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THE GROWTH AND PRODUCTIVITY OF HAZELNUT CULTIVARS (*Corylus avellana* L.) IN AUSTRALIA

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ABSTRACT

During the 1990s, a question posed by new and intending growers of hazelnuts was “What is the best variety to plant when establishing a commercial orchard?” Although existing growers had a range of views on this matter, there had not been any scientific studies to evaluate the range of cultivars available in Australia. Although hazelnut cultivars were introduced to Australia in the mid-Nineteenth Century, there had been very limited industry development compared to other cool climate deciduous tree crops such as pome and stone fruits. In the 1970s many cultivars were imported from overseas, but there was no systematic evaluation of this material.

In 1994, the author of this thesis obtained a grant from the Rural Industries Research and Development Corporation (RIRDC) to undertake an assessment of hazelnut cultivars and their potential for Australian conditions. The evaluation involved planting a range of cultivars at 5 field sites. Two were in New South Wales, 2 in Victoria, and 1 in Tasmania. There was variation between the sites in soil types and climate.

A randomised block design was used with cultivars as treatments within blocks. Observations and measurements were recorded for tree growth, floral phenology, nut yields and the characteristics of both nuts and kernels. All sites had supplementary irrigation and common management practices. 1-year old hazelnut whips were planted at a spacing of 3 m x 5 m. Automatic weather stations were located at each site.

There were major differences between cultivars, in terms of their vigour of growth, floral phenology, nut yields and kernel characteristics. In addition to the cultivar effects, soil type was a major factor influencing tree growth, as was rainfall. Cultivars with high vigour included ‘Barcelona’ and the Australian selection ‘Tokolyi/Brownfield Cosford’ (‘TBC’). Those of low vigour were ‘Tonda Gentile delle Langhe’ (‘TGDL’), ‘Negret’ and ‘Wanliss Pride’. There were significant interactions between cultivars and the sites in tree growth and nut yields.

Timing of male and female anthesis was strongly influenced by cultivar and seasonal conditions. All cultivars were protandrous. The commencement of pollen shed ranged from late-May, for the cultivars ‘TGDL’ and ‘Barcelona’, to early August for ‘Hall’s Giant’. Chill hour requirements appeared to be the main factor influencing timing of pollen shed. Female anthesis was also spread over a period of several weeks with early cultivars being ‘Atlas’ and ‘Tonda di Giffoni’, late cultivars were ‘Ennis’, ‘Casina’ and ‘Hall’s Giant’.

Studies with cut branches in controlled temperature environments indicated that catkins had a relatively high post-chill heat requirement compared to female inflorescences. The differences between cultivars in post-chill heat requirements for catkins were small. The relative dates of flowering across cultivars were found to be highly predictable. This, coupled with published data on genetic incompatibility, made it possible to recommend cultivars as pollinisers for the main nut-yielding cultivars.

There were significant differences between cultivars in the date of bud break; ‘TGDL’ and ‘Tonda di Giffoni’ were early (late August) whereas ‘Hall’s Giant’ was late (late September). Nut yields were highly influenced by cultivar, vigour of growth, site and seasonal rainfall. Low rainfall in one season greatly reduced nut yields. High growth rates at one site lead to a closed canopy 7 years from planting with peak yields. Soil characteristics were a main factor influencing tree growth and nut yields. The best tree growth and highest levels of production were achieved on a deep, well drained, fertile loam soil.

The characteristics of nuts and kernels were strongly influenced by cultivar, although seasonal conditions influenced nut and kernel size and the degree of kernel fill. An overall evaluation of cultivars was based on nut and kernel yields as well as kernel characteristics to meet market requirements. On average, ‘Ennis’ gave the highest yields of the in-shell cultivars. The cultivars ‘Barcelona’ and ‘TBC’ produced the highest average yields, although their relative performance varied between sites. These cultivars were considered best suited for snack foods and catering with 15-17 mm kernels. ‘Tonda di Giffoni’ produced moderately high yields, varying across sites, with kernels suitable for the confectionery market.

Under favourable conditions ‘Barcelona’ achieved nut yields of 3 tonnes/ha within 6 years from planting. Potential areas in Australia for hazelnut production were identified, based on a set of recommended climatic parameters and soil characteristics.

ACKNOWLEDGEMENTS

I wish to acknowledge the help of many people with the research studies described in this thesis. The research would not have been possible without the financial support of the Rural Industries Research and Development Corporation (RIRDC), which provided funding for a total of 12 years. Thanks are extended to the program leaders, David Evans, Max Bourke and Alan Davey for their confidence in the value of the research and support for its on-going funding. At the time that the study commenced, I was an employee of the University of Sydney, Orange Agricultural College. The principal Professor John Chudleigh gave his strong support to the work. The university provided administrative services through its Research Office and travel funding, as a post-graduate student.

Karilyn Gilchrist was employed as a part-time research assistant at the university. She and her husband, Richard, were of great help in the field, particullarly at harvest. Karilyn was of enormous help in maintaining the automatic weather stations, downloading data at Orange and managing the huge volume of data that was generated from all sites as well cracking numerous nuts for kernel assessments.

Lester Snare of NSW Department of Primary Industries was also a great assistance and support. Not only did Lester manage the Orange site but he accompanied me on many field trips to plant trees and harvest nuts. NSW DPI purchased a Tonutti harvester which proved invaluable when Lester took it to Myrtleford for several harvests. NSW DPI also provided facilities for nut drying.

Helen Nicol provided expert advice on experimental design and conducted statistical analyses of some data. My appreciation is extended to her for the advice and analyses conducted.

I wish to express my appreciation for professional advice and support provided by Professor Shawn Mehlenbacher of the Oregon State University (OSU). I also thank Rebecca (Becky) McCluskey of OSU who spent sabbatical leave at the University of Sydney, Orange in 2001 and helped us in many aspects of the field studies, including training in the techniques used by the OSU team for kernel evaluation.

The conduct of this research relied heavily on support provided by collaborating parties at all sites. At Orange it was NSW DPI. Jim and Lauren Gleeson provided the trial site on their

property at Moss Vale and spent many hours tending the trees, recording data and harvesting nuts. Thanks are extended to Agriculture Victoria for the provision of trial sites and support from staff at the Ovens Research Station and the Horticultural Research Institute, Toolangi. Myrtleford.

At first, it was not possible to obtain support for a site in Tasmania until John Zito offered to provide a site on his property at Kettering. John, his wife Connie and daughters Adele and Stephanie were always most welcoming and very supportive with the research.

My thanks are also extended to Milan Paskas, Richard Salt, Janet Brown, Jim Beattie, Lyn and Colin McRae, Bruce West and Simon Hammond for the provision of planting material. Milan Paskas had a collection of cultivars and was most helpful in propagating material from his collection. He was also a valuable source of knowledge on hazelnut growing in Australia.

The support provided by the hazelnut growers of Australia is acknowledged.

Funding for travel was provided by RIRDC and the University of Sydney enabling me to present papers on the research at International Congresses on Hazelnut in Turkey, Oregon, Spain and Italy. Attendance at these Congresses was invaluable, networking with world leaders in hazelnut research and production. I particularly appreciated valuable discussions with Professor Shawn Mehlenbacher of Oregon State University (OSU) who also gave advice on cultivar identification. Thanks also to my supervisor, Emeritus Professor David Kemp, and Dr Yann Guisard, who have given much valuable feedback on the thesis.

Finally I acknowledge the assistance of my wife Jean who accompanied me on many field trips, assisted with harvest and data collection. Jean has also provided valuable editorial advice and suggestions on the thesis. Her patience and moral support over the many years made this study possible.

Basil J. Baldwin
July 2013

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CHAPTER 1 - HAZELNUT PRODUCTION IN AUSTRALIA

1.1 Introduction

Hazelnuts belong to the Birch family (Betulaceae) within the *Corylus* genus. There are nine widely-recognised species in the genus (Thompson et al., 1996). The term “hazelnut” is used worldwide for all *Corylus* species. *Corylus avellana* L., commonly known as the European hazelnut, is the species of greatest economic significance being grown commercially in temperate maritime climates, notably in northern Turkey on the Black Sea Coast, in parts of Italy, Spain and France and in the coastal valleys of Oregon, USA (Thompson et al., 1996).

Corylus avellana L. is native to Europe and Asia Minor. Kasapligil (1964) describes its distribution as being throughout Europe from the west coast of Portugal and Ireland across to the southern part of the Ural Mountains in the east and into Turkey, Lebanon, Syria and Iran. In the north, its distribution extends into Norway, Sweden and to the southern shores of Lake Ladoga in Russia. In the south, it extends into Spain, Sicily and Greece. It is abundant throughout the Balkans.

Corylus avellana L. spread through north-western Europe after the last great Ice Age (Tallantire, 2002) and became the dominant tree species in the early Boreal forest period (Thompson et al., 1996). Hazelnuts were an important food source to hunter-food-gatherers in Europe in the period 8000-5500 BC and were being cultivated in “classical times” in the Mediterranean (Ibid, 1996).

Hazelnuts have been a crop of interest in Australia since early settlement by Europeans, but never successfully developed as an industry with any scale, appropriate for the potential demand for hazelnuts. Reasons for the poor development of this crop are poorly understood.

The European hazelnut is a deciduous shrub or small tree that grows from 3-10 m in height, occasionally up to 15 m (Mehlenbacher 1991). In uncultivated situations, the trees produce many stems but, when grown in cultivation, the plants are usually trained to a single trunk with a vase-shaped branch structure arising from the trunk, 20-80 cm above ground level. In some situations they are trained to just a few stems as a multi-stem bush (Tous et al., 1994).

Hazelnuts are monoecious, with separate male and female flowers (Plate 1.1). The plants are anemophilous (wind pollinated) and self-incompatible. The staminate (male) flowers are catkins. The small pistillate (female) flowers, glomerules, are compound buds with a lower vegetative part and an upper fertile cluster. They are indistinguishable from vegetative buds until flowering, when red stigmas, about 5 mm long, protrude from the tip of a bud (Germain, 1994). Flowering and pollination occur from late autumn through to late winter. However, fertilisation does not occur until late spring or early summer (Mehlenbacher, 1991 and Germain, 1994).

Plate 1.1 Extended catkins of hazelnuts shed pollen which is spread to other plants by the wind. The female, pistillate flowers are small with red coloured stigmas that capture wind-blown pollen.

The fruits are borne in clusters of 1 to 6 or more nuts, which ripen to a brown colour in early autumn. The nuts are 1-2 cm in diameter, depending on the cultivar. The husk, which surrounds the nut, varies from long and tubular, extending well past the nut, to shorter than the nut (Plate 1.2). In the UK, types with a long husk have traditionally been called filberts, whereas those with short husks are known as cobnuts (Woodroof, 1967). When *Corylus avellana* L. was introduced into the USA, the term “filbert” was originally used to differentiate it from the local wild hazelnut species. However, preference is now given to the internationally accepted name, “hazelnut”, which applies to all types of *Corylus* species (Thompson et al., 1996).

Plate 1.2 Nut clusters of ‘Tonda di Giffoni’ (left), a cultivar with short husks enclosing the nut, compared with the cultivar ‘Kentish Cob’ (right) which has long husks. Cultivars with short husks were known as “cob nuts”. The nuts fall free from the fruit cluster when ripe. Cultivars with long husks were called “filberts”; all types are now known as hazelnuts.

1.2 World production

Although wild hazelnuts (*Corylus avellana* L.) are widespread throughout Europe, they are only grown commercially in specific locations. Total world production in the years 2010 -2012 was estimated to be about 800,000 tonnes in-shell, that is, uncracked nuts, figure 1.1 (FAOSTAT, 2013). World production for the triennium 2005-2007 was reported by Fideghilli and De Salvador (2009) to be 19% greater than the previous triennium. However, although data from FAOSTAT (2013) for the period 1992 -2012 indicated an increasing trend in production over that period (Figure 1.1). It was not significant either as a linear or polynomial relationship, probably due to the large variations between seasons. The apparent increasing trend in Turkish production, (Figure 1.1) was also not significant.

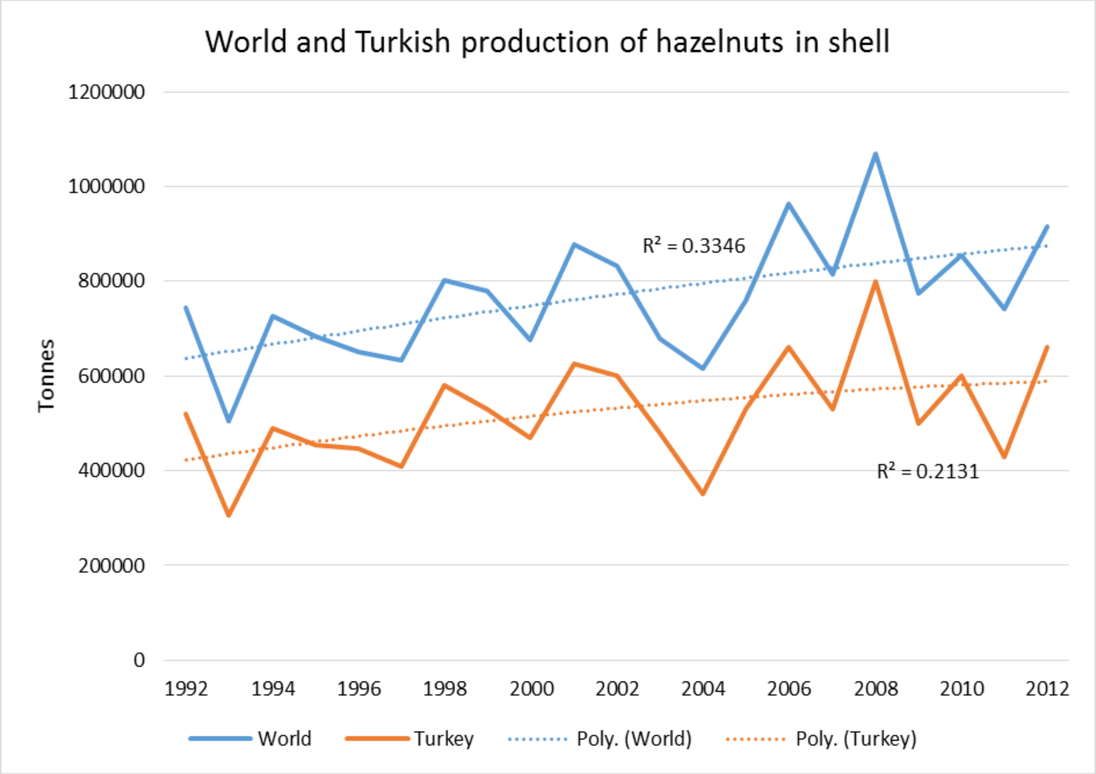


Figure 1.1 Estimates of annual world and Turkish in-shell hazelnut production, (FAOSTAT 2013).

Turkey is the leading hazelnut producer, with approximately 600 000 tonnes nut in-shell per annum in recent years, approximately 70% of world production. The major centre of production is on the Black Sea Coast in the vicinity of Trabzon, Ordu and Giresun. Plantations range from the coast to 30 km inland, from sea level to 1000 m above sea level. Orchards in Turkey are generally small, 1-2 ha, and yields are relatively low, about 1 t/ha. The orchards are on moderately hilly country (Plate 1.3), are unirrigated and the crop is generally picked by hand (Bozolglu, 2005).

Plate 1.3 Hazelnut orchard near Ordu in Turkey on the southern Black Sea coast. Plantations extend inland for 30 km and to an altitude of 1000 m.

Italy is the next most important producer, with about 70 000 ha of orchards producing about 110 000 tonnes, ~15% of the world's hazelnut crop (Tombesi, 2005). There are 4 main regions of production, Piedmont in the north-west (13% of Italy's production), Latium, north of Rome (30% of production), Campania, near Naples (42% of production) and Sicily (12% of production). Each region has its own key cultivars, such as 'Tonda Gentile delle Langhe' ('TGDL') in the Piedmont region, 'Tonda Gentile Romana' in the Latium region and 'Tonda di Giffoni' in Campania'. Italian hazelnuts are generally highly regarded for their flavour, particularly 'TGDL'.

Spain is the next most important producer in Europe with about 22 000 tonnes of nuts in-shell; 3% of world production. The key centre for production is in the coastal district of the "Camp de Tarragona". The main cultivar grown is 'Negret', which produces a small kernel that blanches well, that is the skin or pellicle of the kernel is readily removed following dry heat at 130-150°C for 15 minutes (Plate 1.4).

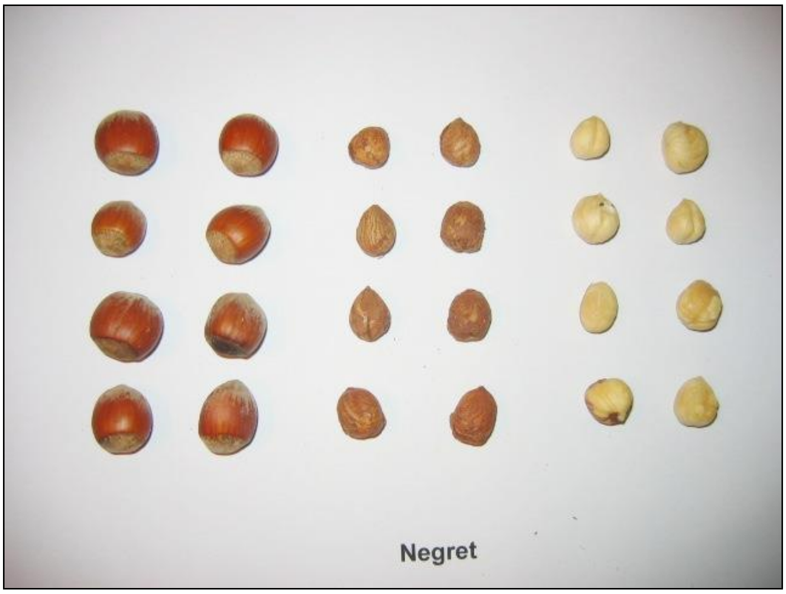


Plate 1.4 Nuts, kernels and blanched kernels of the cultivar 'Negret'. The blanching process involves heating kernels at 130-150°C for 15 minutes, followed by rubbing the kernels to remove the loosened skins. Cultivars vary in their blanching characteristics.

'Negret' is highly sought after by the Spanish confectionery industry (Tous, 2005). Spanish orchards are relatively small, 1-5 ha. Due to the relatively low rainfall (400-600 mm) in this district, the orchards are irrigated, using drip irrigation technology. Annual rates of irrigation are 2.5-3 ML/ha. The crop is harvested mechanically using suction harvesters.

Production in Azerbaijan is currently similar to Spain with a considerable increase during the 2005-2007 triennium (Fideghilli and De Salvador, 2009).

There is a small industry in France where commercial planting commenced in the 1970's. Production in 2005 was 5300 tonnes of nuts in-shell (Sarraquigne, 2005). The main centre of production is Agen in the Aquitane district. Average orchard size is 14-20 ha. The crop is irrigated using drip irrigation; it is mechanically harvested using pick-up harvesters with average yields of 2 t/ha.

Small areas of hazelnuts are grown in some other European countries such as Slovenia (Solar and Stampar, 1997) and Romania (Turcu and Botu, 1997), in locations where conditions are favourable for the crop.

Outside Europe, hazelnuts are grown in the USA, mainly in the Willamette Valley in Oregon, south of the city of Portland. The total area of production is about 11 000 ha, with an average annual crop of about 28 500 tonnes of nuts in-shell; about 5% of world production (Mehlenbacher, 2005). Rainfall is relatively high, 800-1000 mm/annum. The crop is grown without irrigation. Average yields are about 2.5 t/ha, but fluctuate markedly between seasons. The crop is mechanically harvested using pick-up harvesters. The main cultivars have been ‘Barcelona’ and ‘Ennis’, but these are susceptible to the fungal disease, eastern filbert blight (*Anisogramma anomala* Peck) which was introduced into southwest Washington in the 1960s and spread into Oregon (Hummer, 2001). A breeding program was initiated at the Oregon State University in 1969 (Mehlenbacher, 1994) to breed high-yielding cultivars with resistance to eastern filbert blight.

A hazelnut industry is being developed in Chile, where, in 1997, there were 480 ha (Grau et al 2001). There are also plantings in New Zealand (McNeil, 1999). There is a very small area of production in south-east England near Maidstone, Kent, where hazelnuts are known as “cobnuts”. They are picked whilst still green for local consumption. The main cultivar is ‘Kentish Cob’ which is relatively hardy and a reliable cropper. Another cultivar grown in this area is ‘Cosford’ which has a very good flavour and thin shell, but is not a good cropper (Canon et al., 2001).

1.3 Hazelnuts in Australia

Hazelnuts were introduced into Australia in the 19th Century by European settlers. In an early catalogue of plants from a Hobart plant nursery, 3 types of hazelnut were listed for sale by Dickson (1845). A small collection of cultivars of English origin was established in the Royal Tasmanian Botanic Gardens, where some trees still exist. A list of introductions recorded in 1863 included the ‘Cob Nut’ and ‘White Filbert’ (Natalie Papworth, pers. comm., 2005). In 1865, the list included ‘Deviana Prize’, ‘Webb’s Exhibition Red’ and ‘Webb’s Exhibition White’. It appears that the early plant introductions into Tasmania were as named cultivars, principally of English origin.

In 1859, 4 species of *Corylus* were being grown in the Royal Botanical Gardens in Melbourne; these were *C. americana, C. avellana, C. corlurna and C. rostrata*. In 1873, the plant list included *C. avellana* var. barcelonensis. There were no records that indicated the source of these plants (Helen Cohn, pers. comm., 2005). In 1865, Joseph Harris of Melbourne listed Filberts in his nursery catalogue, these included ‘Barcelona’, ‘Cob’, ‘Northamptonshire Prolific’, ‘Red Filbert’ and ‘White Filbert’. In 1886, 12 cultivars were advertised for sale in Melbourne by Law, Somner and Co. (1886).

During the early 1900s, small orchards of hazelnuts were planted in cool climate areas of Victoria, particularly in the upper Ovens Valley, with Wandiligong being the main centre of production (Pescott, 1937). Most of these were removed in the 1950s for higher return enterprises such as tobacco (Paskas, 1988) which has since been abandoned as a crop. One of the main cultivars grown in this area was ‘Wanliss Pride’ (Allen, 1986) which appears to be a selection from the Turkish cultivar ‘Kargalak’, also known as ‘Imperial de Trebizonde’.

Although introduced into Australia more than 100 years ago, hazelnuts have so far only been grown on a relatively small scale, despite the fact that the Australian Bureau of Statistics (ABS) recorded annual imports of 1500-2300 tonnes of kernels and 80-120 tonnes of nut in-shell over the period 1994-2005 (Figure 1.2). . The majority of imported hazelnuts in this period were from Turkey, Oregon and Italy (ABS, 2006).

