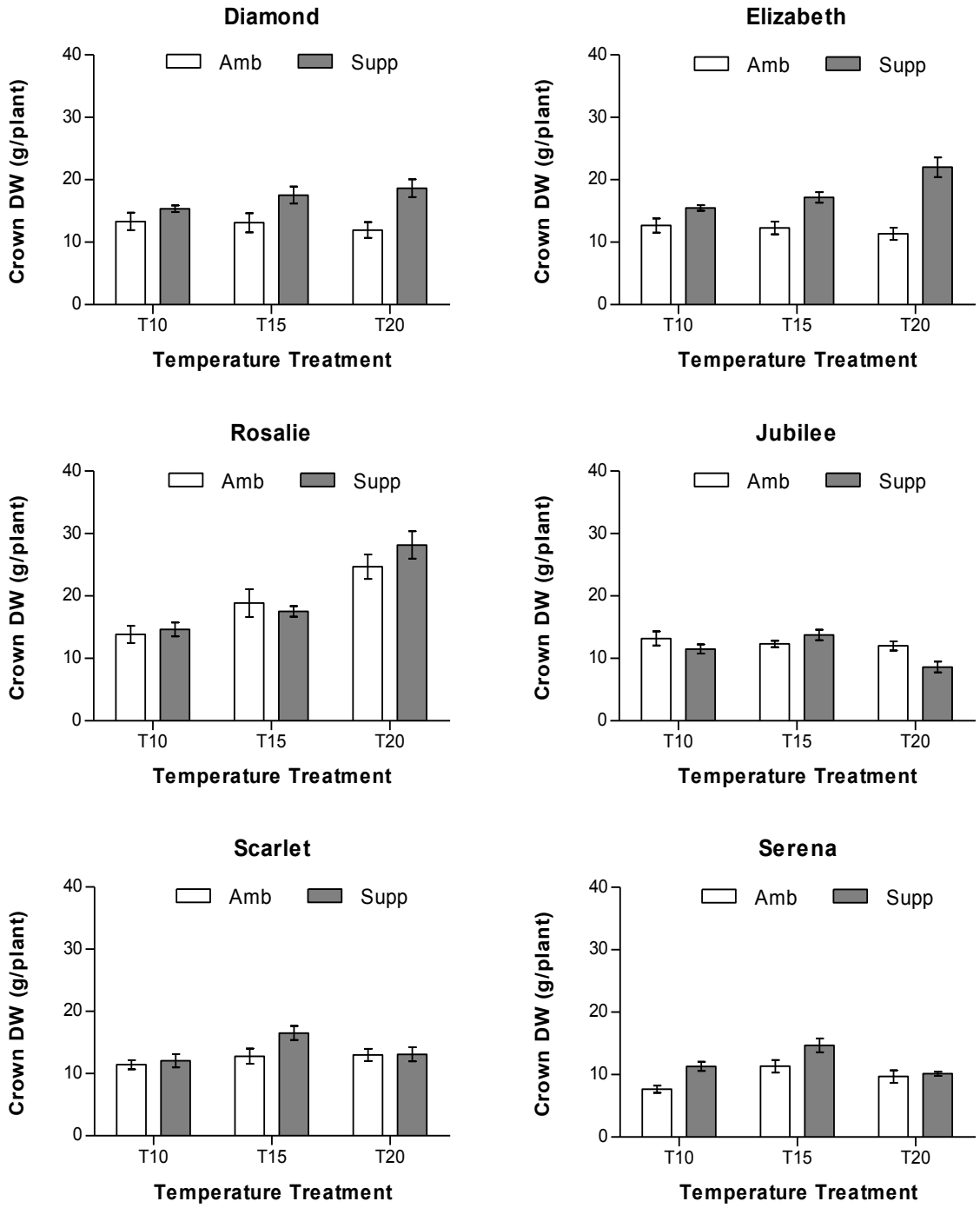

Figure 6.24 Effect of the light and temperature treatments on crown dry weight for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=6). DW=dry weight. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

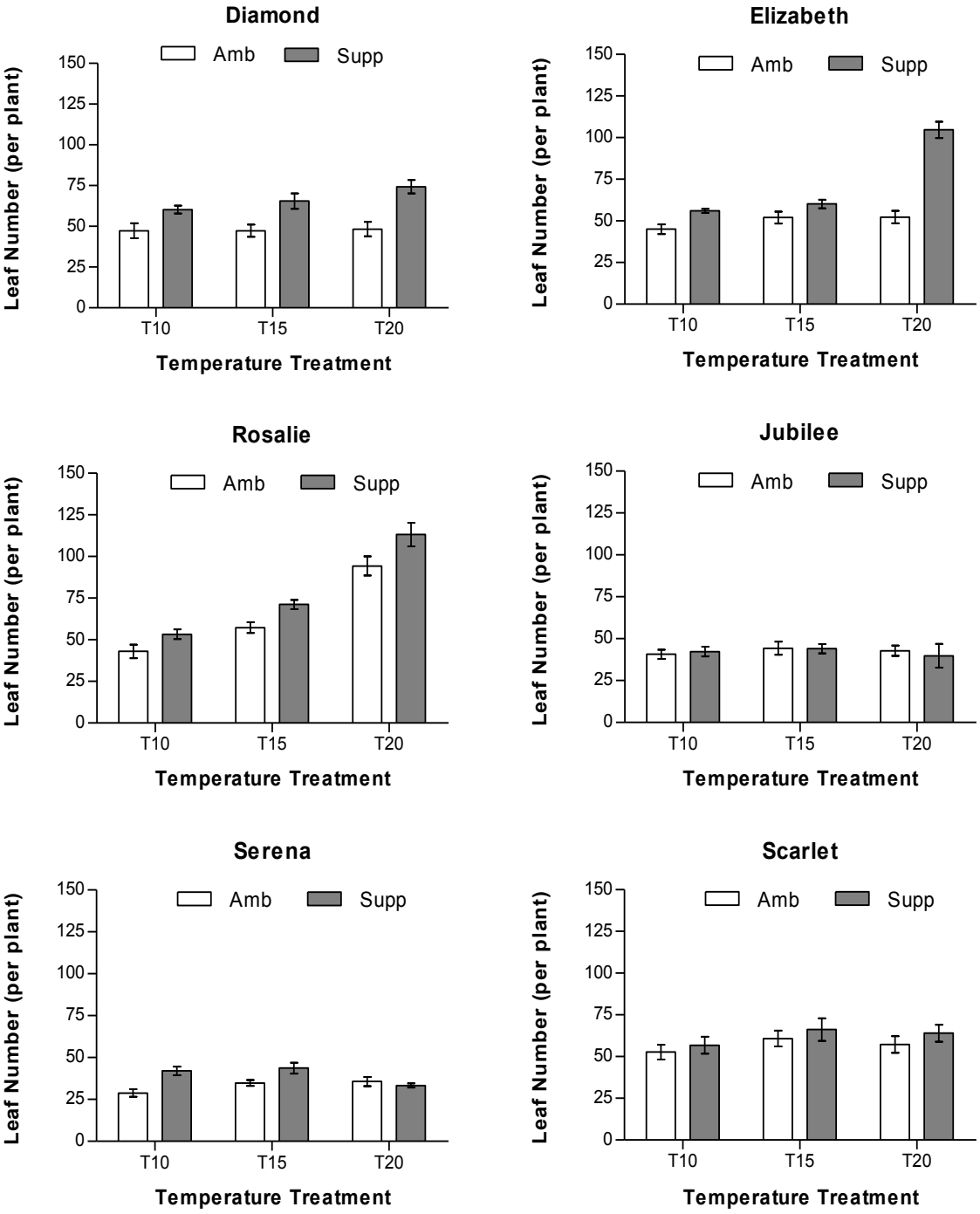

Figure 6.25 Effect of the light and temperature treatments on leaf number for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=6). The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

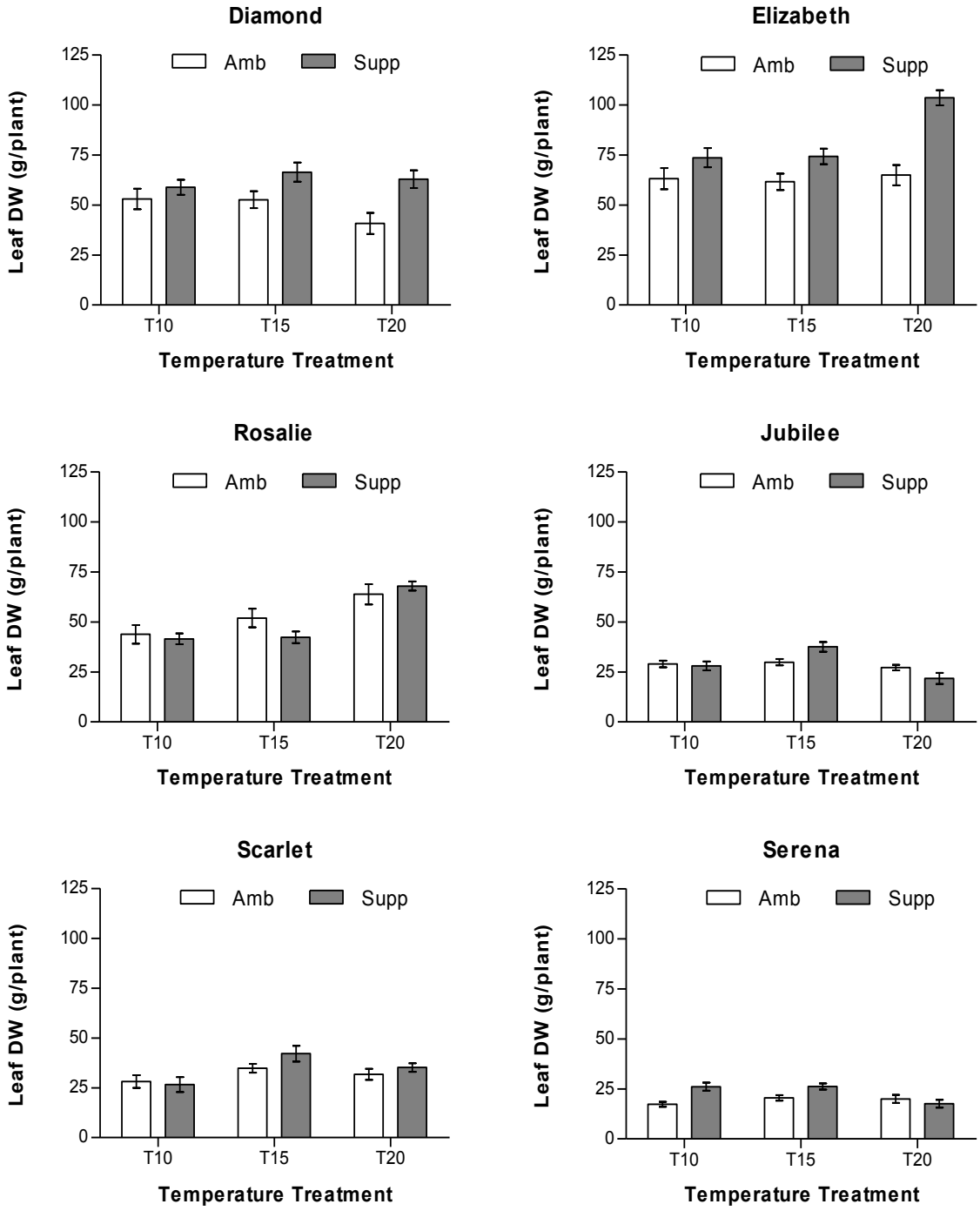

Figure 6.26 Effect of the light and temperature treatments on leaf dry weight for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=6). DW=dry weight. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

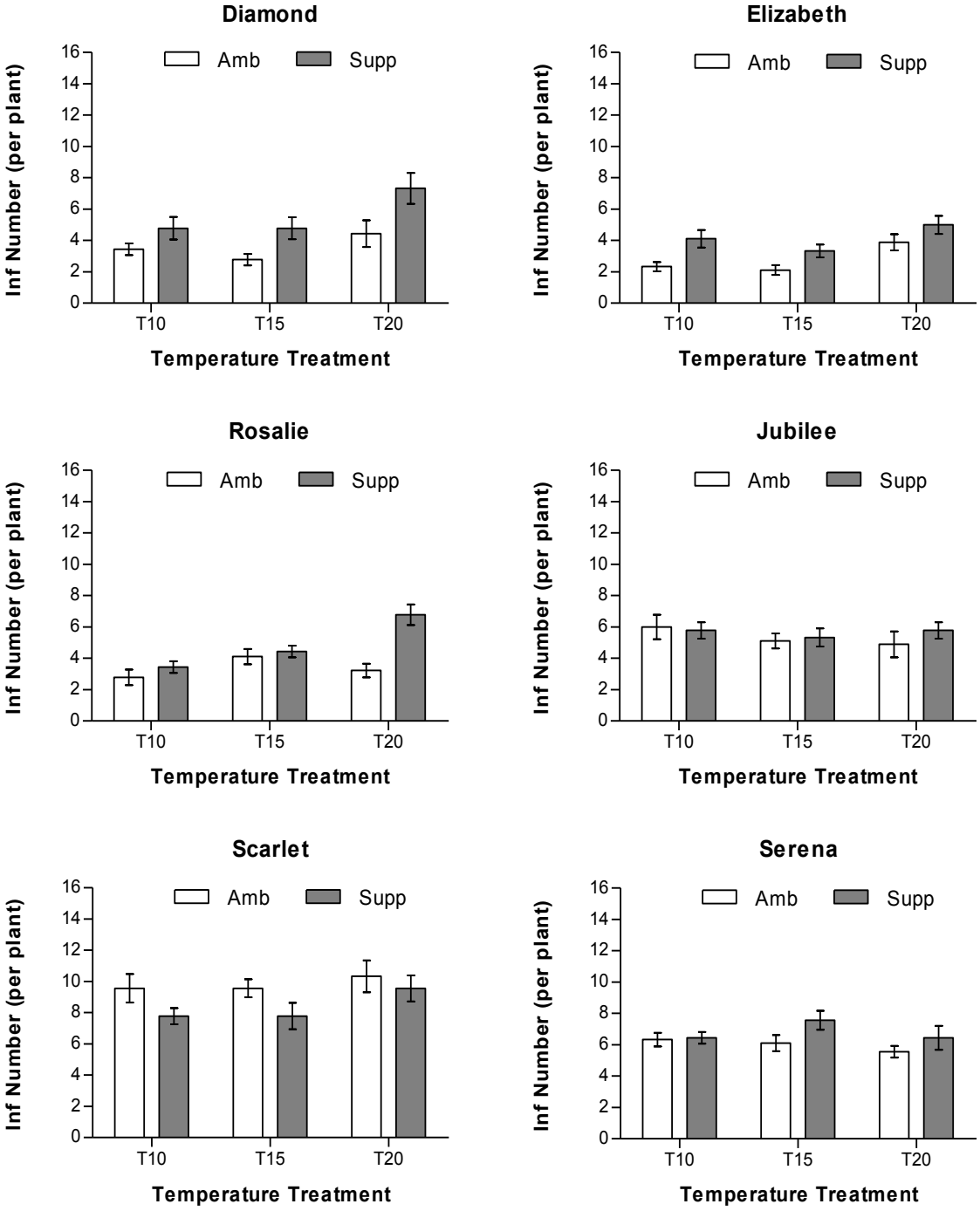

Figure 6.27 Effect of the light and temperature treatments on inflorescence number for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=6). Inf= inflorescence. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

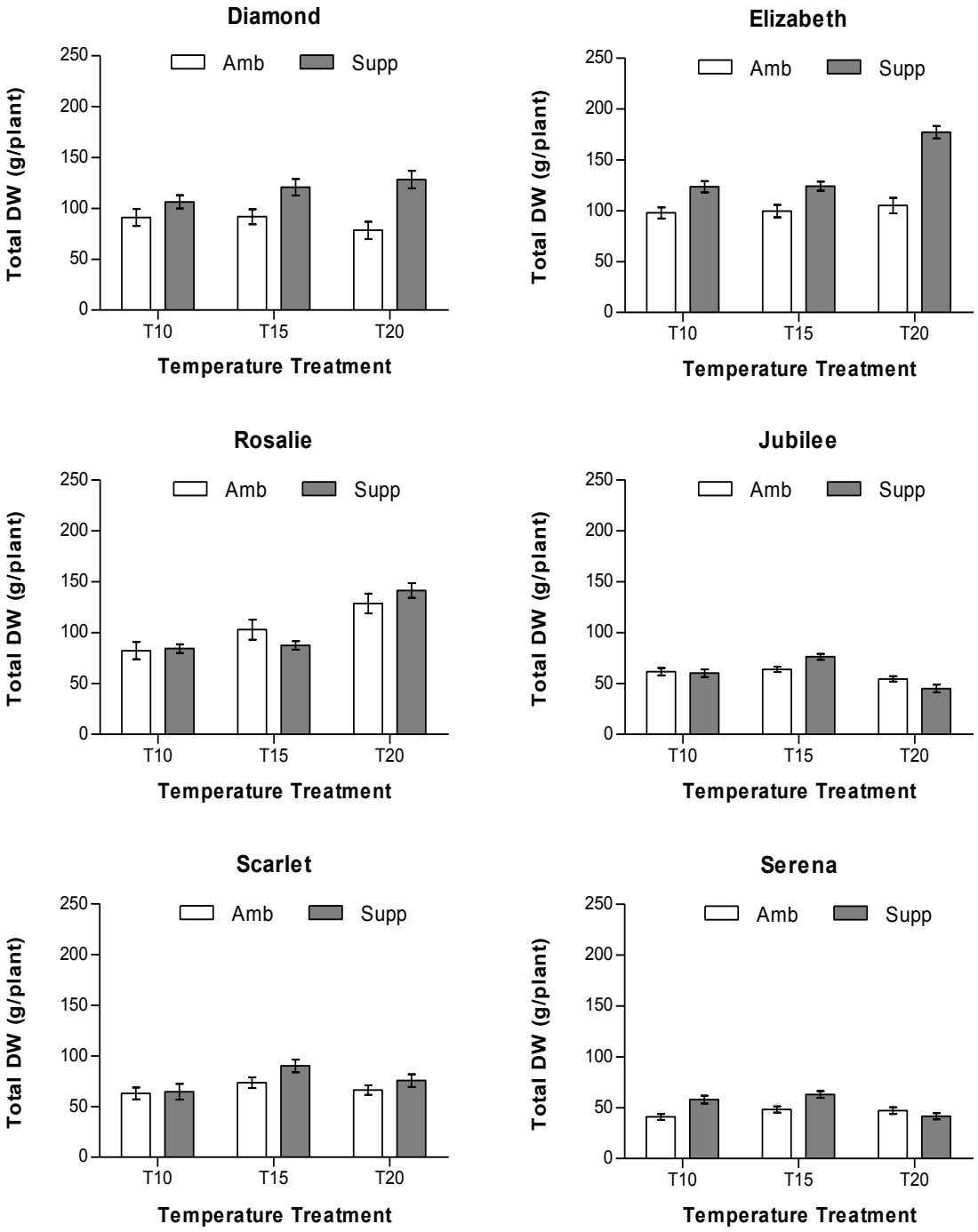

Figure 6.28 Effect of the light and temperature treatments on total plant dry weight for cultivars Diamond, Elizabeth, Rosalie, Jubilee, Scarlet and Serena (n=6). DW=dry weight. The vertical line on each bar shows ±S.E.M. Light treatments were ambient light levels (AMB) and 8-hrs supplementary lighting (SUPP) and temperature treatments were minimum 10°C (T10), minimum 15°C (T15) and minimum 20°C (T20).

6.4 Discussion

The experiment was designed to examine the impact of supplementary lighting and increased temperature during the propagation phase on transplant growth, yield potential and cropping performance of three Junebearer and three Everbearer strawberry cultivars currently cropped in the UK.

In general, supplementary lighting had a positive effect on marketable yield, with the yield of Diamond, Elizabeth, Rosalie and Jubilee significantly greater in the plants propagated under supplementary lighting, although there were no significant differences for Scarlet and Serena. Increased temperature also had a positive effect on marketable fruit yield of Diamond, Elizabeth, Rosalie, Scarlet and Serena (up to 21°C) and Jubilee (up to 16°C).

The two main yield components of strawberry are berry number and berry weight; in this experiment yield increased primarily due to an increase in berry number, rather than berry weight. Supplementary lighting increased marketable berry number on average 29%, or 8.8 berries / plant when compared to plants propagated under ambient light levels. Increased temperature (13 to 21°C) also improved marketable berry number by 36% or 10.3 berries / plant. There can be an antagonistic relationship between berry number and berry weight with berry weight declining as the number of berries increases (Sønsteby et al. 2013). The results of this experiment found average marketable berry weight was greater in plants produced at the ambient light level, and even more so when combined with a low temperature. Plants propagated under high light intensity and high temperature therefore produced a greater number of berries per plant but of a smaller size than those under ambient light levels and a low temperature; un-marketable yield was also greater in these plants (presumably due to more smaller berries being graded out) but the reduction in berry weight and increase in un-marketable yield were not great enough to override the significant yield improvement obtained from the increase in berry number.

Berry number is influenced by inflorescence number, the number of flowers per inflorescence and the total number of the flowers that set fruit. Durner et al. (2015) showed that conditions during the autumn can impact upon both inflorescence number and the number of flowers per inflorescence. In this experiment, only data on the number of inflorescences per plant was collected; the results showed that for the Junebearer cultivars the inflorescence number was, on average, 1.7 per plant greater in plants propagated under supplementary lighting and high

temperature, whereas there were no significant differences in inflorescence number between treatments for the Everbearer cultivars. However, total berry number (marketable and un-marketable) increased in both plant types by 54% (12.5 berries / plant) and 20% (8.3 berries / plant) for the Junebearers and Everbearers respectively, suggesting a positive effect on both the number of inflorescences and flowers per inflorescence.

Berry weight varies depending on the position of the flower within the inflorescence, but crop load (competition), the rate of pollination and plant vigour can also impact upon berry size (Janick & Eggert 1968; Webb et al. 1974; Hansen 1989). In this experiment, average berry weight declined in the plants propagated under the high light intensity particularly when coupled with a high temperature, these plants also produced the greatest number of berries and so average berry weight may have been reduced because of a higher crop load and competition between berries for assimilates (Sønsteby et al. 2013), a greater production of lower order berries (Le Miere et al. 1998), or a combination of these two factors.

Propagation of plants under high intensity lighting improved the marketable yield for four of the six cultivars studied this experiment, primarily due to an increase in berry number per plant. This supports the findings of previous work carried out at the University of Reading where flower number and berry number were greater in plants propagated under higher light levels (Professor Paul Hadley, *pers. comm.*). In the experiment described here only one Everbearer (Jubilee) showed a significant increase in yield with supplementary lighting, this may be due to the short photoperiod which is not suitable for optimal initiation in Everbearer types at the temperature range studied (13-21°C). It could also be due to increase in flower emergence during the propagation phase in Scarlet and Serena produced under supplementary lighting, as removal of flowers at this time would have reduced yield potential.

Overall an increase in temperature during the propagation phase benefited strawberry fruit yield; marketable yield for all six cultivars was greatest in plants propagated at a mean temperature of 21°C except for Jubilee (16°C). The results of this experiment agree with previous findings which has shown improvements in flowering with an increase in autumn temperatures (Le Miere 1997; Sønsteby & Heide 2008). A further increase in temperature is not likely to further improve yield as too high temperatures during strawberry propagation have led to vigorous vegetative growth at the expense of reproductive development. Manakasem & Goodwin (2001) for example, found

that the number for initiated apices increased with temperature up to an optimum of 18/13°C (day/night) but further increases in temperature (30/25°C) reduced this from 83% to 18%. Similarly, Verheul et al. (2006) showed that 100% of 'Korona' plants flowered when conditioned with short-days at 12°C, 15°C and 18°C but an increasing percentage of plants remained vegetative at 24°C and 30°C. Some studies have also shown that a greater number of short-day cycles are required for complete flower initiation when the temperature increases beyond 18°C (Sønsteby & Nes 1998; Verheul et al. 2007; Durner 2015). The photoperiod in the experiment described here was below 8-hrs, and treatments ran for 49 days perhaps explaining why a negative effect on fruiting was not found in the high temperature treatment (21°C).

The results of this experiment differed to those previously conducted at the University of Reading where yield and berry number of two Everbearer cultivars were greater in plants propagated at low temperature (5°C), this was due to a greater number of flowers being expressed during the propagation phase in the higher temperature treatments leading to a loss in yield potential (Professor Paul Hadley, *pers. comm.*). In the experiment described here, there was no significant difference in flower emergence between temperature treatments for the Junebearer cultivars, and although a greater number of flowers were expressed in the high temperature treatment for the Everbearers, the total number of flowers expressed were fewer (maximum of 6 flowers / plant) compared to that in the previous study with a maximum 20 flowers / plant (Professor Paul Hadley, *pers. comm.*) In the previous study, the temperature treatments continued through to spring planting, whereas in the experiment described here, treatments ceased on 1st December and all plants were placed in cool temperatures (2/5°C heating/venting). By placing the plants in dormancy inducing conditions immediately after the cessation of the treatments, fewer flowers were expressed across all treatments, allowing for yield potential to be retained by ensuring flowers were not expressed during the propagation phase. The timing of flowering is very important for commercial fruit production; early emergence of flowers is undesirable whether it be during the propagation phase itself when flowers are removed by nurserymen or very early in the spring when there is still a risk of frost damage, resulting in a loss in yield potential. Results of this experiment show that the number of flower initials in the crown can be increased by propagating plants under high intensity lighting coupled with high

temperature but, to retain the flowers within the crown dormancy needs to be induced after application of these conditioning treatments.

In this experiment, crown size (crown number, diameter and dry weight), canopy size (leaf number, area and dry weight) and total plant weight were greater in plants propagated under supplementary lighting and under higher temperatures. Crown size is considered one of the most important factors in determining quality of strawberry transplants with larger crowns increasing the number of sites for floral initiation (Abbott 1968), but other factors including canopy size and plant weight are also important indicators of transplant quality as plant vigour is important for providing energy during the flowering process. Previous studies have found positive correlation between these different parameters of strawberry transplants and yield performance (Darrow 1966; Hughes 1967; Lacey 1973; Faby 1997; Le Miere et al. 1998; Bussell et al. 2003; Johnson et al. 2005; Takeda & Newell 2006; Bartczak et al. 2010; Cocco et al. 2010; Fridiaa et al. 2016). The increase in yield may therefore be a positive function of transplant size and vigour leading to greater floral development during the autumn.

Transplant size was improved in all cultivars, but yield increases were greater in the Junebearers compared to the Everbearers. When comparing marketable yield from Treatments B (ambient light, mean temperature 13°C) and Treatment E (8-hrs supplemented light, mean temperature 21°C) which represent the opposite ends of the six treatments applied in this experiment, average marketable yield increased 136% (572 g / plant) in the Junebearers and 41% (233 g / plant) in the Everbearers. There was also a stronger effect of the treatments on berry number in the Junebearers which increased on average of 141% (23 berries / plant) compared to the Everbearers which increased by 48% (17 berries / plant). This suggests a greater impact on flower initiation in the Junebearers compared the Everbearers which may be due to the differences in the photoperiod and temperature requirements between the two plant types. In general flower initiation in Junebearers is intensified in shorter day-lengths at an intermediate temperature range (15-24°C) whilst flower initiation is intensified at longer photoperiods in Everbearers (Ito & Saito 1962; Verheul et al. 2006; Sønsteby & Heide 2007; 2007; 2008; Durner 2015; 2016). Day-length during the treatment period was short (no more than 8-hrs) and well below the critical photoperiod for floral induction in Junebearer strawberries with the mean temperature 13- 21°C depending on the treatment. Conditions were therefore more appropriate for intensifying flower

initiation in the Junebearers than the Everbearers perhaps explaining why there was a greater effect on berry number and yield in the Junebearer cultivars.

The light and temperature treatments also appeared to influence cropping profiles. In general, marketable yield was greater during early cropping for plants propagated with supplemented light levels and at a higher temperature, thereafter differences between light treatments declined and were not significant. The largest transplants were produced with high light intensity and high temperature, and these plants also produced the heaviest yield early in the season. All plants were chilled for the same duration, under the same temperature conditions from 1st December until planting on 25th March; during chilling resources are drawn from the leaves into the crown and stored over winter ready to be utilised once dormancy breaks and growth resumes in the spring. Plants propagated under supplementary lighting and high temperature were more vigorous and so may have produced a greater store of reserves leading to increased vigour in the spring giving the plants the ability to crop more heavily early in the season.

The environment during the propagation phase plays a key role in determining the quality of the transplants received by the fruit growers. Overall, the results of the experiment described here clearly show the potential to improve the marketable fruit yield of both Junebearer and Everbearer strawberries by using high intensity supplementary lighting and increased temperature during the propagation phase, stimulating greater vegetative growth and reproductive development. Plants under these conditions produced the largest transplants in terms of crown size, canopy size and plant weight and subsequently produced the greatest marketable fruit yield.

Chapter 7

Influence of supplementary lighting during the propagation phase on cropping performance of four Junebearer strawberry cultivars.

7.1 Introduction

To maximise the yield of strawberry the number of marketable berries per plant and the average berry weight need to be optimised. For Junebearer strawberries, flowers are initiated under the short days and cool temperatures of autumn and this continues until temperatures are too low and the plants become dormant. Although strawberries are perennial plants, commercial strawberry production is increasingly moving toward an annual production cycle with new transplants purchased from specialist propagators each year. Since flower initiation takes place in the autumn prior to fruiting, Junebearer transplants are already "pre-programmed" with all the flower initials present inside the crown when the growers receive them. The conditions in which the strawberry transplants are produced is therefore very important in determining the yield potential.