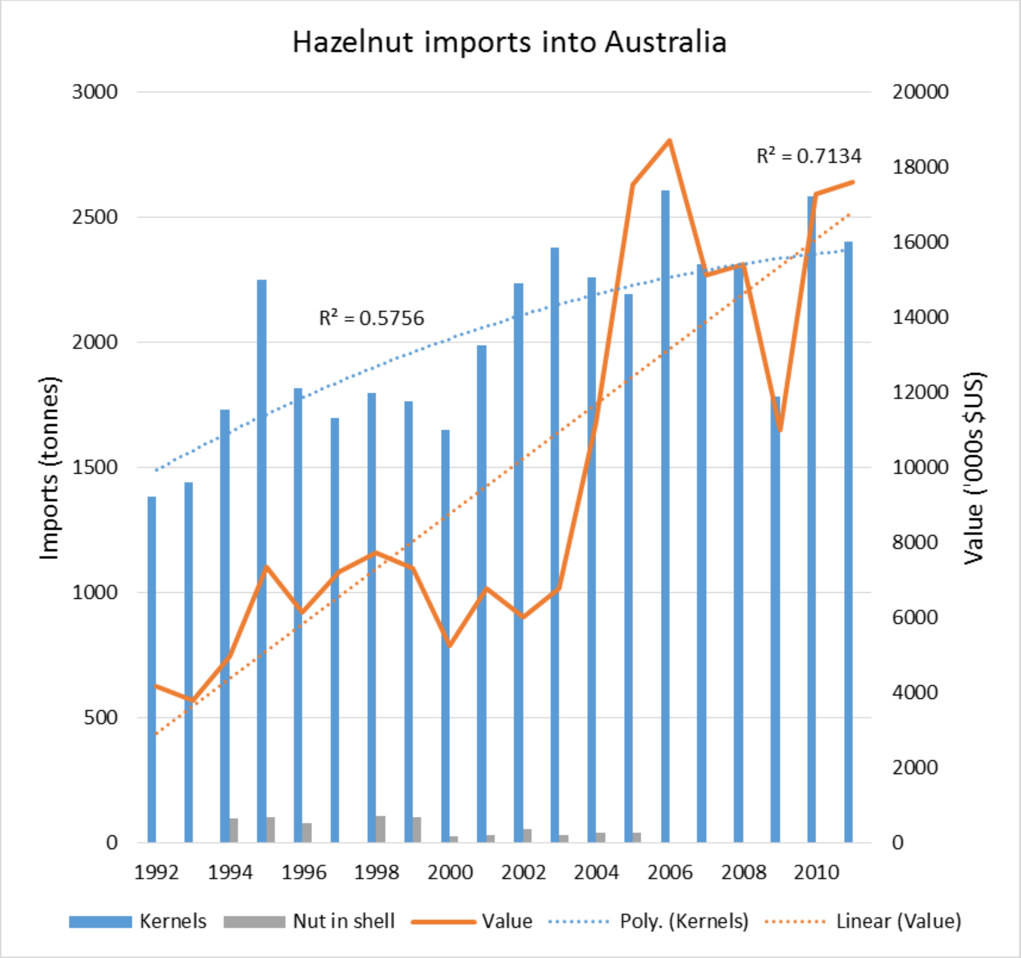


Figure 1.2 The volume and value of hazelnuts imported into Australia 1992-2011 Source: Kernels (shelled nuts) and value FAOSTAT 2013. Nut in shell Australian Bureau of Statistics, 2006.

The records on imports from the ABS only go to 2005; since that date the method of data collection by the ABS has been changed making it difficult to compare data. However, data from FAOSTAT (2013) shows a significant increase (P=0.01) in imports of shelled hazelnuts (kernels) over a period of 20 years from 1992 (Figure 1.2) with considerable price fluctuations, probably related to world supply, but a significant (P=0.001) increasing trend in total value. The volume and value of imports indicates there is an opportunity for the establishment of a local industry to supply the Australian market.

The first recorded experiment to evaluate hazelnut genetic resources was commenced in 1937 at the NSW Department of Agriculture, Glen Innes Research Centre on the Northern Tablelands of New South Wales. The source of the majority of this planting material is unclear. Thirty “cultivars” were planted on a spacing of 3 m x 3 m, with yields of up to 7.5 kg of nuts per tree being reported for some trees 27 years after planting (Trimmer, 1965). The cultivar names listed suggest European origins. Records of plant material imported through the Australian Quarantine Inspection Service (AQIS) at about that time indicate they could have been introduced as plants (Ikin, 1974).

In 1972, the experiment at Glen Innes was discontinued and suckers from there were transferred to an arboretum at the Agricultural Research Centre, at Orange, NSW. At that site, yields obtained for the highest yielding cultivar, 'Atlas', were 1.5 kg per tree in 1981 and 2.2 kg per tree in 1982 (Department of Agriculture NSW, 1982). In 1981, a well-known hazelnut researcher from the Oregon State University, Dr Maxine Thompson, visited the Orange site where she inspected the collection of "cultivars". She considered the collection was of seedling types and that most of the given names were incorrect spellings of known European cultivars (Bean and Kenez, 1991). Nut size, shape and kernel characteristics of the trees in the Orange collection have been described (Baldwin and Baldwin, 1991). Most of the nuts were small with relatively thick shells, a good indication that they were seedling types.

In addition to the above work, some cultivar evaluation was initiated by the Tasmanian Department of Agriculture at the Research Centre at Grove, in the Huon Valley, as reported by Thomas (1951), but no details of the cultivars grown and their production seem to have been published.

During the 1960s and 1970s, Imre Tokolyi, an immigrant from Hungary, was very keen to have fresh Australian hazelnuts for his bakery business. He was frustrated by the lack of Australian-grown nuts and established his own orchard and nursery in the Hoddles Creek area of Victoria. He planted nuts of hazelnuts imported from Turkey, Italy, Spain and the USA and made several selections from his seedling trees (Kenez, 1989). There appear to be 3 key types which he selected and named as 'Tokolyi Cosford', 'Turkish Cosford' and 'White American' (Tokolyi, N.D.). These were subsequently planted in orchards. It appears that the largest plantation (2-3 ha.) was established by the Brown family in the Acheron area of Victoria in the late 1970s (Plate 1.5), another was a planting by Dennis Bear near Beechworth in Victoria.

Plate 1.5 Members of the Brown family with Lester Snare (NSW DPI) on the right, in their orchard of 'Tokolyi Cosford' at Acheron in Victoria, 1994.

During the 1970s, there was a renewed interest in hazelnut growing in Australia, particularly in Victoria, where, in 1978, enthusiastic growers decided to establish the Victorian Hazelnut Growers Association (Allen, 1989). During the 1970s and 1980s, many cultivars of European and North American origin were introduced into Australia through the Australian Quarantine Inspection Service (AQIS) by enthusiastic growers, propagators and the Victorian Department of Agriculture (Baldwin, 1997). In the period 1980-1994, there were 108 introductions of *Corylus* species through AQIS, as rooted plants and scion wood (Table 1.1).

Table 1.1 Imports of *Corylus* species into Australia through the Australian Quarantine Inspection Service (AQIS). (AQIS, 1996).

	Periods			
Number of quarantine approvals	Pre-1980	1980-84	1985-89	1990-94
	23	40	23	45

The imported material was grown in government or approved private post-entry quarantine facilities for a minimum of 9 months, during which time the plants were visually screened for pests and diseases.

Although more than 80% of these cultivars were introduced into Victoria, the introduction of hazelnut cultivars into Australia has been uncoordinated and, consequently, many cultivars have been imported more than once, often to the same State. For example, the cultivar ‘Casina’ was introduced on 7 occasions between 1984 and 1994 (Table 1.2). The identity of importers is kept confidential by AQIS, making it difficult to source cultivars for research. Records of plant introductions are no longer available from AQIS.

Table 1.2 Importation of the hazelnut cultivar ‘Casina’ into Australia (AQIS, 1996).

Date of entry	Plant Quarantine Station
06.12.84	Kingston, Tasmania
15.12.86	Australian Capital Territory
15.12.86	Burnley, Victoria
17.06.88	Burnley, Victoria
20.01.89	Burnley, Victoria
05.03.94	Knoxfield, Victoria
06.04.94	Burnley, Victoria

During the 1980s, collections of hazelnut cultivars were established by the Victorian Department of Agriculture at the Ovens and Toolangi Research Centres. Although these were useful collections, there was little systematic evaluation of the material at these sites. However, Sample (1993) reported that ‘Atlas’ out-yielded all other cultivars at Ovens, with yields of up to 4 kg/tree. At Toolangi, 'good crops' were reported 12 years after planting from the cultivars ‘Atlas’, ‘Barcelona’, ‘Cosford’ (‘Cob’), ‘Du Provence’, ‘Royal Italian’, ‘Wanliss Pride’ and ‘White American’ (Kenez 1993).

In 1988, Professor Lagerstedt from the USA was the guest speaker at the first Australian Nut Conference. Professor Lagerstedt had many years of experience in hazelnut growing and research and at that time had recently retired from the United States Department of Agriculture (USDA) in Oregon. He had close connections with the Oregon State University and its breeding program. He visited several hazelnut farms in Australia as well as the research sites at Toolangi and Ovens. He considered that the cultivar ‘Wanliss Pride’ was worthy of promotion for both the in-shell market, due to its large size and attractive appearance, and also for the kernel market, due to the good blanching characteristics and sweet flavour of its kernels (Lagerstedt, 1990). In general, he considered the cultivar situation in Australia was in a state of chaos with some nurseries selling seedling trees. Although he was of the opinion that in the short-term the in-shell market was the most important, he considered that in the long-term the kernel market would be more important. He suggested that each State should have its own replicated variety trials to assess material for both the in-shell and kernel markets and that there was a need to define the most suitable ecological areas for hazelnut growing in Australia.

In 1990, the author of this thesis moved to Orange, NSW and, along with his wife, commenced some studies on the collection of hazelnut genotypes at the Orange Agricultural Research Centre (Baldwin and Baldwin, 1991). In 1996, funding was received from the Rural Industries Research and Development Corporation (RIRDC) to conduct an evaluation of the growth and productivity of hazelnut genotypes in South-eastern Australia. At that time, the total production of hazelnuts in Australia was estimated to be approximately 25 tonnes of nut in-shell per annum, with several small orchards existing in cool climatic areas of South-eastern Australia, principally in the hills to the west of Melbourne, the river valleys of NE Victoria and on the Central Tablelands of New South Wales. There were very few plantations in Tasmania.

Although hazelnuts had been introduced into Australia in the 1800s, RIRDC considered the crop to have potential and placed it in the category of “New Crops” due to the small size of the industry and the lack of research conducted on this species. The project was supported by RIRDC on the basis that it could provide valuable information for the further development of the industry. The research that was funded by RIRDC and supported by the University of Sydney and the Hazelnut Growers of Australia forms the basis of this thesis.

1.4 The aims and structure of the thesis

Although many hazelnut cultivars have been introduced to Australia, particularly since the 1980s, there has been very little systematic evaluation of this imported material and the factors influencing production, or comparisons made with local selections. Apart from a small industry in north-eastern Victoria in the 1930s and a number of small orchards scattered through Victoria and NSW, hazelnut growing had not advanced as an industry. Why was this? Was it due to a lack of knowledge on the most appropriate cultivars to grow and the appropriate pollenisers for them or was it that hazelnuts are not well-adapted to the soils and climate of the cool temperate areas of south-eastern Australia and do not produce commercially viable yields? An evaluation of cultivars and their growth under a range of environmental conditions is a fundamental need in the early stages of industry development.

The general aim of this thesis was to answer the following questions:

- What are the relative merits of the main hazelnut cultivars available for commercial production in Australia?
- How do environmental conditions affect the growth, phenology and productivity of hazelnut cultivars?
- What is the productive potential of hazelnuts (*Corylus avellana* L.) in Australia?

In order to address these questions, a range of hazelnut cultivars and local selections were grown at 5 field sites in south-eastern Australia. Two sites were in New South Wales, 2 in Victoria and 1 in Tasmania, with some controlled temperature studies on floral phenology in growth cabinets at Orange.

This thesis comprises 9 chapters, viz.:

1. Hazelnut production in Australia – an introduction and background to the research
2. Literature Review – factors influencing the growth and productivity of hazelnuts and a review of the cultivars evaluated
3. Research Methods – field sites, techniques and separate experiments
4. Tree growth – the growth of trees over time as affected by cultivars, seasons and sites
5. Floral phenology of the cultivars – cultivar, seasonal and site effects
6. Effects of temperature on flowering and bud break
7. Nut yields, yield development and yield efficiency
8. Nut fall and the characteristics of nuts and kernels
9. Conclusions – cultivar selection, climate effects on production and the potential for hazelnut production in Australia

Chapters 4-8 include analyses of the data generated in the study with a particular focus on cultivar and site interactions, along with an interpretation and a discussion of the data. The final chapter summarises the conclusions drawn from the work and the scope for further research. In the appendix, an assessment is presented of whether the supplied cultivars were true to type.

CHAPTER 2 - LITERATURE REVIEW

Introduction

The European hazelnut (*Corylus avellana* L.) is native to Europe and Asia Minor and is commonly found growing as wild plants throughout these regions. The natural distribution of this species and its rich genetic diversity indicates its potential for production over a wide range of temperate environments (Mehlenbacher, 1991). However, quite specific climate and soil conditions appear to be needed for commercial production, which occurs in specific geographic regions. To achieve high commercial yields in new areas, there is a need to understand how the species responds to environmental conditions and how cultivars perform in a given locality.

The productivity of crop plants in general is influenced by:

- the environment in which the crop is grown;
- the physiology of the crop species and its management;
- the genetics of the crop species; and
- interactions between these.

To gain a better understanding of the potential of hazelnuts (*Corylus avellana* L.) in Australia, this literature review is written in 4 main parts. The first part provides a review of the influence of climate and soils on hazelnut production. The second part reviews the factors influencing growth, the reproductive processes, nut yields and kernel quality. The third part focuses on the performance of specific cultivars and the effect of the environment on their performance. Finally, there is an overall conclusion that covers the first 3 parts.

Part 1 Climate and soils

2.1.1 Climate

The main areas of commercial hazelnut production are in maritime, Mediterranean-type climates in the latitude range 40-45°N, with mild, humid winters and cool summers (Mehlenbacher, 1991). Examples of the monthly temperature and rainfall for key regions of production in Turkey (Giresun), Italy (Viterbo), Spain (Reus) and Oregon (Corvallis) (Figure 2.1) illustrate the nature of these climates.

The summer temperatures of the key centres are relatively mild, with mean maximum temperatures in the range 25-30°C and mean minimum temperatures in the winter in the range 0-5°C (Figure 2.1). The mean monthly temperature patterns at both Myrtleford and Orange are similar to the four overseas locations, suggesting that these Australian localities would have suitable climates for hazelnut production.

Mean annual rainfall varies from a low of 518 mm in Reus, where hazelnut orchards are irrigated, to over 1000 mm in Giresun and Corvallis, where hazelnuts are grown without irrigation.

Although mean monthly temperature patterns are similar across all these centres, the pattern of rainfall distribution varies between them. The rainfall at Giresun is fairly evenly distributed, with no month receiving less than 50 mm. In contrast, Corvallis and Viterbo receive the majority of their rainfall in the autumn and winter months with little rainfall in the summer months of June, July and August. The implications of low rainfall in June and July, when nuts and kernels are developing, are discussed later in this thesis.

All the northern hemisphere centres have more than 50 mm of rainfall in May, when trees would be making active leaf and shoot growth.

It is recognised that data is required on evaporation rates and soil water-holding capacity to estimate soil moisture availability in the growing season; this is discussed further in the next section, 2.1.2, Soils.

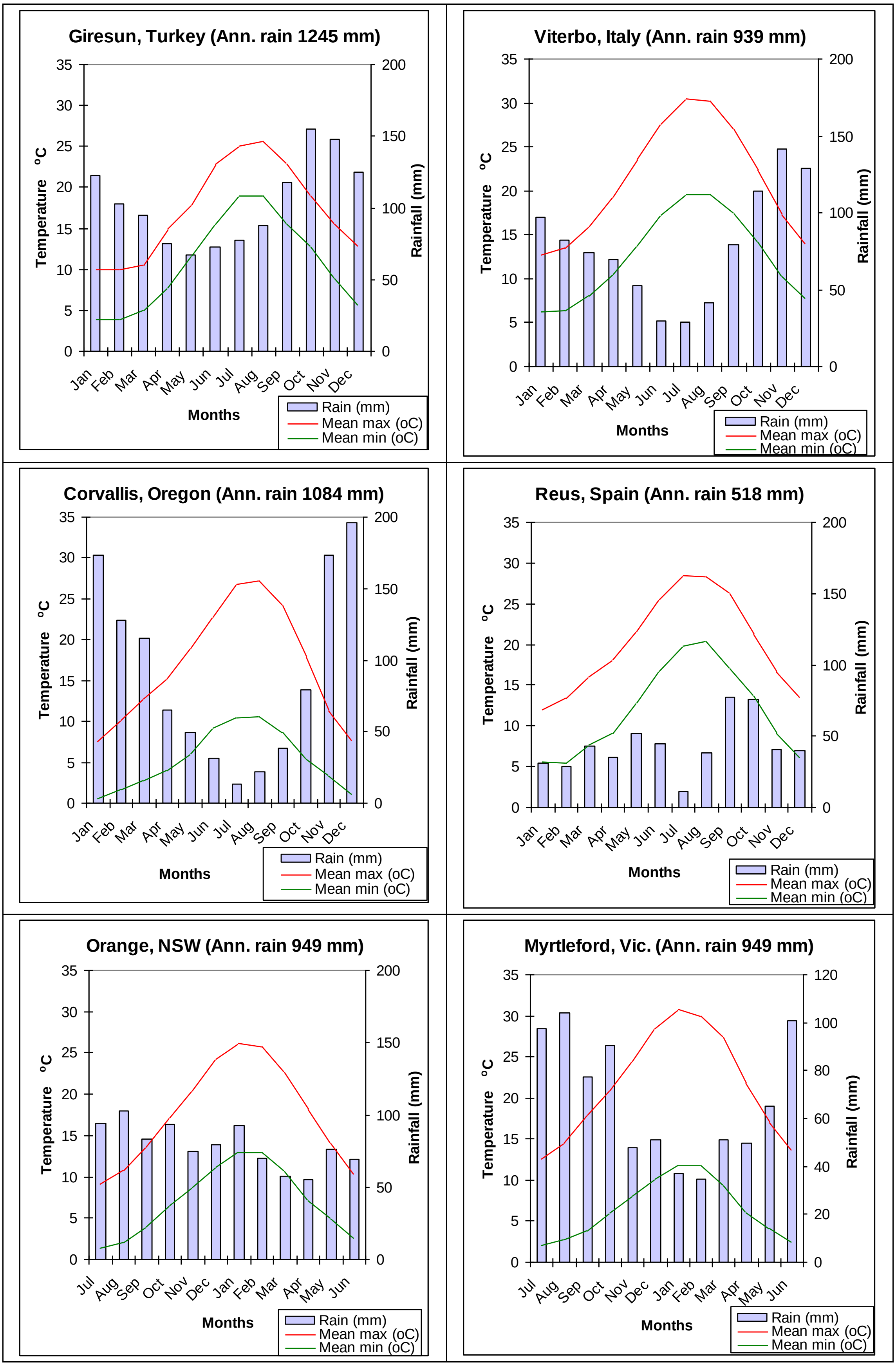


Figure 2.1 Mean monthly temperatures and rainfall along with mean annual rainfall for some key centres of hazelnut production in the world, compared with 2 Australian locations where hazelnuts have been grown.

Source: Overseas data from S. Mehlenbacher, personal communications 1996 and Australian data (Australian Bureau of Meteorology www.bom.gov.au/climate/data/)

Studies on the effects of climate on hazelnut production indicate that although the European hazelnut is a deciduous woody plant, it can be damaged by extremes of cold in winter. In winter, dormant hazelnuts can tolerate temperatures down to -23°C (Thompson, 1981), although Schuster (1944) reported temperatures of -15°C to be damaging to dormant catkins. Extended catkins are less cold tolerant, but can tolerate temperatures down to -8°C (Germain, 1986) with female inflorescences tolerating temperatures down to -10°C (Tous, 2001). However, Thompson (1981) reported that female stigmas that were frozen at temperatures of -12°C to -15°C proceeded normally as temperatures rose. In Romania, Botu and Turcu (2001) reported the catkins, female flowers and one year-old shoots were damaged during winter when temperatures fell below -27°C. Duke (1989) suggested that, in order to minimise the risks of damage from low temperatures, sites in which winter temperatures did not fall below -5°C should be selected

Chilling temperatures in the range 0-7°C are required to break the dormancy of catkins, female inflorescences and vegetative buds (Mehlenbacher, 1991). The chill requirements vary with cultivars. Vegetative buds have the highest requirement; up to 1550 hours for the cultivar ‘Casina’ (ibid, 1991). The chill and post chill warmth requirements for flowering and bud break are discussed further in Chapter 6.

Although pollination occurs in winter, fertilisation does not occur until early summer. The weather conditions at the time of fertilisation are critical. In France, Latorse (1981) found that there was a decrease in nut set and an increase in the number of blank nuts when the maximum day temperatures in the second week of June (early summer) were less than 21°C. In Australia, the period when fertilisation is likely to occur is in late November or early December, probably varying with seasons, localities and cultivars. In the Vila Real region of northern Portugal, Silva et al. (1996) found negative correlations between the hours of sunshine, the maximum temperature in May, and the number of blank (empty) nuts in the cultivar ‘Butler’. These effects of temperature and sunshine on kernel development may be related to a critical period in the development of the hazelnut tree, when fertilisation and early kernel development is occurring whilst shoots are still making active growth. Active photosynthesis would be required to produce materials for these processes.

Hazelnuts are very sensitive to moisture stress (Tombesi, 1994). Soil moisture stress during the spring months can reduce vegetative growth and consequently affect nut production in the following year. Soil moisture stress during nut development and kernel-fill can reduce nut weights, nut yields and kernel-fill (Bignami and Natali, 1997). The most critical period is the time from fertilisation to kernel fill, which is from the end of May to mid July in the Northern Hemisphere (Mingeau et al., 1994). Irrigation is used in some instances to overcome soil moisture stress in this period such as at Reus in Spain (Gispert et al., 2005) where total rainfall in May and June is on average less than 120 mm. In general, 800 mm seems to be the minimum level of annual rainfall for productive unirrigated orchards (Tous et al. 1994). However, this depends on soil type and seasonal distribution of rainfall. On the southern coast of Crimea an annual rainfall of over 1000 mm is considered desirable (Khokhlov, 2001).

In the Willamette Valley, Oregon USA, annual rainfall is about 1100 mm. There is a strong winter–spring incidence with a dry summer (Figure 2.1). Rainfall during the critical period of fertilisation and kernel-fill, May and June in Corvallis, is on average, less than 100 mm. As hazelnuts are not generally irrigated in this region, it appears they are very likely to be drawing from soil moisture reserves at depth to maintain growth and production in the summer, as discussed later in the section on soils, Section 2.1.2.

Hazelnuts are sensitive to hot dry conditions, low humidity and rainfall deficits in summer. Thompson (1981) reported that temperatures greater than 35°C with low humidity can cause leaf burn. The climate of the Willamette Valley is considered to be ideal with temperatures in summer reaching 20-28°C, rarely exceeding 33°C and with cool nights of 8-16°C (ibid, 1981). Climate data recorded over a 30-year period for Corvallis indicates that on average there are only two days per year when temperatures exceed 35°C (Taylor et al., 1991).

In the Catalonia region of Spain, summer temperatures of 30-35°C are commonly recorded with an annual rainfall of 400-600 mm. In the Reus area of this region, crops are irrigated with an average of 2.5 ML/ha (Tous, 2005).

When assessing the most appropriate part of France to develop a hazelnut industry, Bergoughoux et al. (1978) considered rainfall, temperature, relative humidity and wind to be key factors. They were of the opinion that an annual rainfall of 1000 mm was required, although it could be lower if supplementary irrigation was available. The rainfall should ideally be well-distributed throughout the year, but dry conditions were desirable for the period of nut fall and harvest, from mid-September to mid-October. They considered the critical temperatures for winter were a minimum no lower than -15°C, to avoid damage to buds and dormant inflorescences, a minimum of -7°C, to avoid damage to dehiscing catkins and of -3°C in spring, to avoid damage to young shoots after bud break. Under conditions of high evaporative stress, such as hot dry winds, hazelnuts become moisture-stressed. Districts where the relative humidity was less than 70% were considered undesirable. Persistent strong winds were also undesirable. Using these parameters, Germain and Sarraquigne (2004) used long-term climate data to prepare a map showing the area in south-west France where they considered the climate to be suitable for hazelnut production.

The studies presented in this section on the effects of climate on flowering, growth and production have been used to develop a set of critical climate indices, Table 2.1 which could be used to assess the potential suitability of districts in Australia for hazelnut production. The Commonwealth Bureau of Meteorology has a comprehensive data base of climatic averages for weather stations across Australia which can be accessed at www.bom.gov.au/climate/data/ and which potential growers could use to assess the suitability of their location for hazelnut growing. This database contains mean monthly rainfall and temperatures, including highest and lowest recorded for many centres across Australia.

Although the data base does not include chill hours, these can be estimated from mean monthly temperatures by using the formula derived by da Mota (1957):

$$Hc = 485.1 - 28.52x$$

Hc = the monthly chilling hours and x = the mean monthly temperature.

A further limitation of the data base is that relative humidity values are only available for 9 a.m. and 3 p.m. At many sites there are only figures for 9 a.m. A figure of >70% RH at 9 a.m. has been included in the table. There is also limited data on wind strength or wind run for most sites.

There is limited specific information on the effects of high temperatures and low humidity in summer on hazelnuts. In southern Australia, there are days in the summer when temperatures can exceed 40°C and relative humidity can be less than 10%. These conditions occur with hot northerly winds ahead of a cold front. They usually last for only a day, but can be extremely desiccating. It is considered that two days per annum when the maximum temperature exceeds 35°C could be included as a critical level. It is likely these events will have some detrimental effect such as causing leaf burn as reported by Thompson (1981). Other effects would depend on the phenological stage of crop development and available soil moisture levels. As rainfall in Australia is highly erratic, some provision for supplementary irrigation is likely to be highly desirable in most circumstances.

Table 2.1 Key climate requirements for hazelnut production, based on research and observations from major production areas in Europe and the USA

Phenological stage and effects	**Climate parameter and period in Australia**	**Critical level**
Flowering, *low temperatures can adversely affect catkins and female inflorescences*	Lowest air temperature in the coldest months	-7°C Bergoughoux et al. (1978)
Bud break, chill to break dormancy, *insufficient chill may result in poor leafing out*	Total chill hours (0-7°C) April–August (incl.)	>1500 chill hours (Mehlenbacher, 1991)
Bud break and early leafing, *low temperatures can harm emerging leaves*	September/October, lowest minimum air temperature	-3°C Bergoughoux et al. (1978)
Fertilisation, *minimum temperatures for successful fertilisation*	Late November-early December, mean max. air temperature	>21°C Latorse (1981)
Nut and kernel development, *heat stress may affect tree growth and kernel development*	December–February (incl.)	Max. 2 days >35°C Thompson (1981), and (Taylor et al., 1991).
Nut and kernel development and tree growth *adversely affected by moisture stress associated with low humidity*	December - February	>70% mean RH at 9 am Bergoughoux et al. (1978)
Overall growth and production and future crop yields, *inadequate soil moisture adversely affects these processes*	Minimum annual rainfall, unless supplementary irrigation available	>800 mm (Tous et al. 1994)
Tree growth, *adversely affected by strong winds*	October- March	Not persistent Bergoughoux et al. (1978)
Nut harvest, *dry conditions required to facilitate harvest*	March mean monthly rainfall	<50 mm (Tous et al. 1994)

The hypothesis that the key climate characteristics listed in Table 2.1 could be used to determine the suitability of locations in Australia for hazelnut growing was tested for 5 localities where it was known that crop-bearing plantations of hazelnuts existed (Table 2.2). The climate data for these locations was obtained from the Australian Government, Bureau of Meteorology site at www.bom.gov.au/climate/averages.

Generally the data shows that winter (July) and spring (October) temperatures for these sites did not fall below damaging levels. Winters at all sites were relatively mild and all were estimated to have a total of less than 1500 chill hours over the 4 months of May-August, as calculated using the formula of da Mota (1957). The chill hours estimated for the mild winter climate of Manjimup were particularly low, yet the relatively high chill cultivar 'Hall's Giant', which Mehlenbacher (1991) considered requires about 1000 chill hours for bud break, was seen by the author to grow at the Western Australia Department of Agriculture Manjimup Research Station. It is possible that either the da Mota equation generally under-estimates chill hours or hazelnuts require less chill to break bud dormancy than indicated in the literature.

Table 2.2 Evaluation of critical climate data for hazelnut growing in Australia, based on climatic averages for 5 sites where hazelnut plantings have been successfully established

	Location					
	NSW	WA	Victoria		Tasmania	
	Orange (NSW DPI Ag Research Institute)	Manjimup (WA Dept Ag Res Station)	Myrtleford (Post Office)	Toolangi (Mt St Leonards)	Geeveston	Desirable/ maximum levels
Station no.	063254	009573	082034	086142	094137	
Latitude	33.32°S	34.25°S	36.57°S	37.57°S	43.16°S	
Altitude (ASL)	922 m	287 m	223 m	595 m	55 m	
Terrain and climate type	Tablelands, cold winter	Cool wet winter, hot dry summer	Inland valley, warm summers	Coastal hills, cool summers	Cool maritime	
Lowest air temp July	-5.6	-0.1	N/A	-2.5	-4.7	>-7°C
Est Chill hours May-Sept	1367	795	1134	1325	1245	>1500
Lowest air temp. Oct	-2.0	0.1	N/A	-0.6	-1.4	>-3°C
Est Chill hours May-Aug	1373	644	956	1120	1030	>1500
Mean max temp. Nov	21.0	21.9	24.5	18.0	18.2	>21°C
Mean max temp. Dec	24.2	24.8	28.5	20.8	19.9	>21°C
No. days Dec – Feb >35°C	1	6	N/A	1	1	<2 (max)
Mean 9 a.m. RH Dec-Feb	67%	65%	59%	75%	72%	>70%
Ann. rainfall (mm)	933	1005	905	1362	889	>800

At some of the cooler sites, temperatures in November and December were lower than those considered desirable. It is possible that phenological development of the trees is delayed in localities where November temperatures are lower and fertilisation does not occur until December. Mean relative humidity at 9 a.m. in December–February was lower than 70%, at 3 of the sites.

Another consideration is the mean maximum temperature in November and December could be slightly lower than 21°C, provided sunshine hours are high and moisture stress is low, to favour photosynthesis at this critical period. As hazelnuts are very sensitive to moisture stress, the use of supplementary irrigation is likely to be highly advantageous to reduce the impacts of highly variable rainfall, periods of drought and periods of hot dry winds as discussed above.

Manjimup was the site where the highest number of days above 35°C had been recorded. The trees seen growing at Manjimup had been irrigated. Possibly a figure of 2 days above 35°C is a rather arbitrary heat stress indicator. It is highly likely that a combination of high temperature, low humidity and inadequate soil moisture, for an extended period of time, would be the key factors adversely affecting the moisture content of leaves, photosynthesis and growth.

It is considered that for a location to be suitable for hazelnut growing, all of the climatic indices should be favourable, with the possible exception of rainfall, provided supplementary irrigation is available.

Conclusion on climatic indices

It is concluded that, based on limited observations and data, the set of climatic indices developed to assess the suitability of locations for hazelnut production in Australia (Table 2.1) provides a useful guide but may require some modification, such as the estimated chill hours based on the da Mota formula, the duration and the intensity of heat stress. Total rainfall could be less important if irrigation is available.

2.1.2 Soils

The physical and chemical characteristics of soils affect the growth of plants through their effects on the root system of the plants. Roots have 3 main functions; to absorb water and nutrients and transfer these to the above ground parts of the plant, to act as a storage organ and to anchor the plants in the ground. The uptake of water and nutrients is through the unsuberised roots and root hairs near the growing tips of the root system. Root growth is influenced by air in the soil, moisture, temperature and the provision of carbohydrates. Roots grow profusely in well-aerated soils. They can be damaged by a lack of oxygen, excess moisture and high acidity. Oxygen levels of 9-12% are required by many agricultural plants for active root growth (Russell, 1961).

Soil texture and structure have a strong influence on root growth. Many plants produce a large root mass in a sandy soil compared with a heavy clay. By contrast, compacted soils such as poorly-structured clays can impede root growth. Root growth of many agricultural plants slows in soils with penetrometer readings of 1 MPa, falling to zero at 5 MPa, (Passioura, 2002). Benhough et al. (2011) considered that mechanical impedance was a major limitation to root elongation in many plant species, with zero elongation occurring at less than 6 MPa for most species. It is considered that plant roots can sense deteriorating or restrictive environmental soil conditions and produce “feed forward” inhibitory signals that may affect stomatal conductance, cell expansion, cell division and the rate of leaf appearance (Passioura, 2002). However, it is possible that feed forward signals may be lost through selection for high production in agricultural plants. Benhough et al. (2011) reported that root tip traits influence the ability of roots to penetrate soils with differences between genotypes providing potential opportunities to breed cultivars that are better able to exploit the soil, with possible greater drought tolerance.

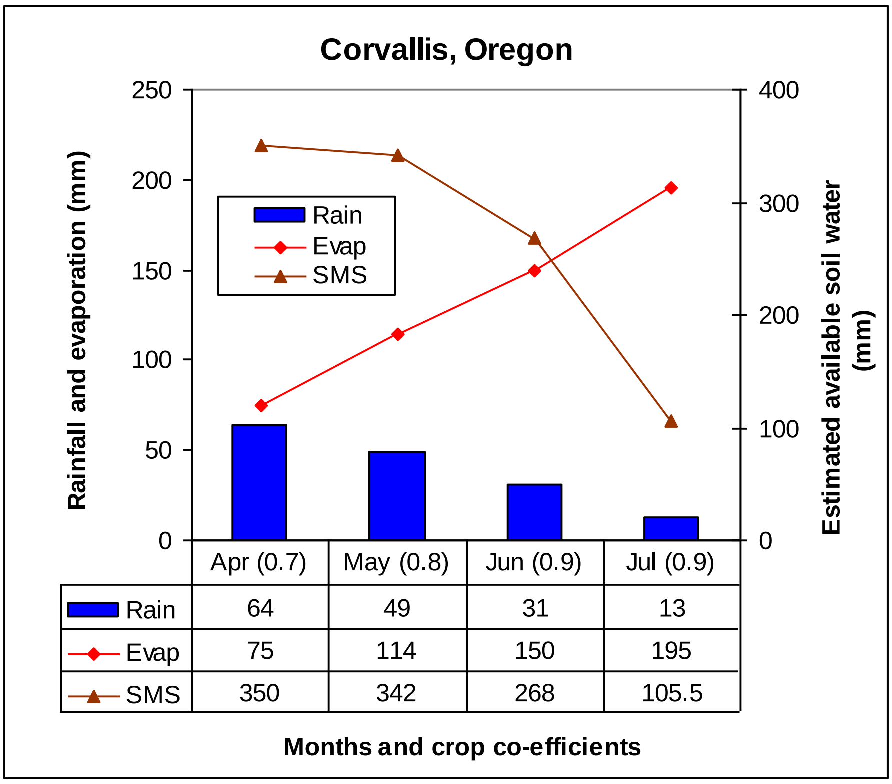
Mehlenbacher (1994) considered soil type had a significant effect on the growth and production of *Corylus avellana* L., with the species growing best on deep, fertile, well-drained soils. Thompson (1981) stated that in Oregon, a high percentage of roots were in the top 0.6–1.0 m, with some going deeper. In France, Germain and Sarraquigne (2004) also found that the majority of hazelnut roots were in the top 0.6 m of soil with some going down to 1.2 m. However, Woodroof (1967) reported that roots can penetrate down to 3.5 m in depth in well-aerated soils. Both Woodroof (1967) and Thompson (1981) emphasised the poor tolerance of hazelnuts to poor soil aeration and the damaging effects of waterlogging, particularly during active vegetative growth. On shallow soils, the hazelnut trees may grow well in their early years but subsequently do poorly and are often stunted, (Thompson, 1981) and (Woodroof, 1967).

In Oregon, hazelnuts are mainly grown on deep, fertile loams with good water-holding capacity as unirrigated crops in the Willamette Valley (Lagerstedt. 1981). Deep, well-drained, fertile soils with a pH of at least 6.0 were recommended by both Woodroof (1967) and Thompson (1981). They considered that soils should be at least 2.4–3 m in depth, to provide sufficient moisture for a dry season. Hazelnut trees can make extensive root growth in winter when temperatures are above 5°C (Thompson, 1981). This presumably enables them to develop a good root structure in spring that can obtain moisture for growth and kernel fill during the relative dry summer months of July and August (Figure 2.2).

There appears to be a relationship between soil type and rainfall. In Oregon, high yields, 1700-2000 kg/ha, are achieved on deep, well drained soils with an annual rainfall of about 1100 mm. Whereas in France, with a 700-800 mm annual rainfall and deep fertile sandy loam soils, some irrigation is needed. In Spain where rainfall in the Camp de Tarrogona region is only 500 mm and summers are dry, irrigation is essential (Tous et al, 1994).

It appears that deep loam soils may provide a reserve of soil moisture. In Oregon, hazelnuts are grown without irrigation, on deep loam soils in the Willamette Valley, where annual rainfall averages 1100 mm. The rain falls mainly in late autumn, winter and spring, summers are relatively dry (Thompson, 1981). Evaporation is very low in winter and high in summer. Water use by dormant trees is negligible in winter and rises to peak levels in summer, following bud-break and leaf expansion, to a full canopy in July. In France, Mingeau and Rousseau (1994) measured the relationship between water loss through transpiration (T) and estimated evapotranspiration (ETP), as calculated using the Penman formula. This relationship provides crop coefficients that can be used to estimate water loss by hazelnut trees from evaporation data.   Based on an available water-holding capacity of 175 mm/m depth for a loam soil (Charman and Murphy, 1991, p. 164) and an assumed rooting depth of 2 m, an estimate was made of the soil moisture levels under a mature hazelnut orchard in Oregon through the growing season, from bud-break in March/April to the start of kernel filling in July, based on the crop coefficients of Mingeau and Rousseau (1994), Figure 2.2. These assumptions, estimates and calculations indicate that in an average year of rainfall, hazelnut trees in the Willamette Valley appear to utilise most of the available stored moisture in the top 2 m of soil by the end of July. At that stage, kernels would be filling and it is likely that trees would need to utilise stored soil moisture from greater depth for the completion of kernel fill and to maintain growth until the autumn. However, modelling beyond July would need to take into consideration the effects of drier soils on transpiration rates.

It is recognised that these are theoretical calculations and there is a need to conduct studies on root development and water uptake by hazelnuts in non-irrigated situations. However, this simple modelling supports the views of Woodroof (1967), Thompson (1981) and Mehlenbacher (1994) that deep well-drained soils are required for commercial hazelnut production. However, there must be a limit to their ability to supply adequate moisture for high yields and well-filled kernels at times when spring and summer rainfall is low.



	Apr (0.7)	May (0.8)	Jun (0.9)	Jul (0.9)
Rain	64	49	31	13
Evap	75	114	150	195
SMS	350	342	268	105.5

Figure 2.2 Estimated available soil moisture levels under a hazelnut orchard in an average season at Oregon, based on rainfall and evaporation data for the Agricultural Experimental Station, Oregon State University (Taylor et al., 1991).

Note: Estimated available soil moisture store is based on a loam soil with a water-holding capacity of 175 mm/m, a rooting depth of 2 m and crop coefficients (T/ETP) developed by Mingeau and Rousseau (1994).

Soil texture and pH

Soil texture is considered to be an important factor for successful hazelnut production. Germain and Sarraquigne (2004b) recommend that in France, soils in the texture range sandy loam to clay loam with a clay content of no more than 20-40%, should be selected. In their studies on soils in Romania, Botu and Turcu (2001) reported soils with a clay content exceeding 35-40% were unsuitable for hazelnut growing. Trees on soils with a high clay content lacked vigour, produced more suckers, were later coming into bearing and produced lower yields. Soils considered suitable were alluvial, brown forest and chernozems (black prairie soils). Germain and Sarraquigne, (2004) considered that very sandy soils are also unsuitable and should be avoided.

Khokhlov (2001) concluded from studies on the growth of hazelnuts on the southern coast of Crimea that the most suitable soils were those that were moist, slightly stony, with a light clay texture and were slightly alkaline.

In the UK, hazelnut growing occurs mainly in the Sevenoaks district of east Kent, where hazelnuts, locally known as cobnuts, are grown on soil derived from soft ragstone rock, derived from limestone (Kent Geologist Group, 2011). This soil is fertile with a sandy texture, is free-draining, and has a neutral pH (Baldwin and Baldwin, 2003).

A slightly acid to neutral soil reaction with a pH in water (pH_w) of 6-7 is considered desirable. However, some cultivars seem well-adapted to mildly alkaline conditions. In France, soil pH is considered to be relatively important, a pH range of 6.2-7.8 is recommended by Germain and Sarraquigne, (2004). In Oregon, liming soils before planting is recommended, when soil pH is below 6.4 (Oregon State University Extension Service, 1985). In Spain, hazelnuts are grown mainly on calcareous loam soils with a pH>7-8 (Tous, 2005). At this level of pH, plants may suffer from iron chlorosis (Tous, 2001). In Croatia, Miljković and Prgomet, (1994) reported the cultivars ‘Barcelona’, ‘Nocchione’, ‘Negret’ and ‘Tonda Romana’ grew well and produced good nut yields on a terra rossa soil overlying limestone with an annual rainfall of 800-900 mm. Terra rossa soils are red soils that have a high content of iron oxides and are well drained.

Conclusion on soil suitability

It is concluded that, as with most agricultural crops, soil type is important. Desirable attributes are a loam texture, fertile, good drainage, a high water-holding capacity, pH 6-7 with a depth of at least 1.5 m. Heavy clay soils should be avoided, particularly if poorly drained.

Relating this to the Australian situation, Charman and Murphy (1991, p225) writing on the suitability of soils for agricultural use in NSW, state that for a given climatic region, soil type is strongly influenced by soil parent material. Soils derived from basalt are generally chemically fertile, have a high clay content, are well structured with good internal drainage and have relatively deep topsoils. They are often used for intensive cropping and horticulture. In contrast, soils from parent materials such as granite and sandstone are relatively infertile, with sandy topsoils overlying poorly structured clay subsoils, duplex profiles. The subsoil or ‘B’ horizons are commonly poorly structured resulting in poor internal drainage. Soils developed from alluvial deposits can vary considerably in texture depending on their origin. This relationship between soils and parent material generally applies to all soils in south-eastern Australia.

The selection of appropriate soils in Australia is likely to be very important and may be a significant factor influencing the places where hazelnuts can be successfully grown. Suitable soil types are likely to be those derived from basalt and well-drained alluvial soils. The soils of the research sites listed in Table 2.2 included soils derived from basalt at Orange and Toolangi, an alluvial loam soil at Myrtleford and a deep well-drained red soil at Manjimup.

2.1.3 Conclusions on Climate and Soils

It is concluded that both climatic conditions and soil type have a significant effect on the growth and production of hazelnuts. A series of climatic parameters were developed from the literature to assess the suitability of locations for hazelnut production. When tested against sites where hazelnuts have been grown in Australia, it appeared that the greatest climatic limitations to hazelnut production in Australia are likely to be related to a combination of high temperatures and low humidity in summer causing moisture stress.

A mean annual rainfall greater than 800 mm appears to be required for unirrigated orchards, but water sources to provide supplementary irrigation are likely to be essential to buffer erratic rainfall.

It is unlikely that in Australia damage will generally occur from low temperatures in winter, although late spring frosts may be a concern. In some warmer locations there may be insufficient chill hours to break dormancy. The chill requirements of cultivars need to be evaluated as part of the research.

Soil type appears to be very important. Relatively deep, well drained, fertile, loam soils appear to be highly desirable. As many Australian soils have a duplex profile, with a heavy textured B horizon, locating a suitable soil type combined with an appropriate climate may limit areas where hazelnuts can be grown. Soil depth and physical characteristics are likely to be an important criterion in site selection. Nutrient levels are likely to be less important as they can be supplied as fertiliser in various forms.

Part 2 Factors influencing growth and production

2.2.1 Physiological process of growth

Photosynthesis provides the primary compounds and energy for plant growth. The rate of photosynthesis changes seasonally and diurnally (Kozlowski and Pallardy, 1997). If moisture is not limiting, the rate of photosynthesis is low early in the morning rising to a maximum about mid-day and declining in the latter part of the day. Major environmental factors that regulate photosynthesis include light intensity, temperature, wind, relative humidity, daylength and physiological state of the plant, available soil moisture and soil fertility (ibid, 1997).

Shading within the canopy of hazelnut trees has a significant effect on photosynthesis. Light intensity and photosynthesis decrease markedly with increasing distance from the top of the tree crown. At low light intensity, lower in the canopy, there is very little photosynthesis, yet there is a release of CO_2 from respiration.

In a study on the physiological aspects of hazelnut training systems, Valentini et al. (2009) found that in an orchard where the tree crown was 4 m above the ground, the photosynthetically active radiation (PAR) was in the range 17-25% at 3 m above the ground with a reduction to 3-7% at 1.5 m above the ground. This indicates the high level of shading often found in the foliage of mature hazelnut trees. The cultivar was 'Tonda Gentile delle Langhe', the trees were 15 years old, trained to a free-vase form and planted at a spacing of 3x5 m. The leaf anatomy was markedly affected by light intensity. Leaves that received more light had a higher stomata density (225/mm^2) and a more developed palisade tissue (49% of leaf thickness) compared with the more shaded leaves with a lower number of stomata (116/mm^2) and less well-developed palisade tissue (29% of leaf thickness). Leaves with a higher proportion of palisade tissue and higher stomatal conductance had higher net assimilation rates.

The age of leaves influences their photosynthetic capacity, increasing from low levels for juvenile leaves to a maximum for fully expanded, adult leaves, declining as leaves senesce. The high levels of photosynthesis in adult leaves are associated with a greater number of chloroplasts per cell, a thicker palisade layer and thicker leaves (Kozlowski and Pallardy, 1997). The changes in photosynthetic capacity with age vary with species.

Training systems can influence light transmission within the canopy and leaf anatomy (Goncalves et al., 2009).

Most temperate-zone woody species are C3 plants, in which the fixation of carbon through photosynthesis uses the Calvin cycle. Photosynthesis occurs over the temperature range of just above 0°C to 40°C. Optimum temperatures are in the range 15-25°C (Kozlowski and Pallardy, 1997). The disadvantage of C3 plants is that under hot dry conditions their efficiency of photosynthesis is greatly reduced due to photo respiration. When the CO^2 concentration in the chloroplasts drops below about 50 ppm, the catalyst rubisco that helps to fix carbon begins to fix oxygen instead, thereby reducing the efficiency of photosynthesis. (Moore et al, 1995.). Studies on photosynthesis in apricot by Lange et al. (1994) showed that some acclimation to higher temperatures can occur.

Photosynthesis is influenced by both drying and waterlogging of the soil. Water deficits cause stomata to close, which decreases the efficiency of carbon fixation. This can lead to a reduction in leaf development and even leaf-shedding under conditions of prolonged water deficits (Kozlowski and Pallardy, 1997).

Tombesi (1994) conducted studies under high light conditions in summer on the effects of soil water deficits on photosynthesis and stomatal conductance on 3 year-old hazelnut trees. The photosynthetic rates of trees with high levels of soil moisture availability were highest at 09:00 h with a slight reduction at 12:00 h and a recovery at 16:00 h. This suggests that water loss at 12:00 h might have been greater than the ability of the plants to take up water from the soil, even from a soil in which water was readily available. Photosynthesis was high until water availability declined to 60%. As water deficits increased, photosynthesis, stomatal conductance and water use efficiency declined. As water deficits approached wilting point, leaves wilted and, with no further addition of water, they became desiccated. Chlorophyll, soluble sugars and starch content declined in stressed leaves. Mingeau et al. (1994) found that if available soil water levels decline relatively slowly, hazelnuts can adjust their transpiration rates, thereby limiting the impact on photosynthesis and growth. When soil moisture deficits were relieved, plants reverted relatively quickly to more normal rates of transpiration and photosynthesis. Water deficits were also shown by Girona et al. (1994) to reduce net photosynthesis in hazelnuts. In a comparison of irrigated and unirrigated hazelnut trees, Dias et al., (2005) recorded lower rates of photosynthesis and lower levels of chlorophyll in the leaves of the unirrigated trees. In contrast, Bignami and Natali (1997) found no differences in assimilation rates between young trees in unirrigated and irrigated treatments, although leaf area index increased significantly in response to irrigation levels.