There are many conditions which influence the growth of strawberry transplants and their rate of flower initiation, but photoperiod and temperature are regarded as the most important factors (Ito & Saito 1962). Junebearer strawberry plants are described as quantitative short-day plants, but the exact photo-thermic requirements for floral initiation are cultivar specific. In general a photoperiod of <15-hrs at an intermediate temperature range (15-24°C) is required (Ito & Saito 1962; Sønsteby & Heide 2006; Verheul et al. 2006; 2007; 2007; 2008; Durner 2015; 2016). However, light intensity also impacts upon floral initiation, in previous studies at the University of Reading flower number was found to be greater in Everbearer strawberries propagated under supplemented light levels compared to ambient conditions (Professor Paul Hadley, *pers*. comm.) and Dennis et al. (1970) found inflorescence number of Everbearer strawberries was greater when light intensity was increased from 220 to 430 µmol m^{-2} s^{-1}.

Demirsoy et al. (2007) showed that when plants were shaded during flower initiation, fruit size and yield were lower in the following fruiting season. Awang & Atherton (1995) also found a

negative effect of reduced light on vegetative growth and floral development in strawberry, with a reduction in the number of leaves, crowns, inflorescences and flowers per inflorescence in plants shaded to reduce the daily light integral from 4.9 to 2.1 MJ m^{-2} day^{-1} which also led to a reduction in the dry weight of the berries and fruit yield. Similarly, Chabot (1978) found reproductive development was supressed in low light environments with a reduction in biomass allocation to flowering in the wild strawberry species *Fragaria vesca*.

The yield potential of strawberry has been closely linked to the vegetative status of transplants, and positive relationships between early and total yield and crown number, crown diameter, leaf number, leaf area and plant weight have been previously established (Hughes 1967; Abbott 1968; Lacey 1973; Faby 1997; Le Miere et al. 1998; Human 1999; Bussell et al. 2003; Johnson et al. 2005; Takeda & Newell 2006; Bartczak et al. 2010; Cocco et al. 2010; Fridiaa et al. 2016). Increased light intensity may therefore also have a positive impact upon floral initiation through effects on vegetative plant growth, and the number of sites for floral initiation. However, since vegetative growth and reproductive growth occur simultaneously in strawberry, it is important to prevent the plants becoming too vigorous at the expense of reproductive development. Smeets & Kronenberg (1955), for example found a greater number of runners were produced in the autumn under higher light levels which is not desirable as runner production can have a detrimental impact on flower initiation by reducing the development of branch crowns and the number of inflorescences. Chabot (1978) also found increased runner production in high light environments, and the production of larger thicker leaves for the wild strawberry species *Fragaria vesca*.

Overall, the environmental conditions in which strawberries are propagated is important in determining the quality of the transplants the fruit growers receive. Results of the previous experiment (see Chapter 6) showed that inflorescence number, berry number and yield were significantly greater in plants propagated with supplementary lighting compared to those under ambient conditions. There is potential to further improve the yield potential of strawberry transplants by extending the period of supplementary lighting during the propagation phase to stimulate greater vegetative and reproductive growth. To determine whether further yield benefits could be obtained, an experiment was designed to examine the impact of the duration of supplementary lighting during the propagation phase on transplant growth, yield potential and subsequent cropping performance of four Junebearer strawberry cultivars.

7.2 Materials and Methods

7.2.1 Propagation Phase

Plant Material and Experimental Treatments

Fresh tray plants of four Junebearer strawberry cultivars were delivered to the University of Reading between 26th and 29th September 2015. Malling Centenary was supplied by Berry Plants Ltd whilst Lusa, Elizabeth and Rosalie were supplied by EU Plants Ltd. Upon arrival, plants were re-potted into 90 x 87 mm (diameter x depth) coir filled pots and transferred to six temperature-controlled glasshouse compartments (45 plants per cultivar per compartment). The compartments were as described in Chapter 2 and set up to provide six experimental treatments; a combination of 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) supplementary lighting supplied for 21, 42 or 63 days. Supplementary lighting was described as in Chapter 2.

Plants were grown under ambient light levels from transfer to glasshouse compartments; light treatments were initiated on 1st October, 22nd October and 12th November 2015 and ended on 3rd December giving 63, 42 or 21 days of supplementary lighting respectively. Temperature set points in all compartments were 12/18°C (heating/venting) from the transfer of the plants into the compartments until the 3rd of December when this was reduced to 2/5°C for chilling. Treatment combinations were coded A to F and are summarised in Table 7.1. The cultivar Lusa was removed from the glasshouse compartments on 5th December 2015 and cold stored at 2°C until planting in the glasshouse on 8th January 2016. The remaining cultivars were chilled in the glasshouse until planting in the polytunnel on 25th March 2016.

Temperatures were logged in each compartment every hour, the average 24-hr temperature calculated at the end of the treatment period (prior to chilling) was 15.8°C, 15.1°C, 14.9°C, 15.8°C and 15.3°C for treatments A-D and F respectively. The data from the logger in Treatment E could not be retrieved. Manually logged daily minimum and maximum temperatures in each compartment are recorded by the glasshouse staff at the University of Reading as a matter of routine; visual inspection of these records did not reveal any unusual temperature differences for Treatment E.

Table 7.1 Summary of the six experimental treatments (A to F) applied to four Junebearer strawberry cultivars: Lusa, Malling Centenary, Rosalie and Elizabeth. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days.

Treatment Code	Hours of Lighting (hrs / day)	Days of Lighting (days)
A	8	63
B	8	42
C	8	21
D	12	21
E	12	42
F	12	63

Propagation Phase Measurements

Ten randomly selected plants of each cultivar in each treatment were tagged upon transfer to the glasshouse compartments. Runners and open flowers were routinely removed on all plants and the number removed on the tagged plants was recorded. At the end of the propagation phase a destructive harvest was carried out on the ten tagged plants and the following measurements made on each plant: crown number, crown diameter, leaf number, leaf area, root score and dry weight of the leaves, crowns, petioles and the removed flowers with a total plant dry weight calculated as the sum of the individual plant components. All measurements were taken using the methods described in Chapter 2.

7.2.2 Production Phase

Experimental Design

The cultivar Lusa was planted on 8th January 2016 in a large compartment of a multi-compartmented glasshouse (compartment 18), as described in Chapter 2. Three bags containing six plants were planted for each treatment giving a total of 18 plants per treatment. The remaining cultivars Malling Centenary, Rosalie and Elizabeth were cropped in a twin span tunnel at the Soft Fruit Technology Group's Field Site at the University of Reading's Sonning Farm.

The polytunnel was set up as described in Chapter 2. Four bags containing five plants were planted for each cultivar and treatment on 25th March 2016 giving a total of 20 plants per treatment per cultivar. In both productions, the experimental area was divided into three (glasshouse) or four (polytunnel) blocks each with one replicate (bag) in a randomised position. Guard bags were placed at the ends of each row to minimise edge effects.

Figure 7.1 and Figure 7.2 shows the layout of the blocks, cultivars and treatments for the glasshouse and polytunnel respectively. Temperature control, plant husbandry and fertigation were set up and carried out as described in Chapter 2.

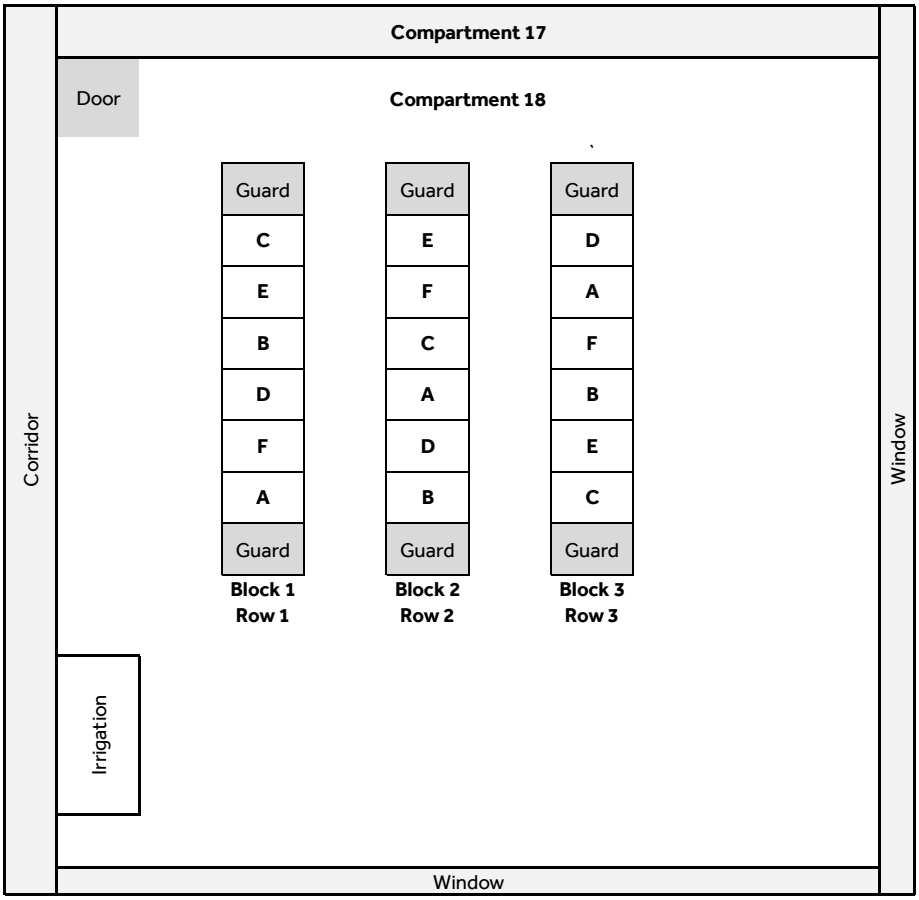

Figure 7.1 Arrangement of blocks and treatments for the production phase of the cultivar Lusa, cropped in Compartment 18 of a multi-compartmented glasshouse situated at the University of Reading's Crops and Environment Laboratory. Each box represents a 1 m substrate bag, each with six plants. Treatments were: 8-hrs / 63D (A), 8-hrs / 42D (B), 8-hrs / 21D (C), 12-hrs / 21D (D), 12-hrs / 42D (E) and 12-hrs / 63D (F).

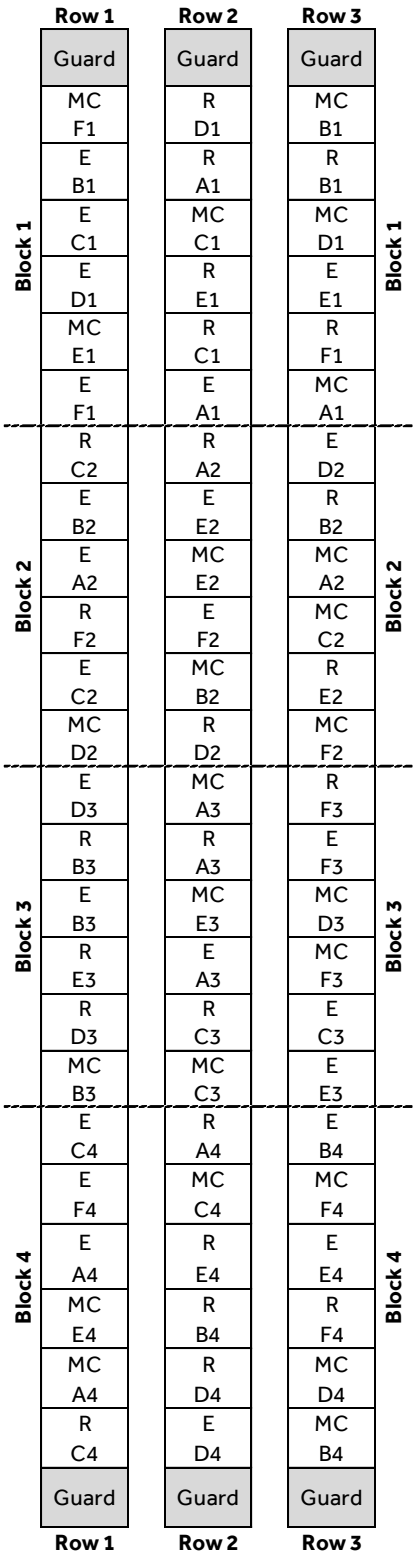

Figure 7.2 Arrangement of blocks, cultivars and treatments for the production phase of cultivars Malling Centenary (MC), Rosalie (R) and Elizabeth (E) cropped in a twin span polytunnel situated at the Soft Fruit Technology Group's Field Site in Sonning, Berkshire. Each box represents a 1 m substrate bag, each with five plants. Treatments were: 8-hrs / 63D (A), 8-hrs / 42D (B), 8-hrs / 21D (C), 12-hrs / 21D (D), 12-hrs / 42D (E) and 12-hrs / 63D (F).

7.2.2.1 *Production Phase Measurements*

Non-Destructive Measurements

On a weekly basis, the following data was collected for five randomly selected plants in each cultivar and treatment: leaf number, petiole length and the number of open flowers and developing fruits. Data was collected for 23 weeks in the glasshouse crop of Lusa (4th January to 6th June 2016) and for 16 weeks in the polytunnel production of Malling Centenary, Rosalie and Elizabeth (11th April to 25th July 2016). The first three new leaves to emerge from the crown were tagged and petiole length was measured every week until there was no change for three consecutive weeks or the leaf had started to senesce. Petiole length was measured from the top of the stipule to the base of the leaf blade using a 30 cm ruler. The total number of inflorescences per plant were counted, and the first three inflorescences to emerge were tagged and the number of flowers per inflorescence counted.

From 10th March 2016, light levels outside the polytunnel and glasshouse were logged every 10 seconds using a PAR sensor (QS5 PAR Quantum Sensor, Delta-T Devices, Cambridge, UK) connected to a data logger (GP1, Delta-T Devices, Cambridge, UK). For four weeks during cropping (1st July to 29th July) a second PAR sensor connected to a handheld logger (SpectroSense 2+, Skye Instruments, Llandrindod Wells, Powys) was used to record light levels at six positions within the canopy of each bag. Light levels were compared to the external light levels (to the nearest 10 seconds) and the percentage light intercepted calculated for each bag.

Cropping Performance

Total, marketable and un-marketable yield and berry number were recorded on a weekly basis. Average marketable berry weight and percentage Class 1 were calculated at the end of cropping. Data was collected at the bag level and converted to a per plant basis for analysis. All data was collected as described in Chapter 2.

Final Destructive Harvest

Two (polytunnel) or three (glasshouse) plants were selected from each bag for each cultivar and treatment combination at the end of cropping and the following measurements were made on each plant: crown number, leaf number, leaf area, inflorescence number and dry weights of the leaves, crowns, petioles and inflorescences with a total plant dry weight calculated as the sum of the individual components. All data was collected using the methods described in Chapter 2.

7.3 Results

7.3.1 Propagation Phase

7.3.1.1 *Open Flower Number*

Treatment effects on flower number for each cultivar are shown in Figure 7.3. Overall, there was a significant difference in flower number between cultivars (P<0.001), flower number of Malling Centenary (3.2±0.3 flowers / plant), Rosalie (3.0±0.4) or Elizabeth (2.8±0.4) was significantly greater than Lusa (0.9±0.2) (by 242%, 217% and 201% respectively). All other differences between cultivars was not significant.

Open flower number was significantly greater (P<0.001) in the 12-hr treatment compared to the 8-hr treatment for 42D and 63D (306% and 112% respectively) whereas there was no significant difference for 21D. Flower number generally increased as the number of days of lighting increased, in the 8-hr treatment there was no significant difference between 21D and 42D, whereas in the 12-hr treatment flower number was 222% greater in 42D compared to 21D. From 42D to 63D, flower number significantly increased in both the 8-hr and 12-hr treatments (by 136% and 23% respectively).

7.3.1.2 *Runner Number*

Figure 7.4 shows the number of runners per plant for each cultivar and treatment combination. The data is a mean of 10 plants, however, many of these produced zero runners. In general, runner number increased with the duration of supplementary lighting from 8-hrs to 12-hrs, and from 21D to 63D. However, overall the interaction between the cultivars and the number of days of lighting was significant (P=0.005); for Lusa runner number was significantly higher in 63D compared to 21D and 42D whereas for Elizabeth there were significantly more runners in 42D than any other treatment. No significant differences in runner number between treatments were found for Rosalie and Malling Centenary.

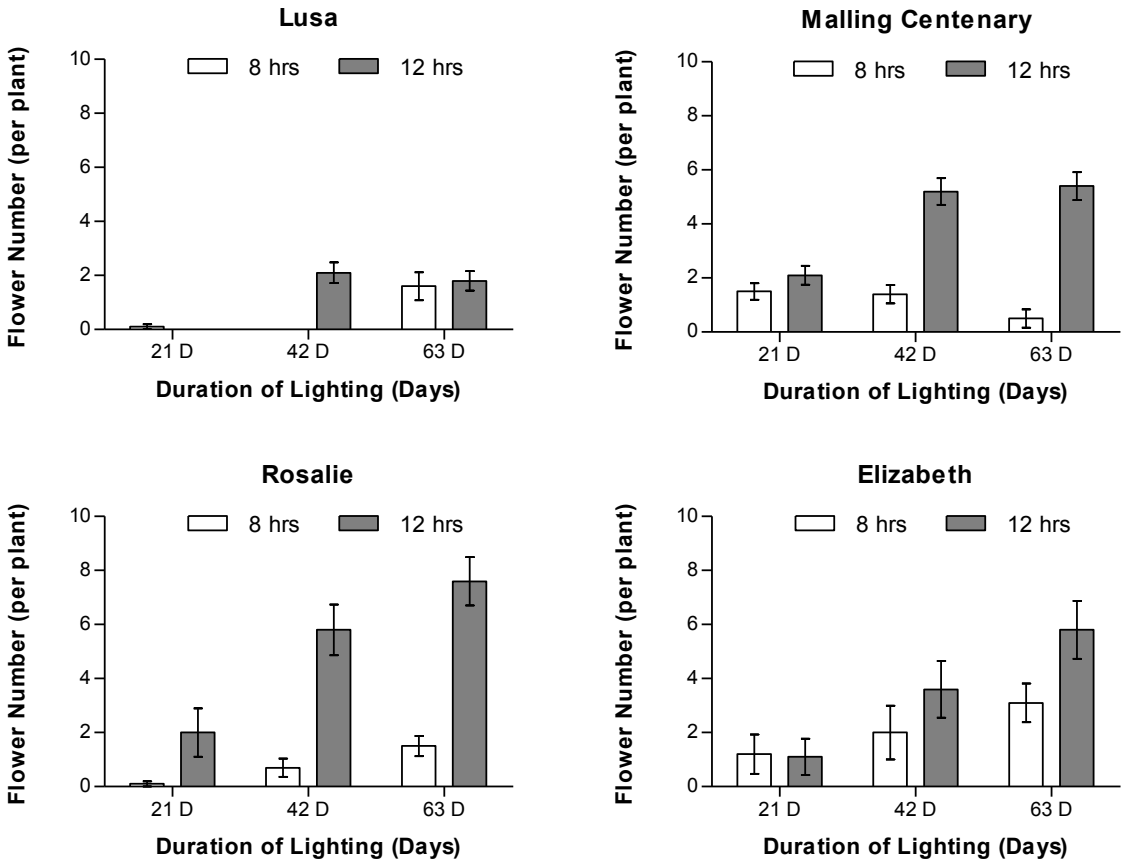

Figure 7.3 Treatment effects on the total number of open flowers per plant during the propagation phase for cultivars Lusa, Malling Centenary, Rosalie and Elizabeth (n=10). The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

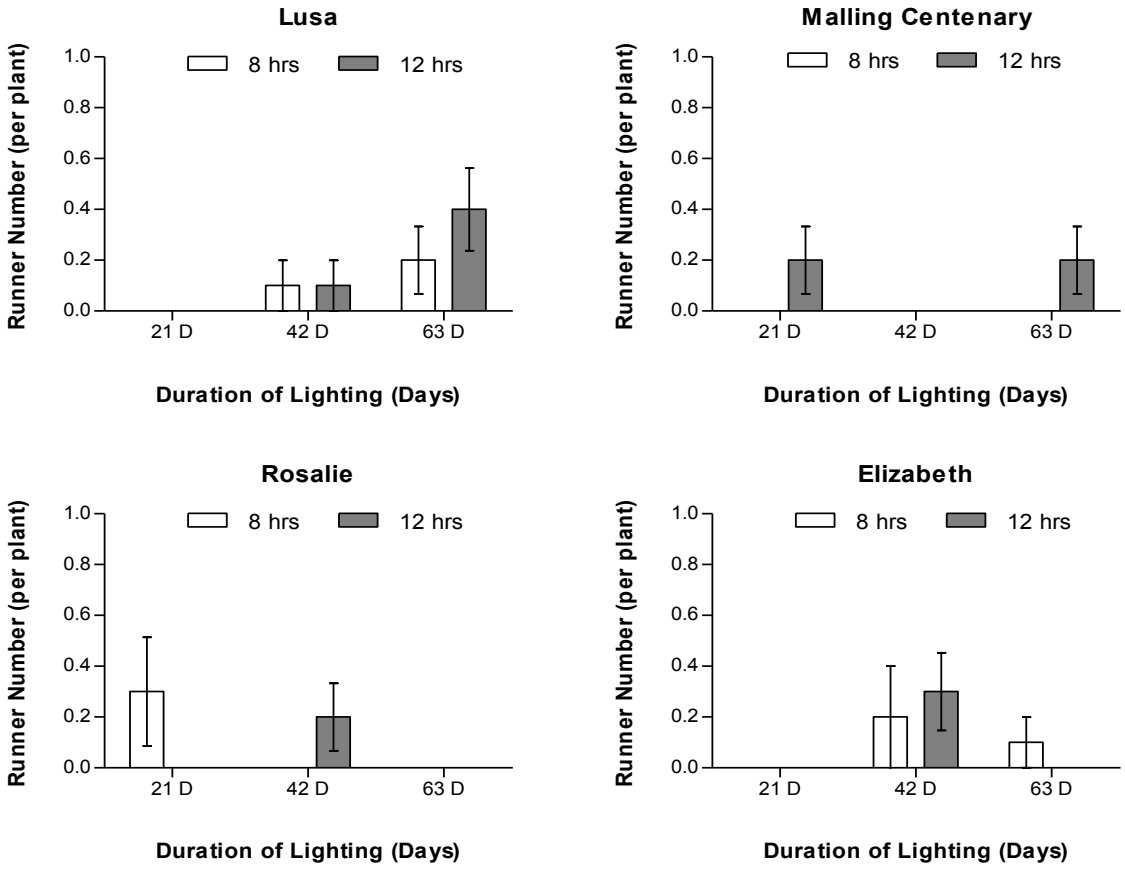

Figure 7.4 Treatment effects on the total number of runners per plant during the propagation phase for cultivars Lusa, Malling Centenary, Rosalie and Elizabeth (n=10). The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

7.3.1.3 *Destructive Harvest (DH1)*

A destructive harvest was carried out at the end of the propagation phase to examine treatment effects on transplant growth and yield potential. Figure 7.5 shows a representative plant for each cultivar and treatment; the photographs show by the end of the propagation phase that larger transplants (crown and canopy size) were produced with an increasing duration of supplementary lighting.

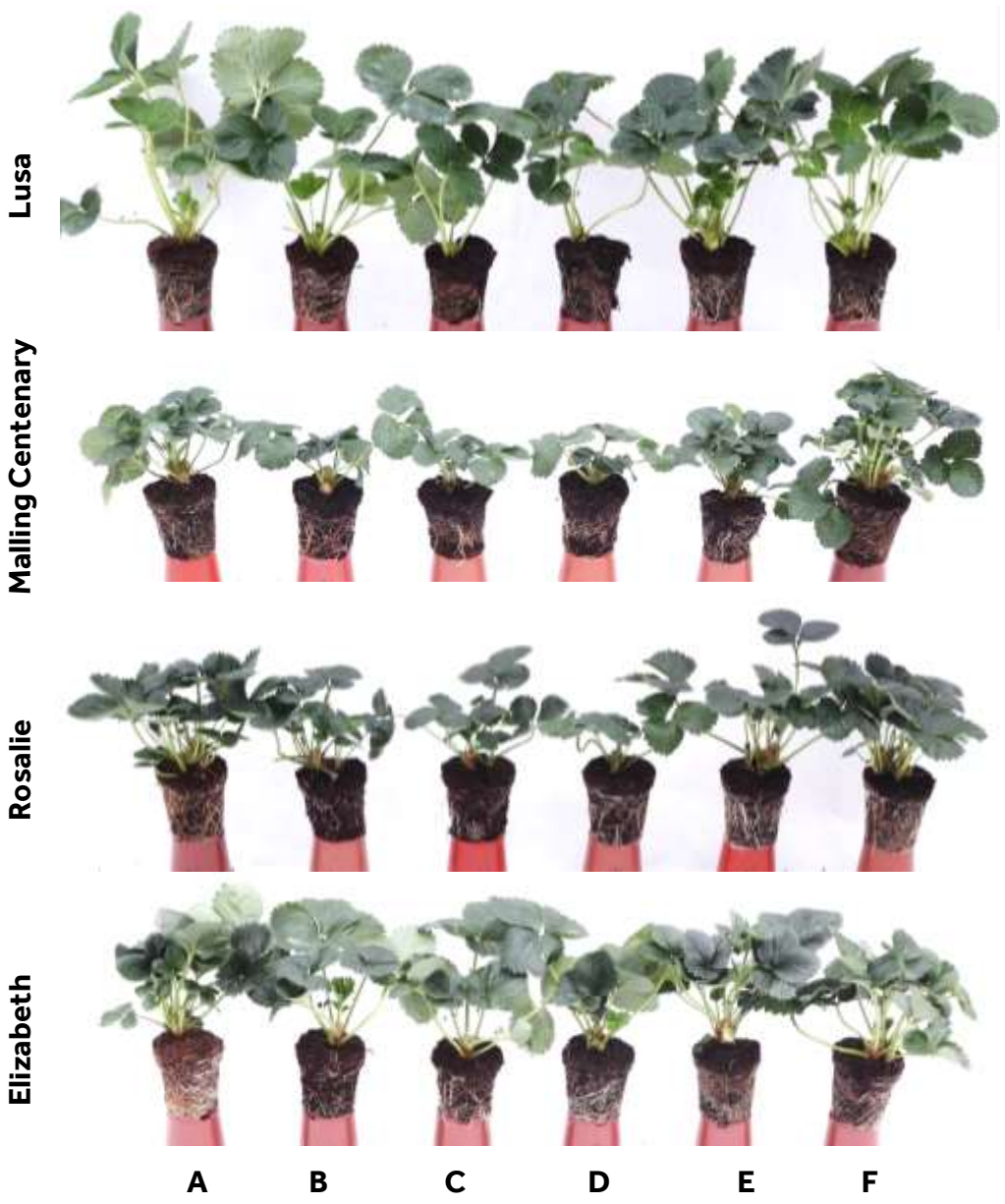

Figure 7.5 Photograph of Junebearer cultivars Lusa, Malling Centenary, Rosalie and Elizabeth. Representative plants of each cultivar from the six treatments (A-F) are shown. Treatments were: 8-hrs / 63D (A), 8-hrs / 42D (B), 8-hrs / 21D (C), 12-hrs / 21D (D), 12-hrs / 42D (E) and 12-hrs / 63D (F). Photographs were taken at the end of the treatment period (22nd November 2015).

Crown Number

For crown number, there were different responses to the treatments depending on the cultivar resulting in significant two and three-way interactions (Table 7.3). Overall, Elizabeth had the greatest number of crowns (4.9±0.3 crowns / plant), significantly (P<0.001) greater than Rosalie (3.7±0.2), Lusa (3.6±0.2) and Malling Centenary (3.2±0.2).

There was a significant interaction between the light treatments (P=0.020); this showed that although crown number was greater in the 12-hr treatment compared to the 8-hr treatment overall, the extent depended on the duration of supplementary lighting (39%, 64% and 35% for 21D, 42D and 63D respectively). The differences between the 8-hr and 12-hr treatments were also greater for Malling Centenary and Elizabeth (66% and 67% respectively) compared to Lusa and Rosalie (28% and 24%) resulting in the significant three-way interaction (P=0.010). The response to the number of days of lighting also differed for the 8-hr and 12-hr treatments; crown number significantly increased from 21D to 42D in both the 8-hr and 12-hr treatments (29% and 53% respectively) whereas from 42D to 63D crown number increased significantly in the 8-hr treatment only (23%).

Crown Diameter

Treatment effects on crown diameter for each cultivar is shown in Table 7.3. Crown diameter was significantly (P<0.001) greater in Rosalie (2.3±0.07 cm) compared to Elizabeth (1.9±0.06), Malling Centenary (1.8±0.04) and Lusa (1.7±0.03). Crown diameter of Elizabeth was also greater than Lusa, and all other differences between cultivars were not significant.

There was no significant interaction between the treatments, but there was a significant interaction between the cultivars and number of hours of lighting (P<0.001) such that crown diameter was significantly higher in the 12-hr treatment for Malling Centenary, Rosalie and Elizabeth (14%, 24% and 30% respectively) whereas there was no significant difference for Lusa. There was no significant interaction between the cultivars and the number of days lighting, but the main effect of the number of days of lighting was significant (P<0.001); crown diameter significantly increased from 21D (1.68±0.03 cm) to 42D (1.93±0.05), and from 42D to 63D (2.17±0.05).

Crown Dry Weight

Treatment effects on crown dry weight for each cultivar is shown in Table 7.3. Only the main effects of the cultivars and treatments were significant (P<0.001). Overall, Rosalie had the greatest crown dry weight (2.45±0.11 g / plant), significantly greater than Elizabeth (2.05±0.11), Lusa (1.60±0.07) and Malling Centenary (1.50±0.09). Crown dry weight of Elizabeth was also significantly greater than Lusa and Malling Centenary and all other differences between cultivars were not significant.

There was no significant interaction between the light treatments, but the main effects of both treatments were significant (P<0.001) with crown dry weight was significantly greater in the 12-hr treatment (2.16±0.08 g / plant) compared to the 8-hr treatment (1.64±0.06), and significantly greater in 63D (2.27±0.09) compared 42D (1.99±0.09) and 21D (1.44±0.07 g / plant).

Leaf Number

Treatment effects on leaf number for each cultivar are shown in Table 7.3. Overall, Rosalie had the greatest number of leaves per plant (16.6±0.7 leaves / plant), significantly (P<0.001) greater than Elizabeth (13.9±0.7), Lusa (12.2±0.5) and Malling Centenary (11.5±0.5). Leaf number of Elizabeth was also greater than Lusa and Malling Centenary and all other differences between cultivars were not significant.

There was only a significant interaction between the light treatments (P=0.005); leaf number increased as the number of days of lighting increased from 21D to 63D in both the 8-hr and 12-hr treatments, but more so in the 12-hr treatment (58%) than the 8-hr treatment (47%). Leaf number was significantly greater in the 12-hr treatment compared to the 8-hr treatment, but the extent varied depending on the duration of supplementary lighting (25%, 53% and 35% for 21D, 42D and 63D respectively).

Leaf Area

For leaf area, there were different responses to the treatments depending on the cultivar resulting in significant two and three-way interactions (Table 7.3). Overall, Lusa had the greatest leaf area (853.7±43.5 cm^2 / plant), significantly (P<0.001) greater than Elizabeth (650.0±32.8), Rosalie (392.1±19.6) and Malling Centenary (381.0±20.4). Leaf area of Elizabeth was also greater than Rosalie and Malling Centenary and all other differences between cultivars were not significant.

There was a significant interaction between the light treatments (P=0.017) which showed that leaf area was significantly higher in the 12-hr treatment compared to the 8-hr treatment for 42D and 63D (by 42% and 15% respectively) but not 21D. However, there was also a significant three-way interaction (P=0.007) as for Elizabeth, unlike the remaining cultivars, leaf area was lower in the 12-hrs treatment than the 8-hr treatment in 63D. Leaf area generally increased as the number of days of lighting increased. However, the interaction between the light treatments showed that from 21D to 42D leaf area increased in both the 8-hr and 12-hr treatment (28% and 58% respectively), but from 42D to 63D leaf area increased significantly in the 8-hr treatment only (22%).

Leaf Dry Weight

Leaf dry weight presented similar results to that of leaf area, with significant two and three-way interactions (Table 7.3). Overall, Lusa had the greatest leaf dry weight (6.46±0.30 g / plant), significantly (P<0.001) greater than Rosalie (4.79±0.23) and Malling Centenary (4.08±0.22) but did not differ significantly from Elizabeth (6.07±0.31).

There was a significant interaction between the light treatments (P=0.032) which showed that leaf dry weight was significantly higher in the 12-hr treatment compared to the 8-hr treatment for 42D (by 38%) but there were no significant differences for 21D or 63D. However, there was also a significant three-way interaction (P=0.004) as for Elizabeth, unlike the remaining cultivars, leaf dry weight was also lower in the 12-hr treatment than the 8-hr treatment in 63D. Leaf dry weight generally increased as the number of days of lighting increased. However, the interaction between the light treatments showed that from 21D to 42D leaf dry weight increased in both the 8-hr and 12-hr treatment (29% and 54% respectively), but from 42D to 63D leaf dry weight increased significantly in the 8-hr treatment only (20%).

Root Score

For root score, there were different responses to the treatments depending on the cultivar resulting in significant two and three-way interactions (Table 7.3). Overall, root score was significantly ($P<0.001$) greater in Elizabeth (7.7±0.1) compared to Rosalie (7.1±0.1), Malling Centenary (6.7±0.2) and Lusa (5.8±0.2).

Root score was generally higher in the 12-hr treatment compared to the 8-hr treatment, but this was only significant for Malling Centenary and Rosalie (27% and 7% respectively). There was no significant difference in root score between 21D and 42D for any cultivar, but from 42D to 63D root score significantly increased for Rosalie (by 15%) but declined for Lusa (by 7%) and there was no significant difference for Elizabeth and Malling Centenary.

Total Dry Weight

Total dry weight presented similar results to that of leaf dry weight, with significant two and three-way interactions (Table 7.3). Overall, total dry weight was significantly ($P<0.001$) greater in Lusa (10.11±0.47 g / plant) compared to Rosalie (8.85±0.40) and Malling Centenary (6.72±0.37) but did not differ significantly from Elizabeth (9.31±0.48).

There was a significant interaction between the light treatments ($P=0.015$) which showed that total dry weight was significantly higher in the 12-hr treatment compared to the 8-hr treatment for 42D and 63D (by 41% and 15% respectively) whilst there was no significant difference in 21D. However, there was also a significant three-way interaction ($P=0.006$) as for Elizabeth, total dry weight was also lower in the 12-hr treatment than the 8-hr treatment in 63D. Total dry weight generally increased as the number of days of lighting increased. However, the interaction between the light treatments showed that from 21D to 42D leaf dry weight increased in both the 8-hr and 12-hr treatment (by 32% and 50% respectively), but from 42D to 63D leaf dry weight increased significantly in the 8-hr treatment only (21%).

Table 7.2 Treatment effects on DH1 results for cultivars Lusa, Malling Centenary, Rosalie and Elizabeth (n=10). Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D). Data shown is crown number (CN), crown diameter (CD), crown dry weight (CDW), leaf number (LN), leaf area (LA), leaf dry weight (LDW), root score (RS) and total dry weight (TDW). Data is presented on a per plant basis. P. Values for the main effects and interactions are shown.

Cultivar	Hours	Days	CN	CD (cm)	CDW (g)	LN	LA (cm^2)	LDW (g)	RS	TDW (g)
Lusa	**8-hrs**	**21 D**	2.3	1.49	1.08	7.2	470.56	4.02	4.5	6.34
		42 D	3.4	1.72	1.70	10.7	722.80	5.96	6.3	9.67
		63 D	3.8	1.88	1.61	12.9	1071.63	7.90	6.5	12.33
	12-hrs	**21 D**	2.9	1.60	1.09	9.5	557.94	4.58	5.3	6.57
		42 D	4.5	1.79	1.96	15.7	1046.98	7.80	6.7	12.34
		63 D	4.8	1.96	2.14	17.0	1252.29	8.52	5.6	13.44
Elizabeth	**8-hrs**	**21 D**	2.0	1.61	1.29	9.1	512.88	4.33	7.0	6.46
		42 D	3.9	1.56	1.71	11.0	661.41	5.90	7.8	8.76
		63 D	5.0	1.75	2.20	12.5	728.18	7.03	8.8	10.74
	12-hrs	**21 D**	4.8	1.81	2.06	14.2	636.07	5.90	8.0	8.95
		42 D	7.4	2.14	2.69	18.5	831.48	8.08	7.6	12.54
		63 D	6.0	2.43	2.36	17.9	529.79	5.18	7.2	8.41
Malling	**8-hrs**	**21 D**	2.0	1.53	0.86	8.8	258.87	2.72	5.5	4.02
Centenary		**42 D**	2.0	1.55	1.08	8.4	297.77	3.14	6.0	5.07
		63 D	3.3	2.00	1.53	12.8	374.67	4.33	6.1	7.22
	12-hrs	**21 D**	2.3	1.67	1.21	8.6	261.84	2.92	7.2	4.80
		42 D	4.2	1.95	1.90	13.4	479.26	4.92	7.3	8.39
		63 D	5.6	2.16	2.42	17.0	613.31	6.45	7.8	10.79
Rosalie	**8-hrs**	**21 D**	3.2	1.64	1.90	12.7	306.45	3.74	6.7	6.75
		42 D	3.0	2.12	2.14	13.1	308.06	4.14	6.8	7.53
		63 D	3.8	2.33	2.56	17.4	391.67	4.80	7.1	8.94
	12-hrs	**21 D**	3.2	2.11	2.06	14.9	327.27	3.81	6.8	6.97
		42 D	4.1	2.59	2.70	18.6	459.14	5.62	6.8	10.45
		63 D	5.1	2.86	3.34	22.9	560.14	6.65	8.5	12.48
P. Value										
Cultivar			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Hours			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Days			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
C x H			<0.001	<0.001	0.204	0.095	0.060	0.667	<0.001	0.428
C x D			0.007	0.075	0.365	0.054	<0.001	0.001	0.001	0.002
H x D			0.020	0.241	0.172	0.005	0.017	0.032	0.039	0.015
C x H x D			0.010	0.398	0.177	0.873	0.007	0.004	<0.001	0.006

[Continued Overleaf]

LSD										

Cultivar		0.42	0.11	0.21	1.21	60.70	0.59	0.34	0.91
Hours		0.30	0.08	0.15	0.85	42.92	0.42	0.24	0.65
Days		0.37	0.10	0.18	1.05	52.57	0.51	0.30	0.79
C x H		0.60	0.16	0.30	1.71	85.85	0.83	0.48	1.29
C x D		0.73	0.19	0.37	2.09	105.14	1.02	0.59	1.58
H x D		0.52	0.14	0.26	1.48	74.35	0.72	0.42	1.12
C x H x D		1.04	0.27	0.52	2.96	148.69	1.44	0.84	2.24

Dry Weight Ratios

The dry weight ratio of the leaves (LDW), crowns (CDW), petioles (PDW) and flowers (FDW) are shown for each cultivar and treatment in Figure 7.6. Overall, there was a significant ($P<0.001$) difference between cultivars for all components. LDW was significantly lower in Malling Centenary (66%) and Rosalie (57%) compared to Lusa and Elizabeth (70% and 71% respectively). All differences in the CDW and PDW were significant ($P<0.001$) with CDW greatest in Rosalie (29%) followed by Malling Centenary, Elizabeth and Lusa (23%, 22% and 16%) and PDW greatest in Lusa (19%) followed by Rosalie, Malling Centenary and Elizabeth (16%, 13% and 12%). FDW was greatest in Lusa (4%) followed by Rosalie, Malling Centenary and Elizabeth (2%, 2% and 0% respectively).

Differences in the dry weight ratio between treatments overall were small, but there were some significant differences. LDW was significantly ($P<0.05$) higher in the 8-hr treatment compared to the 12-hr treatment (by 2%), and in 21D compared to 42D and 63D (by 4% each). CDW was significantly ($P<0.001$) higher in the 12-hr treatment for Elizabeth and Malling Centenary (by 5% and 2%) whilst there were no significant differences for Rosalie and Lusa. CDW was also significantly ($P=0.003$) higher in 63D compared to 42D and 21D for Elizabeth (by 4% and 3%) but there were no significant differences for the remaining cultivars. PDW was significantly ($P<0.001$) higher in the 8-hr treatment for Elizabeth and Lusa (by 2% each) whilst there were no significant differences for Rosalie or Malling Centenary. PDW was significantly ($P<0.001$) higher in 63D and 42D compared to 21D for Elizabeth (by 3% and 2%) and Malling Centenary (by 4% and 3%) whilst there was no significant difference for Rosalie or Lusa. FDW was significantly ($P=0.003$) higher in the 8-hr treatment for Rosalie, Elizabeth, Malling Centenary (by 3%, 1% and 1%) whilst there was no significant difference for Lusa. FDW was also significantly ($P<0.001$) higher in 63D and 42D compared to 21D (by 2% and 1%) and in 42D compared to 21D (by 1%) overall.

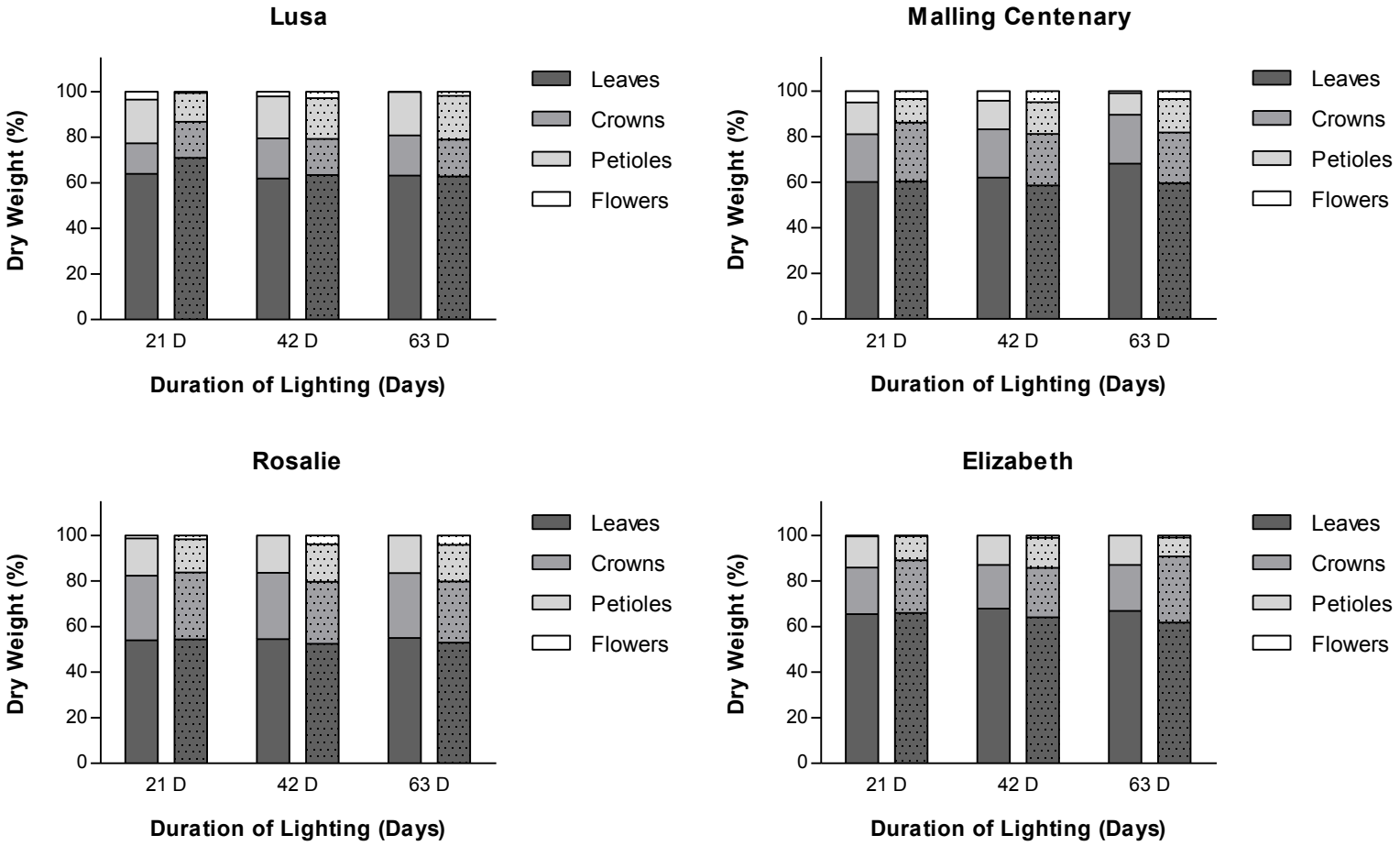

Figure 7.6 Treatment effects on the percentage contribution of the dry weight of the leaves, crowns, petioles and flowers to the total above ground plant dry weight for cultivars Lusa, Malling Centenary, Rosalie and Elizabeth (n=10). Flowers included open flowers collected as removed each week as well as any flower buds. Treatments were 8-hrs (08:00 to 16:00) (plain bars) or 12-hrs (07:00 to 19:00) (spotted bars) of supplementary lighting provided for 21, 42 or 63 days (D).

7.3.2 Production Phase

7.3.2.1 *Non-Destructive Measurements*

Leaf Number

Treatment effects on leaf number counted every week during the production phase are shown for each cultivar in Figure 7.7. In the glasshouse production of Lusa, leaf number was significantly greater in plants from the 12-hr treatment compared to the 8-hr treatment. Leaf number was, on average, 50% greater in the 12-hr treatment until the last two weeks where this increased to 72%. No significant effect of the number of days of lighting was found and there was no significant interaction between the treatments.

For the remaining cultivars in the polytunnel production, there was a significant difference in leaf number between cultivars throughout cropping ($P<0.001$, Figure 7.8A). Rosalie had the greatest leaf number per plant, significantly higher than Elizabeth and Malling Centenary in all weeks; there were no significant differences in leaf number between Malling Centenary and Elizabeth except on 6th and 13th June where leaf number was 16% and 18% greater in Malling Centenary respectively.

In general, leaf number was greater in the 12-hr treatment than the 8-hr treatment (Figure 7.8B) and in 63D compared to 42D and 21D (Figure 7.8C). However, there was significant interaction between the treatments every week except for the 11th and 18th July ($P<0.05$, Figure 7.8D). Where leaf number was significantly greater in the 12-hr treatment compared to the 8-hr treatment for 42D and 63D whilst there was no significant difference for 21D. Differences in leaf number declined with time; overall, in 42D, leaf number 31% was greater in the 12-hr treatment in first six weeks, but then 18% for the remainder of cropping. Similarly, in 63D, for the first nine weeks leaf number was 71% greater in the 12-hr treatment compared to the 8-hr treatment, and then this fell to 47%.

In the 8-hr treatment there were no significant differences in leaf number between 21D, 42D and 63D at any point; whereas in the 12-hr treatment, for the first nine weeks leaf number was greater in 63D and 42D compared to 21D (on average by 53% and 27% respectively) and in 63D compared to 42D (on average 20%). In the final six weeks, leaf number was greater in 63D compared to 21D (on average by 26%), with no other significant differences between treatments.

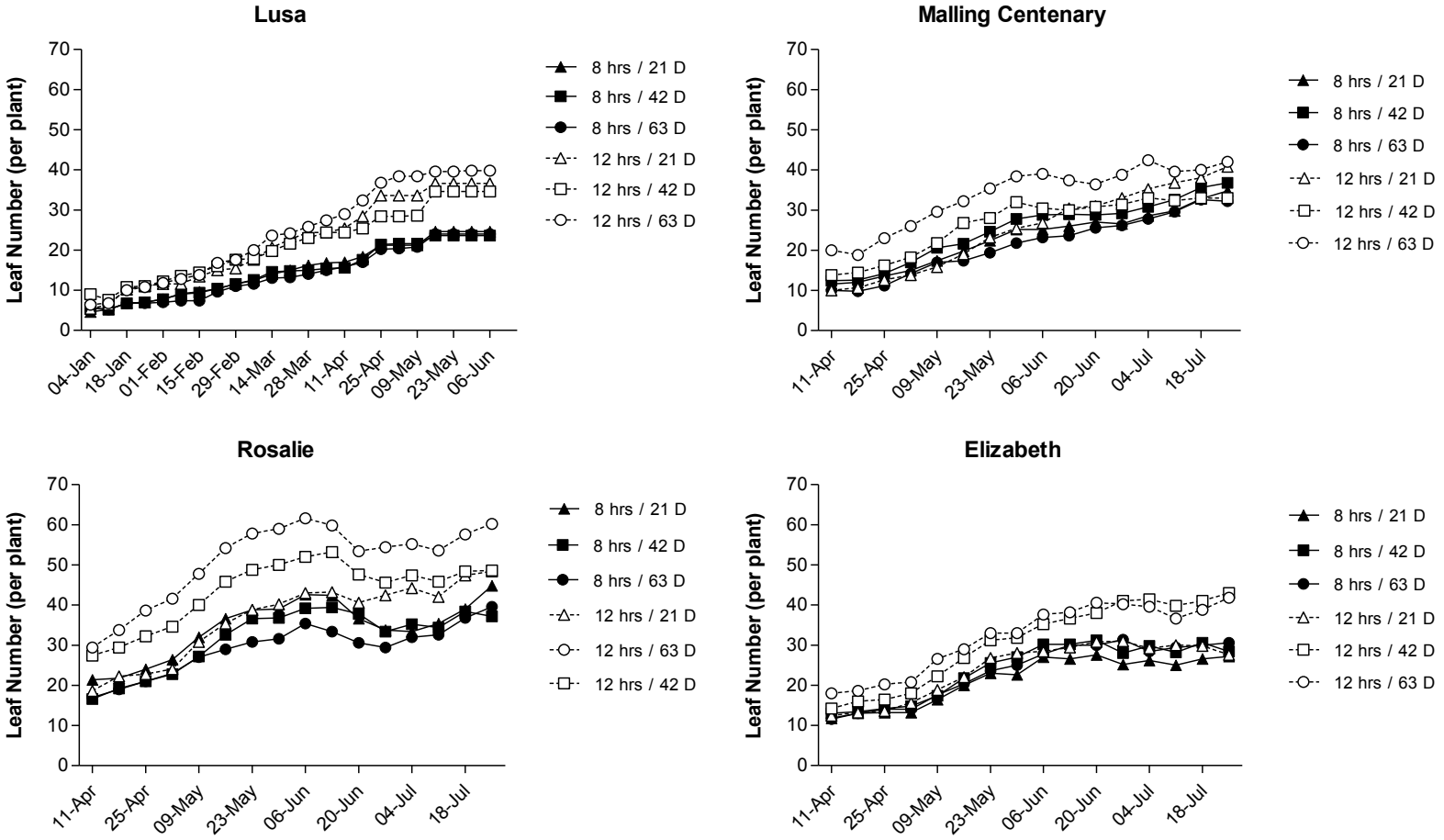

Figure 7.7 Treatment effects on leaf number each week throughout the production phase for cultivars Lusa (glasshouse), Malling Centenary, Rosalie and Elizabeth (polytunnel) (n=5). Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

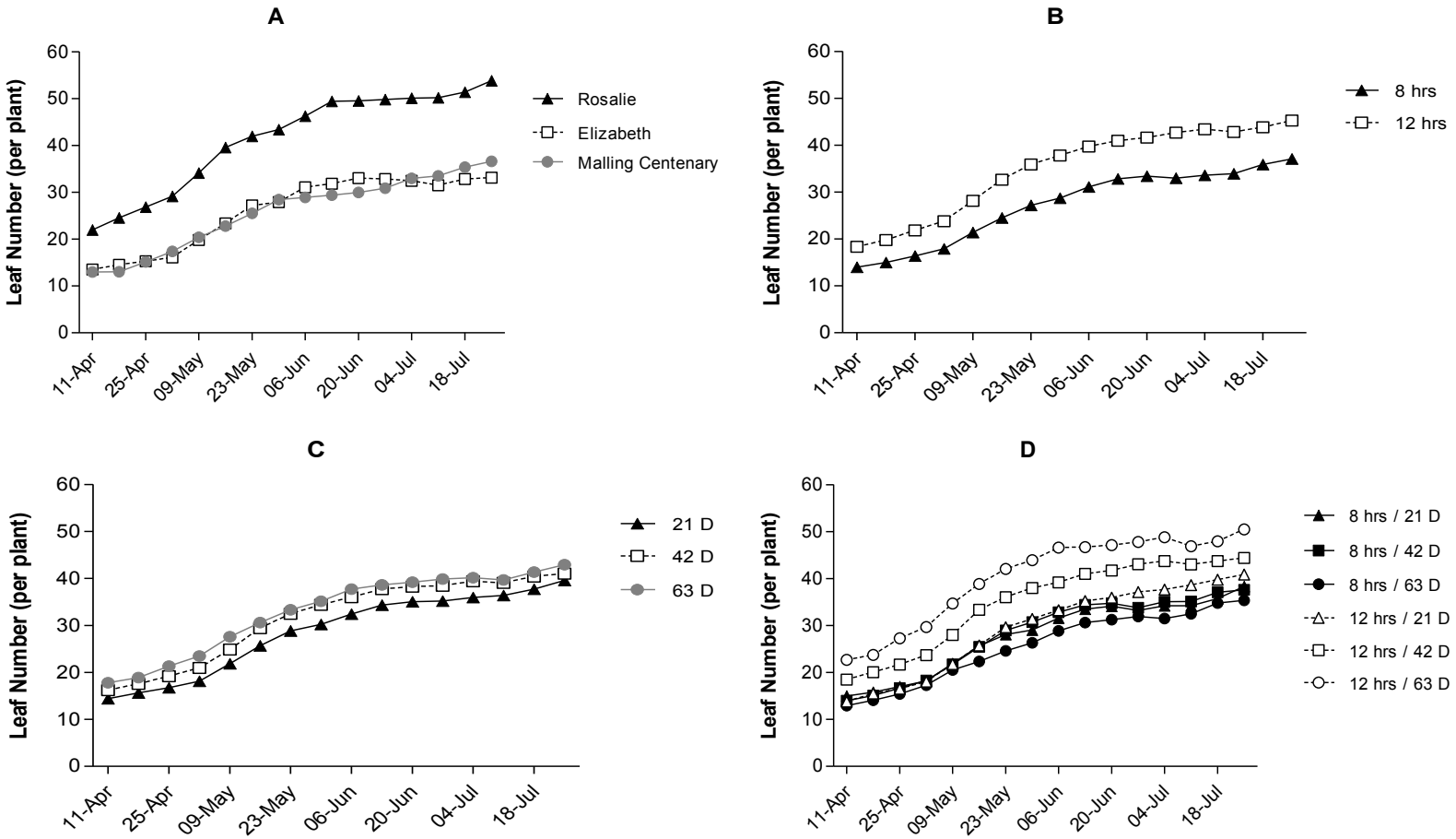

Figure 7.8 Effects of cultivar (A, n=30), number of hours of lighting (B, n=45), duration of lighting (C, n=30) and the interaction between the light treatments (D, n=15) on leaf number throughout the production phase for cultivars Malling Centenary, Elizabeth and Rosalie. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of lighting provided for 21, 42 or 63 days (D).

Petiole Length

Treatment effects on petiole length are shown for each cultivar in Figure 7.9. In the glasshouse crop of Lusa, petiole length was significantly greater in the 12-hr treatment compared to the 8-hr treatment from 18th January to 15th February but the difference between the two treatments declined from 29% to 10% over that period. No significant effect of the number of days of lighting was found, and there was also no significant interaction between the treatments.

For the remaining cultivars in the polytunnel production, there was a significant difference in petiole length between cultivars every week ($P<0.001$, Figure 7.10A). Rosalie had the greatest petiole length, significantly greater than both Elizabeth and Malling Centenary (on average 85% and 240% respectively). There was no significant difference in petiole length between Elizabeth and Malling Centenary during the first two weeks, but thereafter petiole length was significantly greater in Elizabeth (on average 110%).

There were no significant treatment effects or interactions in the first four weeks of cropping. Thereafter, petiole length was generally greater in the 8-hr treatment than the 12-hr treatment (Figure 7.10B) and in 21D compared to 42D and 63D (Figure 7.10C). However, there was also a significant interaction between the treatments every week from 9th May ($P<0.05$, Figure 10D) such that petiole length was significantly greater in the 8-hr treatment compared to the 12-hr treatment every week in 63D (on average 28%), whereas there were no significant differences for 42D and 21D at any time.

In the 8-hr treatment, petiole length was significantly greater in 21D compared to 63D for 23rd May and 30th May (11% and 12% respectively) and there were no significant differences between 21D and 42D or 42D and 63D at any time; whereas, in the 12-hr treatment, petiole length was significantly greater in 21D and 42D compared to 63D every week from 10th May (on average 41% and 27% respectively) and significantly greater in 21D compared to 42D from 16th May to 6th June (on average 14%).