Conditions of low humidity often cause stomatal closure in woody plants (Kozlowski and Pallardy, 1997). Bergoughoux et al. (1978) noted that several days of desiccating winds caused wind burn on leaves and considered ideal relative humidity levels were 70-80%. These relative humidity levels were included in the climatic indices in
Table 2.1.

In studies on changes in the xylem water potential (Ψ) of 3 hazelnut cultivars, ‘Barcelona’, ‘Tonda di Giffoni’ and ‘Tonda Gentile delle Langhe’, Grau and Sandoval (2009) found that the lowest levels of ‘pre-dawn’ (06:00 h) xylem water potential were recorded when the relative humidity on the previous day had fallen to 50%. This suggests there was a lag in the rehydration of tissues following desiccating conditions. Rainfall had no effect on ‘pre-dawn’ water potential. The studies were undertaken in Chile from late January to late April. There were no significant differences between the 3 cultivars in their response to the environmental conditions, nor were there any differences in stomatal density; which averaged 42 stomates/mm^2 for randomly-sampled leaves. This is a low figure compared with that recorded by Valentini et al. (2009), as discussed previously.

Carbohydrates produced from photosynthesis are used in many plant functions. The greatest proportion is used in respiration to provide energy for the synthesis of new cellular material for growth and development. The rate of respiration depends on environmental conditions and physiological factors such as the age of the tissues. Energy losses through respiration can be as high as 60% of the daily production of photosynthesis (Kozlowski and Pallardy, 1997). Carbohydrates not used in metabolic process and growth accumulate in a variety of vegetative and reproductive tissues; the levels varying seasonally. In Turkey, the levels of the monosaccharides fructose and glucose and the disaccharide sucrose in bark tissues of several hazelnut cultivars were found to decrease during spring to their lowest levels in summer. Levels then rose during autumn to winter (Okay et al., 2005). The levels of sucrose in winter were higher in districts with lower winter temperatures. Cold hardiness has commonly been attributed to the accumulation of sugars during early autumn before leaf fall (Kozlowski and Pallardy, 1997). Sucrose and starch are also storage carbohydrates that are used in growth and development. The storage of carbohydrates and nutrients, especially nitrogen, are particularly important for new growth in early spring (Olsen et al., 2001).

2.2.2 The phenology of growth and development

The European hazelnut (*Corylus avellana* L.) is widely distributed in Europe, where its natural growth habit is as a multi-stemmed deciduous shrub to a height of 3-10 m, occasionally up to 15 m. It is a polygenic and polymorphic species, exhibiting a wide diversity in morphological characteristics such as plant size, growth habit, nut size, nut shape and husk length (Mehlenbacher, 1991). A polygene or quantitative gene is one of a group of non-allelic genes that influence a phenotypic trait such as nut size or nut shape. This gives rise to polymorphism with a diverse range of phenotypes, with a great variation in characteristics.

The phenological development in hazelnuts, in Oregon, typifies the general pattern in the Northern Hemisphere and the sequence would apply elsewhere. Flowering and pollination occurs during winter when the plant is dormant. Leaf emergence occurs in March-April, followed by shoot development. Nut development starts in May–June, fertilisation takes place in late June–early July, the embryo and kernel develop in July and August. Nuts mature in late August. The husk slowly matures and nut-drop extends from early September to mid-October (Lagerstedt, 1981). Leaf fall occurs from October onwards.

This general growth pattern is typical of deciduous woody plants, which alternate from a period of active growth under warm seasonal conditions to a dormant, leafless phase under cool–cold, winter conditions. There is a transition between these 2 growth phases, which are influenced by climate. New buds produced during the active growth phase become inactive, moving into a pre-dormancy phase. This dormancy becomes progressively deeper (endodormancy) during autumn until it is gradually terminated through the accumulated exposure to a period of chilling followed by warmth that leads to bud break and the beginning of active growth (Kozlowski and Pallardy, 1997).

A model for seasonal growth and dormancy was proposed by Fuchigami et al. (1982) showing how deciduous woody plants move from a summer growth phase to a period of endodormancy in winter. In some species, shortening daylength in late summer triggers the cessation of growth, leading to a state of ecodormancy; with other species growth ceases with declining temperatures. There is a transition from ecodormancy to endodormancy in which buds are dormant due to a balance of growth-regulating substances. The transition to endodormancy is usually complete by October or November in the northern hemisphere (Westwood, 1993). Endodormancy is strongly influenced by levels of growth-regulating substances such as the inhibitor abscisic acid (ABA), with levels declining during chilling and with flowering being stimulated by growth-promoting cytokinins, as proposed by Lavee (1973). The chilling requirements to break dormancy vary greatly with species and with cultivars within species. It would seem that an important consideration in this model is the transition that occurs between the phases of growth and dormancy, rather than considering these phases as having sharply-defined boundaries. It seems highly likely that the transition times are strongly influenced by seasonal conditions.

In woody plants, growth arises from meristematic tissue. Shoot elongation arises from the expansion of buds, involving cell division in the apical meristem, followed by elongation, differentiation and maturity. Shoot thickening and the increase in trunk diameter arises from the activity of the meristematic tissue in the cambium, resulting in the production of xylem vessels inwardly and phloem outwardly (Kozlowski and Pallardy, 1997).

Seeds contain a radicle or root meristem from which the initial roots develop. Lateral roots arise from the outer layer of the stele, or pericycle. The pericyclic cells become meristematic, and grow out through the outer layers of the root tissues. These lateral roots have an apical meristem and a root cap (Kozlowski and Pallardy, 1997). In temperate regions, root growth of deciduous plants commonly commences before shoot growth and continues after shoot growth ceases.

The date of bud break, which marks the beginning of active growth, varies with cultivar and environmental conditions. For example, in Oregon, it occurs from late February to early April, for hazelnuts, depending on the cultivar (Mehlenbacher, 1991). Studies in Norway on leaf bud-break on a range of deciduous tree species including *Corylus avellana* L. found that time of bud-break decreased with increasing duration of chilling (Heide, 1993). The estimated base temperature for the accumulation of thermal time varied between species from -4°C to +1°C. Another factor was the influence of day length; long days reduced the thermal time to bud break.

Hazelnut cultivars that are early into bud-break include ‘Tonda di Giffoni’ and ‘TGDL’. Intermediate cultivars include ‘Barcelona’ and ‘Imperial de Trebizonde’ (syn. ‘Wanliss Pride’) and late-leafing cultivars include ‘Ennis’, ‘Hall’s Giant’ and ‘Kentish Cob’ (Thompson et al., 1978). In some environments, such as where late frosts can occur, cultivars that leaf-out early may be subject to frost damage (Mehlenbacher, 1991).

The seasonal growth of shoots of 4 cultivars was studied in Portugal by Santos et al. (1998) as the trees developed over a period of 10 years. They found that, with each cultivar, shoot growth followed an S-shaped curve. Over the 10-year period, the highest growth rates were observed in the early stages of tree development, following planting. As tree size increased, the relative growth rates of shoots declined. In their situation, competition between the trees was observed from the fifth year. The trees had been planted at a spacing of 5x3 m. Average annual shoot growth ranged from 25-50 cm, but varied with seasons and cultivars. It was highest in the cultivar ‘Butler’ and lowest in ‘Hall’s Giant’. Shoot growth was positively correlated with rainfall. Poor shoot growth resulted in low nut yields in the following year, which was also reported by Dimoulas (1979). The sensitivity of hazelnuts to soil moisture deficits in the period May to early July in the northern hemisphere and its adverse effects on shoot elongation, trunk growth and nut yields was also reported by (Tombesi, 1994) (Mingeau et al., 1994) and (Bignami and Natali, 1997).

Leaf growth is rapid in late spring, producing a dense canopy by early summer. In Oregon, Hampson et al. (1996) recorded only 10% of full sunlight 2.1 m above the ground in a 6 year-old ‘Ennis’ orchard in mid-summer. A leaf area index (LAI) of 7.6 was estimated for 10 year-old Barcelona trees (ibid). LAI values of 2.4-5.2 were reported by Bignami and Natali (1997) for young trees in an irrigation study in Italy. The higher values were for irrigated trees. Azarenko et al., (1997) found that levels of light in the leaf canopy from late May to early July, when nuts and kernels are developing, had a critical effect on nut yields and kernel quality.

2.2.3 Vigour, growth habit and suckering

Hazelnut cultivars vary markedly in their vigour, growth habit and tendency to produce suckers at their base. Many Turkish cultivars, such as ‘Imperial de Trebizonde’ (syn. ‘Wanliss Pride’), are of low vigour which makes them suitable for hand harvesting. ‘Kentish Cob’ (syn. ‘Longue d’Espange’) is also a cultivar of low vigour (Santos and Silva 2001); it too is hand-picked in the UK for its green nuts (Allens Farm, Kent Cobnuts, 2011).

‘Negret’ and ‘Tonda Gentile delle Langhe’ are of low–medium vigour and are grown as small trees with short trunks for mechanical harvesting (Tous et al., 1994). ‘Casina’, ‘Ennis’ and ‘Willamette’ were reported to be of intermediate vigour compared to ‘Barcelona’ (McCluskey et al., 1997). ‘Barcelona’ and ‘Pautet’ are cultivars of high vigour (Mehlenbacher, 1991) as are ‘Butler’ and ‘Segorbe’ (Lagerstedt, 1975). ‘Hall’s Giant’ is an example of a very vigorous cultivar (Mehlenbacher, 1991). However, the vigour of cultivars varies with environmental conditions. For example, in Croatia, Miljkovic and Prgomet (1994) reported that ‘Negret’ and ‘Tonda Romana’ were cultivars of high vigour, similar to ‘Barcelona’. In Chile, Grau and Bastias (2005) reported that ‘Tonda Gentile delle Langhe’ had similar high vigour to ‘Barcelona’ and ‘Tonda Romana’.

Tree shape is largely determined by the angle of the branches, which varies with cultivars from very erect, as in ‘Daviana’, to very spreading or drooping, such as ‘Imperial de Trebizonde’ (Thompson et al., 1996; Bioversity International, FAO and CIHEAM, 2008). It is generally considered that the ideal shape for hand harvesting is very spreading whereas cultivars with an upright to spreading growth habit combined with a high level of vigour, such as ‘Barcelona’ and ‘Pautet’, are considered ideal for mechanical harvesting (Mehlenbacher, 1991).

Branching density varies from quite sparse as in ‘Butler’ to dense as in ‘Ennis’ (Bioversity International, FAO and CHIEAM, 2008). The natural tendency of the species is to grow as a bush form with many suckers. However, trees are generally trained to either a traditional multi-stem form such as occurs in Turkey, Italy and Spain (Tous et al., 1994) or to a vase shape with a single stem to facilitate the mechanisation of orchard operations including harvesting. In this latter situation, suckers are commonly controlled with herbicides.

There does not appear to be a relationship between the degree of suckering in a cultivar and its vigour. Some cultivars that produce many suckers are vigorous, such as ‘Fertile de Coutarde’ (Thompson et al., 1978); others like ‘Hall’s Giant’ are also vigorous but produce relatively few suckers (Bergoughoux et al., 1978).

The traditional training system in Turkey, Italy and Spain is the multi-stem bush. However, where orchards are mechanically harvested, trees are commonly grown on a single trunk (Tous et al., 1994). Young orchards in Oregon and Europe, of vigorous cultivars such as ‘Barcelona’, are generally pruned to a vase shape. Newly-planted trees are often cut back to produce 3-4 scaffold branches at a trunk height of about 80 cm. However, with lower-vigour cultivars, such as ‘Negret’ in Spain and ‘TGDL’ in Italy, lower trunk heights of 10-40 cm are used (Tous et al., 1994). In the early stages of development, the main aim is to shape the tree and build a strong framework (Woodroof, 1967). The primary branches are often headed back and subsequently the secondary branches to favour the general branching of the tree. During the early-bearing stages, little pruning is done as the trees expand their bearing surface and root systems.

Assessing growth

Vigour of growth is often assessed by measuring the butt circumference of trees. In Chile, Grau and Bastias (2005) took measurements 150 mm above the ground. In Bioversity, FAO and CIHEAM (2008), it is recommended that measurements be taken 400 mm above the ground. Butt circumferences are frequently converted to trunk cross-sectional area (TCSA) to obtain an indication of wood production and to determine nut yield efficiencies (Westwood, 1993). Nut yield efficiencies are determined from the nut yield at some given year of cropping divided by the TCSA. Trees that produce high yields with low TCSA values have high yield efficiencies. It indicates the relative use of assimilates to produce nut yields rather than tree growth. Other measures of yield efficiency include light interception and light use efficiency (Charles-Edwards, 1982) as well as water use efficiency in dryland crops (Feddes et al., 1978) and (French and Schultz, 1984.)

Observations of tree vigour are commonly used to complement measurements of butt circumference. Although measurements of butt circumferences are relatively easy to obtain, they do not give a very good indication of tree size. In Portugal, Santos et al. (1994) found that the crown volume and total stem mean area of 11 hazelnut cultivars grown as multiple stems were poorly correlated.

Lagerstedt, as reported in Westwood (1993), considered that the maximum bearing surface of a hazelnut orchard was achieved when the total trunk cross-sectional area of the trees in an orchard was 91,800 cm^2/ha. The total trunk cross-sectional area is determined from the mean trunk cross-sectional area of the trees multiplied by the number of trees per hectare in an orchard. Although not stated, this estimate was probably for the cultivar 'Barcelona', as the study was in Oregon where 'Barcelona' was the main cultivar grown. It is likely this figure will vary with cultivars and the conditions under which they are grown.

Training systems

Hazelnuts are borne mainly on the shoot growth of the previous season, one-year old wood. It is generally considered that most cultivars need to produce 150-200 mm/annum of new wood on shoots to be fruitful (Tous et al., 1994). Shoots less than 50 mm differentiate few flower buds. Although it is considered highly desirable to produce vigorous growth of young trees to prepare a good framework for crop-bearing, vigour is not necessarily correlated with yield in the early years of production. Female buds are not only borne on the lateral buds of the new season's shoots but, in some cultivars, they also occur on catkin peduncles (Giulivo and Pisani, 1973). The cultivars 'Barcelona' and 'TGDL' produce most of their flowers on stems, whereas 'Ennis' and 'Casina' produce a high proportion of their flowers on catkin peduncles (Azarenko et al., 1994). Cultivars differ markedly in the time they take to come into bearing, for example 'Lewis' and 'Ennis' are early into bearing (McCluskey et al., 2001) which may be because they bear flowers on catkin peduncles.

Traditionally, hazelnuts have been grown as a multi-stemmed bush, but a single stem or vase form is preferred in large orchards where operations, such as spraying and harvesting, are mechanised (Tous et al., 1994). Young orchards in Oregon and Europe, of vigorous cultivars such as 'Barcelona', are generally pruned to a vase shape.

In the early stages of development, the main aim is to shape the tree and build a strong framework. The primary branches are often pruned and subsequently the secondary branches to favour the general branching of the tree. During the early-bearing stages, little pruning is done as the trees expand their bearing surface and root systems (Woodroof, 1967).

In the early stages of tree development, vigorous cultivars such as ‘Barcelona’ are pruned to produce 3-4 scaffold branches at 80 cm above soil level whereas less vigorous cultivars such as ‘Negret’ or ‘TGDL’ are pruned to produce scaffold branches at a height of 40 cm (Tous et al., 1994).

Other training systems such as the V-hedge, “monocone” (vertical axis) and “ipsilon” (2 main stems arising just above the ground) as shown in Figure 2.3, have been evaluated. In Spain, Tous et al., (1994), compared the “free vase”, “monocone”, “ipsilon” and V-hedge systems. The V-hedge involved planting pairs of trees 0.4 m apart down the centre of the row with the individual trees planted with their trunks at opposite angles of 30° from vertical. The trees were planted at a spacing of 6 m x 3 m, 555 trees/ha, except the hedge system which was 1100 trees/ha. These 4 training systems were evaluated on 3 cultivars of differing vigour at 2 sites. There was an interaction effect between cultivars, training systems and sites on 5-year cumulative nut yields. However, the V-hedge system, with its high tree density, produced the highest nut yields in the first years of nut production at both sites. The V-hedge system produced the most suckers; the “monocone” was not suitable for low vigour cultivars whilst the vase system gave the best vegetative growth.

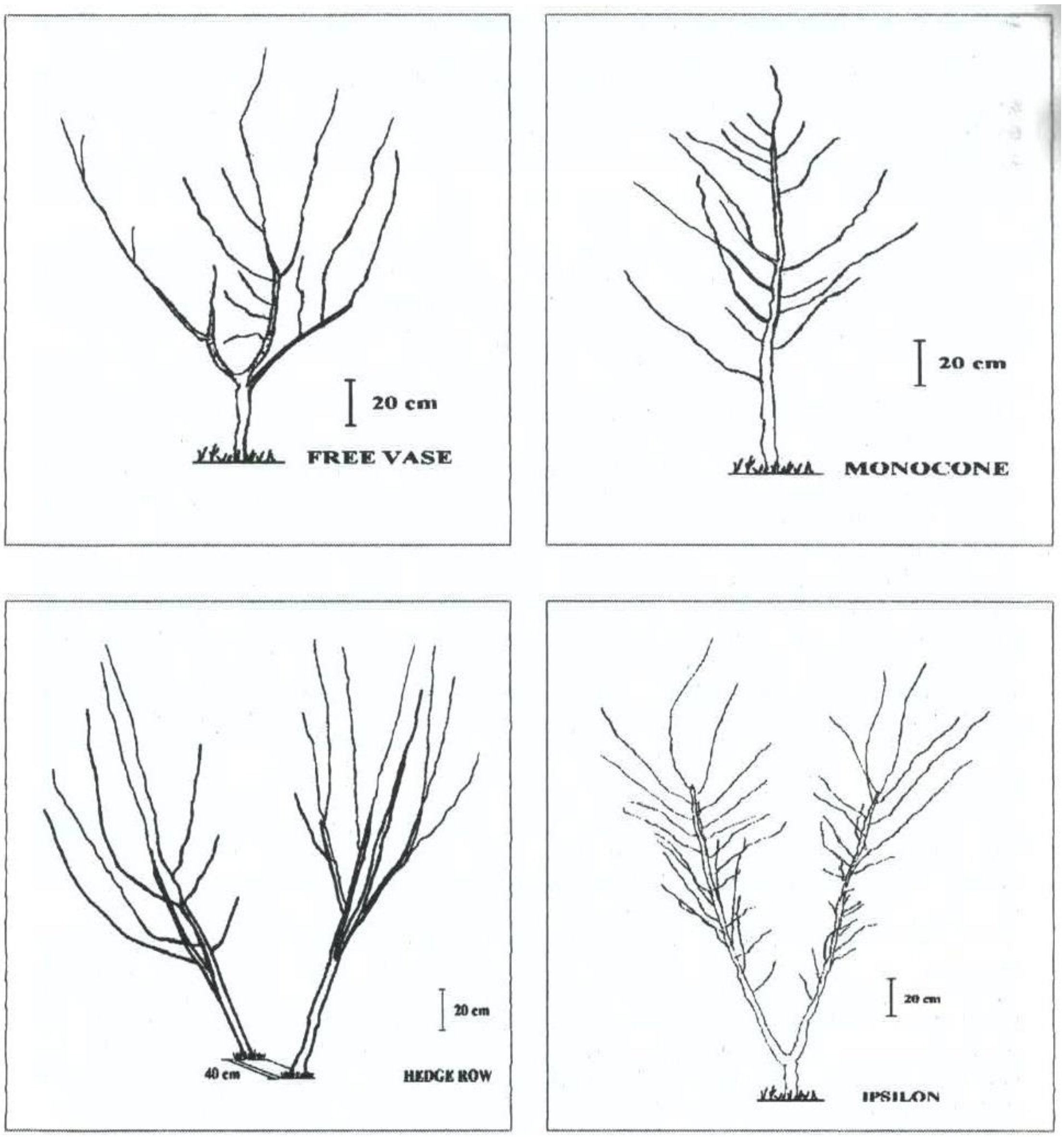


Figure 2.3 Training systems of free or open vase, monocone or vertical axis, V-hedge or hedgerow and ipsilon.
Source: Tous et al. (1994)

Similarly in France, Germain and Sarraquigne (1997) compared 3 training systems; an open vase on a single stem, a vertical-axis form and a V-hedge. The spacing between the pairs in the V-hedge was as for the individual vase and vertical-axis trees. The 3 training systems were evaluated on 3 cultivars, ‘Ennis’, ‘Segorbe’ and ‘Tonda Romana’. Nut yields were recorded over a period of 8 years. In the early years, the V-hedge, with a plant density twice that of the other systems, gave higher yields, particularly with the cultivar ‘Segorbe’. There were no significant differences between the training systems in nut weights, kernel weights or percentage kernel. The V-hedge produced many water shoots and required a great deal of maintenance pruning. The open vase was the preferred form. In Italy, Me et al. (2001) obtained similar results when comparing training systems of an open vase form with a V-hedge for ‘TGDL’ and 7 selection lines. There was an interaction effect with ‘TGDL’ and some selection lines, producing higher initial yields from the V-hedge. These authors also reported the V-hedge required more maintenance pruning.

Planting distances and densities

Spacing in commercial orchards is highly variable, depending on soil type, rainfall, cultivar vigour and the system of mechanisation. It is considered the minimum distance between rows should be 5 m to facilitate the operation of machinery (Tous et al., 1994). In Oregon, the spacing varies from 6x6 m to 5x5 m (270 and 400 trees/ha) for ‘Barcelona’, which is trained to a vase. In south-west France, spacings of 5x3 m and 5x2.5 m (666 and 800 trees/ha) were recommended (Germain and Sarraquigne, 2004a). In the Viterbo region of Italy, the recommendation for ‘Tonda Romana’, a medium-vigour cultivar, is 4.5-5 m between rows and 3 m in the row (740-666 plants/ha). Irrigated orchards in Spain are commonly planted in the range 6x3 m to 7x4 m (550–350 trees/ha) (Tous, 2005). The main cultivar grown is ‘Negret’, which is a small tree of relatively low vigour that is trained to a vase. In their studies on tree growth in the Porto Wine region of Portugal, Santos and Silva (2001) considered that in their situation, vigorous cultivars, such as ‘Fertile de Coutarde’ and ‘Segorbe’, require a tree-spacing of around 7x5 m or 8x6 m. In contrast, cultivars that produce smaller trees, such as ‘Daviana’ and ‘Longue d’Espagne’ are suitable for cultivation at a spacing of 6x4 m.

Pruning mature trees

Generally, hazelnut orchards are not pruned on an annual basis. Pruning is usually restricted to the removal of dead, damaged or low branches (Tous et al., 1994). The effects of regular pruning are not well documented. However, in Kent, pruning is carried out annually to limit the height of the trees to facilitate hand picking of the green “cobnuts” as well as to maintain vigorous shoot growth for crop production (Kentish Cobnuts Association, 2001).

The progressive growth and development of a hazelnut orchard leads to branches meeting down the rows and eventually meeting between the rows, creating a full canopy. During this process, trees lose vigour, there is a reduction in shoot growth and nut yields decline due to competition for resources such as light and moisture (Me et al., 1994) (Santos et al., 1998) and (Roversi and Mozzone, 2005). The time taken to reach this point varies with cultivar, planting density, soil type and rainfall.

In Italy, Me et al., (1994) studied rejuvenation pruning of a ‘Tonda Gentile delle Langhe’ orchard that was 33 years old. The plants were at a spacing of 5.5 x 5.5 m and had been trained as a multi-stem bush form. A full canopy had been achieved with branches crossing between the trees. Average annual yields were only 1.0 t/ha. Severe rejuvenation pruning, which involved cutting the stems back to2.5m, led to an initial drop in yield but stimulated the vigour of the trees which, by their fifth year from the initial pruning, had achieved the same cumulative yield as unpruned trees, but, in the next 2 years, yielded far more than the unpruned trees. Pruning treatments included a reduction in the number of stems per tree. Six stems per tree gave higher yields than 4 stems per tree over the 6-year period of the study. In a similar study, Roversi and Mozzone (2005) found that severe renewal pruning of ‘Tonda Gentile delle Langhe’ led to very high initial yield losses, but increased fruit bearing branches and nut quality.