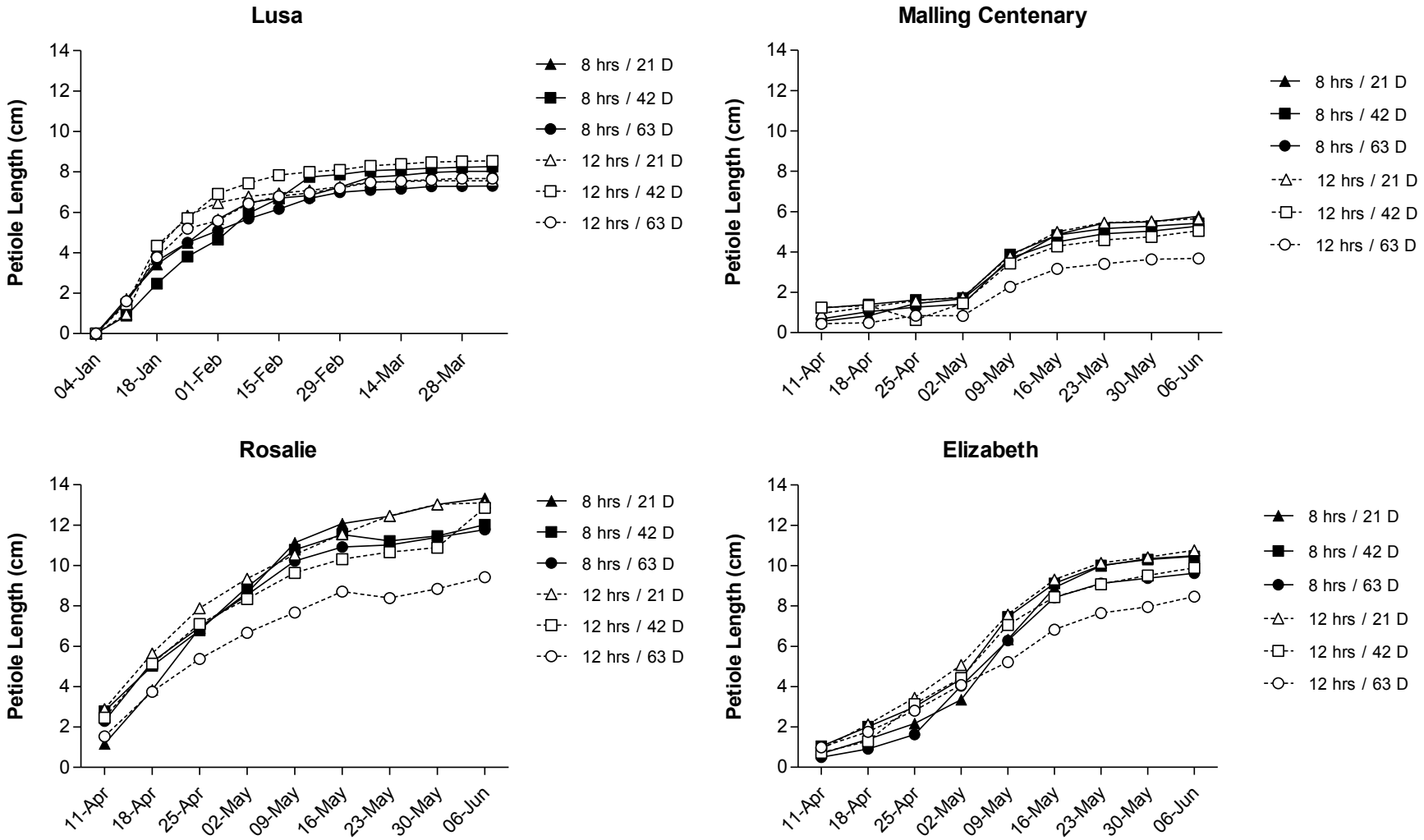

Figure 7.9 Treatment effects on petiole length during the production phase for cultivars Lusa (glasshouse), Malling Centenary, Rosalie and Elizabeth (polytunnel) (n=5). Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

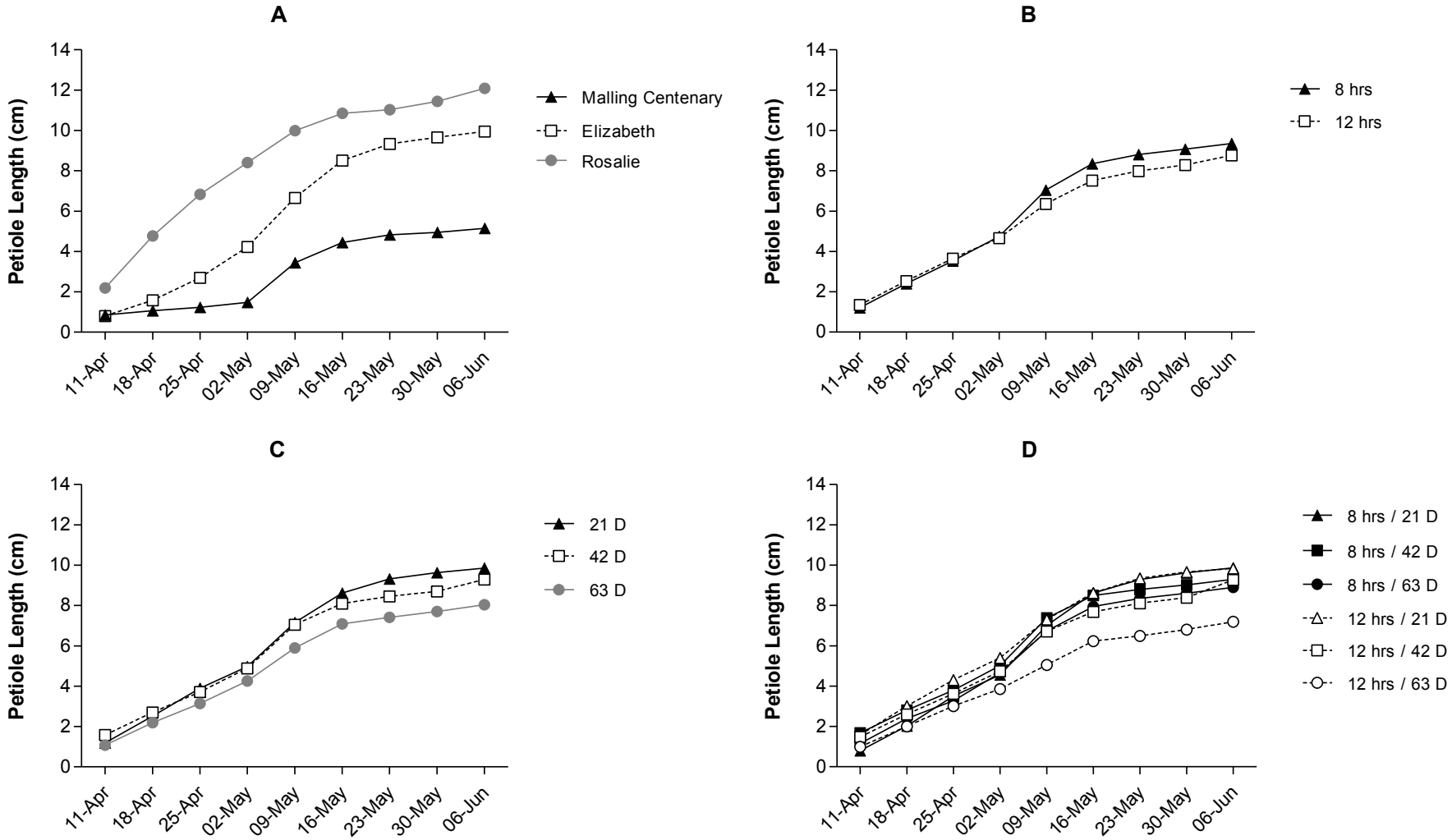

Figure 7.10 Effects of cultivar (A, n=30), number of hours of lighting (B, n=45), duration of lighting (C, n=30) and the interaction between the light treatments (D, n=15) on petiole length during the production phase for cultivars Malling Centenary, Elizabeth and Rosalie. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of lighting provided for 21, 42 or 63 days (D)

Flower and Fruit Number

Treatment effects on the number of open flowers and developing fruits for each cultivar are shown in Figure 7.11. In the glasshouse crop of Lusa there were no significant differences in flower and fruit number between treatments in the first ten weeks of cropping, or in the final week, but from 4th April to 30th May flower and fruit number was significantly greater in the 12-hr treatment compared to the 8-hr treatment (on average of 27%). There was no significant effect of the number of days of lighting, or a significant interaction between the treatments at any time.

For the remaining cultivars in the polytunnel production, there was no significant difference in flower and fruit number between cultivars in the first week or the final week (Figure 7.12A). From 18th April to 20th June flower and fruit number was significantly greater in Rosalie compared to Elizabeth (on average 95%), and from 2nd May to 18th July was also greater than Malling Centenary (on average 72%). Flower and fruit number was also significantly greater in Elizabeth compared to Malling Centenary from 23rd May to 11th July (on average 41%).In general, for the first seven weeks of cropping, flower and fruit number was greater in the 8-hr treatment compared to the 12-hr treatment (on average 47%, Figure 7.12B) and in 21D and 42D compared to 63D (on average 127% and 136%, Figure 7.12C) whilst for the remainder of cropping this trend was reversed with flower and fruit number greater in the 12-hr treatment on average 27% and in 63D compared to 42D and 21D (on average 25% and 15%). However, there were significant interactions between the treatments ($P<0.05$, Figure 7.12D) such that for three weeks at the start of cropping (18th April to 2nd May), flower and fruit number was significantly greater the 8-hr treatment compared to the 12-hr treatment for 21D (on average 177%), but there was no significant difference in 42D and 63D; whereas, from 6th June, there was no significant difference in flower and fruit number between the 8-hr and 12-hr treatments for 21D, but in 42D and 63D flower number was significantly higher in the 12-hr treatment (on average 28% and 47%). In the first four weeks of cropping, flower and fruit number was significantly greater in 21D compared to 63D in the 8-hr treatment (on average 271%) whereas in the 12-hr treatment flower and fruit number was significantly greater in 42D compared to 21D and 63D (on average 273% and 198%). From 6th June, in the 8-hr treatment there were no significant difference in flower and fruit number between 21D, 42D and 63D. Whereas, in the 12-hr treatment flower and fruit number was significantly higher in 63D compared to 42D and 21D (on average 18% and 41% respectively), and in 42D compared to 21D (on average 20%).

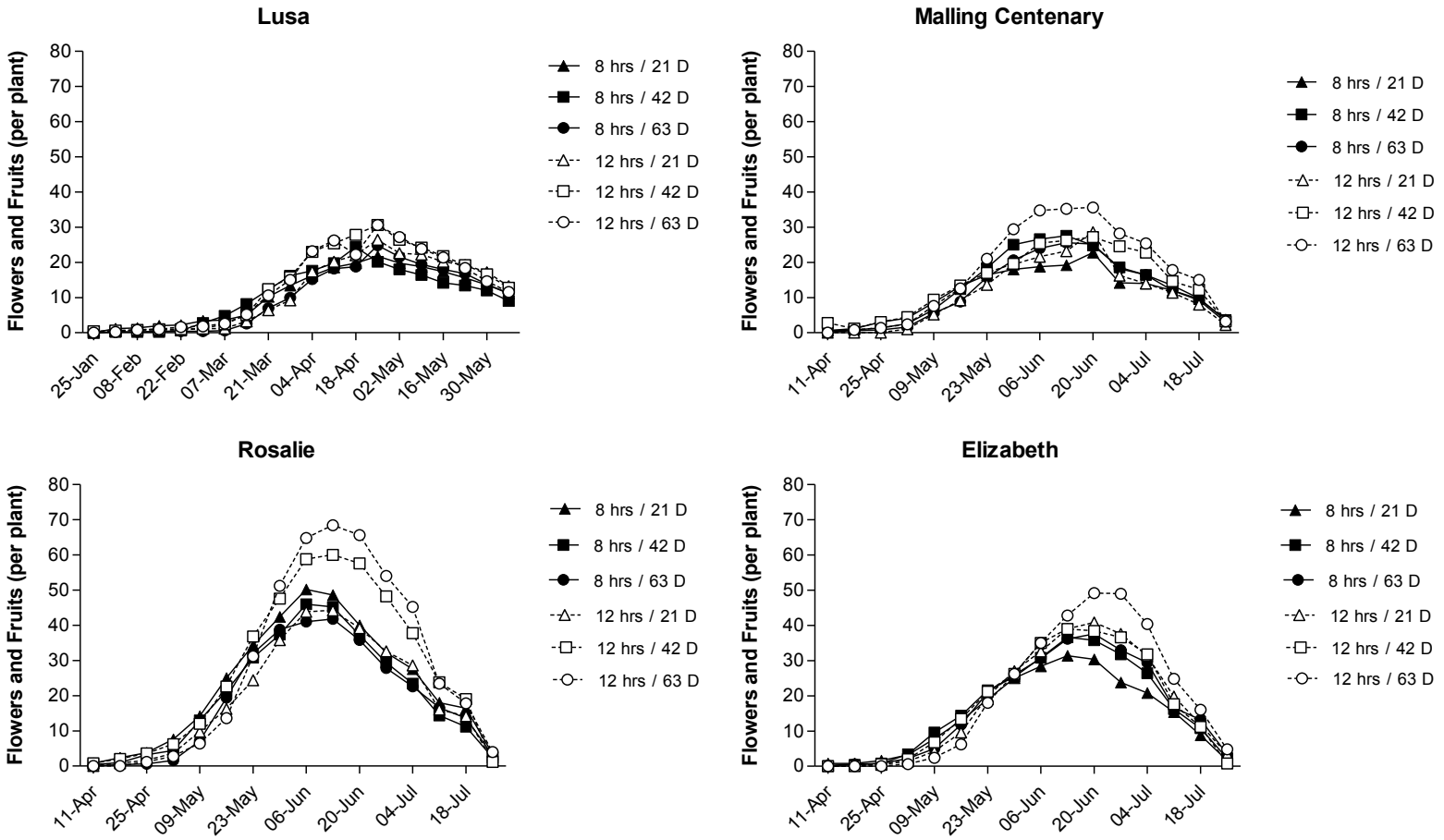

Figure 7.11 Treatment effects on the number of flowers and developing fruits per plant during the production phase for cultivars Lusa (glasshouse), Malling Centenary, Rosalie and Elizabeth (polytunnel) (n=5). Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

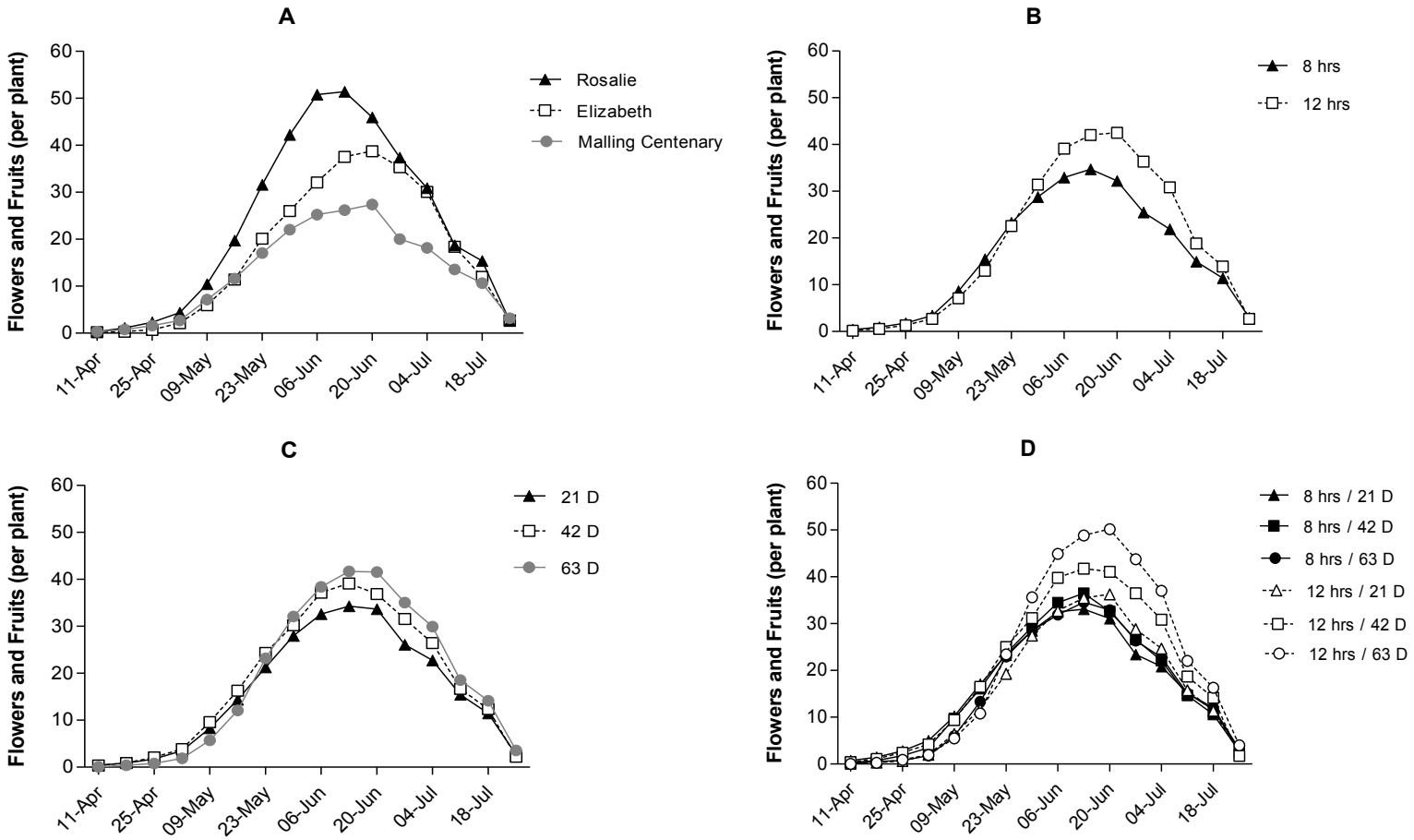

Figure 7.12 Effects of cultivar (A, n=30), number of hours of lighting (B, n=45), duration of lighting (C, n=30) and the interaction between the light treatments (D, n=15) on the number of flowers and developing fruits throughout the production phase for cultivars Malling Centenary, Elizabeth and Rosalie. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of lighting provided for 21, 42 or 63 days (D).

Flowering Time

Overall no significant treatment effects or interactions were found on the number of days from planting to the first open flower for Lusa, the mean number of days to flower was 66.3±1.9 days from planting (Table 7.3).

Treatment effects on flowering time for the remaining cultivars are shown in Table 7.4. Flowering time did not significantly differ between Elizabeth (35.7±1.8 days from planting) and Malling Centenary (33.4±2.1) but this was significantly later for both compared to the Rosalie (27.8±1.4) (P=0.002). There was also a significant interaction between the treatments (P=0.004) such that in 21D flowering was 12 days later in the 12-hr treatment compared to the 8-hr treatment whereas there was no significant difference in 42D or 63D.

In the 12-hr treatment flowering was significantly later in 63D and 42D compared to 21D (by 10 days and 7 days respectively) and there was no significant difference between 63D and 42D; whereas, in the 8-hr treatment flowering was significantly earlier in 42D compared to 63D and 21D (by 12 days and 8 days respectively).

Inflorescence Number

Treatment effects on the number of inflorescences for Lusa is shown in Table 7.3. There were a greater number of inflorescences in the 12-hr treatment compared to the 8-hr treatment, but overall no significant treatment effects or interactions were found and the mean number of inflorescences per plant was 12.6±0.5.

Treatment effects on inflorescence number for the remaining cultivars are shown in Table 7.4. All differences in inflorescence number between cultivars were significant (P<0.001), Rosalie had the greatest number of inflorescences (15.0±0.6 per plant), 46% and 47% greater than Elizabeth (10.3±0.4) and Malling Centenary (10.2±0.5) respectively. Only the main effects of the treatments were significant; inflorescence number was 15% greater in the 12-hr treatment (12.6±0.6 per plant) compared to the 8-hr treatment (11.0±0.5) (P=0.004) and inflorescence number increased 6% from 21D (10.9±0.7 per plant) to 42D (11.6±0.6), and a further 13% from 42D to 63D (13.1±0.7) (P=0.004).

Flowers per Inflorescence

Treatment effects on the number of flowers per inflorescence for Lusa is shown in Table 7.3. Overall there were no significant main effects of interactions found, the mean number of flowers per inflorescence was 5.8±0.2.

Treatment effects on the number of flowers per inflorescence for the remaining cultivars are shown in Table 7.4. Only the differences in the number of flowers per inflorescence between cultivars was significant (P<0.001); Elizabeth had the greatest number of flowers per inflorescence (5.2±0.2 flowers / inflorescence), followed by Rosalie (4.8±0.1) and Malling Centenary (4.5±0.1). There were no significant effects of the treatments or interactions found.

Table 7.3 Treatment effects on flowering data for the cultivar Lusa. Data shown is flowering time, number of inflorescences per plant and number of flowers per inflorescence (n=5). Inf= inflorescence. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D). P. Values and LSDs for the main effects and interactions are shown.

Cultivar	Hours	Days	Flowering Time (days from planting)	Inf Number (per plant)	Flower Number (per inflorescence)
Lusa	**8-hrs**	**21 D**	58.8	11.2	5.6
		42 D	60.2	11.8	5.8
		63 D	70.0	11.8	6.0
	12-hrs	**21 D**	71.4	13.4	5.5
		42 D	67.2	13.8	6.5
		63 D	70.0	13.4	5.4
P. Value			0.060	0.059	0.951
Hours			0.280	0.914	0.377
Days			0.312	0.967	0.333
H x D					
LSD					
Hours			6.84	2.02	0.75
Days			8.38	2.47	0.92
H x D			11.85	3.50	1.30

Table 7.4 Treatment effects on flowering data for Malling Centenary, Rosalie and Elizabeth. Data shown is flowering time, number of inflorescences per plant and number of flowers per inflorescence (n=5). Inf= inflorescence. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D). P. Values and LSDs for the main effects and interactions are shown.

Cultivar	Hours	Days	Flowering Time (days from planting)	Inf Number (per plant)	Flower Number (per inflorescence)
Malling Centenary	**8-hrs**	**21 D**	20.8	8.4	4.7
		42 D	30.6	11.0	4.6
		63 D	39.0	10.2	4.5
	12-hrs	**21 D**	43.2	8.0	4.9
		42 D	26.4	11.4	4.1
		63 D	40.4	12.4	4.3
Rosalie	**8-hrs**	**21 D**	23.6	14.6	4.6
		42 D	26.4	12.6	5.0
		63 D	34.8	13.8	4.9
	12-hrs	**21 D**	27.8	14.0	4.7
		42 D	20.8	16.6	4.6
		63 D	33.4	18.4	4.9
Elizabeth	**8-hrs**	**21 D**	29.2	8.8	5.2
		42 D	36.2	8.4	5.5
		63 D	29.2	11.6	5.3
	12-hrs	**21 D**	37.6	11.4	5.0
		42 D	36.2	9.4	4.9
		63 D	46.0	12.0	5.5
P. Value					
Cultivar			0.002	<.001	<.001
Hours			0.010	0.004	0.247
Days			0.001	0.004	0.740
C x H			0.082	0.310	0.926
C x D			0.371	0.117	0.393
H x D			0.004	0.337	0.180
C x H x D			0.082	0.158	0.906
LSD					
Cultivar			4.33	1.28	0.34
Hours			3.53	1.04	0.28
Days			4.33	1.28	0.34
C x H			6.12	1.81	0.48
C x D			7.50	2.22	0.59
H x D			6.12	1.81	0.48
C x H x D			10.60	3.13	0.84

7.3.2.2 *Light Interception*

Percentage light interception was calculated for five weeks during cropping in the polytunnel and the results for Treatment C (8-hrs / 21D) and Treatment F (12-hrs / 63 D) are shown in Figure 7.13. Only the three-way interaction between the date, cultivars and treatments was significant (P=0.008) which showed that in the first week (1st July) the percentage of light intercepted was significantly higher in Treatment F compared to Treatment B by 6% for Elizabeth, and in the following week (7th July) in Treatment B compared to Treatment F for Malling Centenary by 14%. No other significant differences between treatments were found for any cultivar at any time. Mean percentage light interception was 88% for both treatments and each cultivar.

7.3.2.3 *Yield Results*

Marketable Yield

Treatment effects on the marketable yield for each cultivar is shown in Figure 7.14. In the glasshouse crop of Lusa there were no significant treatment effects or interactions, the mean marketable yield per plant was 640±16.2 g.

For the remaining cultivars under the polytunnel production, there was a significant difference in marketable yield between cultivars (P<0.001); the marketable yield of Rosalie (828±15.6 g / plant) was significantly greater than Elizabeth (728±21.7) and Malling Centenary (658±17.3), and the marketable yield of Elizabeth was significantly greater than Malling Centenary. For the treatments, only the main effect of the number of hours lighting was significant (P=0.003) where the marketable yield was 9% greater in the 8-hr treatment (768±18.5 g / plant) compared to the 12-hr treatment (708±18.0).

Un-Marketable Yield

Treatment effects on the un-marketable yield for each cultivar is shown in Figure 7.15. In the glasshouse crop of Lusa there were no significant treatment effects or interactions, the mean un-marketable yield per plant was 33±2.2 g.

For the remaining cultivars under the polytunnel production, there was a significant difference in un-marketable yield between cultivars (P<0.001); the un-marketable yield of Rosalie (115±6.3 g / plant) and Elizabeth (112±9.2) did not differ significantly but were both greater than Malling Centenary (54±4.4). There was a significant interaction between the treatments (P=0.004) such

that the un-marketable yield was 48% greater in the 12-hr treatment compared the 8-hr treatment in 42D but there was no significant difference in 21D or 63D. In the 8-hr treatment the un-marketable yield was significantly higher in 63D compared to 42D and 21D (46% and 24% respectively) whereas in the 12-hr treatment the un-marketable yield was significantly greater in 63D and 42D compared to 21D (91% and 64% respectively).

Total Yield

Treatment effects on total yield for each cultivar is shown in Figure 7.16. In the glasshouse crop of Lusa there were no significant treatment effects or interactions, the mean total yield per plant was 672±16.7 g.

For the remaining cultivars under the polytunnel production, there was a significant difference in the total yield between cultivars ($P<0.001$); the total yield of Rosalie (943±14.8 g / plant) was significantly higher than Elizabeth (841±25.3) and Malling Centenary (713±17.3). For the treatments, only the main effect of the number of hours lighting was significant ($P=0.021$), where the total yield was 6% greater in the 8-hr treatment (857±21.6 g / plant) than the 12-hr treatment (808±22.7).

Percentage Class 1

Treatment effects on the percentage Class 1 for each cultivar is shown in Figure 7.17. In the glasshouse crop of Lusa there were no significant treatment effects or interactions, the mean percentage Class 1 was 95±0.3%.

For the remaining cultivars under the polytunnel production, there was a significant difference in percentage Class 1 between cultivars ($P<0.001$); percentage Class 1 did not significantly differ between Rosalie (88±0.7%) and Elizabeth (87±0.9) but was significantly lower in both compared to Malling Centenary (92±0.6). There was a significant interaction between the treatments ($P=0.003$) such that in 42D and 63D percentage Class 1 was significantly lower in the 12-hr treatment compared to the 8-hr treatment (4% respectively) whereas there was no significant difference in 21D. Additionally, in the 8-hr treatment percentage Class 1 was 3% greater in 42D compared to 63D and there were no other significant differences between treatments whereas in the 12-hr treatment, percentage Class 1 was significantly greater in 21D compared to 42D and 63D (4% and 7% respectively) and 3% greater in 42D compared to 63D.

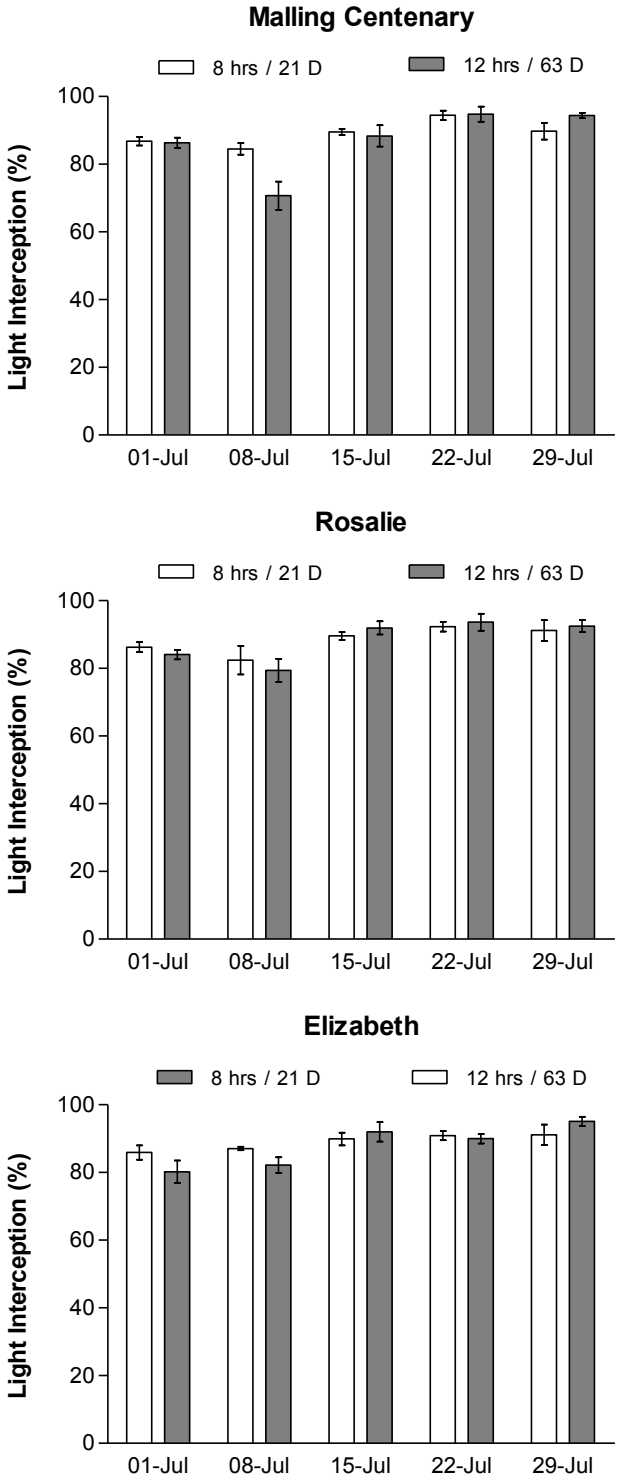

Figure 7.13 Percentage light interception for cultivars Malling Centenary, Elizabeth and Rosalie calculated for five weeks during cropping (n=4). The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs of supplementary lighting provided for 21 days (8-hrs / 21 D) and 12-hrs supplementary lighting provided for 63 days (12-hrs / 63 D).