Studies were conducted by Cristofori et al. (2005) on pruning intensity on 50-year old trees of ‘Tonda Romana’ in Central Italy. Treatments involved the removal of 20% and 40% of the wood from the upper part of the trees to renew the vigour of shoot growth. This involved shortening vigorous branches and removing those that were badly orientated. High intensity pruning produced higher 3-year cumulative nut yields after pruning than the light intensity pruning, but better light penetration was obtained from both pruning treatments. Cumulative nut yields 3 years after pruning from the high intensity pruning were not significantly different from the unpruned control. The pruning treatments had no significant effect on nut traits and kernel quality.

No significant differences were found between pruning treatments of 10 year-old ‘Ennis’ trees planted at 3.1x6.1 m. Treatments included unpruned trees, selected scaffold removal and the removal of alternate trees within the row. Average yields were about 2.9 t/ha (Azarenko et al., 2005).

It is concluded that mature hazelnut trees that have achieved full canopy closure, are producing little annual shoot growth and have declining nut yields, can be rejuvenated through severe pruning. In general, severe pruning causes a high yield loss in the first 2 years from pruning, but leads to improved shoot vigour, which, under some circumstances, results in higher yields. The positive relationship between shoot vigour and yield is well documented, as pointed out by Tous et al. (1994) in their review of pruning and other cultural practices in hazelnuts. Pruning mature trees generally has a high labour and cost component, but there do not appear to be studies on the value of regular mechanical pruning to manage tree size.

Nutrition and fertilizers

There is a considerable diversity in fertiliser practices; however, nitrogen is widely recognised as an important element for hazelnut development and crop yield (Tous et al., 1994). Nitrogen can increase the growth rate of annual shoots and subsequent nut yields. It is the main fertiliser recommended for developing hazelnut trees in Oregon (Olsen, 2001). Nitrogen reserves in the tree are very mobile. The main source of nitrogen for leaf growth in spring and early summer is from root reserves (Olsen, 1997).

Uptake of nitrogen in early spring is slow, increasing to late summer. Fertilizer nitrogen only forms a small proportion of nitrogen in new growth, with an uptake of only 28% of spring-applied ground fertiliser (Olsen et al., 2001). Time of fertiliser application influenced partitioning in the plant. Spring applications were mainly partitioned into fruit growth; the later N was applied, the more likely it was to be partitioned into the frame of the tree. Post-harvest applications of foliar urea were absorbed into the tree and partitioned into buds and one-year wood reserves, which were readily available for spring growth (Olsen, et al., 2001).

Although phosphorus is an important element for plant growth, responses to phosphorus fertiliser seem to be variable. Olsen (1995) recorded no responses to phosphorus fertilisers in Oregon, as did Bergoughoux et al. (1978) in France. Yet in his review of cultural practices in hazelnut orchards, Tous et al. (1994) recorded recommendations ranging from nil to 30 kg/ha P. This raises the questions, were the soils in Oregon and France high in phosphorus or do hazelnut trees have the ability to extract phosphorus from soils and hence have low phosphorus fertiliser requirements on some soils? It is possible that hazelnuts host mycorrhizal fungi that enable them to extract their phosphate requirements from soils. In Italy, seedling hazelnut trees were reported to commonly host a range of ectomycorrhizal fungi (Lefevre and Hall, 2001). Desirable levels of phosphorus in hazelnut leaves are given in table 2.3.

Hazelnut kernels are high in potassium (Alphan et al., 1997) and an increase in kernel size has been recorded from applications of this element. Potassium is commonly recommended as a fertiliser for hazelnuts (Tous et al., 1994).

Calcium is an important element in hazelnut production. Calcium is generally applied as ground limestone to raise soil pH. Olsen (1995) considered the minimum pH for hazelnut production was pH 5.0. Excessive levels of calcium in the soil can have an adverse effect on the uptake of iron. The ideal soil pH is generally considered to be pH 6.5 (Germain and Sarraquigne, 2004a), with calcium representing 75-85% of the soil's cation exchange capacity (CEC).

Boron seems to be an important minor element that can have an influence on yield, nut quality and the proportion of blank nuts. Beneficial responses to foliar applications of this element have been reported by some authors, as reviewed by Olsen and Cacka (2009), however, foliar applications of boron are not always beneficial, as reported by Borges et al. (2001). It is concluded that there is a need for further studies on how boron is taken up by hazelnut trees and its role in plant nutrition and kernel development.

Recommendations on the desirable mineral content of hazelnut leaves have been developed by several authors and reviewed by Tous et al., 1994 (Table 2.3). Leaf contents of 2.2% nitrogen, 0.18% phosphorus and 0.9% potassium in fully-developed leaves in mid-summer are considered to be about optimum (Table 2.3). More recently, Olsen (2001) has developed recommendations for the desirable level of elements in hazelnut leaves in Oregon (Table 2.3). These are generally similar to those recommended by earlier authors, as cited by Tous et al. (1994).

Table 2.3 Desirable levels of elements in hazelnut leaves as a proportion of dry matter, as recommended by several authors

Source of data	**Elements**									
	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Cu (ppm)	Zn (ppm)	B (ppm)	Mn (ppm)
Tous et al., 1994	2.0–2.6	0.1–0.6	0.7–1.0	1.1–3.0	0.2–1.0	0.12–0.2	2–180	13–200	25–80	25–800
Olsen, 2001	2.2–2.5	0.14–0.45	0.8–2.0	1.0–2.5	0.25–0.5	0.12–0.2	0.8–2.0	15–60	30–75	26–650

Source: Tous et al., 1994, authors cited included Painter 1963, Molne, 1976, Chaplin, 1981, Romisiondo et al., 1963, Lopez-Acevedo, 1983 and Kowalenko, 1984.

Propagation and rootstocks

A common method of propagation of hazelnuts is through rooted suckers in a stool bed. The "whips" produced from this technique, when planted in orchards, also produce suckers. A considerable amount of time, energy and expense goes into the control of suckers in hazelnut orchards. Scion wood of cultivars can be grafted onto rootstocks of other cultivars through the use of a hot callusing tube (Lagerstedt, 1981). Rootstocks can affect the growth, production and kernel quality of the scion cultivar. Tous et al. (1997) reported that ‘Negret’ grafted onto rootstocks of ‘Tonda Bianca’ and the hybrid rootstocks of ‘Newberg’ and ‘Dundee’ produced very good vegetative growth and nut yield compared with ‘Negret’ on its own roots. Thompson (1981) reported that ‘Daviana’ had a deeper rooting system than ‘Barcelona’ with ‘Daviana’ being less susceptible to “wind-throw”, that is trees being blown over by a very strong wind when soils are saturated and unable to provide support to the root system.

Corylus colurna, the Turkish hazelnut tree, does not produce suckers and has some potential for use as a rootstock for sucker control and improving drought tolerance (Fideghelli and De Salvador, 2009). However, Lagerstedt (1981) reported rootstocks of *Corylus colurna* tended to overgrow all but the most vigorous cultivars. When ‘Barcelona’ is grafted on to rootstocks of the Turkish hazelnut tree, nut yields are reduced compared with ‘Barcelona’ on its own roots. Lagerstedt initiated a rootstock breeding program in Oregon with the objective of producing non-suckering rootstock from crosses of *Corylus avellana* L. with *C. chinensis* and *C. colurna* (Thompson, 1981). Two hybrid rootstocks were produced, ‘Newberg’ and ‘Dundee’, but unfortunately these were susceptible to eastern filbert blight, limiting their use in Oregon. The higher cost of producing grafted hazelnut trees seems to be a factor limiting interest in the use of non-suckering rootstocks.

Pests and diseases in Australia

At the initiation of this research, the only major disease of hazelnuts recorded in Australia was hazelnut blight (*Xanthomonas arboricola pv corylina*), which adversely affects new shoot growth in spring. This was discovered in Australia in the 1970s (Allen, 1986). None of the major global pests of hazelnuts, including big bud mites (*Phytocoptella avellanae* and *Cecidophyopsis vermiiformis*), were considered to be present. The major pest problem reported in Australian orchards was native birds, particularly sulphur-crested cockatoos (*Cacatua galerita*), destroying nuts (Allen, 1986). It was concluded that many of the common pests and diseases of hazelnuts orchards in Europe and Oregon were not likely to be a problem in Australia, although cockatoos could be.

2.2.4 Reproduction in hazelnuts

The productivity of hazelnuts is strongly influenced by the number of female flowers on a tree, the proportion being effectively pollinated then fertilised and subsequently developing into nuts and kernels, as indicated in Figure 2.4.

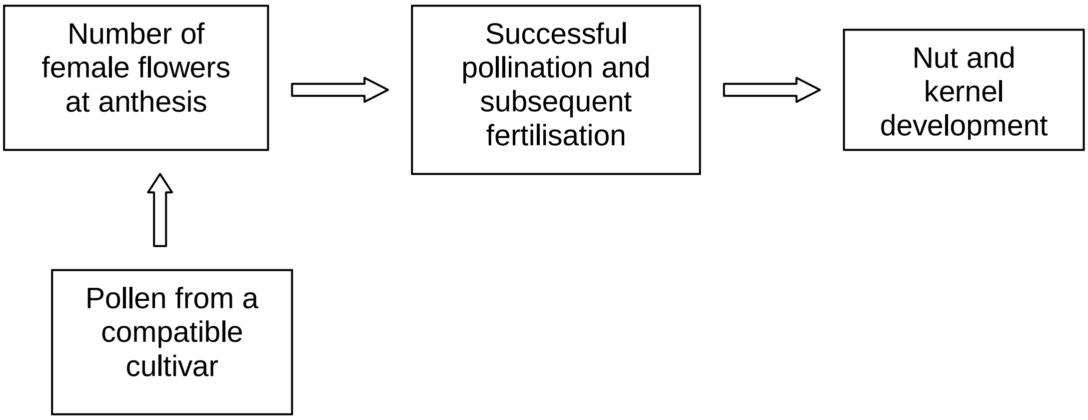


Figure 2.4 Pathway of yield development from flowering to nut and kernel development

An understanding of the process of reproduction in hazelnut and how it is influenced by environmental conditions is important in evaluating the performance of genetic material. A very comprehensive review of this topic was conducted by Germain (1994). The European hazelnut (*Corylus avellana* L.) is a monoecious plant with separate male and female flowers on the same tree (Figure 2.5). These flowers are borne on one year-old shoots.

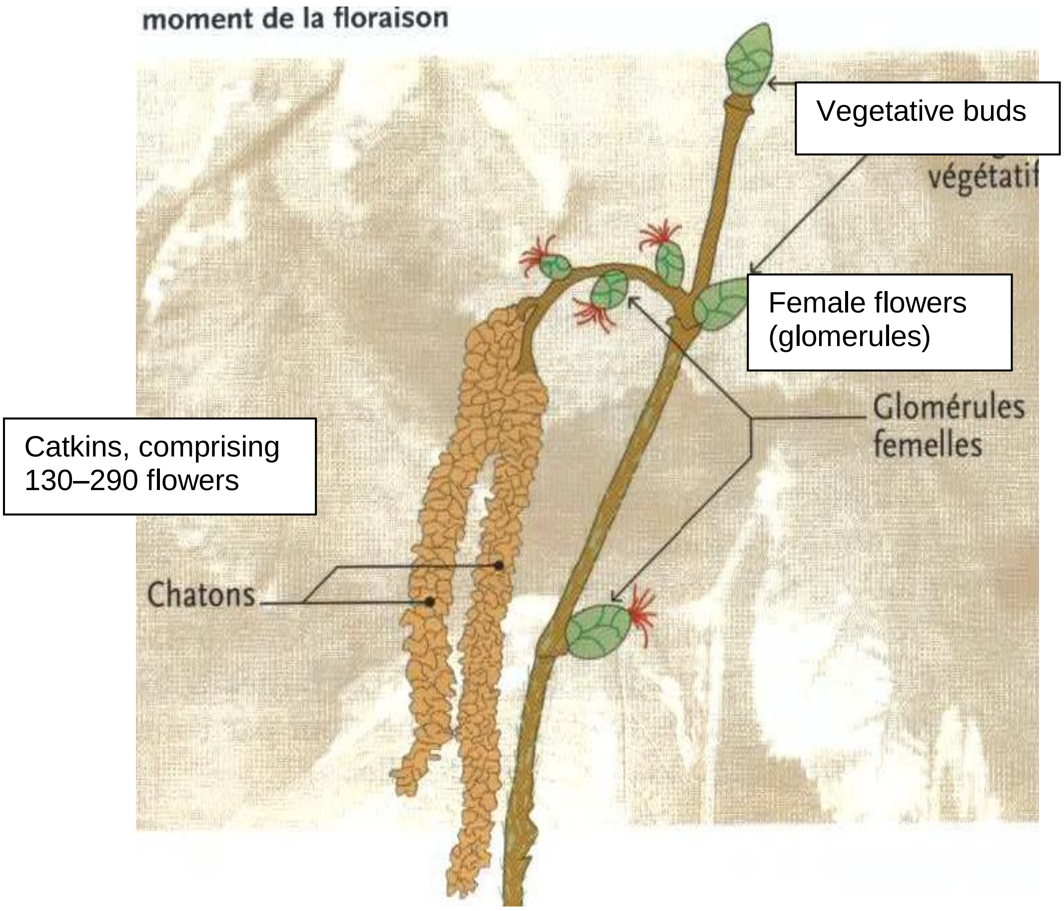


Figure 2.5 One year-old hazelnut shoot with vegetative buds, and separate male and female flowers
Source: Germain and Sarraquigne (2004) in Le Noisetier

The male inflorescences (catkins) are comprised of 130-290 flowers (Germain, 1994). Each flower contains 4 bifurcated stamens, each terminating in 2 anthers.

The female flowers (glomerules) are compound buds with a lower vegetative part and an upper fertile cluster, comprising on average, 4 bracts, each with 2 flowers (Figure 2.6). The female flowers are small; they comprise a pair of elongated stigmatic styles, each with a minute embryonic ovary at its base.

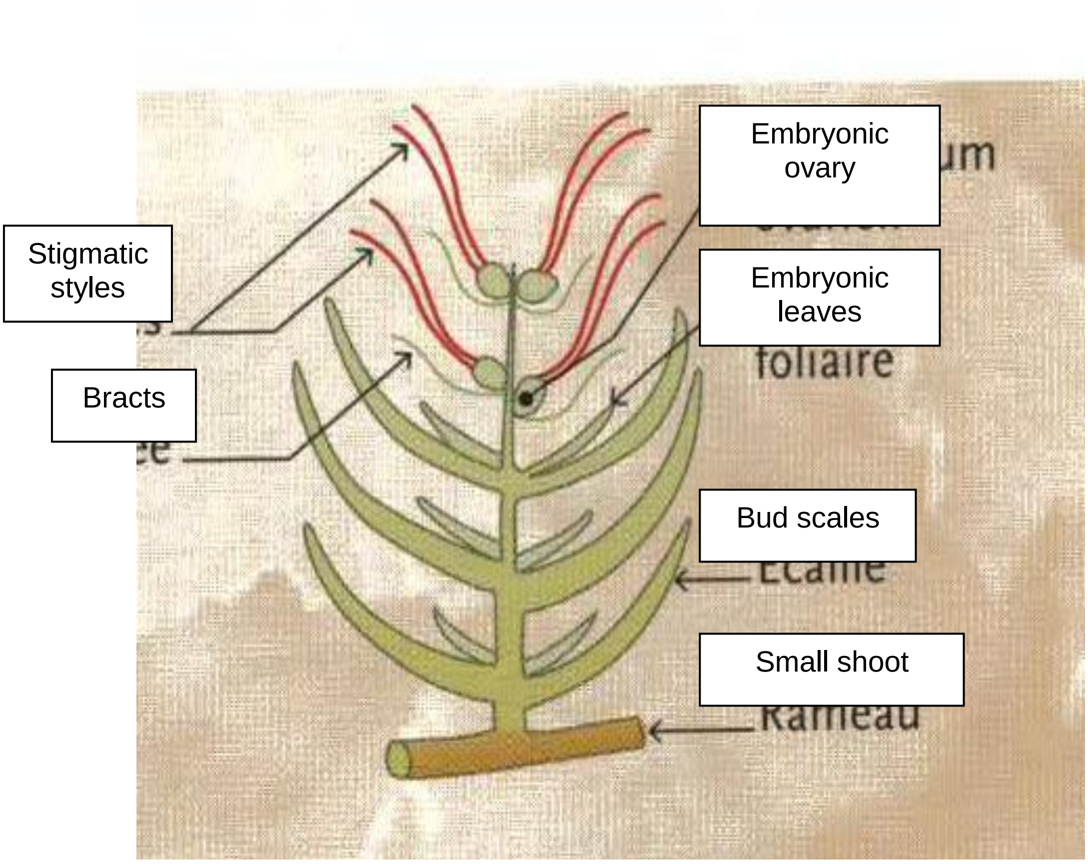


Figure 2.6 Cross-section of a female flower, showing the upper fertile part with stigmatic styles, embryonic ovaries and a lower vegetative part.
Source: Germain and Sarraquigne (2004) in Le noisetier

Male flowers are initiated before female flowers. In France, Germain and Dimoulas (1979) reported the first signs of catkin differentiation occurred in buds from mid-May. Female flower induction was not observed until late June to mid-July. After the formation of female flower primordia in the second half of July, it is possible to see rudimentary styles in late August. Style growth continues with female flowers being completely formed by early October (Germain, 1994).

The number of female flowers formed each year is influenced by the level of light received by one year-old shoots, their origin and vigour. The total number of female inflorescences increases with shoot length, irrespective of cultivar and tree age. Bergoughoux et al. (1978) reported that shoots of low vigour, less than 150 mm in length, have a lower percentage of female flowers relative to vigorous shoots. Very vigorous shoots, longer than 350-400 mm in length, have a strong tendency to vegetative bud development in their apical part. In a study of flowering in ‘TGDL’, it was found that on one year-old branches, that ranged in length from 50-250 mm, the relative number of pistillate flowers per bud remained constant at about 0.5 (Maija et al. 1994). The number of nuts per cluster does not appear to be related to shoot length. Cartechini et al. (1989) found late spring and early summer applications of urea enhanced flower differentiation, possibly by providing nitrogen at a critical stage in the development of shoots and fruits.

Shoots receiving plenty of light bear 1.5–3 times as many female flowers as shoots in shaded foliage. In a study on shading trees with black polypropylene cloth, in which light levels were reduced by 63% for certain periods in their growth, the number of catkins and female inflorescences were reduced in the period late May to the end of September in Oregon (Azarenko et al., 1997). This coincides with the periods of floral initiation and development reported by Germain and Dimoulas, (1979).

Flowering occurs in winter after chilling breaks the dormancy of the inflorescences. For a given cultivar, chilling requirements for catkins are considered to be lower than those for female flowers, Kavardzhikov (1980), Mehlenbacher (1991) and Germain, (1994). Mehlenbacher (1991) recorded chilling requirements for catkins ranging from 100 to 860 hours and for female flowers from 290 to 1550 hours, depending on the cultivar.

Pollen grains are very small, 25-40 μm in diameter. They are easily carried by the wind over long distances. Concentration decreases rapidly within 15-20 m of the dispersal site. Pollen quality depends on the climatic conditions at the time of release. Catkins can each produce 40 million pollen grains, but in some cultivars 30-50% of the pollen grains are not viable (Germain, 1994).

The stigmas can be receptive for at least 2 months from the time of exertion from their enclosed scales (the red dot stage). In time, the stigmas darken and wither. Stigmatic receptivity is at its optimum about 15 days from the beginning of anthesis (Germain, 1994).

Genetic incompatibility

Both self- and cross-incompatibility is found in hazelnuts, which is diploid, $2n = 22$. This incompatibility is sporophytically controlled by a single locus or gene with multiple alleles, (Germain, 1994). The genetic incompatibility of hazelnut cultivars has been studied by many researchers, Schuster (1924), Bergoughoux et al. (1978), Thompson (1979a) and Mehlenbacher (1997). To date, 25 S-alleles have been identified, Mehlenbacher (1997). In the pistillate flowers, the alleles exhibit independent action whereas in the pollen they act either in a dominant or co-dominant manner.

Identification of the S-alleles for each cultivar enables compatibility relationships between cultivars to be determined, which is important when selecting pollinisers for commercial production. Each cultivar has two S-alleles and both of these are expressed in the female flowers. In the pollen, both alleles may be expressed when they are of equal dominance, that is, they are co-dominant. However, if 1 allele in the pollen is dominant over the other, only the dominant allele is expressed in the pollen. For cultivars to be compatible, the S-alleles of the female must differ from the dominant or co-dominant alleles of the pollen, as illustrated in Table 2.4. The dominant allele is underlined in each case (Thompson, 1979a).

Table 2.4 Example of some cultivars that are compatible with 'Barcelona' and can be used as pollinisers, compared with an incompatible cultivar, 'Ennis'; the alleles expressed in the pollen are underlined.

Example:			**S-alleles**	
Nut producing cultivar	-	'Barcelona'	$\underline{1}$	2
Polliniser cultivars	-	'Butler'	2	$\underline{3}$
	-	'Casina'	$\underline{10}$	$\underline{21}$
	-	'Hall's Giant'	$\underline{5}$	$\underline{15}$
BUT NOT	-	'Ennis'	$\underline{1}$	11

In 'Barcelona' the alleles are $S_{\underline{1}}$ and S_2, but only the dominant allele $S_{\underline{1}}$ is expressed in the pollen, whereas in 'Hall's Giant' ($S_{\underline{5}}S_{\underline{15}}$) the S-alleles are co-dominant and therefore both are expressed in the pollen.

The dominant allele of 'Butler' is the $S_{\underline{3}}$ allele. Therefore, although 'Butler' has an S_2 allele, this is recessive in the pollen, so cross-pollination with 'Barcelona' can occur. 'Casina' and 'Hall's Giant' have co-dominant S-alleles but they are different from the $S_{\underline{1}}S_2$ alleles of 'Barcelona', therefore 'Casina' and 'Hall's Giant' are compatible with 'Barcelona'. However, 'Ennis' pollen is not compatible with 'Barcelona' as 'Ennis' has a dominant $S_{\underline{1}}$ allele.

Pollination, fertilisation and nut development

Only a few of the pollen grains caught by the stigmas produce a pollen tube that reaches the base of the style after germination. Pollen growth within the style is rapid, taking 4-10 days for the pollen tube to reach the base of the style, where its growth ceases at the apex of the ovary. The tip broadens, develops a callose coat and goes into a quiescent phase (Germain, 1994). In the case of incompatible pollen, the pollen germinates but fails to penetrate between the cells of the stigma (Germain, 1994).

In pollinated flowers, the ovules slowly develop and produce megaspores. The pollen tubes, which had been at rest for several months, grow again and fertilisation occurs about the end of May to late June, that is, early summer in the northern hemisphere, depending on the cultivar. This is equivalent to the end of November to late December in Australia. Of the 2 ovules, the most advanced is fertilised, generally producing only 1 kernel per nut, although in some cultivars, such as ‘Barcelona’, both ovules can be fertilised, resulting in 2 kernels in some nuts (Germain, 1994).

During the 3 weeks after fertilisation, the embryo grows very slowly, attaining only 3-5% of its final volume. When the shell begins to harden in early July (equivalent to early January in Australia), the embryo grows very quickly and fills the nut in 3-5 weeks. Nuts ripen over a period of 2-3 weeks for most cultivars, with nut fall from the end of August to early October in the northern hemisphere (equivalent to the end of February to early April in Australia).

Nut clusters may fail to develop before fertilisation and abscise in late spring or early summer. This loss is considered to be due to competition between flowers and is related to apical dominance in 1 year-old shoots. In some situations, applications of foliar boron and other nutrients may reduce cluster drop, (Barone, 1973) and (Stebbins, 1977), although Silva et al., (2003) did not obtain such responses.

Blank nuts, those in which the kernel has not developed, can result in a significant loss of yield in some seasons. Many factors can adversely affect the normal development of kernels. These include environmental stress at the time of fertilisation, such as low temperatures (Ribaldi, 1968) and (Latorse, 1981), inadequate nutrition and moisture stress (Bignami and Natali, 1997). Blank nuts occur more frequently in some cultivars, such as ‘Barcelona’, ‘Negret’ and ‘Tonda di Giffoni’, with considerable variation between seasons (Thompson et al., 1996). The application of boron and other nutrients to the foliage of trees during nut and kernel development has given variable results. For example, in Slovenia, Solar and Stampar (2001) obtained yield increases and a reduction in the proportion of blank nuts from foliar applications of boron and zinc to the cultivar ‘Tonda di Giffoni’, whereas in Portugal, Borges et al. (2001) did not obtain any increase in yield or a reduction in the proportion of blanks with foliar treatments of boron on the cultivars ‘Fertile de Coutard’ and ‘Segorbe’. However, they obtained differences between seasons and cultivars in the proportion of blanks. In Oregon, Olsen and Cacka (2009) evaluated a range of foliar treatments, which included boron, other elements and cytokinins. None of their treatments had any effect on nut yield or kernel quality. Although, in a separate experiment, Cacka and Smith (2009), obtained yield increases from foliar applications of proprietary blends of calcium, boron and other micronutrients, with nutrient-enhancing amino acids. The treatments were applied during shell development in mid-May and during kernel development in mid-June.

Leaf shedding

Leaf shedding in the autumn is generally a response to decreasing day length and temperature. The movement of nutrients and carbohydrates from the leaves into twigs and branches occurs prior to leaf senescence. This is followed by the development of an abscission layer of cells at the base of the leaf petiole and subsequent leaf fall.

2.2.5 Floral phenology

An understanding of floral phenology is very important for the selection of suitable polliniser cultivars in a commercial orchard. As discussed in the previous section, hazelnuts are wind-pollinated. At anthesis, the pollen from the catkins drifts through the orchard on dry days in winter and is caught by the stigmas of open female flowers. For pollination to be successful, the male pollen donor cultivar must be genetically compatible with the female receptor cultivar, as previously discussed.

The keys to successful pollination are:

- Good supplies of viable pollen
- Synchronous flowering of genetically compatible cultivars

Effective pollination is an essential component of high productivity. When planting a hazelnut orchard, it is important to know which cultivars are genetically compatible with the selected nut-bearing, main-crop cultivars; when these trees will have exerted stigmas; and, when the pollinating cultivars will shed their pollen. The incompatibility alleles of most commercial cultivars have been well-documented (Mehlenbacher, 1997). However, the periods of pollen shed and female anthesis vary markedly between locations and seasons, being influenced by climatic conditions, particularly temperature (Bergoughoux et al. 1978). Flowering occurs in winter after chilling to break dormancy (Mehlenbacher, 1991).

The literature on flowering commonly refers to cultivars as being either protandrous, that is pollen shed occurs before the stigmas of female flowers are exerted, or protogynous when the opposite occurs. Homogamous refers to the situation when pollen shed and female anthesis commence at about the same time (Mehlenbacher, 1991). However, it is arguably more appropriate to describe cultivars as behaving in either a protandrous, homogamous or protogynous manner. The basis for this reasoning is that the timing of pollen shed relative to female anthesis for a given cultivar is not constant but varies with the climatic conditions under which the cultivar is grown. For example in Slovenia, Solar and Stampar (1997) reported that ‘Butler’ and ‘Ennis’ were protandrous, whereas Turcu et al. (2001) found the degree of dichogamy varied between seasons and that ‘Butler’ and ‘Ennis’ were protogynous in some seasons and homogamous in others. In general, most European cultivars behave in a protandrous manner in maritime climates with relatively mild winters, such as southern France (Germain, 1994), Italy (Manzo and Taponi, 1982) and Oregon (Mehlenbacher, 1991). Bergoughoux et al., (1978) reported that in the Gironde region of France, the cultivar ‘TGDL’ normally commences pollen shed in the second week of December, but, if the autumn is very mild, pollen shed occurs a little after mid-November. Stritze (1962) found that, in Germany, protandry occurred in winters that were relatively mild, with protogyny being more common in cold winters. However, cultivars are more commonly protogynous or homogamous in locations with very cold winter climates such as Romania (Turcu et al., 2001).

In Romania, Turcu et al. (2001) studied the floral phenology of 14 cultivars over a period of 13 years. They confirmed that flowering period was influenced by cultivar and winter temperatures. They considered that rest had been achieved in all cultivars following a period of 3-6 days when daytime temperatures had been below zero. They obtained correlations between accumulated heat units, Growing Degree Days (GDD) above zero, following the completion of rest, and the commencement of pollen shed. These ranged from 98.5 GDD for ‘Tonda Romana’ to 149 GDD for ‘Du Chilly’ (‘Longue D’Espagne’), with an average of 126.5 for all the cultivars. For female flowers, the GDD units to stigma exertion ranged from 102 for ‘TGDL’ to 147 for ‘Romavel’, with an average of 105 GDD for all the cultivars. In their environment, of very cold winters, ‘Ennis’ and ‘Butler’ were generally protogynous, as were the majority of cultivars. ‘TGDL’ had a tendency to being protandrous.

Piskornik et al. (2001) studied the degree of dichogamy in 46 genotypes in southern Poland. After 2 mild winters, with mean temperatures below 0°C for 42 and 62 days, most genotypes showed protogyny. In a severe but short winter, with mean temperatures below 0°C for 77 days, many genotypes showed homogamy, but after a long severe winter, with mean temperatures below 0°C for 99 days, some genotypes were protandrous, with fewer being protogynous. They concluded that the length and severity of the winter influenced the type of dichogamy and that temperatures after the period of rest had a lesser effect. In their situation, they considered that endodormancy was followed by a period of ecodormancy, in which temperatures were too low for active growth and the length of the ecodormant period varied between seasons. It is unclear from their publication how Piskornik et al knew when the chill requirements to break endodormancy were achieved. In their studies, ‘TGDL’, ‘Ennis’ and ‘Hall’s Giant’ were protandrous in some years and protogynous in others.

Mehlenbacher (1991) undertook a study in Oregon to assess the chilling requirements of staminate and pistillate flowers as well as vegetative buds of a range of cultivars. Shoots of hazelnut cultivars were cut at weekly intervals from 16 October until 26 February and placed in a warm greenhouse. Chill hour requirements of flowers were calculated from cutting dates as the number of hours in the temperature range 0-7°C from 1 October until the cutting date when either 50% of catkins had shed pollen, or at least 4 female flowers had exerted stigmas. Similarly, the chill requirements of vegetative buds were based on the cutting dates when more than 50% of leaf buds were swollen in the greenhouse. The estimated chilling requirements of catkins ranged from 100–860 hours and female flowers from 290–1550 hours, according to cultivar. There was a high correlation between the number of chilling hours for both catkins and female inflorescences and observations of the beginning of pollen shed and exerted stigmas in the field. However, there was no correlation between the chilling requirements of catkins and those of female inflorescences. The amount of chilling required to break the dormancy of the catkins was generally lower than that for female flowers. Mehlenbacher's correlations indicate that chill hour requirements were the main factors influencing the commencement of pollen shed and female anthesis.

Similar studies by Tiyayon (2008) indicated that chilling occurred over a wider temperature range, 5-15°C. Post-chilling heat requirements for catkin elongation were considered to be constant for cultivars, but were found to be less with increased chilling. The optimum temperature for catkin elongation was 15°C.

Barbeau (1972), Kavardzhikov (1980), Mehlenbacher (1991) and Turcu et al. (2001) considered that post-chill warmth was required for flowering and this was generally considered to be greater for catkins than female inflorescences, as stated above. Turcu et al. (2001) estimated an average of 126.5 GDD for catkins and 105 GDD for female inflorescences, for the 14 cultivars studied in Romania. They used a base temperature of 0°C in their calculations of GDD. Tiyayon (2008) reported much higher post-chill heat requirements of approximately 53 000 GDH (equivalent to 2208 GDD) for catkins of 'TGDL', Barcelona' and 'Hall's Giant'. The heat requirements were similar for all 3 cultivars, but were reduced following additional chilling.

The studies presented indicate that hazelnut flowers require chilling to break the period of endodormancy ("rest') followed by warmth to stimulate development. The chilling requirements vary with cultivars, catkins and female inflorescences. For example, Mehlenbacher (1991) estimated the chill requirements for the catkins of TGDL to be <100 hours compared with 290–365 hours for 'Ennis' and 'Hall's Giant'. Whereas he estimated the chill requirements of the female inflorescences for these three cultivars to be 760–860 hours for 'TGDL', 1170–1255 hours for 'Ennis' and 600–680 hours for 'Hall's Giant'.

It would appear that a combination of chill hour requirements and post-chill warmth might be factors influencing the degree of dichogamy of cultivars. Kavardzhikov (1980) and later Mehlenbacher (1991) were of the opinion that catkins required a greater degree of post-chill warmth than the pistillate flowers. Barbeau (1972) concluded from his studies in France that the daily sum of temperatures following chilling influenced the start of flowering.

Where winter climates are very cold, post-chill warmth seems to become a more significant factor. When winters are prolonged, such as in Poland, the accumulation of post-chill warmth in late winter would be protracted, delaying flowering. However, the difference in the post-chill heat requirements of catkins and female inflorescences, presented by Turcu et al. (2001), seem minor compared with the much larger differences in chill requirements estimated by Mehlenbacher (1991). For example, the average GDD requirements of catkins compared with female inflorescences seemed to vary by only 1 GDD for both 'TGDL' and 'Hall's Giant' and only 8 GDDs for 'Ennis'.

For any given cultivar, the duration of pollen shed and female anthesis varies with winter temperatures, being shorter in locations with low temperatures (Kavardzhikov, 1982). Piskornik et al. (2001) noted that the duration of flowering was influenced by temperature, ranging from about 22 days, when the mean temperature was 5-10°C, to 43 days when it did not exceed 3°C. Catkin development was found by Germain et al. (1979) to cease once temperatures fell to about 0°C.

There do not appear to be any studies reported on the possible effects of day-length on floral phenology of hazelnuts. As seasonal variations in floral phenology vary from the commencement of flowering, before and after the shortest day, it seems unlikely that day-length is a significant factor.

It is concluded that the factors influencing the floral phenology of hazelnuts are not well understood. There is a need to gain a better understanding of the processes involved and the chill and post-chill heat requirements of hazelnut flowers under a range of climatic conditions. Studies on other deciduous fruit trees could play a part in improving our understanding of flowering in hazelnuts.

Bud and flower development in other deciduous fruit and nut tree species

Numerous studies have been undertaken on deciduous temperate fruit trees to determine the effects of climate, particularly temperature, on the date of bud burst and flowering. There is widespread agreement that a period of chilling is required to break the dormancy of buds in deciduous fruit trees, based on the studies of Richardson et al. (1974) on peach, Coullivon and Erez (1985) on apple, cherry, peach and pear, Felker and Robitaille (1985) on sour cherry, Smith et al. (1992) on pecan, Barone and Zappila (1993) on walnuts and Rattigan and Hill (1986) and Egea et al. (2003) on almonds. These results suggest a common mechanism in each case, although the extent of the stimulus required varies. Chill hours were generally considered to be accumulated when temperatures were in the range 0-7°C. However, Richardson et al. (1974), in their work on peach, considered temperatures in the range 2.5-9.1°C were the most effective for breaking the dormancy of peach buds, with no chilling below 1.5°C and none above 12.5°C. They developed the concept of chill units based on the effectiveness of temperature on chilling, with temperatures in the range 2.5-9°C contributing 1 chill unit (CU) per hour. Tiyayon (2008) considered chill units to be more effective in estimating date of catkin elongation than chill hours.

It is generally considered that, following the completion of rest, i.e. at the end of dormancy, there is the need for a period of warmth to stimulate both flower and bud development. Richardson et al. (1975) used growing degree hours (GDH) as a measure of accumulated warmth for peaches with a base temperature of 4.5°C and maximum of 25°C. This model was used to predict bud burst or flowering for specific cultivars of peach, based on their needs for a given number of hours of chill to break dormancy and a given number of accumulated heat units for bud and flower development. However, many studies have shown the dynamics of flowering are more complex than this. For example, Felker and Robitaille (1985) found that, with sweet cherry, temperatures over 15°C could nullify chilling. Whereas under conditions where there was prolonged exposure to chilling, the post-dormancy accumulated heat requirements were reduced in apple, cherry, peach and pear (Couvillon and Erez, 1985). Herter et al. (2000) reported similar results with peach.

Studies by Garcia et al. (1999) on apricots in 2 differing climatic environments, 1 in Spain and the other in Italy, found that more heat could partially compensate for a low amount of chilling. They found considerable differences between seasons that were not predicted by models using a specific number of chill units and growing degree hours for the cultivars. They considered that the presence of ecodormancy, that is conditions unsuitable for growth, may have had an effect on flower development.

Rattigan and Hill (1986) attempted to determine the specific chill requirement to break dormancy and the specific heat units required for flower development in a range of almond cultivars grown in Australia. They used a chill unit model, based on the work of Anderson and Richardson (1982), to determine the chill requirements and growing-degree-hours to determine the post-chill warmth to 50% flowering. The hourly temperatures for their analyses were calculated from daily maximum and minimum temperatures. The cultivar requirements for chill ranged from 220-320 CUs and the post-chill heat units ranged from 5300-7200 GDHs. They considered chilling hour requirements to be the main factors influencing the date of flowering. Their predictions of flowering date were variable between seasons and to a lesser extent between cultivars. Their studies on flowering were only in 1 locality and were within a 5-6 day range, with an accuracy of about 80%.

It is concluded from the research reviewed in this section that, like most deciduous fruit and nut crops, hazelnut flowers require chill to break their dormancy. The study conducted by Mehlenbacher (1991) on the chill requirements of cultivars indicated that these vary between cultivars. However, studies on a range of deciduous fruit and nut crops indicate that the chilling requirements are not a constant for any given cultivar and can vary between seasons, depending on climatic conditions, particularly variations in temperature between seasons. Some post-chill warmth appears to be required for flowers to develop and the thermal sums for this process may vary between cultivars and seasons. As hazelnuts are monoecious, that is the male and female flowers are separate on the same plant, they might not have the same temperature requirements for their development. The dates these separate inflorescences commence flowering may vary between male and female flowers, cultivars and seasons. The development of a universal model to predict the complex biological process of flowering may be difficult. It would require the model to be tested over a wide range of cultivars and environmental conditions.

This thesis will investigate a range of questions that relate to floral phenology in hazelnuts:

- What will be the phenological response of the cultivars being evaluated?
- How might this vary between seasons and sites?
- In what way might climatic conditions influence the timing of pollen shed and female flowering?
- Which genetically compatible pollinating cultivars shed pollen when the stigmas of selected main-crop cultivars are exerted?
- Can this information be used to develop pollination plans for commercial orchards in Australia?

2.2.6 Nut yields and yield improvement

Physiology of nut yield

As discussed in the section on hazelnut reproduction, factors influencing nut yields include the number of female flowers produced and the proportion that are pollinised and subsequently fertilised (Figure 2.3). As discussed previously, the amount of new growth in the previous season and the level of light in the canopy are factors influencing the number of female inflorescences.

Fertilisation occurs around the end of May or early June in the northern hemisphere. This is a critical period of growth and development and it is highly likely there is competition between plant parts for photosynthates. At that time of year, shoot growth and leaf growth is still occurring, nuts are growing and catkins are being initiated (Germain, 1994). Female flowers for the next season are initiated a little later, at the end of June and early July, a time when the kernels are beginning to develop rapidly, following the end of shell growth. Water stress in the period just before fertilisation and for the next 50 days can result in a marked loss in yield and kernel quality in that season (Mingeau et al., 1994). It can also adversely affect canopy size and leaf area index (Bignami and Natali, 1997).

Nutrition of the tree during this period also appears important with some authors recording responses in this period to foliar-applied nutrients, such as boron and zinc (Solar and Stampar, 2001), and to calcium and boron plus a range of micronutrients (Cacka and Smith, 2009).

The development of both nuts and kernels follows a sigmoid growth pattern (Ebrahem et al., 1994). The oil content, proportion of fatty acid and vitamin E content, represented mainly as α-tocopherol, also increase in a sigmoid pattern. However, the water content declines over the whole period of kernel development.

Nuts, kernel percentage and kernel quality

Nut weight, shell thickness and kernel percentage are highly heritable characteristics (Mehlenbacher, 1994). ‘Ennis’ is an example of a cultivar that produces large nuts with a mean weight of about 4.5 g; in contrast ‘Casina’ is a cultivar that produces small nuts with a mean nut weight of about 1.8 g (McCluskey et al., 1997). However, cultivar nut weight varies with seasonal conditions, particularly with rainfall during the period of shell growth in late spring through to early summer (Mingeau et al., 1994). Pacerisa et al., (1993) reported that nut weight was also affected by "*crop load"*.

The ratio of kernel weight to nut weight, or kernel percentage is an important cultivar attribute. A high kernel percentage is obviously a desirable characteristic when cracking nuts for the kernel market. The cultivar 'TGDL', which is often prized for its high-quality kernels, has a relatively thin shell and generally a high kernel percentage. However, this varies between sites and seasons; for example an average of 52% kernel was obtained in field studies by McCluskey et al., (1997) in Oregon and by Turcu and Botu (1997) in Romania, whereas a lower average figure (47%) was obtained by Miletic et al. (1997) in eastern Serbia, where dry conditions were experienced during the "second part" of the growing season.

The proportion of poorly-filled and shrivelled kernels is of low heritability (Mehlenbacher, 1994), but is strongly influenced by environmental conditions, particularly during kernel-fill in mid to late summer (Mingeau, 1994) and (Bignami and Natali, 1997). Romero et al. (1997) undertook a very comprehensive study of the quality of kernels from the cultivar 'Negret' in Spain over 7 seasons and from 14 zones. The average kernel percentage was 46% but it varied across seasons and sites. Kernel samples with the best physical characteristics were those from highly productive (2.5 t/ha), well-managed orchards. In a separate study, an evaluation of clones of 'Negret' and 'Gironell' was undertaken; clones with superior quality kernels were identified (Rovira et al., 1997).

Some cultivars, such as 'Barcelona', produce a relatively high proportion of twins; that is there are 2 kernels in the shell. This is a relatively highly heritable trait (Mehlenbacher, 1994).

When kernels are blanched, that is heated in an oven at 140-150°C for 15 minutes, the pellicle of some cultivars becomes loose and can be readily removed. Ease of pellicle removal after blanching is a moderately heritable trait (Mehlenbacher, 1994) but is also influenced by seasonal conditions. The cultivar 'Negret' blanches very well whereas 'Casina', 'Ennis' and 'Tonda Romana' do not blanch well (McCluskey et al., 1997).

Oil and crude protein content vary with cultivars. In a study of cultivars in eastern Serbia, Miletic et al. (1997) found crude protein levels varied from 13.8% for 'TGDL' to 16.1%

for ‘White Lambert’, with oil content ranging from 58% for ‘White Lambert’ to 66% for ‘TGDL’. In a Spanish study by Romero et al. (1997) on ‘Negret’ kernels, an average oil content of 63%, with a small variation between sites and seasons, was reported. This compared with an average oil content of 62% for ‘Pautet’ and 59% for ‘Tonda di Giffoni’.

In a study on 17 cultivars of hazelnuts, Ebrahem et al. (1994) found oil content ranged from a low of 58% for ‘Hall’s Giant’ to a high of 66% for the Turkish cultivar ‘Tombul’. Richardson, (1997) also reported a similar range from a low of 57% for ‘Hall’s Giant’ to 65% for ‘Tombul’.

Piskornik (1994) found that lower temperatures in Poland during kernel fill, compared with Mediterranean environments such as Italy, resulted in a lower content of oil in the kernels, grown under cooler conditions, but a slightly higher content of the longer-chained unsaturated fatty acid, linoleic acid (C18:2). The main fatty acid found in hazelnuts is the desirable unsaturated fatty acid oleic acid (C18:1), which is found in the range 77-84% of all the fatty acids, with levels varying between cultivars (Botta et al., 1997). Linoleic acid, an essential fatty acid, is the next most commonly-occurring fatty acid with levels varying from 7-13% depending on cultivar.

2.2.7 Summary of growth and development

The studies presented in this review on the growth and development of hazelnut plants throughout the year are summarised in Table 2.5. As discussed, the critical period of growth and development is considered to be in the months of November to January. This is when there are high demands for photosynthates for stem and leaf growth to produce the current season’s growth and to produce reproductive structures for the next season’s production, whilst fertilisation and fruit development are also occurring. Environmental factors that adversely affect photosynthesis in this period, such as moisture stress and extremes of temperature (low and high), have been shown to result in reduced levels of productivity.

Table 2.5 Generalised pattern of growth and development of hazelnut trees in Australia based on studies in the northern hemisphere. Variations will exist with cultivars and seasonal conditions.

Months		**Phases of growth and development**	
June – August		Catkins extend and shed pollen, stigmas exerted and flowers pollinated	
September		Transfer of stored nutrients from roots and stems to buds Bud break and leaf growth	
October		Stem and leaf growth continuing to late December or into January	
November	Critical period of growth and development	Fertilisation, late November–mid December	*Next season* Initiation of catkins
December		Nut growth	Initiation of female flowers
January		Kernel growth	
February		Nut maturity	
March		Nut fall	
April		Transfer of nutrients from leaves to stem and roots	
May		Leaf fall	

Yield potential in South-eastern Australia

Considering the climate and soil requirements of hazelnuts, along with the physiology of their growth and development, it is postulated that hazelnuts grown in the Ovens Valley of Victoria, for example, with its deep alluvial soils and similar climate to Corvallis, might produce similar commercial nut yields of 2-2.5 t/ha as those obtained in Oregon (Mehlenbacher, 2005). The effects of duplex soils, which are common throughout South-eastern Australia, on the growth and production of hazelnuts are unknown.

2.2.8 Conclusion

This section of the Literature Review shows how the growth, reproduction and development of hazelnuts are influenced by environmental conditions. Temperature in late autumn and winter appears to be a key factor influencing floral phenology. The literature indicates that chilling and post-chill heat are required to break the dormancy of male and female flowers and this varies between catkins and female inflorescences, as well as between cultivars. There does not seem to be a published formula to predict the time of flowering for a given cultivar or for a set of environmental conditions based on chill and post-chill warmth requirements. Yet it is important to plant cultivars in which the timing of pollen shed is synchronous with female anthesis between genetically compatible cultivars in order to achieve successful pollination, which is the starting point for crop yield.

Hazelnuts do not seem to be able to take up moisture from the soil sufficiently quickly to cope with conditions of high evaporation, such as might arise in periods of low humidity and high temperature, coupled with strong wind. Moisture deficits cause the closure of stomata, reducing photosynthesis and the supply of assimilates to developing parts of the plant. The literature clearly shows how moisture stress can cause reductions in growth, nut development and kernel-fill, depending on the period and duration of the moisture deficit.

Erratic rainfall, coupled with periods of low humidity and high temperatures, is likely to be a key factor influencing the growth and development of hazelnuts in Australia. The extent of such potentially harmful effects needs to be understood. Supplementary irrigation is likely to be needed at some stage of crop development in most environments.

Part 3 Cultivars, their attributes and relative merits

There are nearly 400 distinct, named hazelnut cultivars worldwide, although Mehlenbacher (1991) stated that fewer than 20 of these are considered worthy of cultivation. So what makes a good cultivar and how can cultivars be compared? When evaluating cultivars of any crop there are usually two key criteria, viz:

- Characteristics required by the market; and
- Characteristics required by the grower, such as high yield.