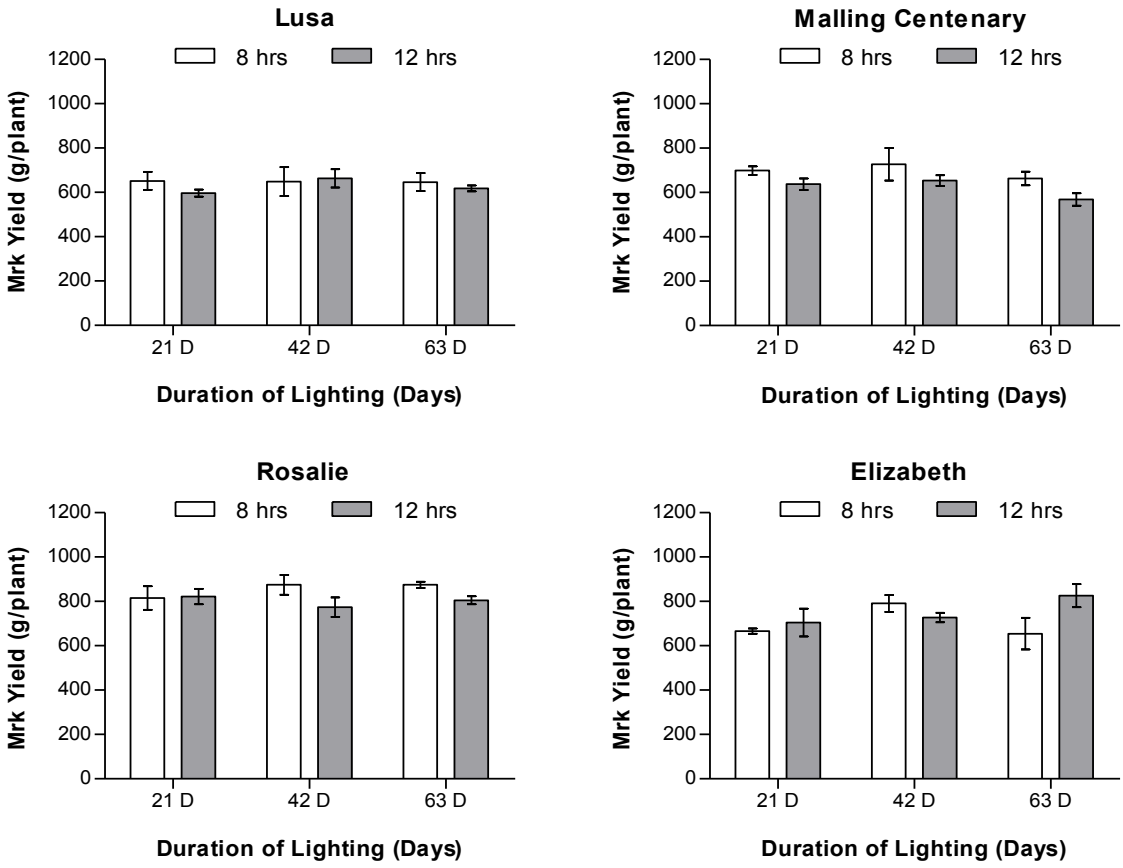

Figure 7.14 Treatment effects on marketable yield of cultivars Lusa (n=3) and Malling Centenary, Rosalie and Elizabeth (n=4). Mrk= marketable. The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

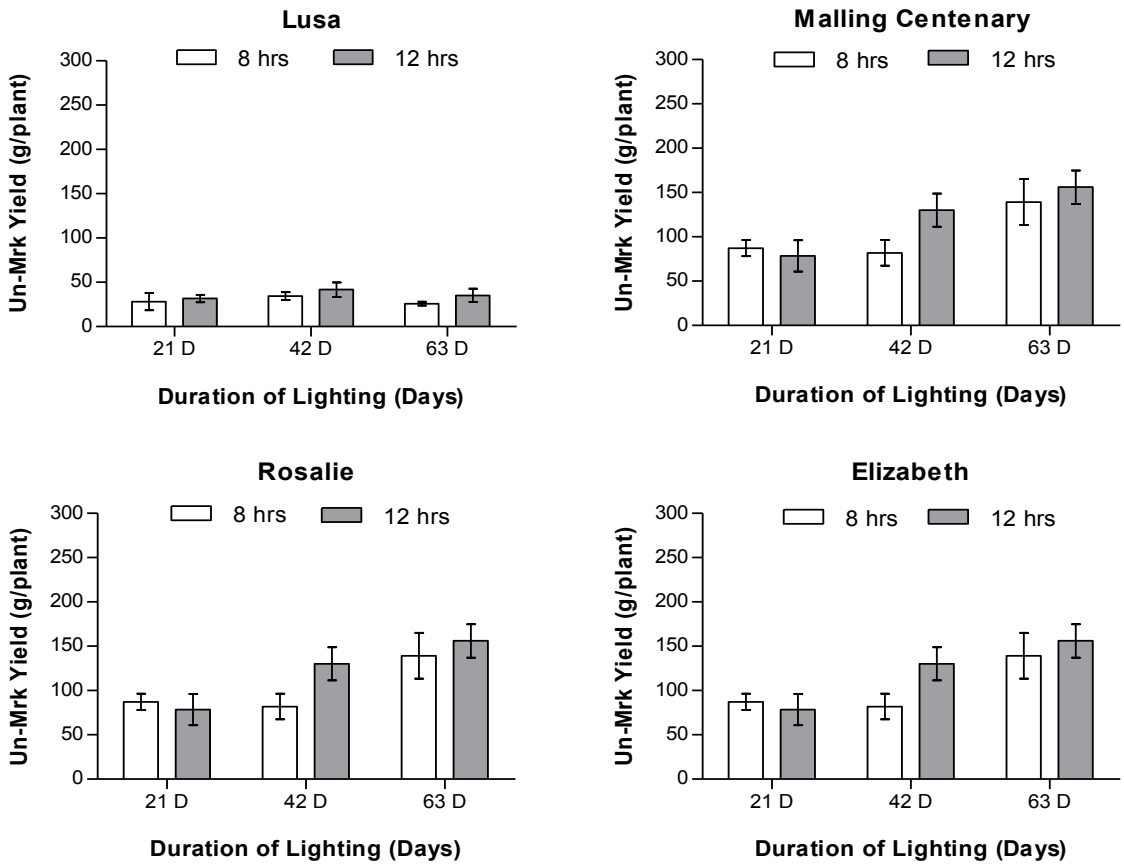

Figure 7.15 Treatment effects on un-marketable yield of cultivars Lusa (n=3) and Malling Centenary, Rosalie and Elizabeth (n=4). Un-Mrk= un-marketable. The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

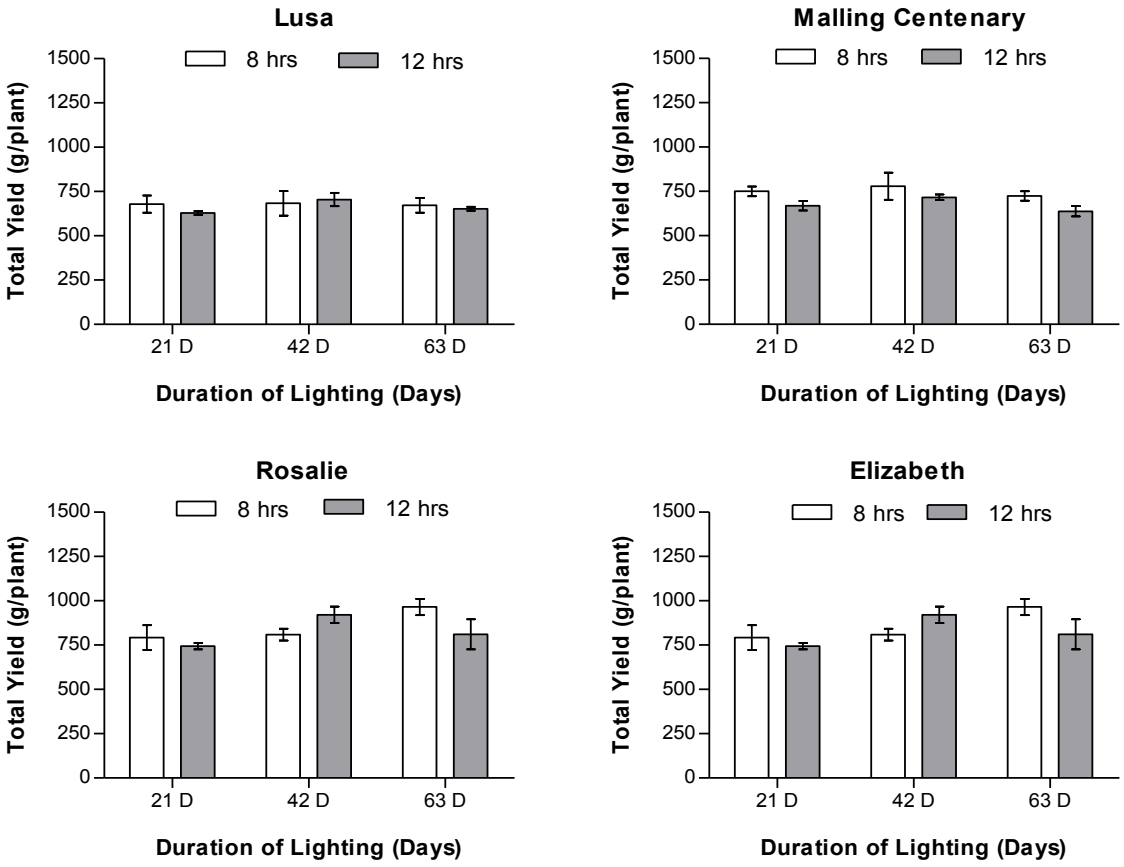

Figure 7.16 Treatment effects on total yield of cultivars Lusa (n=3) and Malling Centenary, Rosalie and Elizabeth (n=4). The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

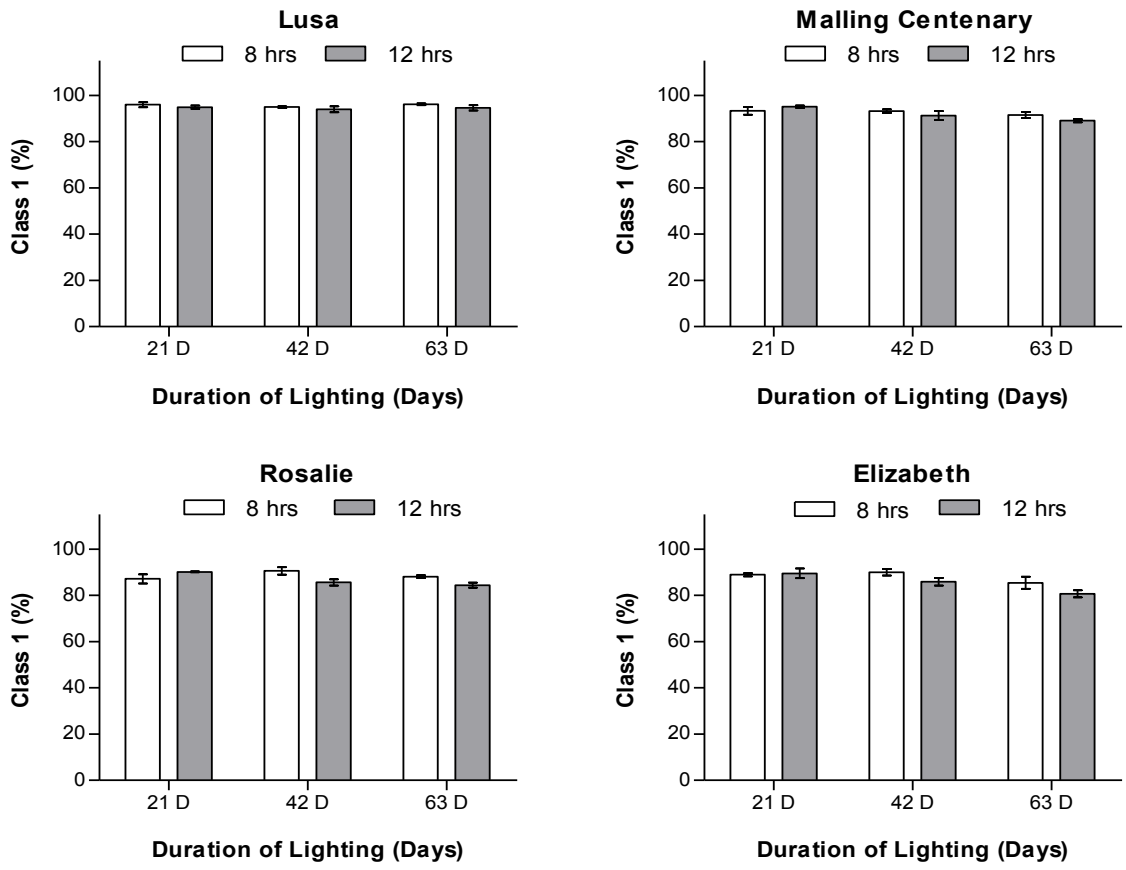

Figure 7.17 Treatment effects on percentage Class 1 of cultivars Lusa (n=3) and Malling Centenary, Rosalie and Elizabeth (n=4). The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

Marketable Berry Number

Treatment effects on marketable berry number for each cultivar are shown in Figure 7.18. In the glasshouse crop of Lusa there were no significant treatment effects or interactions, the mean marketable berry number per plant was 39.4±1.0.

For the remaining cultivars under the polytunnel production, there was a significant difference in marketable berry number between cultivars (P<0.001); marketable berry number was significantly greater in Rosalie (53.6±1.2 berries / plant) compared to Elizabeth (44.7±1.4) and Malling Centenary (38.7±0.9). The interaction between the treatments was significant (P=0.022) such that marketable berry number was 14% greater in the 12-hr treatment compared to the 8-hr treatment in 42D but there was no significant difference in 21D or 63D. Additionally, in the 8-hr treatment berry number was significantly greater in 63D compared to both 42D and 21D (13% and 12% respectively) whilst in the 12-hr treatment berry number was significantly higher in 63D and 42D compared to 21D (23% and 18% respectively).

Un-Marketable Berry Number

Treatment effects on un-marketable berry number for each cultivar are shown in Figure 7.19. In Lusa, only the main effect of the number of hours of lighting was significant (P=0.013) where un-marketable berry number was 47% greater in the 12-hr treatment (5.4±0.6 berries / plant) compared to the 8-hr treatment (3.7±0.3).

For the remaining cultivars under the polytunnel production, there was a significant difference in un-marketable berry number between cultivars (P<0.001). There was no significant difference between Rosalie (15.9±1.0 berries / plant) and Elizabeth (15.5±1.5), but berry number of both was significantly greater than Malling Centenary (7.6±1.1). The interaction between the treatments was significant (P=0.002) such that un-marketable berry number was significantly greater in 12-hr treatment compared to the 8-hr treatment in 42D and 63D (93% and 41% respectively) whereas there was no difference in 21D. Additionally, in the 8-hr treatment berry number was significantly greater in 63D compared to 42D by 56% whereas there in the 12-hr treatment berry number was significantly greater in 63D and 42D compared to than 21D (106% and 82% respectively).

Total Berry Number

Treatment effects on total berry number for each cultivar are shown in Figure 7.20. In the glasshouse crop of Lusa there were no significant treatment effects or interactions, the mean total berry number per plant was 44.0±1.1.

For the remaining cultivars under the polytunnel production, there was a significant difference in total berry number between cultivars (P<0.001); total berry number was significantly higher in Rosalie (69.5±1.8 berries / plant) compared to Elizabeth (60.2±2.5) and Malling Centenary (46.4±1.7). The interaction between the treatments was also significant (P<0.001) such that berry number was greater in the 12-hr treatment than the 8-hr treatment in 42D and 63D (27% and 13% respectively) whereas there was no significant difference in 21D. Additionally, in the 8-hr treatment, berry number was significantly greater in 63D compared to 42D and 21D (20% and 14% respectively) whilst in the 12-hr treatment berry number was greater in 63D and 42D compared to 21D (38% and 30% respectively).

Marketable Berry Weight

Treatment effects on average marketable berry weight for each cultivar is shown in Figure 7.21. In Lusa, average berry weight was significantly greater in the 8-hr treatment (16.7±0.0 g / berry) compared to the 12-hr treatment (15.8±0.0) (P=0.004) and significantly higher in 21D (16.8±0.0) compared to 42D (16.1±0.0) and 63D (15.9±0.0) (P=0.027).

For the remaining cultivars under the polytunnel production, there was a significant difference in average berry weight between cultivars (P<0.001), average berry weight was significantly higher in Malling Centenary (17.2±0.6 g / berry) and Elizabeth (16.4±0.4) compared to Rosalie (15.5±0.3). The interaction between the treatments was also significant (P<0.001) such that average berry weight was greater in the 8-hr treatment compared to the 12-hr treatment in 42D and 63D (22% and 21% respectively) whereas there was no significant difference in 21D. Additionally, in the 8-hr treatment average berry weight was significantly greater in 21D and 42D compared to 63D (6% and 12% respectively) whereas in the 12-hr treatment, average berry weight was greater in 21D compared to 42D and 63D (30% and 14% respectively) and 14% greater in 42D than 63D.

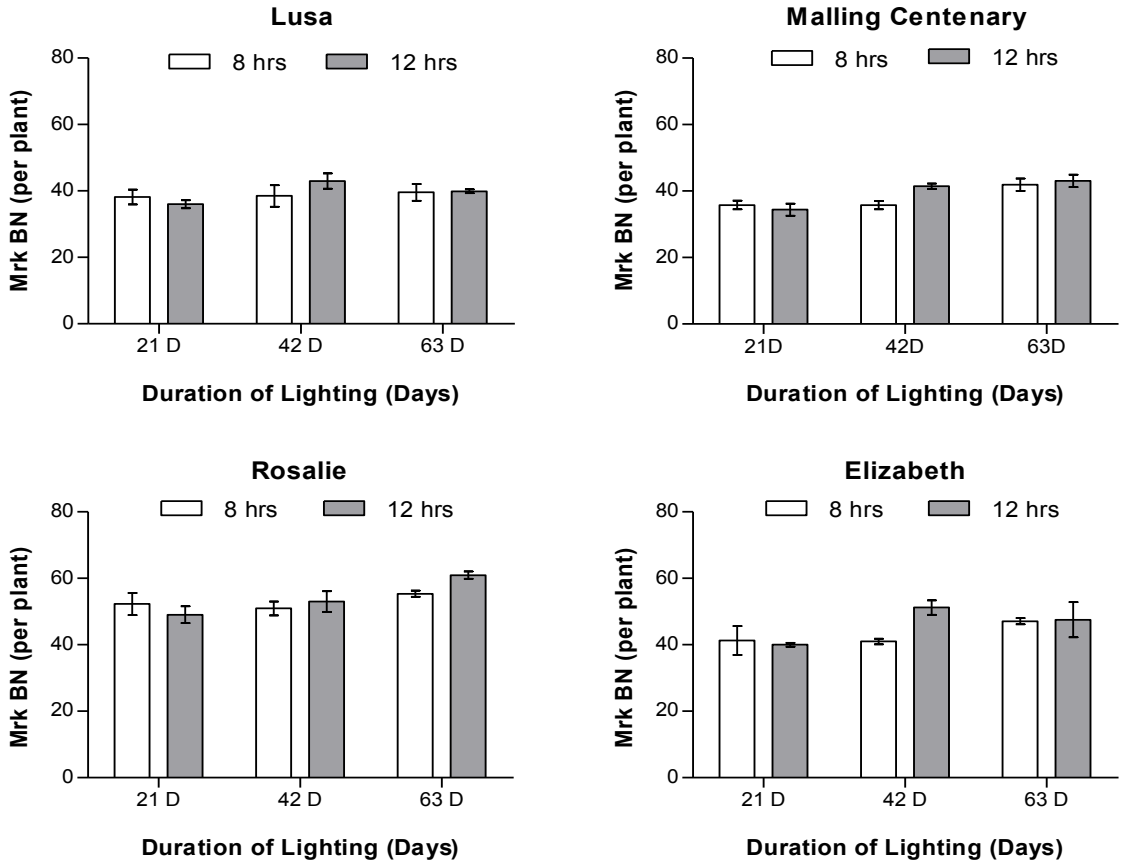

Figure 7.18 Treatment effects on marketable berry number of cultivars Lusa (n=3) and Malling Centenary, Rosalie and Elizabeth (n=4). Mrk= marketable. BN= berry number. The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

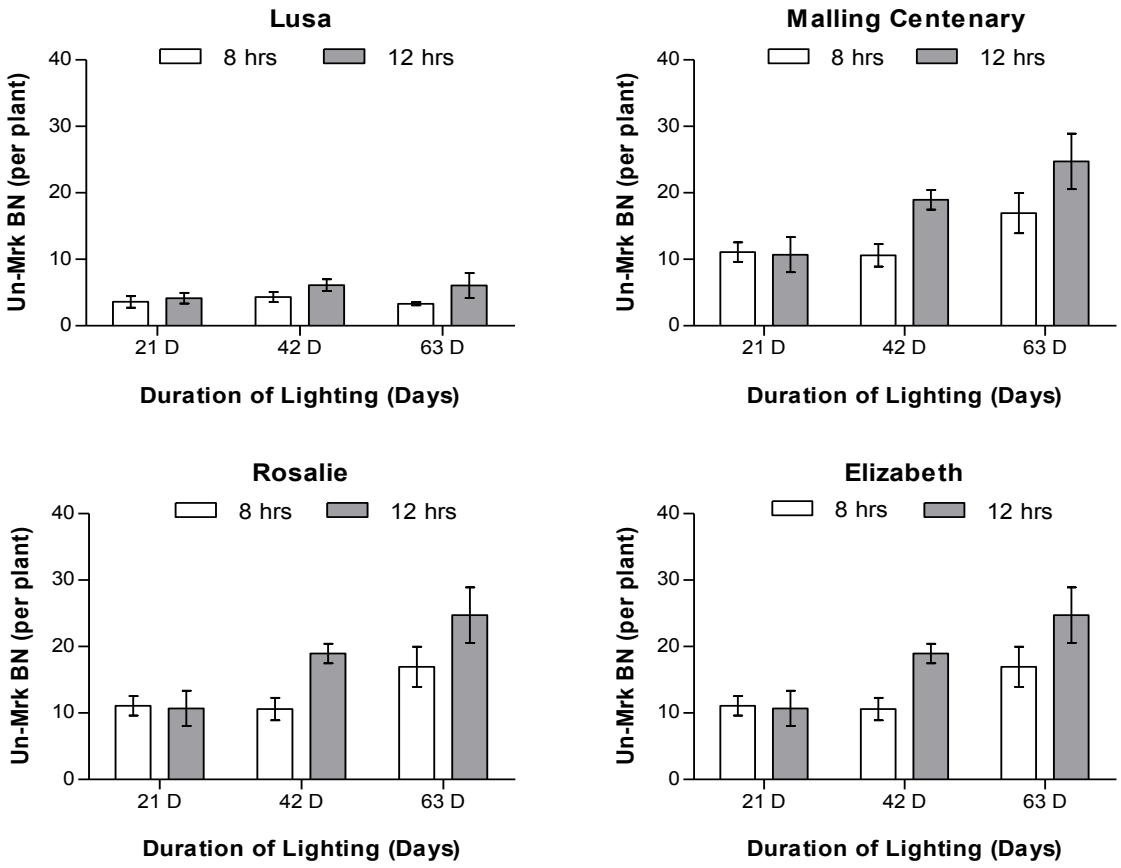

Figure 7.19 Treatment effects on un-marketable berry number of cultivars Lusa (n=3) and Malling Centenary, Rosalie and Elizabeth (n=4). Un-Mrk= un-marketable. BN= berry number. The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

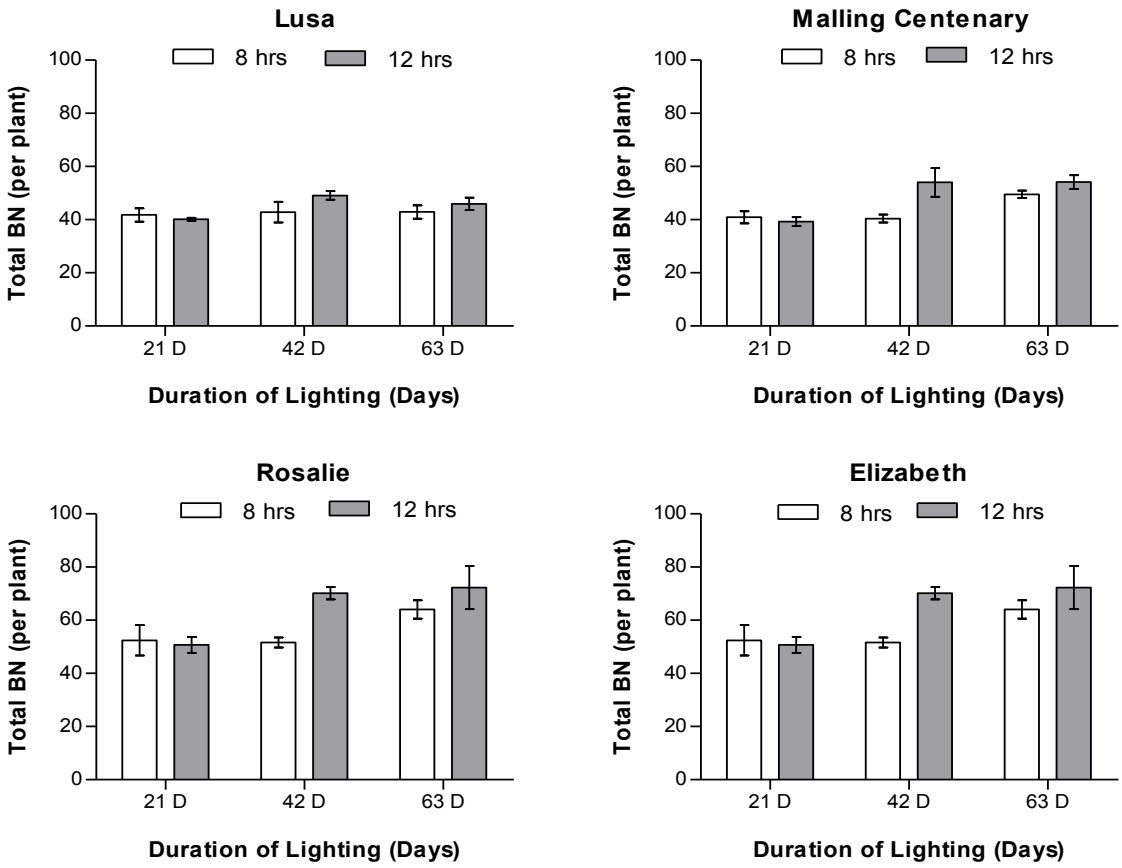

Figure 7.20 Treatment effects on total berry number of cultivars Lusa (n=3) and Malling Centenary, Rosalie and Elizabeth (n=4). BN= berry number. The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

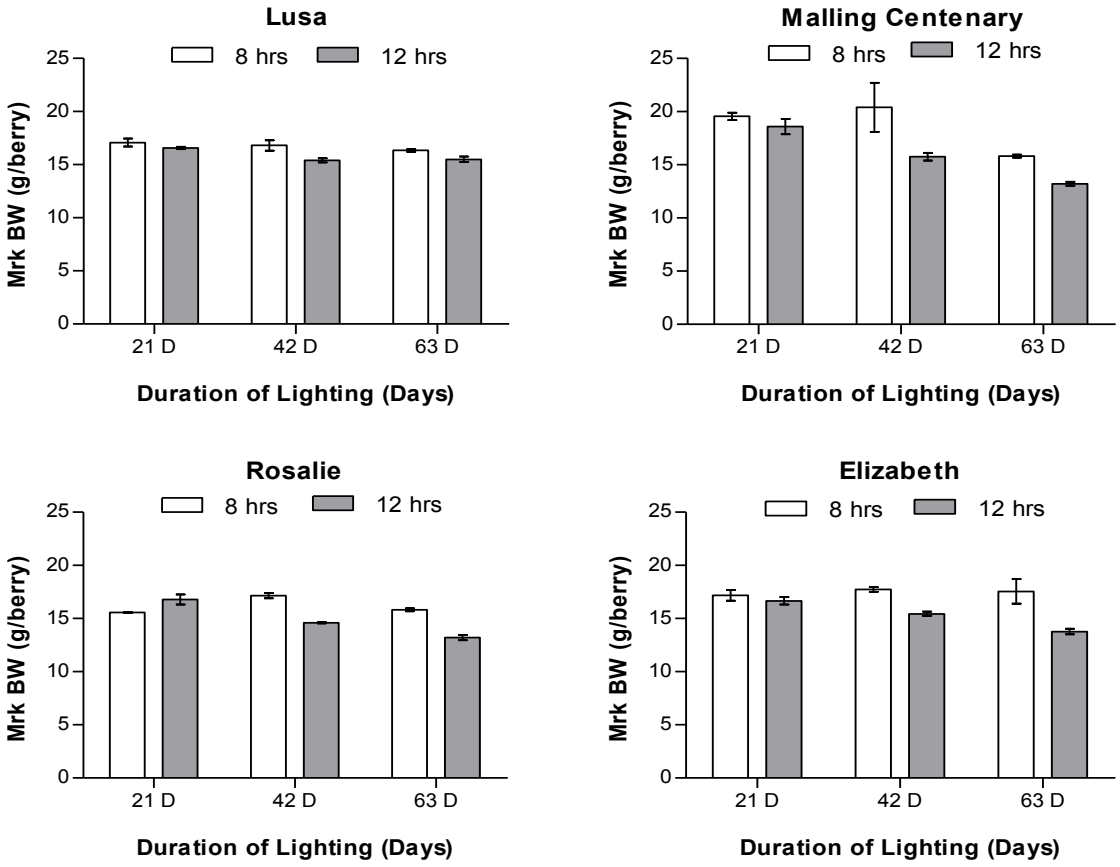

Figure 7.21 Treatment effects on average marketable berry weight of cultivars Lusa (n=3) and Malling Centenary, Rosalie and Elizabeth (n=4). Mrk= marketable, BW= berry weight. The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

7.3.2.4 *Cropping Profiles*

In the glasshouse production of Lusa, weekly marketable yield for each treatment was recorded for 16 weeks (15th March to 5th July 2016) (Figure 7.22). Overall there were only minor differences between the treatments for each harvest. In Week 4, marketable yield was greater in 42D compared to 63D and this was just significant (P=0.048) and in Week 13, marketable yield was significantly higher in the 8-hr treatment compared to the 12-hr treatment by 35% and this was just significant (P=0.046).