2.3.1 Market requirements

There are 2 main market outlets for hazelnuts, the in-shell market and the kernel market. The kernel market is by far the largest, with 90-95% of the world crop being cracked and sold this way (Mehlenbacher, 1991). The kernels are sold to confectioners, bakers and other processors, in either the raw, blanched or roasted form. Sometimes kernels are diced, sliced or ground into meal (Lobb, 1995). They can also be used to make paste, oil and flour. Kernels used in this market sector are often referred to as being for "industrial use" (Tombesi et al., 1994). Kernels are also used by restaurateurs in a wide variety of dishes. During the last decade there has been an increasing interest in the use of nuts for snack foods, including hazelnuts (Australian Nut Industry Council, 2009).

There has been an increasing awareness of the value of nuts in a healthy diet. In Australia, the Australian Nut Industry Council (ANIC) has invested in a "Nuts for Life" campaign, which has researched the health benefits of nuts and promoted their value to the medical profession and the general community (www.nutsforlife.com.au). There are numerous publications on the nutritional value of hazelnuts (Alphan et al., 1997; Richardson, 1997; Stone et al., 2000) and their role in reducing the risk of coronary heart disease and some types of cancer. One recent publication (Tey et al., 2011) provides guidelines for hazelnut consumption. The health-promoting substances in hazelnuts include the anti-oxidant vitamin E (α-tocopherol), vitamin B-6 and mono-unsaturated fatty acids, particularly oleic acid. There are some differences between cultivars in their content of these substances. Ebrahem et al. (1994) measured the oil content of 17 cultivars and found this ranged from 57.9% in 'Hall's Giant' to 65.7% in 'Tombul'. He also measured the α-tocopherol levels which ranged from 8 μg/g of oil in 'Ennis' to 36 μg/g in 'Tombul'. Large differences between cultivars in their content of phenolic compounds were also reported by Solar et al., (2009).

Australia imports approximately 2300 t/annum of hazelnut kernels, as discussed in Chapter 1, Section 1.3. Current imports of nut in-shell are not readily available, but the quantities in the period 1994 -2005 were less than 100 tonnes per annum and appeared to be declining. A survey of users of hazelnuts in Australia in 2002 showed that the major use was as roasted kernels in confectionery products, in hazelnut spreads, as diced hazelnuts, as paste and in snack foods (Baldwin and Simpson, 2003). The supply chain of hazelnuts from overseas producers and local growers is shown in Figure 2.7. As Australian production is low, the majority of sales are into local markets and to caterers and small confectionery companies.

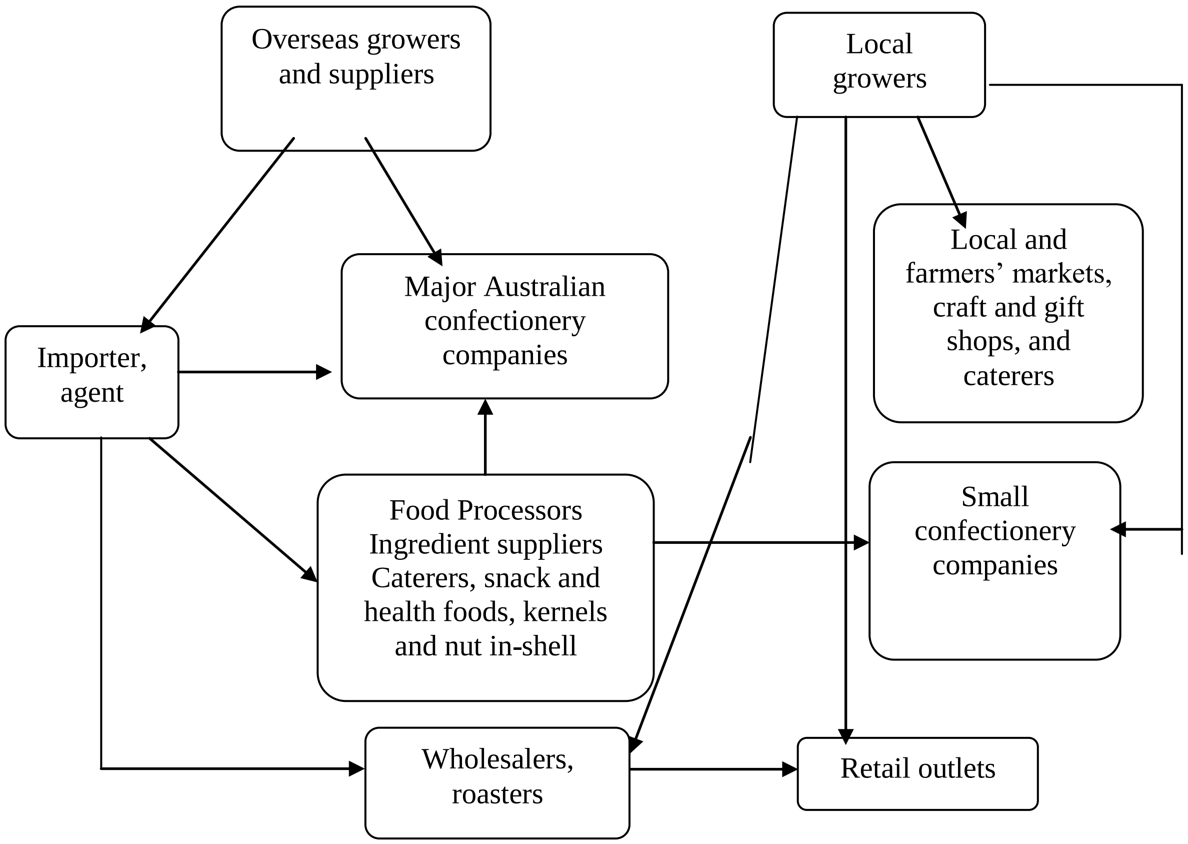


Figure 2.7 Australian supply chain from overseas and local production to manufacturers and retail outlets
Source: Baldwin and Simpson, 2003

The ideal cultivar for industrial use in the confectionery market has small round nuts with a thin shell and a crisp textured kernel from which the pellicle can be easily removed by dry heat (Mehlenbacher, 1991). Other attributes are a good aroma and the "*right amount of fats"* (Tombesi et al., 1994). Kernel size seems to be less important for the snack and health food markets but appearance is important. There is a preference for kernels with a smooth, thin pellicle (Baldwin and Simpson, 2003).

Although the market for kernels for use in the snack and health food market segment is quite small, it is growing as the health benefits of nuts are increasingly recognised. The type of kernel preferred for this market segment is not very different from that of the confectionery market, although as the kernels are eaten raw, blanching is less important; however, a thin smooth pellicle is important. Slightly larger kernels are acceptable up to about 17 mm (Baldwin and Simpson, 2003). For the in-shell market segment, the relative size and appearance of the nuts are the most important characteristics (Table 2.6), with a preference for large, shiny nuts.

Table 2.6 Key characteristics of hazelnuts and kernels for the main segments of the hazelnut market.

Market segment	Key characteristics of nuts and kernels
Confectionery, roasted, used in chocolates and nougat, also paste mixed with chocolate (e.g. ‘Nutella’ ®)	Small, (≤15 mm diameter) round, plump, bright white kernels (readily blanched)
Baked goods and restaurant trade, also unprocessed kernels for snack and health foods (e.g. in muesli)	‘Good’ flavour, smooth, round, thin pellicle, medium brown, crisp texture, small medium size (≤17 mm)
In-shell	Large, shiny, medium brown nuts

2.3.2 Cultivar evaluation

In Europe, hazelnuts are a relatively traditional crop with cultivars having been selected from the wild by growers for their own districts. These include ‘Tonda Gentile delle Langhe’ (‘TGDL’) from the Langhe district of north-west Italy, ‘Tonda Gentile Romana’ in the Latium region of Italy, ‘Negret’ in Spain and ‘Tombul’ and ‘Palaz’ in northern Turkey (Thompson et al., 1996). In some newer areas of production in Europe, such as the Agen region of France, the cultivars grown are based on the results of field-testing of a range of cultivars (Germain and Sarraquigne, 2004). However, a new cultivar ‘Fercoril-Corabel’ that is suited to the environment of the Agen region was selected from ‘Fertile de Coutard’ for the in-shell market (Germain and Sarraquigne, 2004).

The cultivar ‘Barcelona’, probably named from a Spanish import, was introduced into the USA by the horticulturalist Gillette in the 1880s (Hummer, 2001). It was found to grow and produce well in the Willamette Valley. However, by the 1980s the European hazelnut cultivars grown there had succumbed to local strains of the fungal disease, eastern filbert blight (Thompson et al., 1996). As this disease is not readily controlled by fungicides, it was considered that the most effective method of control was to breed resistant cultivars, which has led to a very active hazelnut breeding program (Mehlenbacher, 1994). This has been undertaken by the Oregon State University (OSU) and is probably the largest and most significant hazelnut breeding program in the world. Two cultivars from this program have been introduced into Australia, 'Willamette' and 'Lewis'.

There is a huge range of hazelnut cultivars, mostly selected for specific local environments. This raises the question; do most cultivars have specific environmental requirements? If so, have they been selected for specific soil types or specific climates or is it a combination of the two? Also, what influence has human culture and regional or commercial preferences had on the selection of cultivars? For example, the cultivar 'TGDL' is considered to have characteristics of good nutty flavour, texture and size that makes it highly sought-after by the Italian confectionery industry (Tombesi, 2005). Similarly, in Spain, the cultivar 'Negret' is highly prized by the local confectionery industry for the quality of its kernels (Tous, 2005). In Turkey, cultivars have been selected for their long, clasping, restricted husks and several small nuts per cluster (Mehlenbacher, 1991). The trees are relatively small and the nuts do not fall free from the husks. The large nut clusters are picked by hand, when the nuts are mature.

In recent decades, there has been an interest in evaluating cultivars with useful commercial traits from "foreign" countries for new areas of production, such as in Chile (Grau and Bastias, 2005). Foreign cultivars are also evaluated as an alternative to traditionally-grown cultivars, such as by Miletic et al. (1997) in Serbia, Miljkovic and Prgomet (1994) in Croatia, Solar and Stampar (1997) in Slovenia and Wertheim (1994) in Holland. There has also been an interest in breeding higher-yielding cultivars and those with disease resistance (Mehlenbacher, 1994) or cultivars with greater cold tolerance (Xie et al. 2005). Research has also been undertaken to try to select better clones of existing cultivars such as 'Tonda Gentile Romana' in Italy (Monastra et al., 1997) and 'Negret' and 'Gironell' in Spain (Rovira et al., 1997).

Most of the studies on cultivar evaluation have been in a single location, with very few studies being done across locations to test for any interactions between cultivars and environmental conditions. The main exception to this is the work of Grau et al. (2001)

who evaluated a range of cultivars in 3 different locations in Chile with some differences in the yields of cultivars being reported for the different sites. An example of an interaction between sites and cultivars was with 'TGDL'. Grau et al. reported high vigour of growth of 'TGDL' compared with 'Barcelona' at Los Robles in Chile on a "low stress" site, whereas, in more "stressful" situations, 'TGDL' displayed low vigour.

In many countries that produce hazelnuts, there have been programs of cultivar evaluation to try to find superior types for their industries, with an emphasis on small kernels suitable for the confectionery market. Such programs of cultivar evaluation have led to industry expansion and development through the planting of cultivars that are more productive and of superior quality, such as 'Pautet' in France (Germain and Sarraquigne, 2004). Some cultivars have been bred for better adaptation to the environment as well as being of good quality, such as the breeding of the cultivar 'Arutela' in Romania (Botu et al., 2009). In many cases, the limitations of existing cultivars have become apparent. There has been a need to breed cultivars with resistance to serious diseases, such as eastern filbert blight (*Anisogramma anomola* Peck) in Oregon, as well as to increase yields and kernel quality, as has been achieved with recent releases from the OSU breeding program (McCluskey et al., 2009).

Some studies have included sensory evaluation, using panels to describe characteristics such as taste, texture and aroma, Valentini et al. (2001), Tombesi et al. (1994) and Botu et al. (2009). Fatty acid content has been considered in some studies. Tombesi et al. (1994) reported they sought the "right amount of fats", but did not elaborate on what this constituted.

Nearly all cultivars are assessed on their own roots, but it has been found that rootstocks can affect yield. Tous et al. (2009) reported the Spanish cultivar 'Negret' grew more vigorously and gave higher yields when grown on the non-suckering rootstocks of 'Dundee' and 'MB69'. However, kernel quality was superior when 'Negret' was grown on its own roots.

Growth, nut yields and some aspects of nut and kernel characteristics appear to be strongly influenced by the genetic traits of cultivars and the environment in which they are grown. At Vâlcea in the Oltenia region of Romania, which is on the southern foot slopes of the Carpathian Mountains, north-west from Budapest, the winters are very cold with temperatures going down to -20°C (Botu and Turcu, 2001). Turcu et al. (2001) reported that in this region of Romania, nut yield was directly influenced by the time of female anthesis. The staminate flowers of cultivars that were late commencing anthesis, when temperatures did not fall below -5°C, were not damaged by low temperatures and these cultivars produced higher yields. In Poland, Piskornik (1994) also reported reductions in yields caused by late frosts at flowering.

The cultivars ‘Merveille de Bollwiller’, ‘Du Chilly’ (syn ‘Kentish Cob’) and ‘TGDL’, which are late into female anthesis, all showed good adaptability to the environmental conditions of Vâlcea, in Romania (Parnia and Botu, 1994). It seems possible that in this environment, late female anthesis has an advantage by avoiding late frosts or maybe occurring at a time when there was abundant pollen being shed. The mean annual rainfall in the Vâlcea region is 715 mm with about 300 mm falling in the months of May, June and July, the period of greatest water usage (Turcu and Botu, 1997). The mean yield of ‘TGDL’ over a 9-year period, 5 years after planting, was 3.7 kg/tree, compared with 3.1 kg/tree for ‘Merveille de Bollwiller’. Not only did ‘TGDL’ yield well, 12 kg/tree in 1989, but its variability in yield over the 9 years was relatively low at 29% compared with 51% for ‘Merveille de Bollwiller’. Other high-yielding cultivars in this experiment were ‘Butler’, ‘Ennis’ and the local selection ‘Vâlcea 22’. ‘Langi de Spania’ (syn. ‘Longue d’Espagne’) was slightly lower-yielding at a mean of 2.7 kg/tree. ‘TGDL’ produced many suckers per tree whereas ‘Merveille de Bollwiller’, ‘Ennis’ and ‘Butler’ were all lower suckering.

Conversely, in places where the winters are mild, such as the Tarragona region of Spain, which is near the Mediterranean Sea, Rovira and Tous (2001) reported that cultivars with late stigma exertion did not produce well due to a lack of pollen at that time.

The cultivar ‘Barcelona’ (syn ‘Fertile de Coutard’) appears to be a vigorous, strongly-growing, cultivar over a wide range of conditions, including Sicily, Baratta et al. (1994); Croatia, Miljković and Prgomet (1994); Oregon, McCluskey et al. (1997); Portugal, Santos and Silva, (2001); and Chile, Grau and Bastias, (2005) with generally high nut yields. The main disadvantages of this cultivar are its relatively low yield efficiency, thick shells and low kernel percentage, McCluskey et al. (1997).

Yield efficiency in tree crops is commonly related to the relative efficiency of assimilates being used for fruit or nut production compared with those for overall tree growth. Calculations of yield efficiency for cultivar comparisons are determined from cumulative nut or kernel yields compared with the trunk cross-sectional area (TCSA) of the trees, as measured after harvest in the last year of yield assessment after a period of 5 or 10 years (Westwood, 1993). Although other measures of yield efficiency, as discussed in Section 2.2.3, can be used, that which is based on cumulative nut yield/growth (TCSA) is the most common in cultivar evaluation. This is probably because it is easy to undertake.

On a per tree basis yield efficiency (YE) is:

$$\frac{\text{Cumulative nut yield per tree (kg)}}{\text{TCSA in last year of production (cm}^{2)}}$$

The Italian cultivar ‘Tonda di Giffoni’ is also vigorous and shows wide adaptation with good quality kernels. Clonal selections have been made to improve its productivity and kernel quality, Petriccione et al., (2010). ‘Tonda di Giffoni’ grew well in Oregon, McCluskey et al. (1997), producing higher yields than ‘Tonda Romana’. However, ‘Tonda Romana’ was reported by Baratta et al. (1994) to have wide adaptation in a study at the Nebrodi area near Messina in Italy. It also grew and yielded well in the Oltenia area of Romania, Turcu and Botu (1997) and in the Chillan, Grau et al. (2001) and Camarico regions of Chile, Grau and Bastias (2005). Miljković and Prgomet (1994) considered that ‘Tonda Romana’ and ‘Nocchione’ demonstrated “*good drought resistance*” when grown on a terra rossa soil in the Istria region of Croatia, where the average annual rainfall is 800-900mm.

The cultivar ‘TGDL’ seems to be variable in its growth and production. It grew well and was productive under the arid conditions of Serbia, Miletic et al. (1997) and performed well at Valcea in Romania, Turcu and Botu (1997). Moderately good growth and nut yields were obtained in Croatia, Miljković and Prgomet (1994). In Chile, growth and yield of ‘TGDL’ varied considerably with site, making poor growth with low yields in the Camarico region, Grau and Bastias (2005). In Oregon, McCluskey et al. (1997) reported ‘TGDL’ was of low vigour with low nut yields.

‘Hall’s Giant’, (syn ‘Merveille de Bollwiller’) is a cultivar that is late commencing pollen shed and female anthesis. It is generally reported to be a vigorous-growing cultivar but with variable yields. High yields were reported by Turcu and Botu (1997) in Romania. In Oregon, McCluskey et al. (1997) reported good growth and moderately good yields of medium-sized nuts that had thick shells and a low kernel percentage. Bergoughoux et al. (1978), consider it to be a cultivar that was well adapted to regions with a continental climate that was cold in winter and spring. This cultivar was used in a breeding program in Romania to produce a new cultivar 'Arutella' which was derived from a cross between 'Merveille de Bollwiller' and 'TGDL' (Botu et al., 2009). 'TGDL' is also a cultivar that appears to be tolerant of cold conditions (Parnia and Botu, 1994). The cultivar 'Arutella' combines the vigour of 'Merveille de Bollwiller' with the good kernel quality of 'TGDL'.

The cultivar 'Negret' also seems to vary greatly in growth and productivity, depending on the situation in which it is grown. Good vigour and productivity were reported by Miljković and Prgomet (1994) on a terra rossa soil in Croatia, whereas poor growth and productivity were reported by both McCluskey et al. (1997) in Oregon and Grau and Bastias (2005) in Chile. In Spain, where it is the main commercial cultivar, 'Negret' appears to be susceptible to iron deficiency on calcareous soils. Grafting onto more vigorous rootstocks has enhanced yield, (Tous et al. 2009).

Two cultivars that were developed as part of the OSU breeding program and which are available in Australia are 'Willamette' and 'Lewis'. 'Willamette' was released in 1990 for the blanched kernel market. It has a thin shell and a high kernel yield. Over a 6-year period, 1985-1990, 'Willamette' produced a higher kernel yield than 'Barcelona' and a higher cumulative yield efficiency (Mehlenbacher et al. 1991). Similarly, 'Lewis' has relatively thin shells and a high kernel yield. Over a 6-year period, 1985-1990, 'Lewis' also produced a higher kernel yield than 'Barcelona', with a higher cumulative yield efficiency. Its productivity is similar to 'Willamette', but it has greater tolerance to eastern filbert blight, McCluskey et al. (2001). Both cultivars have a more compact habit of growth than 'Barcelona' and are more precocious. These are characteristics sought in modern cultivars by utilising products of photosynthesis more efficiently in the production of nuts and kernels rather than tree growth.

2.3.3 Breeding programs

Although most of the commercial cultivars grown in Europe are from local selections, several plant improvement programs have been undertaken in the last 50 years. These have included selections from wild types to produce cultivars suited to organic production (Schepers and Kwanten, 2005), the evaluation of introduced cultivars from other lands (Solar and Stampar, 1997), clonal selections (Monastra et al., 1997; Rovira et al., 1997) and breeding through open (Tombesi et al., 1994) and controlled (Botu et al., 2009) cross-pollination. Public breeding programs commenced in Italy in the 1960s, in France, Spain and Romania in the1970s and in Turkey in the 1990s (Mehlenbacher, 1994). In Oregon, a breeding program was initiated in 1969, following a decade of cultivar evaluation.

In these breeding programs, the main objectives were generally to produce higher yielding cultivars for both the in-shell and kernel markets but other attributes are commonly included, such as lower suckering, later bud-burst and tolerance or resistance to pests and diseases, depending on the local situation (Mehlenbacher, 1994). In Romania, Miletic et al. (1997) tried to evaluate cultivars for their sensitivity to the arid conditions of eastern Serbia. In Holland, Wertheim (1994) aimed for high yields and considered 2 t/ha as the minimum economic production requirement.

Examples of the objectives in a cultivar breeding program are those of the Oregon State University (Mehlenbacher, 1994):

a. Resistance to eastern filbert blight
b. Cultivars for the kernel market
    - Resistance to big bud mite
    - Round nuts of medium size
    - High percentage kernel
    - Precocity and high nut yields
    - Easily blanched kernels
    - Few nut and kernel defects
    - Early maturity
    - Free-falling nuts

Breeding programs need to be complemented by programs in which the seedlings produced are compared with existing standard cultivars. Such cultivar and hybrid evaluations generally include assessments of nut and kernel yields, kernel percentage, and kernel quality. Some include assessments of yield efficiency. Progress is slow in breeding, due to the number of years taken for trees to bear nuts. It is accentuated by the number of characters that are required for the selection of improved types.

In Oregon, kernel quality is assessed by cracking a sample of 100 nuts per treatment to obtain nut and kernel weight (g), the number of blank nuts as well as kernel defects, such as kernels that are shrivelled or poorly-filled, are mouldy, have black tips or are twins (McCluskey et al., 2001). Thompson et al. (1978) devised a method for assessing blanching ability by heating whole kernels in an oven at 130-150°C for 15 minutes followed by rating the ease of pellicle removal on a 1-7 scale, with 1 indicating complete removal and 7 indicating no removal of pellicle.

2.3.4 Cultivars available for evaluation in Australia

Discussions with propagators, growers and those who had imported cultivars from overseas led to the identification of 30 varietal types that could be available for evaluation in this research. These included imported cultivars and Australian selections with potential for the in-shell market, the kernel market and as pollinisers. A general description of the origins of these varietal types and their key horticultural and botanical characteristics, as obtained from the literature and discussions with growers and propagators, is presented in Appendix A.

The correct identification of hazelnut cultivars in research studies is essential in order to compare the results of new research with that of published research. As the author of the thesis was not familiar with the cultivars available for evaluation, there was a need to develop a method of identification. Thompson et al. (1978) developed a system to describe hazelnut cultivars based on a wide range of heritable plant characteristics. This was subsequently expanded and adopted internationally in a booklet published by Bioversity International, FAO and CIHEAM (2008). Some of the highly heritable characteristics from these systems were used to verify that the cultivars in this research were true to type. The characteristics chosen and how the data was gathered are explained in Chapter 3 Methods, Section 3.5.1 ‘Cultivar characteristics’.

2.3.5 Predicting cultivar performance in the Australian environment

There are 2 key considerations that need to be taken into account when assessing the potential of cultivars for production in Australia. These are the market segments they might suit and their potential nut and kernel yields. Based on the attributes and performance of the cultivars reported in this literature review and in Appendix A, the cultivars available for evaluation could be placed into 1 of the following 4 categories or market segments:

- the confectionery (industrial) sector (≤15mm diameter kernels);
- general kernel use in baking and health foods;
- the in-shell market; or
- as a polliniser.