For the remaining cultivars in the polytunnel production, weekly marketable yield for each cultivar and treatment was recorded for 11 weeks (24th May to 2nd August 2016) (Figure 7.22). There was a significant difference in marketable yield between cultivars for the first eight weeks (P<0.001, Figure 7.23A); the yield of Malling Centenary was significantly higher than Rosalie and Elizabeth in the first three weeks of cropping and there was no significant difference between Rosalie and Elizabeth until the third week where the yield of Rosalie was 186% greater than Elizabeth. In Weeks 4 to 6, Rosalie had the greatest marketable yield, significantly higher than both Elizabeth and Malling Centenary (on average 50% and 33% respectively), there was no significant difference between Elizabeth and Malling Centenary until Week 6 when the yield of Elizabeth was 49% greater than Malling Centenary. Marketable yield was significantly higher in Elizabeth compared to Rosalie and Malling Centenary in Week 7-8 (on average 71% and 36%) and the difference between Rosalie and Malling Centenary was only significant in Week 8 where the yield of Rosalie was 21% greater than Malling Centenary.

The main effect of the number of hours of lighting per day is shown in Figure 7.23B; marketable yield was significantly (P<0.05) greater in the 8-hr treatment compared to the 12-hr treatment in Week 4, 8 and 9 (by 17%, 18% and 54% respectively), all other differences in marketable yield between the 8-hr and 12-hr treatments were not significant. The main effect of the number of days of lighting is shown in Figure 7.23C; an increase in the duration of lighting led to a shift in the cropping profile, as marketable yield was significantly higher in 21D and 42D compared to 63D in Week 3 and 4 (112% and 91% respectively) but by Week 6 and 7 this had reversed, and marketable yield was significantly higher in 63D compared to 42D and 21D (on average 39% and 32%). All other differences in yield between 21D, 42D and 63D were not significant.

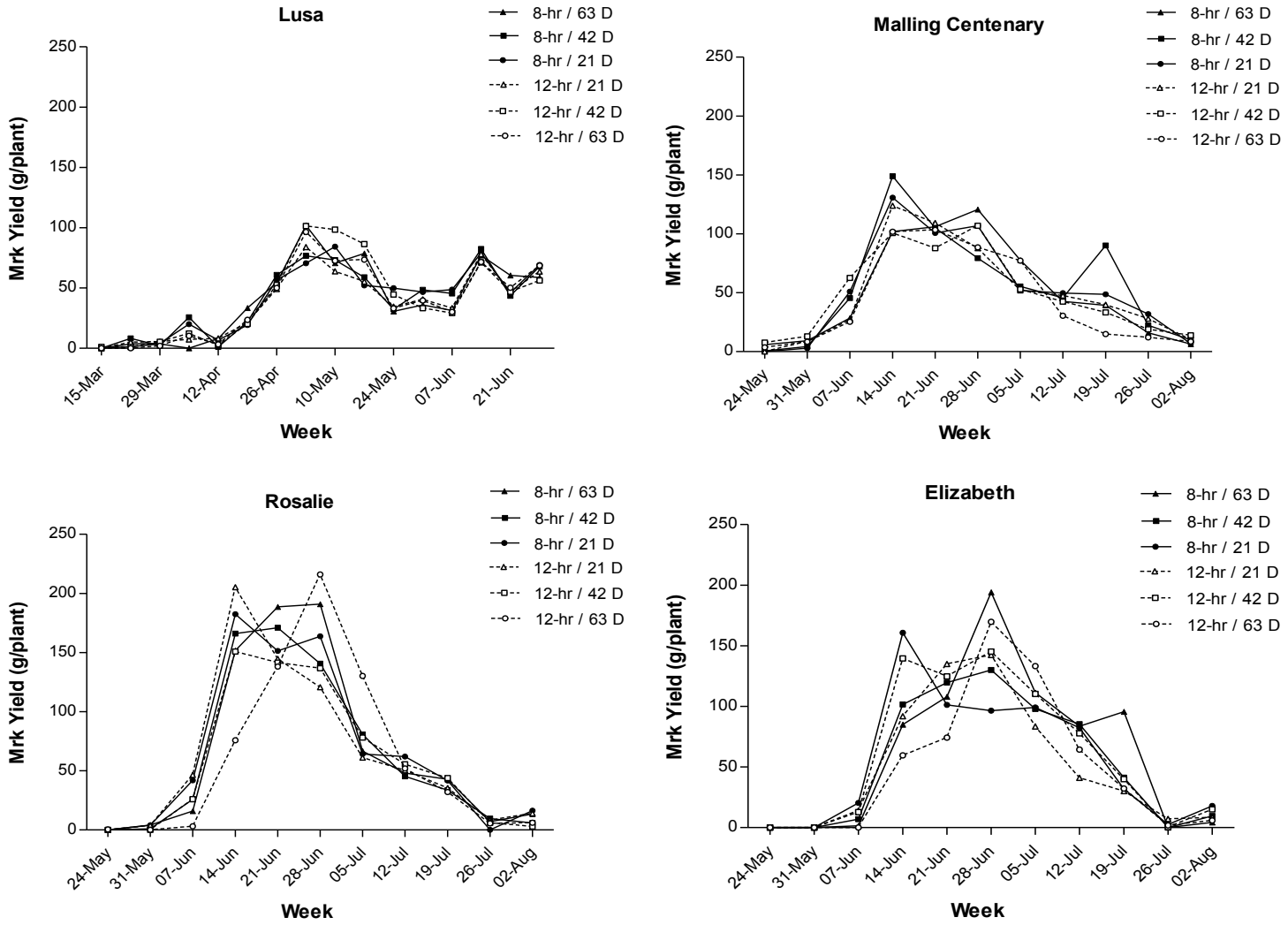

Figure 7.22 Treatment effects on weekly marketable yield for cultivars Lusa (n=3) and Malling Centenary, Rosalie and Elizabeth (n=4). Mrk= marketable. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

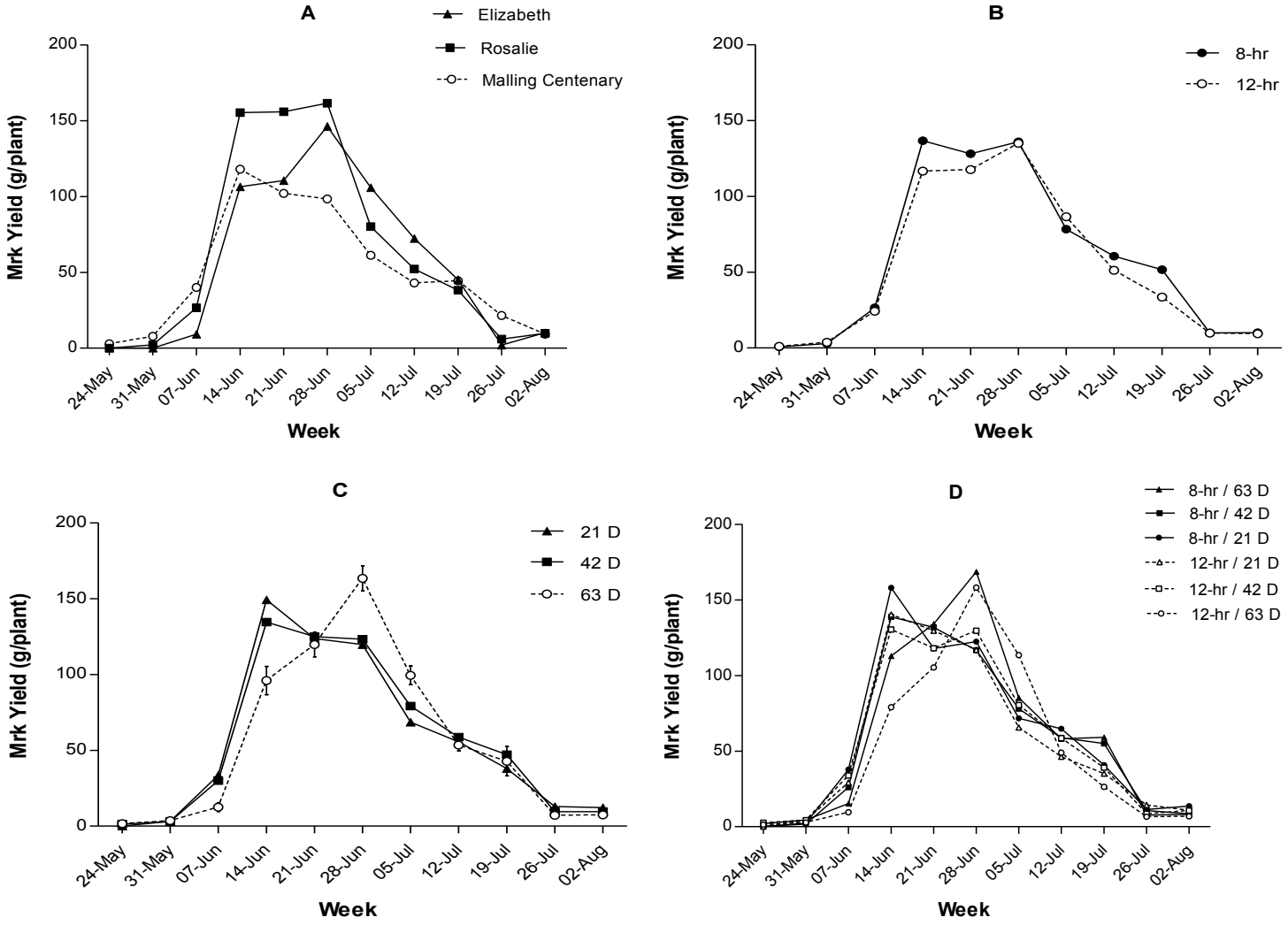

Figure 7.23 Effect of cultivar (A, n=24), number of hours of lighting (B=36), number of days of lighting (C, n=24) and interaction between the light treatments (D, n=12) on weekly marketable yield for Malling Centenary, Rosalie and Elizabeth (n=4). Mrk= marketable. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D).

7.3.2.5 *Combined Treatment Effects*

Figure 7.24 and Figure 7.25 shows a representative bag containing six strawberry plants for Treatment C and Treatment F for Lusa in the glasshouse production and the remaining cultivars Malling Centenary, Rosalie and Elizabeth in the polytunnel production. The photographs for the polytunnel cultivars show that the plants propagated with 12-hrs per day of supplementary lighting for 63 days (Treatment F) had a greater number of trusses, developing fruits (white and green) and ripe fruits compared to those propagated with 8-hrs per day of supplementary lighting for 21 days (Treatment C) whereas no such differences are seen for Lusa.

Figure 7.26 shows the marketable yield, berry number, berry weight and percentage Class 1 for each cultivar in Treatment C (8-hrs / 21D) and Treatment F (12-hrs / 63D). For Lusa no significant differences in yield, berry number or percentage Class 1 between treatments was found, but there was a significant reduction in average berry weight of 9% from Treatment C to Treatment F (P=0.033). In the polytunnel production of Malling Centenary, Rosalie and Elizabeth there was also no significant differences in yield between the treatments. However, marketable berry number was significantly greater in Treatment F compared to Treatment C by 15%, 20% and 17% for Malling Centenary, Rosalie and Elizabeth respectively (P=0.022). There was a significant reduction in average berry weight in Treatment F compared to Treatment C of 33%, 20% and 15% respectively (P<0.001), and a significant reduction in the percentage Class 1 (P<0.001) by 5%, 3% and 9% respectively.

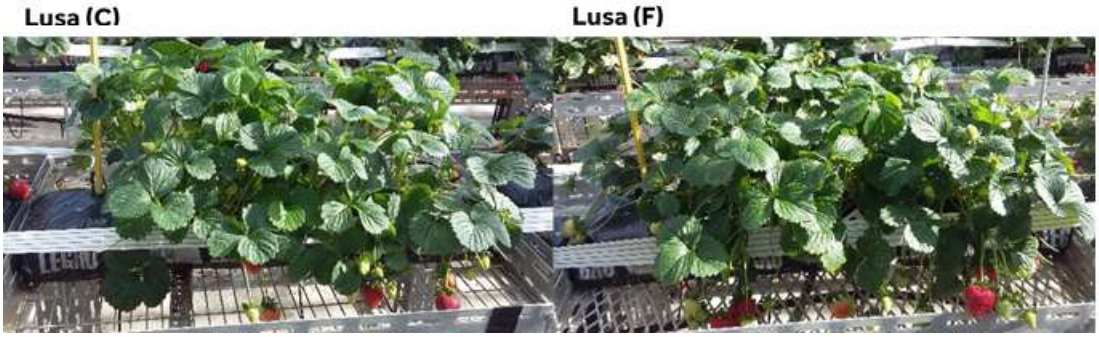

Figure 7.24 Photograph of the Junebearer cultivar Lusa. A representative bag from Treatment C (left) and Treatment F (right). Each bag contains six plants. Treatments were: C (8-hrs supplementary lighting per day for 21 days) and Treatment F (12-hrs supplementary lighting per day for 63 days). Photographs were taken 29th April June 2016.

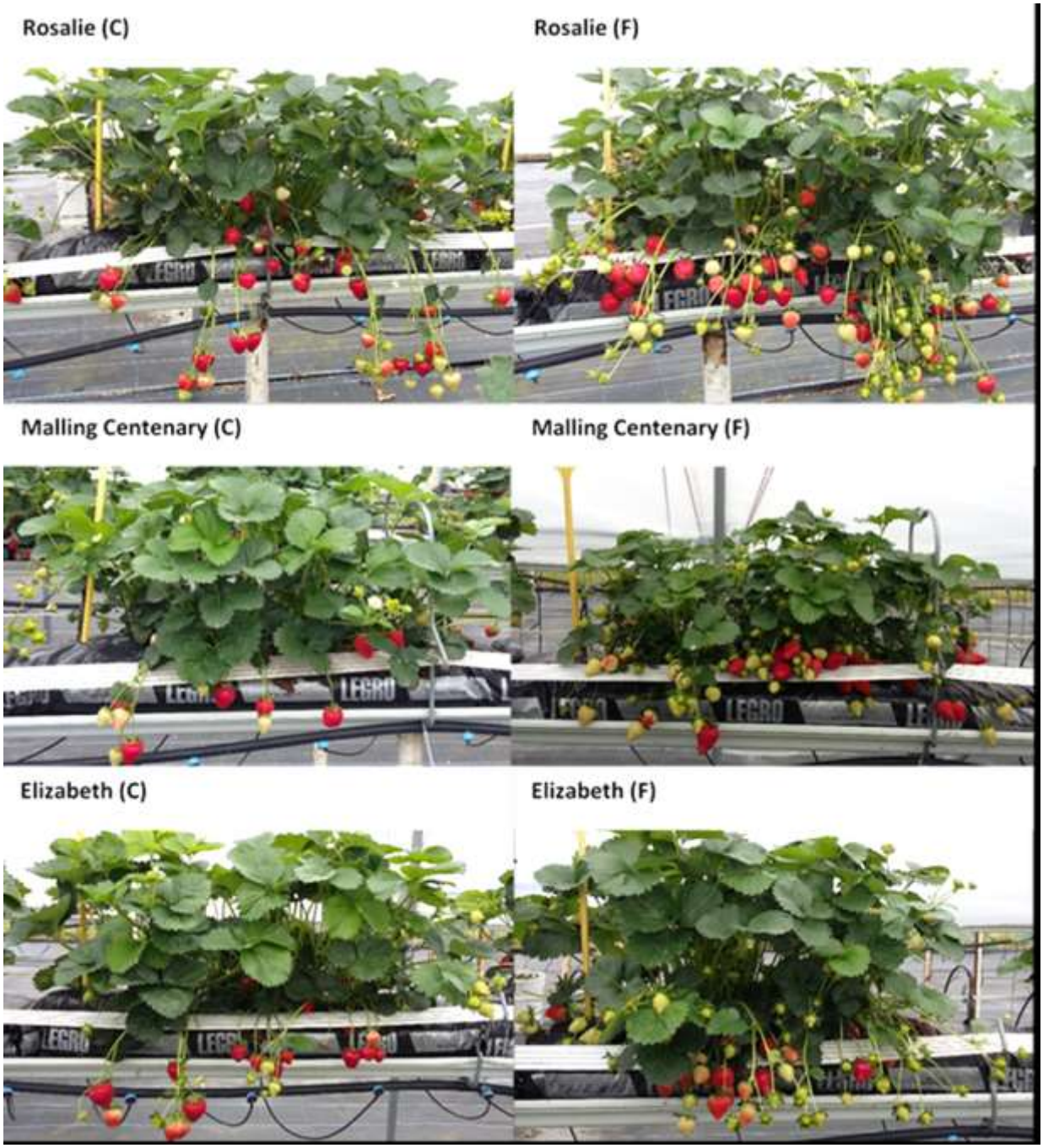

Figure 7.25 Photograph of Junebearer cultivars Rosalie (top), Malling Centenary (middle) and Elizabeth (bottom). A representative bag of each cultivar from Treatment C (left) and Treatment F (right). Each bag contains six plants. Treatments were: C (8-hrs supplementary lighting per day for 21 days) and Treatment F (12-hrs supplementary lighting per day for 63 days). Photographs were taken on 21st June 2016.

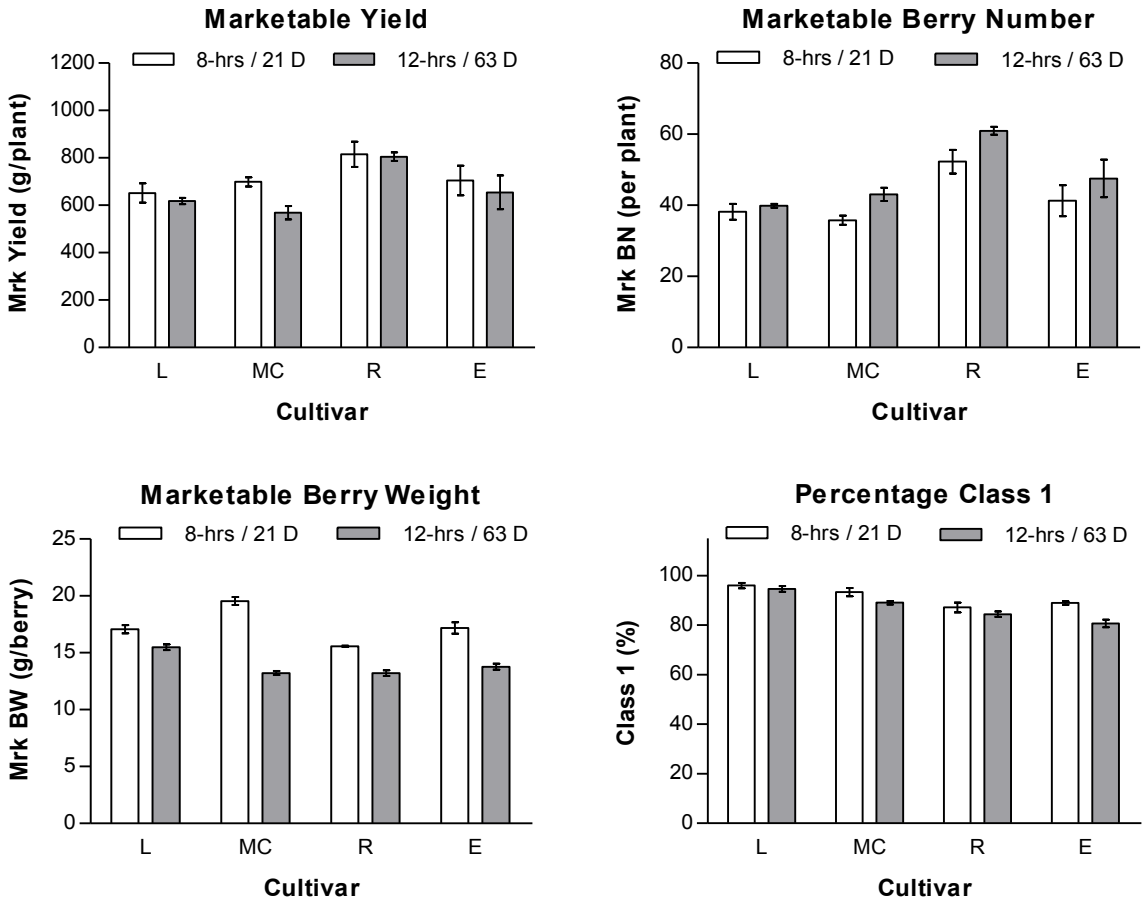

Figure 7.26 Treatment effects on marketable yield, berry number, berry weight as well and percentage Class 1 of cultivars Lusa (L) (n=3), Malling Centenary (MC), Elizabeth (E) and Rosalie (R) (n=4). Mrk= marketable, BN= berry number, BW= berry weight. The vertical line on each bar shows ±S.E.M. Treatments were 8-hrs of supplementary lighting provided for 21 days (8-hrs / 21 D) and 12-hrs supplementary lighting provided for 63 days (12-hrs / 63 D).

7.3.2.6 *Final Destructive Harvest (DH2)*

Crown Number

Treatment effects on crown number for Lusa is shown in Table 7.5, there were no significant main effects or interactions between the treatments, the mean crown number per plant was 5.3±0.2.

Treatment effects on crown number for the remaining cultivars is shown in Table 7.6; there was a significant difference between cultivars (P<0.001). The difference between Elizabeth (7.2±0.3 crowns / plant) and Rosalie (7.4±0.3) was not significant, but crown number of both was significantly greater than Malling Centenary (5.8±0.2). Crown number was significantly higher in 63D and 42D compared 21D by 28% and 17% respectively (P<0.001). Crown number was also 9% greater in the 12-hr treatment than the 8-hr treatment, but this was just not-significant (P=0.051).

Crown Dry Weight

Treatment effects on crown dry weight for Lusa is shown in Table 7.5, there were no significant main effects or interactions between the treatments, the mean crown dry weight was 13.7±0.29 g / plant.

Treatment effects on crown dry weight for the remaining cultivars is shown in Table 7.6, there was a significant difference between cultivars (P<0.001). The difference between Elizabeth (7.23±0.44 g / plant) and Rosalie (7.89±0.41) was not significant, but crown dry weight of both was significantly greater than Malling Centenary (4.53±0.17). The interaction between the cultivars and number of hours of lighting per day was significant (P=0.021) such that for Elizabeth crown dry weight was 52% greater in the 12-hr treatment compared to the 8-hr treatment whereas there was no significant difference for Malling Centenary and Rosalie. Crown dry weight generally increased as the number of days of lighting increased, but overall no significant effect of the number of days of lighting was found.

Leaf Number

Treatment effects on leaf number for Lusa is shown in Table 7.5, there were no significant main effects or interactions between the treatments, the mean leaf number per plant was 27.8±0.9.

Treatment effects on leaf number for the remaining cultivars is shown in Table 7.6, there was a significant difference between cultivars (P<0.001). The difference between Elizabeth (45.9±1.8

leaves / plant) and Rosalie (49.5±1.7) was not significant, but leaf number of both was significantly greater than Malling Centenary (36.7±1.3). Leaf number did not differ significantly between 63D and 42D but was significantly ($P<0.001$) higher in both compared to 21D (31% and 22% respectively). Leaf number was generally greater in the 12-hr treatment than the 8-hr treatment, but this was not significant.

Leaf Area

The leaf area of Lusa was not collected. Treatment effects on leaf area for the cultivars Malling Centenary, Rosalie and Elizabeth is shown in Table 7.6. Leaf area was significantly ($P<0.001$) greater in Elizabeth (4.1 m^2 / plant) and Rosalie (3.9) compared to Malling Centenary (3.3) and there was no significant difference between Elizabeth and Rosalie. Leaf area was generally lower in the 12-hr treatment compared to the 8-hr treatment, and in 42D and 63D compared to 21D but no significant differences between the treatments or interactions were found.

Leaf Dry Weight

Treatment effects on leaf dry weight for Lusa is shown in Table 7.5. Leaf dry weight was significantly greater in the 8-hr treatment compared to the 12-hr treatment (by 22%); there was no significant effect of the number of days of lighting on leaf dry weight or an interaction between the treatments.

Treatment effects on leaf dry weight for the remaining cultivars is shown in Table 7.6, there was a significant difference between cultivars ($P<0.001$); leaf dry weight was significantly greater in Elizabeth (25.86±1.16 g / plant) compared to Rosalie (17.98±0.91) and Malling Centenary (13.26±0.56). There was a significant interaction between the cultivars and number of days of lighting ($P=0.005$) such that for Elizabeth, leaf dry weight was significantly greater in 42D compared to both 21D and 63D (37% and 19% respectively) whereas, for Malling Centenary and Rosalie there were no significant differences between treatments. Leaf dry weight was generally greater in the 12-hr treatment compared to the 8-hr treatment, but no significant effect of the number of hours of lighting was found.

Total Dry Weight

Treatment effects on leaf number for Lusa is shown in Table 7.5, total dry weight was significantly greater in the 8-hr treatment compared to the 12-hr treatment by 13%; there was no significant

effect of the number of days of lighting on leaf dry weight or an interaction between the treatments.

Treatment effects on total dry weight for the remaining cultivars is shown in Table 7.6. Total dry weight did not significantly differ between Elizabeth (48.34±2.15 g / plant) and Rosalie (44.01±1.79) but was significantly (P<0.001) greater in both compared to Malling Centenary (29.26±0.96). There was a significant interaction between the cultivars and number of days of lighting (P=0.044) such that in Elizabeth, total dry weight was significantly greater in 63D and 42D compared to both 21D (20% and 32% respectively), whereas for Malling Centenary and Rosalie there were no significant difference between any treatments. Total dry weight was generally greater in the 12-hr treatment compared to the 8-hr treatment, but no significant effect of the number of hours of lighting was found.

Table 7.5 Treatment effects on DH2 results for the cultivar Lusa. Data shown is crown number (CN), crown dry weight (CDW), leaf number (LN), leaf dry weight (LDW) and total dry weight (TDW) (n=9). All data is presented on a per plant basis. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D). P. Values and LSDs for the main effects and interactions are shown.

Cultivar	Hours	Days	CN	CDW (g)	LN	LDW (g)	TDW (g)
Lusa	**8-hrs**	**21 D**	5.1	14.1	26.7	35.4	79.7
		42 D	5.0	13.6	25.9	30.3	74.2
		63 D	5.9	14.3	31.8	30.7	75.8
	12-hrs	**21 D**	4.6	123	26.4	28.3	66.4
		42 D	5.8	13.3	30.4	26.8	68.7
		63 D	5.3	14.5	25.3	23.9	68.3
P. Value							
Hours			0.758	0.172	0.690	0.009	0.026
Days			0.201	0.206	0.616	0.212	0.941
H x D			0.227	0.373	0.045	0.745	0.683
LSD							
Hours			0.72	1.13	3.52	4.30	7.64
Days			0.88	1.38	4.31	5.27	9.36
H x D			1.25	1.96	6.10	7.46	13.24

Table 7.6 Treatment effects on DH2 results for the cultivars Malling Centenary, Rosalie and Elizabeth. Data shown is crown number (CN), crown dry weight (CDW), leaf number (LN), leaf dry weight (LDW) and total dry weight (TDW) (n=8, except leaf area n=4). All data is presented on a per plant basis. Treatments were 8-hrs (08:00 to 16:00) or 12-hrs (07:00 to 19:00) of supplementary lighting provided for 21, 42 or 63 days (D). Probability values for the main effects and interactions are shown.

Cultivar	Hours	Days	CN	CDW (g)	LN	LA (m^2)	LDW (g)	TDW (g)
Malling	**8-hrs**	**21 D**	5.0	3.9	31.0	3.8	12.5	27.9
Centenary		**42 D**	5.4	3.8	33.1	3.5	13.3	28.4
		63 D	6.4	4.1	41.5	3.1	14.2	31.2
	12-hrs	**21 D**	4.9	5.3	34.3	3.8	16.4	34.2
		42 D	6.0	4.7	39.0	3.5	12.1	27.4
		63 D	7.0	5.3	41.0	3.1	11.2	26.5
Rosalie	**8-hrs**	**21 D**	7.0	8.1	44.6	4.2	18.5	46.4
		42 D	7.6	7.7	50.5	4.2	16.3	42.8
		63 D	7.4	7.3	53.8	4.2	17.1	40.8
	12-hrs	**21 D**	6.5	6.7	38.8	3.8	22.0	42.4
		42 D	7.0	9.2	51.8	3.5	19.1	48.0
		63 D	7.0	8.4	57.8	3.7	15.1	43.7
Elizabeth	**8-hrs**	**21 D**	5.5	5.2	37.0	3.7	22.3	39.1
		42 D	7.5	6.1	51.1	3.9	30.1	50.6
		63 D	6.8	5.9	44.1	4.5	22.2	41.2
	12-hrs	**21 D**	6.5	6.6	38.8	4.2	22.0	42.4
		42 D	8.0	8.8	48.8	4.3	30.3	56.5
		63 D	8.6	10.8	55.6	3.9	28.5	60.2
P. Value								
Cultivar			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Hours			0.051	<0.001	0.210	0.084	0.271	0.056
Days			<0.001	0.107	<0.001	0.534	0.218	0.317
C x H			0.349	0.021	0.609	0.205	0.679	0.103
C x D			0.581	0.205	0.439	0.397	0.005	0.044
H x D			0.126	0.126	0.423	0.518	0.675	0.712
C x H x D			0.714	0.387	0.269	0.480	0.150	0.146
LSD								
Cultivar			0.68	0.95	4.03	0.40	2.45	1.09
Hours			0.56	0.77	3.29	0.33	2.00	0.89
Days			0.68	0.95	4.03	0.40	2.45	1.09
C x H			0.97	1.34	5.70	0.57	3.47	1.54
C x D			1.19	1.64	6.99	0.69	4.25	1.89
H x D			0.97	1.34	5.70	0.57	3.47	1.54
C x H x D			1.68	2.32	9.88	0.98	6.01	2.68

7.4 Discussion

There are many ways in which the conditions during the propagation phase influence the growth and development of strawberry transplants; the most important conditions include photoperiod, temperature and nutrition. However, a positive effect of increased light intensity on floral development in strawberry has also been demonstrated (Dennis 1970; Chabot 1978) and, similarly, negative effects of shading during the period of flower initiation have been found (Awang & Atherton 1995; Demirsoy et al. 2007). The results of the experiment (Chapter 6) showed that inflorescence number, berry number and marketable yield were significantly improved in Junebearer strawberry plants propagated with 8-hrs of high intensity supplementary lighting compared to those under ambient light levels. In that experiment, 8-hrs of supplementary lighting was provided for 49 days (13th October to 1st December 2014) and, on average, marketable fruit yield was improved 48% for the Junebearer cultivars. The experiment described in the present chapter was designed to examine the impact of the duration of supplementary lighting provided during the propagation phase on cropping performance of Junebearer strawberry cultivars to see if an additional yield benefit could be obtained.

Supplementary lighting was provided for 8-hrs or 12-hrs per day for 63, 42 or 21 days from 1st October, 22nd October and 12th November to 3rd December 2015 respectively. Overall, increasing the duration of supplementary lighting had a positive effect on flower and fruit number in the polytunnel production of cultivars Malling Centenary, Rosalie and Elizabeth; the results showed that the number of flowers and fruits per plant were generally greatest in plants propagated with 12-hrs of supplementary lighting for 63 days, although there was a delay at the start of cropping. There was less of a difference between treatments in the glasshouse production of Lusa, but the results did show flower and fruit number was higher in the 12-hr treatment compared to the 8-hr treatment later into cropping (after 10 weeks). The number of inflorescences and marketable berries per plant were also improved in the polytunnel cultivars, with an additional 3.7 inflorescences and 7.4 berries per plant in Treatment F (12-hrs of supplementary lighting per day for 63-days) compared to Treatment C (8-hrs per day, 21-days). In Lusa, although inflorescence number and marketable berry number also generally increased with a longer duration of supplementary lighting, no significant differences between treatments were found.

The duration of supplementary lighting also influenced the cropping profiles since the smaller transplants flowered earlier than the larger transplants. Overall, flowering was 15 days earlier in the plants in Treatment C (8-hrs / 21D) compared to those in Treatment F (12-hrs / 63D) and the weekly flower and fruit counts showed that in the early stages of cropping the number of flowers and developing fruits was higher in treatments where a shorter duration of supplementary lighting was provided.

Despite the positive effects of increased lighting on inflorescence number and marketable berry number for the cultivars in the polytunnel, there were no significant differences in marketable yield found. This was because the average berry weight declined approximately 4 g / berry, and the un-marketable berry number increased by 8.2 berries per plant leading to a 5% reduction in the percentage Class 1. The increase in un-marketable berry number in the polytunnel was likely due to a greater number of berries being graded out due to their small size as berries less than 10 g were not equivalent to being 22 mm across the shoulder, the smallest acceptable size for marketability in the EU (UNECE 2010). To ensure that this was the reason for the increase in un-marketable berry number it would have been beneficial to have separated out the un-marketable berries into those that were un-marketable only due to small size and those that were un-marketable due to other characteristics (non-uniform shape or colour, pest or disease damage). However, although inflorescence number increased by 3.7 per plant there was only an additional 7.4 berries in Treatment F (12-hrs / 63 D) compared to Treatment C (8-hrs / 21 D) which does suggest that berries were being graded out. In the glasshouse production of Lusa, a reduction in average berry weight of 1.5 g / berry was also found, although there was no significant difference in the un-marketable yield and the percentage Class 1 between treatments suggesting that, although, average berry weight declined this was not to a great enough extent to negatively affect the yield.

The reduction in average berry weight in both the polytunnel and glasshouse suggest that the crop load was too great for the plants to support meaning, un-like in the previous experiments, berry weight could not be sustained. The cultivars Rosalie and Elizabeth were used in both this experiment and the previous experiment (Chapter 6); in the previous experiment, the maximum number of berries (marketable and un-marketable) recorded for these cultivars was 54 and 44 per plant respectively with an average marketable berry weight of 27 and 23 g / berry whereas in this experiment the maximum number of berries per plant was 82 and 72 per plant with an

average marketable berry weight of 13 and 14 g / berry respectively. This shows that there was a much higher number of berries per plant (and a higher crop load) in the present experiment which likely led to the reduction in average berry weight. Vegetative growth in early spring is important to ensure a large plant is established to support the following crop, and canopy size is particularly important for light interception so that enough assimilates are produced to supply the developing berries which are a strong sink, with typically 40-50% of dry matter allocated to the fruit (Olsen et al. 1985 cited in Pérez De Camacaro et al. 2004). Vegetative growth was tracked during the production phase through non-destructive leaf counts and petiole measurements made every week throughout cropping. Percentage light interception was also calculated for five weeks during cropping. Petiole length of the first new leaves to emerge from the crown in the spring was measured and this is a reliable indicator of plant vigour and petiole length declined from 21 days of supplementary lighting to 63 days and was lower in the plants propagated under 12-hrs of supplementary lighting compared to those with 8-hrs of supplementary lighting. This indicates that these plants were not as vigorous. Leaf number on the other hand was greater in the 12-hr plants compared to the 8-hr treatment and in 63D compared to 42D and 21D but leaf area analysis did not reveal any significant differences between treatments showing that although leaf number was greater, the individual leaf size must have been smaller as the total leaf area was un-affected and thus there was very little difference in light interception between treatments. The lack of vegetative support for an increased number of berries may also explain why berry weight declined, thus neutralising the effect of increased berry number on the marketable yield.

The size of the transplants increased with the duration of supplementary lighting, and few differences in the dry weight ratio of the leaves, crowns, petioles and flowers between treatments were found. This shows that the size of the whole plant had increased uniformly rather than just an individual plant component. In winter glasshouse crops, Ceulemans et al. (1986) showed that strawberry plants under supplementary illumination had longer petioles, inflorescences and a greater leaf area; they also observed in controlled environment conditions that CO_2 exchange rates increased up to PPFD 500-600 µmol m^{-2} s^{-1} in strawberry and so increased radiance led to increased CO_2 uptake as the plants were at a higher point on the photosynthetic light response curve. Chabot (1978) and Jurik et al. (1982) also demonstrated that net CO_2 exchange, individual leaf and thickness as well expansion rate were greatest in high

light environments in wild strawberries which also reached their maximum photosynthetic rate more quickly that plants in low light conditions. These results suggest that radiation is a limiting factor in strawberry, and potentially during the propagation phase when the natural light levels are low. Increasing light intensity would therefore be beneficial to CO_2 uptake and growth of the strawberry transplants.

The increase in inflorescence number resulting from the increase in the duration of supplementary lighting was likely to be due to the greater size of transplants produced since positive correlations between crown size, canopy size and plant weight of strawberry transplants and early and total yield have previously been reported (Darrow 1966; Hughes 1967; Abbott 1968; Lacey 1973; Faby 1997; Le Miere et al. 1998; Human 1999; Bussell et al. 2003; Johnson et al. 2005; Takeda & Newell 2006; Bartczak et al. 2010; Cocco et al. 2010; Fridiaa et al. 2016). Excessive vegetative growth during plant propagation however is considered un-desirable as the rate of vegetative growth may occur at the expense of reproductive development; runner production in the autumn is particularly undesirable as it prevents the reproductive development of axillary buds and thus reduces the number of inflorescences and flowers per plant (Smeets & Kronenberg 1955). However, despite the greater size of the transplants, inflorescence number was greater in the 12-hr treatment compared to the 8-hr treatment (17% or 1.9 per plant) and with 63 days lighting compared to 21 days lighting (18% or 2.0 per plant), and there was no significant difference in the number of flowers per inflorescence between treatments. This indicates that there was no negative effect of the increased vegetative growth resulting from the treatments on reproductive activity.

The results of this experiment show that there is a potential to further improve fruit yield by extending the period of supplementary lighting. However, a significant reduction in average berry weight, increase in un-marketable yield and consequential reduction in the percentage Class 1 meant there was no effect on marketable yield overall. This is potentially due to light interception becoming a limiting factor during fruiting and so further investigation is required to find a way to ensure that the average berry weight is maintained so that marketable fruit yield can also be improved.

Chapter 8 General Discussion

8.1 Background and Research Objective

The British horticultural industry is an important sector valued at £3.1 billion in 2015 with a large contribution from outdoor and glasshouse cultivated fruit (£695 million) and strawberries in particular (£284 million) (DEFRA 2016). The strawberry sector has changed dramatically in recent times with heavy investment in breeding programmes and development of new technologies. The introduction of polytunnels, greater uptake and improvement of Everbearer cultivars, as well as the move to out-of-soil production has led to a step-change in strawberry production in the United Kingdom, which is now regarded as a remarkable success story in British farming. Home production levels have increased dramatically, from 46.8 thousand tonnes (1985-89) to 115.5 thousand tonnes (2010-15) despite a decline in the total crop area during the same period (5.7 to 4.5 thousand ha) (DEFRA 2016). Overall, what once was a seasonal crop and risky to grow profitably at a commercial scale, has become one of the most valuable crops in the UK, with high quality fresh-fruit available for six months of the year. Currently, the UK supplies 68% of its total strawberry requirement, with imported fruit primarily to satisfy the out-of-season demand. However, consumer demand for home-grown produce continues to grow and so one of the main goals of the British strawberry industry is to supply the market 12 months of the year. New technology and cultivar breeding are important in achieving this goal and have paved the way for further season extension in the UK in recent times; winter glasshouse cropping for example, was once considered un-economical, but with the introduction of specialist low chill cultivars, such as Driscoll's© Lusa™, profitable greenhouse growing using supplementary lighting and heating to force early cropping has enabled fresh British strawberries to be available as early as mid-March. The improvement of the yield and quality of Everbearer strawberries had also enabled season extension later into the year, with fruit available from late summer through to mid-autumn.

It is not only strawberry fruit production that has seen some dramatic changes, the way in which strawberry plants are produced has also been revolutionised in recent years. The commercially cropped strawberry (*Fragaria x ananassa* Duch.) is a hybrid, and so vegetative propagation is essential to ensure the next generation of plants are genetically identical to the last. The traditional method of producing strawberry transplants involves the establishment of mother

plants in field nurseries, where genetically identical daughter plants formed on runners (stolons) produced in late summer are dug up once rooted and either cold stored or dispatched to the fruit growers. These are known as bare-root transplants, and whilst strawberry transplants continue to be produced this way, the relatively new plug-plant method is rapidly gaining popularity. In this method, mother plants are grown hydroponically on raised gutters in either a polytunnel or glasshouse and the runners hang down from the mother plant; the daughter plants are unable to root and are instead cut and struck into multi-celled trays filled with substrate and overhead misted for three to four weeks in a high humidity environment to promote rooting and the formation of a plug. These plugs can then be dispatched to the growers or potted on to produce larger transplants with a high yield potential known as tray plants. The use of plug plants is increasing in popularity, particularly in Northern Europe, as although costlier to produce, they have a better uniformity, survival rate and reduced disease risk compared to traditional bare-root plants (Crawford et al. 2000; Durner et al. 2002; Bish et al. 2003; Takeda et al. 2004; Cocco et al. 2010; Husaini & Neri 2016).

There are now many different types of propagated plant material available for growers including: misted tips, tray plants, bare-roots, frigo plants, waiting bed and variations within these types. The combination of different growing systems, plant types and propagation material have contributed to the lengthening of the British strawberry season; fruit is available mid-March to May (from glasshouse crops) through May, June and July (early and main-season Junebearer crops) and into August, September and October (late-Junebearer and Everbearer crops). Growers will use various plant types and propagation material to schedule a programme of production on farm to extend the season and make the best use of space, labour and resources to maximise profits. This means that although strawberries are perennials, the plants are replaced each year with new transplants supplied by specialist plant propagators. The quality of the plant material supplied is therefore becoming ever more important. Verheul et al. (2006) stated that plant quality is the most important factor in annual strawberry production and many other researchers have highlighted the importance of the quality of the growers starting plant material over the years (Fernadez et al. 2001; Johnson et al. 2005; Bartczak et al. 2010; Cocco et al. 2010; Kirschbaum et al. 2010a; Andriolo et al. 2014). However, with conditions primarily to optimise the quality of the most widely grown and researched cultivar 'Elsanta' there is limited knowledge on the most appropriate conditions in which to propagate the new strawberry

cultivars being released from modern breeding programmes. This is particularly problematic for varieties which were not bred under UK conditions and considering the way in which plants are propagated has evolved from the traditional bare-root method.

The objective of the experiments carried out in this study was to examine the impact of crop management during the propagation phase on transplant growth, yield potential and cropping performance of a range of new Junebearer and Everbearer strawberry (*Fragaria x ananassa* Duch.) cultivars currently grown on a commercial scale in the UK. Five experiments were conducted between September 2013 and 2016 examining several conditions during the propagation process which impact upon the growth and development of strawberry transplants, these included: tipping date (Chapter 3), daughter plant position (Chapter 4), nitrogen concentration and winter chill accumulation (Chapter 5), temperature and light intensity (Chapter 6 and 7). The results obtained show the importance of the propagation phase in determining the yield potential of strawberry transplants as well as the subsequent productivity in the following fruiting season. In the remainder of this chapter, the key results and their potential implications are discussed.

8.2 Impact of conditions during the propagation phase on strawberry transplant growth and yield potential

There are many factors growers use to assess the quality of strawberry transplants including the maturity, size and uniformity of the plants as well as the physical condition (free from root damage, tip burn, nutrient deficiencies), phyto-sanitary condition and trueness to type (Kirschbaum et al. 2010b). The promotion of vegetative growth in the early stages of the plant propagation process is essential to ensure strawberry daughter plants can reach an optimal vegetative state for maximal flower number by providing a larger number of flowering sites, and to support a high rate of initiation. Crown diameter is regarded as one of the most important indicators of plant yield potential in the industry, and many researchers have found positive correlations between crown diameter and fruit yield over the years. Bussell et al. (2003) for example showed a linear relationship between crown size at planting and fruit yield, with a 15 g and 27 g increase in marketable and total fruit yield with every 1 mm increase in crown size and Le Miere et al. (1998) found that smaller crowned plants of 'Elsanta' produced the smallest leaf number, leaf area and intercepted the lowest amount of PAR during cropping, resulting in a lower

yield. Strawberry transplants are therefore typically graded and sold according to crown size. However, Fridiaa (2016) suggested that a range of parameters should be used to assess plant yield potential, particularly for Day-Neutral and Everbearer cultivars which continue to flower and fruit through the season and so crown size alone may not be a reliable indicator of yield potential (as in the case of Junebearers where all the flower initials are present within the crown at planting time). As well as crown diameter, positive relationships between crown number, leaf number, leaf area, root development and plant weight on cropping performance have also been reported for strawberry, supporting the suggestion of a more plant based approach to the assessment of yield potential (Lacey 1973; Human 1999; Johnson et al. 2005; Takeda & Newell 2006; Bartczak et al. 2010; Cocco et al. 2010; Kirschbaum et al. 2012). In this research, at the end of the propagation phase for each experiment, a destructive harvest was carried out to determine the effect of the treatments on transplant growth and yield potential; larger more vigorous transplants had a greater yield potential than those of a smaller size due to the positive correlations between these various parameters and fruiting performance previously established in strawberry.

Results of the experiments presented in this thesis, showed that conditions during the propagation phase strongly influenced transplant growth, with larger transplants produced through a number of different means including earlier tipping, selection of earlier positioned daughters as well as increased nitrogen concentration, temperature and light intensity during the raising of the daughter plants. This shows that there are several opportunities for improving crop management to enhance transplant growth which is beneficial to the industry as stronger transplants mean fewer losses during the propagation phase and increased survival during storage, transport and after transplanting.

The effect of daughter plant position and tipping date on transplant growth was tracked through weekly leaf counts, root scores and measurements of crown diameter. The initial size of the daughter plant was shown to be important and had a lasting effect on the growth of the transplants throughout the propagation phase. This is likely to be due to the conditions in which the daughter plant was formed; earlier tipping, for example, gives the daughter plant time to grow and establish in conditions more suitable for vegetative growth, as the shortening days and falling temperatures mean conditions are continuously becoming more inductive for reproductive growth as the season progresses from late summer into autumn. The same applies to the first daughter plants produced on the stolon, as these are formed earlier in the season compared to

those further down the runner string which develop under conditions less favourable for vegetative growth. The benefits to the initial establishment and growth of the daughter plants did not appear to be nullified by subsequent growth, meaning that at the end of the propagation phase there was a still a positive effect on the size of the transplant. Increased nitrogen, temperature and light intensity also had a positive effect on the size and condition of the transplants, nitrogen having an important role in plant establishment and the promotion of vegetative growth including the development of branch crowns which have been identified as a pre-requisite for satisfactory flowering strawberry (Abbott 1968) whilst increased temperature and light intensity is known to have a positive effect on photosynthetic performance, carbon assimilation and biomass production (Chabot 1978; Jurik et al. 1982; Ceulemans et al. 1986).

The promotion of vegetative growth during plant propagation means that there was also a positive effect on yield potential, since as previously stated, larger transplants were assumed to have a greater yield potential than smaller transplants. In three of the five experiments, the treatments in which the largest transplants were produced also had the greatest marketable fruit yield demonstrating that the size of the transplant (and individual components) can be used as a measure of yield potential. Transplants grown at a higher concentration of nitrogen (120 ppm) had a greater total dry weight than those at a lower concentration (60 ppm) by 1.2 g / plant on average and the marketable fruit yield in the following season was improved by 7% (57 g / plant). Earlier tipping led to greater transplant size and a higher yield in the following season with an average increase in the transplant dry weight of 4.8 g / plant and marketable fruit yield of 19% (170 g / plant) in daughter plants tipped on 1st July compared to 30th July. Increased light intensity and temperature during the propagation phase had the most profound effect on transplant growth and subsequent fruit production; plants produced with 8-hrs of high intensity supplementary lighting and an average temperature of 21°C produced larger transplants than those under ambient light levels and an average temperature of 13°C, and overall marketable yield was substantially higher in these plants (71%, 403 g / plant).

However, there were two experiments where larger transplants were produced but a yield benefit was not obtained. Larger transplants were produced when daughter plants were harvested from the first position on the runner (primary daughters) but there were no significant differences in yield found between the primary, secondary and tertiary daughters. This was likely to be because (although significant) the differences in crown size, canopy size and plant weight

between treatments were very small, and possibly not large enough to result in a yield benefit. In contrast, large differences in transplant size were obtained in the final experiment where plants were propagated with different durations of supplementary lighting ranging from 8-hrs per day for 21 days to 12-hrs per day for 63 days; overall, the largest transplants were produced with 63 days of supplementary lighting for 12-hrs per day (total dry weight of 11 g / plant). However, at the end of the production phase, despite a significant increase in the number of inflorescences, flowers and fruits per plant, there were no differences in marketable yield between treatments. This was due to a reduction in average berry weight which was not found in the previously described experiments were a significant yield benefit was obtained. The fact that inflorescence number, flower number and berry number were significantly increased does show that these plants had a higher yield potential and so overall the transplant size was still a good indicator of plant yield potential.

Overall the quality and yield potential of strawberry transplants is determined by the conditions in which they are propagated. The results of the experiments presented in this study show that the growth and yield potential of both Junebearer and Everbearer strawberry transplants can be improved through manipulating the conditions during the propagation phase, with the aim of driving greater plant growth to maximise the number of available flowering sites. There is therefore the potential to improve crop management during plant propagation to stimulate greater vegetative growth and this can be achieved through many different methods. In this work a positive effect of earlier tipping, increased nitrogen concentration and increased temperature and light intensity was demonstrated.

8.3 Impact of conditions during the propagation phase on strawberry yield and yield components

Like many other commercial crops, the economic success of strawberry production depends primarily on the yield. The yield of strawberry is a function of various components including the number of inflorescences per plant, the number of flowers per inflorescence, the number of flowers per plant, the number of berries per plant and the average berry weight. Correlations between several of these yield components and fruit yield have previously been established in strawberry (Lacey 1973; Hortynski 1989; Shokaeva 2008). The components are interrelated, and so an increase in one component does not necessarily lead to an increase in fruit yield. For

example, excessive flowering can lead to an increase in berry number but could lead to a reduction in average berry weight which means the overall effect on yield may be negligible or even negative (Sønsteby et al. 2013). These correlations are not always negative and so a reduction in one yield component can sometimes be compensated for by an increase in another; a reduction in the number of berries per plant for example, tends to lead to an increase in berry weight. There are also components that indirectly influence yield including crown size, canopy size and plant weight as these affect the number of inflorescences and flowers per plant. In this study, the influence of conditions during the propagation phase on yield and yield components were investigated, with the assumption that the changes in yield would be a direct result of a change in one or more yield components resulting from the treatments applied during the propagation phase.

The results of the experiments carried out have been discussed individually within each experimental chapter, but overall it has been shown that the way in which the crop is managed during the propagation phase has a major impact upon yield potential of strawberry. Primarily, the effect of the various propagation treatments was on berry number rather than average berry weight, which is in line with previous research which has shown that berry number is the primary factor influencing strawberry yield rather than berry weight (Lacey 1973; Shokaeva 2008). Earlier tipping had a significant positive effect on marketable fruit yield with an average increase in marketable yield of 170 g and 141 g / plant for plants tipped on 1st July and 15th July compared to 30th July respectively. This was due to an increase in the number of inflorescences and berries per plant whilst there was no significant effect on average berry weight. Similar results for increasing N concentration, light intensity and temperature during the propagation phase were also found. The provision of supplementary lighting and increased temperature during the propagation phase in particular had a positive impact on fruit yield; three Junebearer and three Everbearer cultivars were studied and there was an average increase in yield of 136% (573 g / plant) and 41% (233 g / plant) for each plant type respectively when comparing the combined effects of the treatments (ambient light levels, average temperature 13°C compared to 8-hrs supplemented light levels, average temperature 21°C). This was primarily because inflorescence number and berry number were improved and there was no significant effect on berry weight.

In an additional study at the University of Reading the reproductive efficiency of plants propagated under 8-hrs supplementary lighting was found to be greater than those under

ambient conditions, with dry weight analysis showing that the allocation of resources to the fruit was much greater in these plants compared to those propagated under ambient light levels and a lower temperature. The greater diversion of assimilates to the fruits explains why a negative effect on berry weight was not found, meaning yield increased due to an increase in berry number and there was no effect of a reduction in berry weight. However, for the final experiment when the duration of supplementary lighting was extended, no significant difference in yield between treatments were found despite a significant effect on inflorescence number, flower number and fruit number per plant. This was because there was a significant reduction in average berry weight and increase in un-marketable yield which was likely to be due to more berries being graded out for being too small for Class 1 standards. This shows that when crop load becomes high, assimilate availability is likely to become limiting with a consequential negative effect on berry weight. Strawberry fruits act as strong sinks with 40-50% of dry matter allocated to the fruit (Olsen et al. 1985 cited in Pérez De Camacaro et al. 2004). Hansen (1989) described how competition for assimilates between fruits can be high, especially when the fruit/leaf ratio is high. In the final experiment fruit number was significantly higher in the plants propagated with 63 days of supplementary lighting for 12-hrs per day but there was little difference in leaf number and leaf area between these and the plants produced with 21 days of lighting for 8-hrs per day. This high fruit/leaf ratio may explain the reduction in berry weight due to the greater sink with the same source capacity.

The importance of ensuring that flowers are retained in the crown has been demonstrated in this work when compared to previous studies. For example, in previous studies at the University of Reading, flower number of Everbearer cultivars increased with supplementary lighting, but at high temperature these flowers emerged during plant propagation leading to a loss of yield potential (Professor Paul Hadley, *pers. comm.*). The results of that experiment concluded that supplementary lighting in combination with low temperature (5°C) were the best conditions for optimal fruiting. However, the results presented here show a positive effect of high temperature (20°C) combined with supplementary illumination, and this was because the plants were placed in dormancy inducing conditions (short days, low light intensity and cool temperatures) after the cessation of the treatments. The plants therefore became dormant, preventing flowering until the following spring after sufficient chill had accumulated to break dormancy. The optimal photoperiod and temperature conditions for flower initiation in strawberry has been extensively

researched (Darrow 1936; Ito & Saito 1962; Smeets 1980; Sønsteby & Nes 1998; Manakasem & Goodwin 2001; Nishiyama et al. 2003; 2006; Sønsteby & Heide 2006; Verheul et al. 2006; 2007; 2007; 2008; Bradford et al. 2010; Durner 2015; 2016) and the optimum temperature for many cultivars has been established including 'Korona' (18°C), Frida (18°C) and Florence (15°C) (Sønsteby & Heide 2007). This supports the results of the experiment conducted in this study which showed a higher temperature during plant propagation benefitted the rate of reproductive development.

Overall the main components of yield in strawberry are the number of inflorescences, flowers and fruits and berry weight. The production of larger transplants was enabled through earlier tipping, increased nitrogen concentration and increased temperature and light intensity during the propagation phase and, consequently, there was a positive effect of increased transplant size on the number of inflorescences, and subsequently on marketable berry number and yield per plant. However, when crop load was high, berry weight became an important factor, and limitations on assimilate availability nullified the positive effect of extending the period of supplementary lighting on marketable fruit yield. Therefore, in order to push the ceiling of yield in strawberry further both berry number and berry weight during fruiting need to be optimised.

8.4 Impact of conditions during the propagation phase on strawberry cropping profiles and early fruit yield

Over the last thirty years, the British strawberry season has been successfully extended from as little as six weeks to more than six months; this was largely due to the introduction of polytunnels in the mid-1990s and successful breeding to improve the yield and quality of Everbearer strawberries. Further season extension has been made possible through the introduction of low-chill cultivars making winter glasshouse cropping more cost-effective. Results from this research show that conditions during the propagation phase impact upon cropping profiles, and that there is the potential to manipulate these conditions to improve early season yield. This is important for the industry as season extension and increased production on the fringes of the main season are an important goal, especially in glasshouse crops where the profitability of the system is reliant on fruit being produced outside of the main season when demand for home produce is high and so fruit prices are also high. On a large scale commercial farm, 8-12 strawberry plants are

established per running metre, and so even a small increase in yield could make a difference in terms of early season yield and profit for large-scale strawberry producers.

Earlier tipping had a positive effect on early fruit yield of the Everbearer cultivars studied and selection of earlier positioned daughter plants was also shown to have a small but beneficial effect. Increases in light intensity and temperature during the propagation phase also influenced the cropping profiles and enhanced early fruit yield of both Junebearer and Everbearer strawberry cultivars. The larger transplants had a greater yield in the early season which may be because the plants were more able to establish quickly once planted and reach the required stage of maturity to flower. Cocco et al. (2010) described how although spring flowering is determined by the accumulation of thermal time, plants must still attain a minimum size in their current development stage before progressing to the next; this means regardless of favourable environmental conditions smaller, less vigorous transplants may flower later than their larger counter parts which have been able to reach the appropriate physiological condition for flowering.

Earlier fruiting in the larger transplants may also be due to a greater availability of stored resources, which strawberry plants rely on heavily during early spring growth. During chilling resources are drawn from the leaves into the crown and stored over winter ready to be utilised once dormancy breaks and growth resumes in the spring (Archbold & MacKown 1995; Demirsoy et al. 2010; Kirschbaum et al. 2010a). Larger transplants produced prior to dormancy induction have a greater pool of resources to draw from, leading to a greater store of reserves for vigorous growth in the spring, enabling the plants flower earlier and crop more heavily early in the season.

For Everbearer cultivars, often when a significant effect on early fruiting was found there was no significant effect on yield by the end of fruiting. In the tipping date experiment for example, early fruit yield was significantly higher in plants tipped on 1st July compared to 15th and 30th July, but at the end of fruiting there was no significant difference in fruit yield between the plants tipped on 1st July and 15th July. Similarly, for daughter plant position there were small but significant increases in early season yield with the earlier positioned daughters but no significant differences in total yield between treatments. This is likely to be due to the buffering effect of continued flowering and fruiting in Everbearer strawberries, causing a dilution of the earlier treatment effects until there was a complete disappearance by the end of fruiting. Cocco et al. (2010) found this when comparing different sized crowns of the Junebearer cultivar 'Arazá' where larger crowned plants had higher early season yield than smaller crowns but there was no difference in

total season yield. They described how the effect of transplant vigour becomes diluted on the scale of total yield.

Earlier fruit production, and increased production on the fringes of the main season are important goals for the soft fruit industry at present as consumer demand for fresh, home-produced strawberry is high. Early fruiting is especially important for the profitability of glasshouse cropping where there are higher investment and production costs due the supplementary lighting and heating required to force early cropping. The results of these experiments show that conditions during the propagation phase can influence cropping profiles, and there is the potential to enhance valuable early season yield which would be of benefit to the industry providing that the yield benefit obtained out-weighed the cost. Increased production costs for the propagator as a result of implementing some of the treatments described in this research may be passed onto the grower which could be un-desirable unless the higher priced plants result in a significant increase in profit further down the production chain. Further investigation is therefore required to ensure that these solutions are cost-effective.

8.5 Future Work

There are many different factors within the propagation phase that impact on the quality and yield potential of strawberry transplants and the subsequent cropping performance, of which only a few have been studied within the time-frame of this work. Although the interaction between some factors was studied, others were examined independently and so it would be beneficial to combine factors to see if further improvements in yield can be obtained. It cannot be assumed that this will be the case for strawberry as an optimal balance between vegetative growth and reproductive development is key for successful cropping. Combining these factors (early tipping, high nitrogen concentration, increased temperature and a long duration of supplementary lighting for example) is likely to produce large, multi-crowned transplants with a high number of inflorescences, indicative of a high yield potential. However, this many not necessarily lead to a greater yield in the following season as a high crop load may lead to reduced berry weight, as shown in the final experiment. Subsequent studies are therefore required to understand how yield potential can be fully translated into actual yield in strawberry. A more physiological approach is required to optimise fruiting in strawberry, with a detailed study on light interception, canopy structure, assimilate partitioning and reproductive efficiency. This would

allow for improved crop management for current cultivars, but also provide valuable information for plant breeders for the development of new cultivars in the future with increased yield potential and reproductive efficiency. In recent studies at the University of Reading, the reproductive efficiency of plants propagated under supplementary lighting was found to be greater than those under ambient conditions, with dry weight analysis showing that the allocation of resources to the fruit was much greater in these plants. Differences between cultivars were also found, and the cultivar Rosalie was found to allocate more resources to the fruit than the cultivar Elizabeth indicating that there are inherent differences in reproductive efficiency between cultivars that could be exploited in new cultivar breeding.

A second area of future work related to the results obtained here is to study the effect of the treatments on fruit quality. Although yield is one of the most important factors for strawberry production, fruit quality is also important especially in commercial production where standards must be met for saleability. Important fruit quality characteristics include flavour, firmness, shelf life and uniformity of colour, size and shape and cleanliness and increasingly the nutritional content has also become an important issue. Strawberries have a high Vitamin C content and are very nutrient rich. The effect of the treatments on yield, may also therefore impact upon the quality and nutritional content of the fruit and so this needs to be explored. In the experiments conducted here the effect of the propagation treatments on yield, yield components and cropping profiles was the primary aim of the study, and so although fruit was sorted into marketable and un-marketable based on size (< 10 g), appearance (uniform shape and colour) and cleanliness (free from pest or disease damage), the effect of the treatments on other quality markers such as flavour, firmness, shelf-life and fruit chemistry (phenolics, flavonoids, anthocyanins) were not examined and this should be investigated further.

8.6 Concluding Remarks

The research presented in this thesis clearly shows that the propagation process plays a key role in determining the quality and yield potential of strawberry transplants which is becoming increasingly recognised as an important factor in determining cropping performance, particularly with the move to production of strawberries as an annual system. The results of the experiments revealed that there are several ways in which the yield potential of strawberry transplant can be improved including earlier tipping, increased nitrogen concentration, and increased temperature and light intensity during plant propagation. Overall, larger strawberry transplants (in terms of crown size, canopy size and plant weight) have a greater yield potential than smaller transplants and crop more heavily in the following season due to positive effects on the number of inflorescences, flowers and marketable berries produced per plant. Results of the final experiment showed that the yield potential of strawberry can be further increased by extending the period of high intensity supplementary lighting provided during the propagation phase providing an exciting opportunity to push the ceiling of strawberry production in the UK. However, to fully translate this yield potential into actual yield in the following season, assimilate availability needs to be optimised during fruiting to maintain berry size. Additional research is therefore required to truly unlock the full yield potential of modern strawberry cultivars.

References

Abbott, A.J., 1968. Growth of the strawberry plant in relation to nitrogen and phosphorus nutrition. *Journal of Horticultural Science and Biotechnology*, 43, pp.491–504.

Acuna-Maldonado, L.E. & Pritts, M.P., 2008. Carbon and nitrogen reserves in perennial strawberry affect plant growth and yield. *Journal of the American Society for Horticultural Science*, 133(6), pp.735–742.

Agarwal, S.K., 2013. Blueberries, cranberries and strawberries: heart healthy fruits. *Medical Science*, 1(1), pp.4–6.

Albregts, E.E., 1968. Influence of plant size at transplanting on strawberry fruit yield. *Proceedings of the Florida State Horticultural Society*, 81, pp.163–167.

Albregts, E.E. & Chandler, C.K., 1994. Effect of transplant chilling and planting date on fruiting response of 4 strawberry clones. *Proceedings of the Florida State Horticultural Society*, 107, pp.323–325.

Anderson, H.M. & Guttridge, C.G., 1982. Strawberry truss morphology and the fate of high-order flower buds. *Crop Research*, 22, pp.105–122.

Andriolo, J.L., Janisch, D.I., Picio, M.D., Schmitt, O.J. & Lerner, M.A., 2014. Nitrogen accumulation and monitoring by strawberry stock plants for runner tips production. *Horticultura Brasileira*, 32(3), pp.273–279.

Archbold, D.D. & MacKown, C.T., 1995. Seasonal and cropping effects on total and fertilizer nitrogen use in June-bearing and day-neutral strawberries. *Journal of the American Society for Horticultural Science*, 120(3), pp.403–408.

Armstrong, H., 2004. Strawberries Revived. *Fruit & Veg Tech*, 4(3), pp.4–9.

Atkinson, C.J., Brennan, R.M. & Jones, H.G., 2013. Declining chilling and its impact on temperate perennial crops. *Environmental and Experimental biology*, 91, pp.48–62.

Awang, Y.B. & Atherton, J.G., 1995. Growth and fruiting responses of strawberry plants grown on rockwool to shading and salinity. *Scientia Horticulturae*, 62, pp.25–31.

Bartczak, M., Lisiecka, J. & Knaflewski, M., 2010. Correlation between selected parameters of planting material and strawberry yield. *Folia Horticulturae*, 22(1), pp.9–12.

Beattie, J., Crozier, A. & Duthie, G.G., 2005. Potential health benefits of berries. Cu*rrent Nutrition & Food Science*, 1, pp.71–86.

Bish, E.B., Cantliffe, D.J. & Chandler, C.K., 2003. Plantlet size affects growth and development of strawberry plug transplants. *Proceedings of the Florida State Horticultural Society*, 116, pp.105–107.

Boriss, H., Brunke, H. & Kreith, M., 2006. *Commodity Profile: Strawberries*. Available at: http://aic.ucdavis.edu/profiles/strawberries-2006.pdf [accessed May 2017].

Bradford, E., Hancock, J.F. & Warner, R.M., 2010. Interactions of temperature and photoperiod determine expression of repeat flowering in strawberry. *Journal of the American Society for Horticultural Science*, 135(2), pp.102–107.

British Summer Fruits, 2012. *Why polytunnels are used*. Available at: http://www.britishsummerfruits.co.uk/html/news_polytunnels.htm [accessed December 2013].

Bussell, W.T., Ennis, I.L., Pringle, G.J., Perrl, F.A. & Triggs, C.M., 2003. Relationships between crown size at planting, yield and growth in strawberries. *Agronomy Society of New Zealand*, 32, pp.9–12.

Calleja, E.M., 2011. *The potential impacts of climate change on diseases affecting strawberries and the UK strawberry industry*. PhD Thesis, University of Warwick.

Ceulemans, R., Baets, W., Vanderbruggen, M. & Impens, I., 1986. Effects of supplemental irradiation with HID lamps, and NFT gutter size on gas exchange, plant morphology and yield of strawberry plants. *Scientia Horticulturae*, 28(1–2), pp.71–83.

Chabot, B.F., 1978. Environmental influences on photosynthesis and growth in Fragaria vesca. *New Phytologist*, 80(1), pp.87–98.

Chapin, F.S., Schulze, E.D. & Mooney, H.A., 1990. The ecology and economics of storage in plants. *Annual Review of Ecology and Systematics*, 21, pp.423–447.

Choi, J.H., Latigui, A. & Yoon, M.K., 2010. Growth and nutrient uptake of "Seolhyang" strawberry (Fragaria x ananassa Duch) responded to elevated nitrogen concentrations in nutrient solution. *Korean Society for Horticultural Science and Technology*, 28(5), pp.777–782.

Cocco, C., Andriolo, J.L., Cardoso, F.L., Erpen, L. & Schmitt, O.J., 2011. Crown size and transplant type on the strawberry yield. *Scientia Agricola*, 68(4), pp.489–493.

Cocco, C., Andriolo, J.L., Erpen, L., Cardoso, F.L. & Casagrande, G.S., 2010. Development and fruit yield of strawberry plants as affected by crown diameter and plantlet growing period. *Pesquisa Agropecuária Brasileira*, 45(7), pp.730–736.

Crawford, T.D., Himelrick, D.G., Sibley, L. & Pitts, J.A., 2000. Effect of runner plantlet size on performance of strawberry plug plants. *Small Fruits Review*, 1(1), pp.15–21.

D'Anna, F.D. & Iapichino, G., 2002. Effects of runner order on strawberry plug plant fruit production. *Acta Horticulturae*, 567, pp.301–303.

D'Anna, F.D. & Iapichino, G., 2003. Influence of planting date and runner order on strawberry plug plants grown under plastic tunnels. *Acta Horticulturae*, 614, pp.123–129.

Darrow, G.M., 1936. Interrelation of temperature and photoperiodism in the production of fruit buds and runners in the strawberry. *Journal of the American Society for Horticultural Science*, 34, pp.363.

Darrow, G.M., 1966. *The Strawberry: History, Breeding, and Physiology*. Holt, Rhinehart and Winston, New York, USA.

DEFRA, 2016. *Basic Horticultural Statistics*. Available at: https://www.gov.uk/government/collections/horticultural-statistics [accessed August 2017].

Demirsoy, L., Demirsoy, H., Ersoy, B., Balci, G. & Kizilkaya, R., 2010. Seasonal variation in N, P, K and Ca content on leaf, crown and root of "Sweet Charlie" strawberry under different irradiation. *Zemdirbyste-Agriculture*, 97(1), pp.23–32.

Demirsoy, L., Demirsoy, H., Uzun, S. & Öztürk, A., 2007. The effects of different periods of shading on growth and yield in "Sweet Charlie" strawberry. *European Journal of Horticultural Science*, 72(1), pp.26–31.

Deng, X. & Woodward, F.I., 1998. The growth and yield responses of Fragaria ananassa to elevated CO2 and N supply. *Annals of Botany*, 81, pp.67–71.

Dennis, F.G., 1970. Effects of photoperiod and other factors open flowering and runner development of three strawberry cultivars. *Journal of the American Society for Horticultural Science*, 95, pp.750–754.

Domoto, P., Gleason, M. & Lewis, D., 2008. *Production Guide for Commercial Strawberries*. Available at: https://store.extension.iastate.edu/Product/Production-Guide-for-Commercial-Strawberries-Iowa-Commercial-Fruit-Production-Series [Accessed December 2013].

Durner, E.F., 2015. Photoperiod affects floral ontogeny in strawberry (Fragaria × ananassa Duch.) plug plants. *Scientia Horticulturae*, 194, pp.154–159.

Durner, E.F., 2016. Photoperiod and temperature conditioning of "Sweet Charlie" strawberry (Fragaria x ananassa Duch.) plugs enhances off-season production. *Scientia Horticulturae*, 201, pp.184–189.

Durner, E.F. & Poling, E.B., 1985. Comparison of three methods for determining the floral or vegetative status of strawberry plants. *Journal of the American Society for Horticultural Science*, 109, pp.396–400.

Durner, E.F. & Poling, E.B., 1987. Flower bud induction, initiation, differentiation and development in the "earliglow" strawberry. *Scientia Horticulturae*, 31, pp.61–69.

Durner, E.F., Poling, E.B. & Maas, J.L., 2002. Recent advances in strawberry plug plant technology. *Hort Technology*, 12(4), pp.545–550.

Faby, R., 1997. The productivity of graded of "Elsanta" frigo plants from different origins. *Acta Horticulturae*, 439, pp.449–456.

FAOSTAT, 2017. *Food and Agriculture Organization of the United Nations, Statistics Division*. Available at: http://faostat3.fao.org/browse/q/qc/e [accessed August 2017].

Fernadez, G.E., Butler, L.M. & louws, F.J., 2001. Strawberry growth and development in an annual plasticulture system. *Hortscience*, 36(7), pp.1219–1223.

Fridiaa, A., Winardiantika, V., Lee, Y. & Cho, H., 2016. Influence of crown size on plant growth, flowering and yield of day-neutral strawberry cultivars. *International Society for Horticultural Science*, 1117, pp.347–354.

Gautier, H., 2001. Modulation of competition between fruits and leaves by flower pruning and water fogging, and consequences on tomato leaf and fruit growth. *Annals of Botany*, 88(4), pp.645–652.

Gilbert, E.G., 1970. *Soft Fruit Growing*. Penguin Books Ltd, London, UK.

Guttridge, C.G., 1960. The physiology of flower formation and vegetative growth in the strawberry. *The physiology of flower formation and vegetative growth in the strawberry*, 2, pp. 941–948.

Hamann, K.K. & Poling, E.B., 1997. The influence of runner order, night temperature and chilling cycles on the earliness of "Selva" plug plant fruit production. *Acta Horticulturae*, 439, pp.597–604.

Hancock, J.F., 1999. *Strawberries (Crop Production Science in Horticulture, 11)*. CAB International, Wallingford, UK.

Hansen, P., 1989. Source-sink relations in fruit IV. Fruit number and fruit growth in strawberries. In *International Strawberry Symposium*, 265, pp. 377–381.

Heide, O.M., Stavang, J.A. & Sønsteby, A., 2013. Physiology and genetics of flowering in cultivated and wild strawberries - a review. *Journal of Horticultural Science and Biotechnology*, 88(1), pp.1–18.

Himelrick, D.G. & Dozier, W.A., 1994. "Chandler" strawberry response to hydroponic solution nitrogen concentration. *Hortscience*, 29(7), pp.735.

Hortynski, J.A., 1989. Correlations in strawberry breeding programmes. In *International Strawberry Symposium*, 263, pp. 169–173.

Hughes, H.M., 1980. *Strawberries (No 95)*. Her Majesty's Stationary Office, London, UK.

Hughes, H.M., 1967. The effects of planting time, runner size and plant spacing on the yield of strawberries. *Journal of Experimental Botany*, 42, pp.253–262.

Human, J.P., 1999. Effect of number of plants per plant hole and of runner plant crown diameter on strawberry yield and fruit mass. *South African Journal of Plant and Soil*, 16(4), pp.189–191.

Husaini, A.M. & Neri, D. eds., 2016. *Strawberry Growth Development and Diseases*. CAB International, Boston, Massachusetts, USA.

Hyams, E., 1953. *Strawberry Cultivation*. Faber and Faber, London, UK.

Hytönen, T., Palonen, P., Mouhu, K. & Juntilla, O., 2004. Crown branching and cropping potential in strawberry (Fragaria x ananassa Duch.) can be enhanced by daylength treatments. *Journal of Horticultural Science and Biotechnology*, 79(3), pp.466–471.

Ingestad, T., 1977. Nitrogen and plant growth: maximum efficiency of nitrogen fertilizers. *Ambio*, 6(2), pp.146–151.

Ito, H. & Saito, T., 1962. Studies on the flower formation in the strawberry plants I. Effects of temperature and photoperiod on the flower formation. *Tohoku Journal of Agricultural Research*, 13(3), pp.191–203.

Jahn, O.L. & Dana, M.N., 1970a. Crown and inflorescence development in the strawberry Fragaria ananassa. *American Journal of Botany*, 57(6), pp.605–612.

Jahn, O.L. & Dana, M.N., 1970b. Effects of cultivar and plant age on vegetative growth of the strawberry, Fragaria ananassa. *American Journal of Botany*, 57(8), pp.993–999.

Janick, J. & Eggert, D.A., 1968. Factors affecting fruit size in the strawberry. *Journal of the American Society for Horticultural Science*, 93, pp.311–16.

Johnson, A., Whitehouse, A. & Simpson, D., 2008. HDC: A summary report of useful information gathered for UK strawberry growers, 6th International Strawberry Symposium. Huelva, Spain.

Johnson, C., Raiford, T. & Whitley, K., 2005. Initial crown diameter of transplants influences marketable yield components of two strawberry cultivars in annual hill production system. *International Journal of Fruit Science*, 5(4), pp.23–29.

Jurik, T.W., Chabot, J.F. & Chabot, B.F., 1982. Effects of light and nutrients on leaf size, CO2 exchange, and anatomy in wild strawberry (Fragaria virginiana). *Plant Physiology*, 70, pp.1044–1048.

Kadir, S., Carey, E. & Ennahli, S., 2006. Influence of high tunnel and field conditions on strawberry growth and development. *Hortscience*, 41(2), pp.329–335.

Karapatzak, E.K., Wagstaffe, A., Hadley, P. & Battey, N.H., 2012. High-temperature-induced reductions in cropping in everbearing strawberries (Fragaria × ananassa) are associated with reduced pollen performance. *Annals of Applied Biology*, 161, pp.255–265.

Kirschbaum, D.S., Larson, K.D., Weinbaum, S.A. & Dejong, T.M., 2012. Accumulation pattern of total non-structural carbohydrate in strawberry runner plants and its influence on plant growth and fruit production. *African Journal of Biotechnology*, 11(96), pp.16253–16262.

Kirschbaum, D.S., Larson, K.D., Weinbaum, S.A. & Dejong, T.M., 2010a. Late-season nitrogen applications in high-latitude strawberry nurseries improve transplant production pattern in warm regions. *African Journal of Biotechnology*, 9(7), pp.1001–1007.

Kirschbaum, D.S., Larson, K.D., Weinbaum, S.A. & Dejong, T.M., 2010b. Relationships of carbohydrate and nitrogen content with strawberry transplant vigour and fruiting pattern in annual production systems. *The Americas Journal of Plant Science and Biotechnology*, 4, pp.98–103.

Konsin, M., Voipio, I. & Palonen, P., 2001. Influence of photoperiod and duration of short-day treatment on vegetative growth and flowering of strawberry (Fragaria x ananassa Duch). *Journal of Horticultural Science and Biotechnology*, 76(1), pp.77–82.

Kronenberg, H.G., Wassenaar, L.M. & Van de Lindeloof, C.P.J., 1976. Effect of temperature on dormancy in strawberry. *Scientia Horticulturae*, 4, pp.361–366.

Kurokura, T., Iwama, T., Inaba, Y. & Sugiyama, N., 2005. Effect of day-length on the developmental pattern of axillary buds in June-bearing strawberry plants. *Journal of Horticultural Science and Biotechnology*, 80(1), pp.139–142.

Lacey, C.N.D., 1973. Phenotypic correlations between vegetative characters and yield components in strawberry. *Euphytica*, 22, pp.546–554.

Lamont, J.W., 2005. Plastics: modifying the microclimate for the production of vegetable crops. *Hort Technology*, 15(3), pp.477–481.

Larson, K.D., 1994. *Strawberry*. In Handbook of Environmental Physiology of Fruits Crops, 1, pp. 271–297.

Leshem, Y. & Koller, D., 1966. The control of flowering in the strawberry Fragaria ananassa Duch. *Annals of Botany*, 28(112), pp.569–578.

Lieten, P., 2009. Chilling requirement of strawberry cv. "Sonata" and "Figaro." *Acta Horticulturae*, 842, pp.749–752.

Lieten, P., 2002. The effect of nutrition prior to and during flower differentiation on phyllody and plant performance of short-day strawberry "Elsanta." *Acta Horticulturae*, 567, pp.345–348.

Lieten, P., Kinet, J. & Bernierb, G., 1995. Effect of prolonged cold storage on the production capacity of strawberry plants. *Scientia Horticulturae*, 60(94), pp.213–219.

Lieten, P. & Waite, G., 2006. Chilling unit model for greenhouse production of strawberry cv. "Elsanta." *Acta Horticulturae*, 708, pp.381–388.

López, S., Maroto, J. V, San Bautista, A., Pascual, B. & Alagarda, J., 2002. Differences in carbohydrate content of waiting-bed strawberry plants during development in the nursery. *Scientia Horticulturae*, 94, pp.53–62.

Luedeling, E., Girvets, E.H., Semenov, M.A. & Brown, P.H., 2011. Climate change affects winter chill for temperate fruit and nut trees. *PLOS ONE*, 6(5).

Manakasem, Y. & Goodwin, P.B., 2001. Responses of day neutral and June bearing strawberries to temperature and daylength. *Journal of Horticultural Science and Biotechnology*, 76(5), pp.629–635.

Manganaris, G.A., Goulas, V., Vicente, R. & Terry, L.A., 2014. Berry antioxidants: small fruits providing large benefits. *Journal of the Science of Food and Agriculture*, 94(5), pp.825–833.

Marschner, H., 1995. *Mineral Nutrition of Higher Plants 2nd ed*. Academic Press, London, UK.

Le Miere, P., 1997. *The effect of environmental conditions on flower initiation and yield components in Fragaria x ananassa cv. Elsanta*. PhD Thesis, University of Reading.

Le Miere, P., Hadley, P., Darby, J. & Battey, N.H., 1998. The effect of thermal environment, planting date and crown size on growth, development and yield of Fragaria x ananassa Duch. cv. Elsanta. *Journal of Horticultural Science and Biotechnology*, 73(6), pp.786–795.

Miner, G.S., Poling, E.B., Carroll, D.E. & Nelson, L.A., 1997. Influence of fall nitrogen and spring nitrogen-potassium applications on yield and fruit quality of "chandler" strawberry. *Journal of the American Society for Horticultural Science*, 122(2), pp.290–295.

Motamedi, S., Jafarpour, M. & Shams, J., 2013. Evaluation of nutrition on flower number and yield of strawberry in greenhouse. *International Journal of Agriculture and Crop Sciences*, 5(18), pp.2091–2095.

Nishiyama, M., Ohkawa, W. & Kanahama, K., 2003. Effect of photoperiod on the development of inflorescences in everbearing strawberry "summerberry" plants grown at high temperature. *Tohoku Journal of Agricultural Research*, 53(3–4), pp.43–52.

Nishiyama, M., Ohkawa, W., Kanahama, Y. & Kanahama, K., 2006. Critical photoperiod for flower bud initiation in everbearing strawberry "summerberry" plants grown at high temperatures. *Tohoku Journal of Agricultural Research*, 56(3–4), pp.1–8.

Nishizawa, T., Shishido, Y. & kumakura, H., 1998. Mobilization of 14C-carbohydrate reserves in relation to vegetative growth and inflorescence development in June bearing strawberry plants. *Journal of Horticultural Science and Biotechnology*, 73(4), pp.499–505.

Novoa, R. & Loomis, R.S., 1981. Nitrogen and plant production. *Plant and Soil*, 58(1–3), pp.177–204.

Olsen, J.L., Martin, L.W., Pelofske, P.J., Breen, P.J. & Forney, C.F., 1985. Functional growth analysis of field grown strawberry. *Journal of the American Society for Horticultural Science*, 110(1), pp.89–93.

Opstad, N., Espelien, H.G., Roos, U.M. & Sønsteby, A., 2013. Effects of fertigation timing on growth and development in strawberry "Korona." *Acta Horticulturae*, 984, pp.143–150.

Papadopoulos, I., 1987. Nitrogen fertigation of greenhouse-grown strawberries. *Fertilizer Research*, 13(3), pp.269–276.

Pérez de Camacaro, M.E., Camacaro, G.J., Hadley, P., Dennett, M.D., Battey, N.H. & Carew, J.G., 2004. Effect of plant density and initial crown size on growth, development and yield in strawberry cultivars Elsanta and Bolero. J*ournal of Horticultural Science and Biotechnology*, 79(5), pp.739–746.

Pipattanawong, N., Fujishige, N., Yamane, K. & Ogata, R., 1995. Growth and development of four day-neutral strawberries under hydroponic system with or without chilling. *Journal of the Japanese Society for Horticultural Science*, 64(1), pp.95–102.

Rogers, C.O., Izsak, E., Kafkafi, U. & Izhar, S., 1985. Nitrogen rates in strawberry (Fragaria ananassa) nursery on growth and yield in the field. *Journal of Plant Nutrition*, 8(2), pp.147–162.

Savini, G., Neri, D., Zucconi, F. & Sugiyama, N., 2005. Strawberry growth and flowering: an architectural model. *International Journal of Fruit Science*, 5(1), pp.29–50.

Shokaeva, D.B., 2008. Relationships between yield components in first cropping year and average yield of short-day strawberries over two main seasons. *Scientia Horticulturae*, 118, pp.14–19.

Smeets, L., 1982. Effect of chilling on runner formation and flower initiation in the everbearing strawberry. *Scientia Horticulturae*, 17, pp.43–48.

Smeets, L., 1980. Effect of temperature and daylength on flower initiation and runner formation in two everbearing strawberry cultivars. *Scientia Horticulturae*, 12, pp.19–26.

Smeets, L. & Kronenberg, H.G., 1955. Runner formation on strawberry plants in autumn and winter. *Euphytica*, 4, pp.53–57.

Sønsteby, A. & Heide, O.M., 2006. Dormancy relations and flowering of the strawberry cultivars Korona and Elsanta as influenced by photoperiod and temperature. *Scientia Horticulturae*, 110, pp.57–67.

Sønsteby, A. & Heide, O.M., 2007. Long-day control of flowering in everbearing strawberries. *Journal of Horticultural Science and Biotechnology*, 82(6), pp.875–884.

Sønsteby, A. & Heide, O.M., 2008. Temperature responses, flowering and fruit yield of the June-bearing strawberry cultivars Florence, Frida and Korona. *Scientia Horticulturae*, 119, pp.49–54.

Sønsteby, A. & Nes, A., 1998. Short days and temperature effects on growth and flowering in strawberry (Fragaria x ananassa Duch.). *Journal of Horticultural Science and Biotechnology*, 73(6), pp.730–736.

Sønsteby, A., Opstad, N. & Heide, O.M., 2013. Environmental manipulation for establishing high yield potential of strawberry forcing plants. *Scientia Horticulturae*, 157, pp.65–73.

Sønsteby, A., Opstad, N., Myrheim, U. & Heide, O.M., 2009. Interaction of short day and timing of nitrogen fertilization on growth and flowering of "Korona" strawberry (Fragaria × ananassa Duch.). *Scientia Horticulturae*, 123, pp.204–209.

Stewart, P.J. & Folta, K.M., 2010. A review of photoperiodic flowering research in strawberry (Fragaria spp.). *Critical Reviews in Plant Sciences*, 29, pp.1–13.

Strik, B., 2007. Berry crops: worldwide area and production systems. *Berry fruit: value-added products for health promotion*, pp. 3-51.

Sunley, R.J., Atkinson, C.J. & Jones, H.G., 2006. Chill unit models and recent changes in the occurrence of winter chill and spring frost in the United Kingdom. *Journal of Horticultural Science and Biotechnology*, 81(6), pp.949–958.

Tagliavinia, M., Baldia, E., lucchic, P., Antonellia, M., Sorrentia, G., Baruzzi, G. & Faedib, W., 2005. Dynamics of nutrients uptake by strawberry plants (Fragaria x ananassa Dutch.) Grown in soil and soilless culture. *European Journal of Agronomy*, 23, pp.15–25.

Taiz, L. & Zeiger, E., 2002. *Plant Physiology 3rd ed.*, Sinauer Associates, Sunderland, Massachusetts, USA.

Takeda, F., Hokanson, S.C. & Enns, J.M., 2004. Influence of daughter plant weight and position on strawberry transplant production and field performance in annual plasticulture. *Hortscience*, 39(7), pp.1592–1595.

Takeda, F. & Newell, M., 2006. A method for increasing fall flowering in short-day "carmine" strawberry. *Hortscience*, 41(2), pp.480–481.

Tanino, K.K. & Wang, R., 2008. Modelling chilling requirement and diurnal temperature differences on flowering and yield performance in strawberry crown production. *Hortscience*, 43(7), pp.2060–2065.

Tehranifar, A., 1997. *The chilling requirement and dormancy of Fragaria x ananassa cv. Elsanta*. PhD Thesis, University of Reading.

Torres-Olivar, V., Villegas-Torres, O.G., Domínguez-Patiño, M.L., Sotelo-Nava, H., Rodríguez-Martínez, A., Melgoza-Alemán, R.M., Valdez-Aguilar, L.M. & Alia-Tejacal, I., 2014. Role of nitrogen and nutrients in crop nutrition. *Journal of Agricultural Science and Technology*, 4, pp.29–37.

Tunnel Facts, 2004. *The UK soft fruit industry is a rare British agriculture success story*. Available at: http://www.tunnelfacts.co.uk/index.html [accessed December 2013].

UNECE, 2010. UNECE Standard FFV-35: Concerning the marketing and commercial quality control of strawberries. United Nations, New York and Geneva.

Verheul, M.J., Sønsteby, A. & Grimstad, S.O., 2007. Influences of day and night temperatures on flowering of Fragaria x ananassa Duch., cvs. Korona and Elsanta, at different photoperiods. *Scientia Horticulturae*, 112, pp.200–206.

Verheul, M.J., Sønsteby, A. & Grimstad, S.O., 2006. Interactions of photoperiod, temperature, duration of short-day treatment and plant age on flowering of Fragaria x ananassa Duch. cv. Korona. *Scientia Horticulturae*, 107, pp.164–170.

Wagstaffe, A. & Battey, N.H., 2006. Characterisation of the thermodormancy response in the everbearing strawberry "Everest." *Journal of Horticultural Science and Biotechnology*, 81(6), pp.1086–1092.

Webb, R.A., Purves, J. V, White, B.A. & Ellis, R., 1974. The components of fruit size in strawberry. *Scientia Horticulturae*, 2, pp.165–174.

Webb, R.A., White, A. & Ellis, R., 1973. The effect of rooting date on fruit production in the strawberry. *Journal of Horticultural Science and Biotechnology*, 48, pp.99–110.

Wilson, D., 1997. *Strawberries under protection*. Grower Guide 6. 2nd series.

Yoshida, Y. & Motomura, S., 2011. Flower initiation in June-bearing strawberry as affected by crown depth, age, and size of tray plants. *Journal of the Japanese Society for Horticultural Science*, 80(1), pp.26–31.

Zhang, X., Himelrick, D.G., Woods, F.M. & Ebel, R.C., 2000. Effect of temperature, photoperiod and pre-treatment growing condition on floral induction in spring-bearing strawberry. *Hortscience*, 35(4), pp.556.