Some cultivars have attributes that make them suitable for more than 1 use; for example, as ‘Lewis’ produces a small kernel with a thin pellicle which is readily blanched (McCluskey et al., 2001), it could be acceptable to both the confectionery trade and the health food market segments. The Australian selection ‘Wanliss Pride’ produces a fairly large, attractive, shiny nut that is commonly sold in-shell. However, it is also used in the baking and confectionery trade in Australia. In Oregon, ‘Butler’ is commonly used as a polliniser for ‘Ennis’ (Lagerstedt, 1980) as well as being suited to the in-shell market.

Cultivars for the confectionery market

Currently the production of small (≤15mm) diameter kernels for the Australian confectionery market is limited, with most of the larger confectionery companies importing all their kernel requirements. However, there are several cultivars of overseas origin that would appear to have potential for this market and are worthy of evaluation (Table 2.7).

Table 2.7 Potential cultivars for the blanched, roasted confectionery market
Attributes: Small kernels (<15mm diameter) round, plump, and readily blanched

Cultivar	Female anthesis	Vigour of growth	Yield potential	Kernel %	Other comments
‘Lewis’	Mid	Medium	High	44-47	High yield efficiency
‘Montebello’	Early	Medium			Relatively small tree
‘Negret’	Mid	Low-High	Medium-High	55	Relatively small tree, important cultivar in Spain
‘Riccia di Talanico’	Mid	-	Medium	-	Italian cultivar
‘Tonda di Giffoni’	Early	Medium-High	Medium-High	46-48	Important cultivar in Italy, relatively small nuts
‘Tonda Romana’	Mid-Late	Low-Medium	Medium-High	44-48	Relatively small tree from Italy
‘TGDL’	Mid	Low-High	Low-High	45-52	High quality kernels
‘Whiteheart’	Late	Low	Medium	47-48	Grown in New Zealand
‘Willamette’	Early	High	High	50	High yield efficiency

Cultivars for general kernel use, baking and health foods

Cultivars with medium-sized kernels that can be used for the snack and health food markets, as well as in baking and general catering, are shown in Table 2.8. ‘Barcelona’ is a very productive cultivar in Oregon (Thompson, 1981) with wide adaptation and may perform well in Australia. ‘Atlas’ (Trimmer, 1965), ‘TBC’ and ‘Tonollo’ (Trimmer, 1965) are cultivars that have yielded well in Australia. High nut yields of ‘Casina’ have been obtained in Oregon (McCluskey et al., 1997) and of ‘Segorbe’ in France (Bergoughoux et al., 1978). An evaluation of all these cultivars, along with the Australian selections ‘Eclipse’ and ‘Square Shield’, should provide some very valuable data on comparative yields and kernel quality.

Table 2.8 Potential cultivars for the health food and general catering markets.
Attributes: Kernels ≤17mm diameter, good flavour, smooth, round with thin pellicle.

Cultivar	Female anthesis	Vigour of growth	Yield potential	Kernel %	Other comments
‘Atlas’	Early	High	High	-	Nuts similar in size to ‘Barcelona’
‘Barcelona’	Mid	High	High	42-44	Wide adaptation
‘Casina’	Late	Medium - High	High	56	Small nuts and kernels, poor blanching
‘Eclipse’	-	-	-	-	Medium size nuts
‘Segorbe’	Late	High	Medium - High	40-45	Small nuts, and kernels, poor blanching
‘Square Shield’	-	-	-	-	Medium size nuts
‘TBC’	-	Medium	Moderate	-	Medium sized nuts
‘Tonollo’	Mid	High	High	-	Similar to ‘Barcelona’

Cultivars for the in-shell market

‘Ennis’ is a high yielding cultivar grown in Oregon for the in-shell market (Lagerstedt, 1980) and would appear to have high potential for the Australian situation. However, ‘Royal’ may also perform well in Australia. How these 2 cultivars compare with the local cultivar ‘Wanliss Pride’ is unknown.

Table 2.9 Potential cultivars for the Australian in-shell market
Attributes: Medium-large size, shiny, brown nuts

Cultivar	Female anthesis	Vigour of growth	Potential nut yield	Other comments
‘Butler’	Mid-Late	High	High	Attractive blocky nuts
‘Ennis’	Late	Medium	High	Large, attractive nuts 50% >22mm
‘Hall’s Giant’	Late	High	Low-high	Nuts with thick shell
‘Hammond #17’	-	Medium	High	Similar to ‘Butler’
‘Royal’	-	-	-	Large, attractive nuts
‘Victoria’	-	High	-	Medium–large nuts
‘Wanliss Pride’	Mid	Medium	High	Attractive large nuts, straggly tree growth
‘White American’	-	Medium	High	Attributes similar to ‘Wanliss Pride’
‘Woodnut’	-	Small tree		Potential polliniser

‘Hammond#17’, which was found as a very high-yielding tree in a garden near Orange, has nuts similar to Butler, with some potential for the in-shell market. As with other cultivars discussed above, no comparative data on the growth, nut yields and kernel quality is available for Australian conditions. The potential cultivars available for evaluation for the in-shell market are shown in Table 2.9.

Polliniser cultivars

Some cultivars may not have attributes of high quality or high yield but may be valuable as pollinisers because they shed large quantities of pollen, may shed pollen late in the season or may be genetically compatible with a range of main crop cultivars. Such cultivars have been placed in Table 2.10.

Table 2.10 Cultivars grown mainly as pollinisers, commonly with low yield potential

Cultivar	Pollen shed	Female anthesis	Vigour of growth	S-alleles	Comments
‘Daviana’	Mid-Late	Late	Medium	3 11	Erect growth habit, medium size, long nuts
‘Kentish Cob’	Late	Late	Medium	10 14	Long nuts
‘Jemtegaard 5’	Late	Late	High	2 3	Medium size, round nuts
‘Merveille de Bollwiller’	Late	Late	Medium	5 15	Fairly large nuts, variable yield
‘Turkish Cosford’	Mid	-	-	-	Used to pollinate ‘TBC’, small nuts (Cox, 2010)
‘White Avelline’	Late	-	Low-Medium	5 10	Small tree, small nuts

2.3.6 Conclusions on cultivar merits

In regions that experience mild winter climates, cultivars behaved in a protandrous manner; it is therefore likely that this will occur in Australia due to the relatively mild winter temperatures of southern Australia compared with the continental climates of Europe. If the mild Australian winter climate causes pollen shed to occur during the late autumn and early winter, it is likely that attributes of early to mid-season female anthesis could be important to ensure that they receive adequate quantities of pollen for pollination, especially if potential polliniser cultivars are early in pollen shed.

Vigour of growth might be an important factor in production as female flowers are borne on wood of the previous season. As soil type influences growth, with a loam soil being the most favourable, cultivars with high vigour or the ability to grow in clay soils might be important as many Australian soils have a duplex soil profile, often with a heavier textured ‘B’ horizon at 150-200mm depth. Such a profile might be unfavourable to root growth, particullarly for cultivars with low vigour of growth.

High nut yield potential would obviously be desirable and a high kernel percentage, to give a high yield of kernels for cultivars that are to be sold into the kernel market. Another advantage of cultivars with a high kernel percentage is that they generally have relatively thin shells which are more easily separated form the kernel during processing. Air separation is commonly used after nut cracking to separate kernels from the cracked shells.

There is limited information in the literature on interaction effects of the environment on the growth and productivity of cultivars. Some cultivars, such as ‘Barcelona’, seem to display wide adaptation, growing vigorously with high nut yields in Sicily (Baratta et al., 1994), Croatia (Miljković and Prgomet, 1994), Oregon (McCluskey et al., 1997) and Chile (Grau and Bastias, 2005). However, the productivity of some cultivars, such as ‘TGDL’ was found to vary with the environment in which they were grown. ‘TGDL’ grew and yielded well in Serbia (Miletic et al., 1997) and Romania (Turcu and Botu, 1997) but was of low vigour and yield in Oregon (McCluskey et al., 1997). Differences in growth and production recorded between environments for a given cultivar appeared to be caused by differences in both climatic and soil factors. Management factors related to fertilizers, irrigation, planting density, pruning or other cultural practices could also have influenced cultivar performance. It is considered that, as with most crop species, it is not possible to predict the performance of cultivars without evaluating them under the potential range of environments in which they might be grown.

Part 4 Overall Conclusions

In Chapter 1, Introduction, it was stated that the general aims of the research that forms the basis of this thesis were to:

- determine the most suitable hazelnut cultivars that could be used for the establishment of a hazelnut industry in south-eastern Australia;
- assess the effects of geographical region and climate on hazelnut production and varietal performance;
- assess the productive potential of hazelnuts (*Corylus avellana* L.) in Australia.

This Literature Review is now considered in the context of these general aims of the research, to frame key research questions. This review guided the research methodology and the management practices at the field sites.

2.4.1 The effects of climate and soils

The first part of this chapter reviewed studies on the effects of climate and soils on hazelnut production generally. Climatic conditions were found to have a major impact on the growth and productivity of hazelnuts. The review led to the development of some general climate indices (Table 2.1) that were considered desirable for commercial hazelnut production. These were used to guide the selection of the 5 field sites used.

Soil type is an important factor in hazelnut production. Soils that are slightly acid to neutral with a loam texture are free-draining and have a depth of at least 600 mm, preferably 1-2 m, are highly desirable. These general parameters should be considered in the selection of field sites to ensure satisfactory tree growth.

It is recognised that there are likely to be confounding effects between climate and soil types on the growth and productivity of hazelnuts. That is, it may be very difficult to determine whether differences observed between sites, in some attributes of production, are related to climate or soil conditions.

2.4.2 Growth, development and yield potential

The second part of the Literature Review focussed on the physiology of growth and development in hazelnuts and how this is influenced by environmental conditions. A model was developed, showing the periods of key growth and development (Table 2.5).

Temperature patterns in late autumn and winter appear to be critical in influencing floral phenology. The literature showed that the amount of chilling and the post-chill heat requirements to break the dormancy of male and female flowers vary between catkins and female inflorescences, cultivars and seasonal conditions. It appears that factors influencing the time of pollen release and flowering are complex and not sufficiently well understood to accurately predict phenology. That is, it is not yet possible to model phenology of various cultivars for different climates.

Hazelnuts do not seem to be able to take up moisture from the soil sufficiently quickly to cope with conditions of high evaporation, such as might arise in periods of low humidity and high temperature, coupled with strong wind. Moisture deficits can cause the closure of stomata, with a decline in the intercellular CO_2 concentration resulting in decreased photosynthesis (Tromp, 2005). The literature clearly showed how moisture stress can cause reductions in growth, nut development and kernel fill, depending on the period and duration of the moisture deficit. The few studies on water relations in hazelnuts suggest they have difficulty maintaining turgor under conditions of high evaporative demand. It was concluded that the inclusion of supplementary irrigation would be highly desirable for the proposed study sites.

2.4.3 Cultivar evaluation

An assessment of the relative merits of cultivars was undertaken in the final section of the literature review. Unfortunately, much of the data available on Australian varietal types is limited and anecdotal. The literature on overseas cultivars indicates that some have wide adaptation, whilst others seem to be suited to specific environmental conditions of climate or soils. It seems likely that cultivars that are early to mid-season in female anthesis and are of high vigour might be those most suited to the Australian environment. Cultivars that are late into female anthesis may suffer from a lack of pollen from other cultivars in the orchard and hence not reach their full yield potential.

Many characteristics such as vigour of growth, nut size, shape, colour and kernel blanching ability are genetically determined, but are influenced by environmental conditions. For example moisture stress during nut development can influence nut weights (Mingeau et al., 1994 and Bignami and Natali, 1997).

The Literature Review identified interactions between the growth, floral phenology and nut yields of cultivars and the environment. It is considered that data from the literature is insufficient to predict cultivar productivity in a new location with any precision. Therefore, there is a need to conduct research with a wide range of cultivars over several environments and seasons to try and understand how cultivars perform and are influenced by environmental conditions.

As the cultivars available for the study were drawn from a number of sources, there was a need to include a method of identification to ensure they were true to name.

2.4.4 Research questions

The review of literature has shown that there are several areas where knowledge is currently inadequate to predict how cultivars will grow, develop and yield in Australia. The following key questions were formulated to achieve the aims of this thesis:

A. Tree growth
   1. How vigorously will the cultivars grow and how will their growth rates vary between sites and seasons?

B. Floral phenology
   1. When will the cultivars come into anthesis and how will the floral phenology differ between cultivars and across sites and seasons?
   2. How will environmental conditions influence floral phenology?

C. Nut yields
   1. When will the cultivars commence bearing nuts, what will be the development of yield over years from planting and what will be their yield potential?
   2. What will be the variation in nut yields between cultivars and the environments in which they are grown?

D. Kernel quality
   1. How will kernel attributes vary between cultivars and how will these attributes be influenced by environmental conditions?

The general methods developed to address the above research questions are explained in the next chapter.

CHAPTER 3 - METHODS

3.1 Introduction

The background to the Australian hazelnut industry was given in Chapter 1. In that chapter it was explained that although the first hazelnuts were introduced to Australia in the 19th century, plantings had been limited to a few small orchards in Victoria and NSW. During the 1980s there was a renewed interest in industry development and several hazelnut cultivars of European origin were imported by individuals and some by government agencies. However, there had been no systematic evaluation of this material, nor had there been any significant research to study how hazelnuts performed in the Australian environment. In the 1990s there were still relatively few orchards with little Australian production, yet more than $20 million worth of hazelnuts were being imported annually.

In Chapter 2, a review of the literature on the effects of environmental conditions on the growth, development and productivity of hazelnut cultivars was conducted. This included a review of the cultivars and Australian selections available for evaluation in Australia, with descriptions of the cultivars in Appendix A. The review identified that the phenotypic response of cultivars is variable under a range of environmental conditions, demonstrating a need to evaluate cultivars at more than 1 site, in order to quantify the extent and possible causes of interactions between cultivars and environmental conditions.

The principal research methodology used for this study was to assess the growth, floral phenology, nut production and kernel quality of a range of cultivars at 5 different field sites. Some additional experiments were conducted to investigate some issues that arose from the field studies, to elucidate the possible mechanisms that caused the observed effects.

This chapter outlines the methods used for the 5 field experiments that provided the main data for this thesis. It explains where the field experiments were located, which cultivars were evaluated and the cultural practices used at the field sites. This research focused on the evaluation of genetic resources under a range of environmental conditions with the same orchard management methods being used at all the sites, as much as possible.

3.2 The field sites

Five experiments were established in South-eastern Australia at locations where it was known that hazelnuts could be grown, as there were existing plantings at each of the 5 sites.

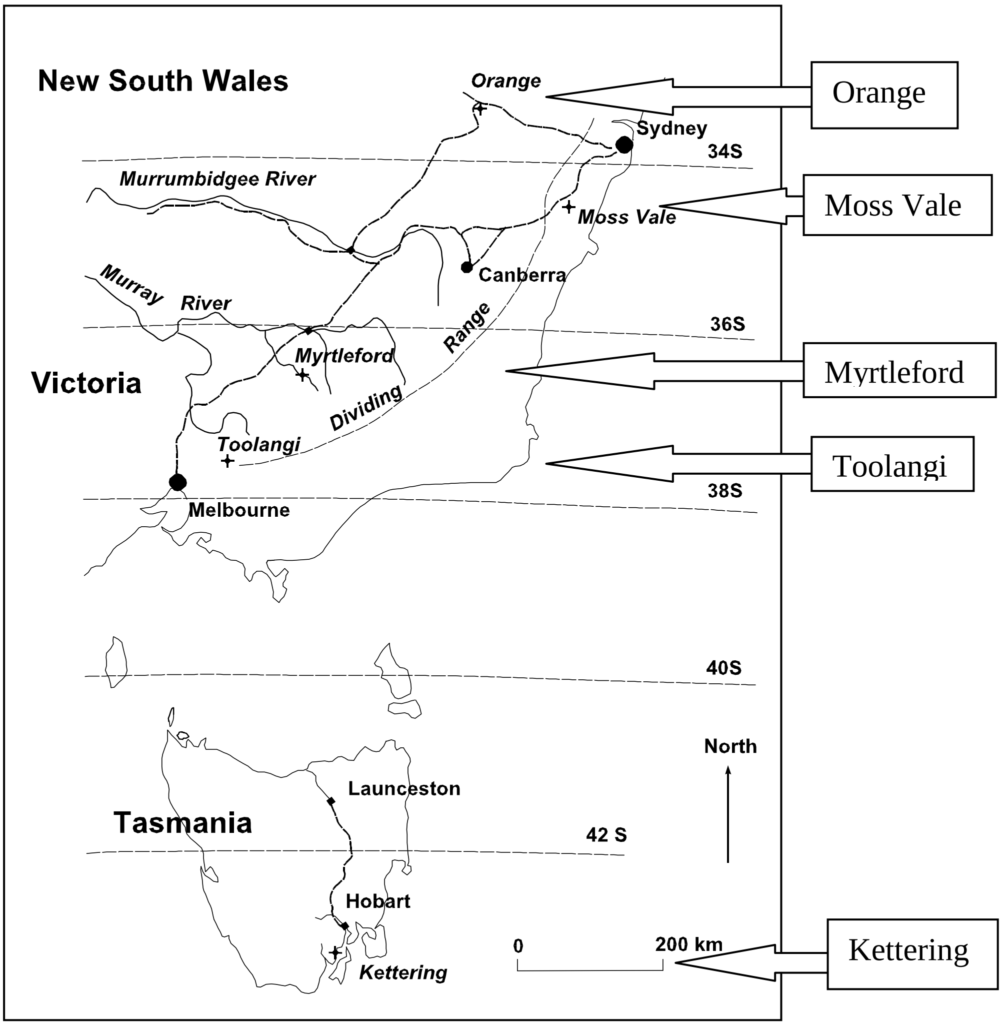


Figure 3.1 Location of the 5 field experimental sites in South-eastern Australia
Note: In the Northern Hemisphere, key production areas lie in the latitude range 40-45°N

The 5 sites were chosen principally to represent different rainfall and temperature patterns, but the sites also had different soil types. The key climatic parameters identified in the Literature Review (Table 2.1), are shown in Table 3.1, along with other climatic data and the soil types at the sites. Two sites were in NSW, at Orange and Moss Vale, 2 in Victoria, at Myrtleford and Toolangi and 1 in Tasmania at Kettering (Figure 3.1). Three sites were on land owned and managed by State Government authorities and 2 were on private land. The general climatic characteristics of the districts where the sites were established are shown in Table 3.1.

Table 3.1 Climatic characteristics of the localities where the hazelnut field experiments were established, including climate criteria developed from the literature review, (Table 2.1).

Attribute	**Orange** (Orange Ag. Inst.) 063254	**Moss Vale** (Hoskins Street) 068045	**Myrtleford** (Post Office) 082034	**Toolangi** (Mount St Leonard) 086142	**Kettering** (Kingston) 094036
Distance from coast (direct - km)	200	40	200	60	2
Altitude (m ASL)	922	675	223	595	52
Latitude	33.3° S	34.5° S	36.7° S	37.6° S	37.6° S
Mean min temp coldest month °C	1.5°C	1.3	2.1	3.8	2.4
Lowest recorded temp °C (>-5°C)	-5.6	-6.4	N/A	-5.0	-7.2
Mean temp °C coldest month (July)	5.2	6.6	7.3	6.1	7.5
Total chill hours (0-7°C) May - Sept	1370	1237	1133	1327	1217
Lowest temp Oct °C (> -3°C)	-2.0	-2.8	N/A	N/A	N/A
Mean max temp Nov °C (>21°C)	21.1	22.6	24.5	18.0	17.6
Mean max temp Dec °C (>21°C)	24.4	25	28.5	20.8	19.8
Mean max temp hottest month °C	26.5	25.8	30.8	23.2	26.9
Highest Jan/Feb temp °C	38.3	38.3	N/A	42	36.6
Mean number of days/annum ≥35°C	0.7	2.0	N/A	0.9	1.1
Mean temp °C hottest month	19.4	18.9	20.9	17.5	16.3
Mean RH Jan >70%	53%	N/A	44%	N/A	N/A
Mean annual rainfall (> 800 mm)	934	965	905	1358	674
Mean annual evaporation (mm)	1460	1500	1460	1020	985
Growing period rain (Sept–Jan) (mm)	415 (44%)	376 (39%)	339 (37%)	602 (44%)	293 (44%)
Three wettest months in succession	July–Sept	Jan–Mar	June–Aug	Aug–Oct	Oct–Dec
General rainfall pattern	Winter – spring dominance,	Summer – autumn rain, dry spring	Winter – spring rain, dry summer	Late winter – spring dominance	Spring – early summer dominance
Annual rainfall variability	0.68	0.7	0.66	0.49	0.7
Mean rainfall March (mm) <50mm	55	93	60	88	52
Mean number of rain days in March	6.8	11	6	12.9	9.3
Soil type	Krasnozem	Red podsol	Alluvial	Krasnozem	Yellow podsol

Source of climatic data: Commonwealth Bureau of Meteorology, Climate data on-line 2010 www.bom.gov.au/climate/data/. *The closest Bureau of Meteorology recording stations to the sites were used. Note: N/A not available*

Although the sites were selected to investigate interactions between cultivars and climate on tree growth and nut yields, it is recognised that the differences between the soil types at the sites were likely to have an effect and confound these interactions. The characteristics of the soils were assessed and nutrient levels were monitored. Standard procedures for site management were implemented, as much as it was feasible, to minimise variation due to management.

3.2.1 Description of the field sites

Orange (149.08°E, 33.32°S, 910 m ASL)

This site was on land owned by the then NSW Department of Agriculture (subsequently NSW Department of Primary Industries) at the Orange Agricultural Institute, 3 km south of the city of Orange on the Central Tablelands of NSW. It was flanked by Forest Road on the eastern side and Cadia Road to the south-east. The site was level and had been an apple orchard, which was bulldozed in the year prior to planting, with the piles of dead trees having been burnt. The site had very little wind protection (Plate 3.1) except from the south-east, where a row of old hazelnut trees had previously been planted from genotypes brought from the experimental site at the Glen Innes Research Station in 1971. The land was limed at 5 t/ha and cultivated before planting, which commenced in July 1995. The trees were planted in rows with a north-east to south-west orientation to provide the best fit into the land area available. The experiment comprised 4 replicates of 16 cultivars in a randomised block design, with 4 trees per treatment (cultivar) plot; only the centre 2 trees were used to obtain yield data. A row of buffer trees was planted on each side of the outer rows, with a buffer tree also being planted at the end of each row. The layout of the individual trees is shown in Appendix B. In 1998, an additional 2 rows of hazelnut trees were planted on the south-eastern side of the experimental block, adjacent to the outside buffer row. These were trees that had been imported by the company Ferrero.

A double row of native Casuarina trees (*Casuarina cunninghamiana)* was planted in 1995 on the south-western, north-western and north-eastern sides of the experimental block; these were set back about 10 m from the outer trees of the block to provide additional wind protection.

An Environdata automatic weather station was located on the western side of the site (Plate 3.1). This provided readings of temperature, relative humidity, rainfall, wind run and direction, and solar radiation on an hourly basis.

The soil was a krasnozem developed from tertiary basalt (Tables 3.2 and 3.3). A drip irrigation system was installed in the year of planting, with one 4 L/hr dripper adjacent to each tree. In the spring of 2002, the drip irrigation system was converted to micro-sprinklers (5 m^2 coverage) with 1 sprinkler per tree as per the other 3 mainland sites. Water was supplied from a dam at the research centre. Irrigation strategies at each site are described in Section 3.8.

The site was managed by Lester Snare, the Senior Technical Officer (Horticulture) stationed at the Orange Research Institute. An annual calendar of operations was prepared for site management. This was standardised annually for all sites.

Plate 3.1 Hazelnut trees in their first growing season after planting at the Orange site. The trees were mulched with old hay. The Environdata automatic weather station is to the right of the picture, with the automatic rain gauge located on the ground. The site had very little wind protection from SW winds that are common in winter.

Moss Vale (150 42°E, 34 52°S, 690 m ASL*)*

This site was located on the property of Jim and Lauren Gleeson, Filbert Farm, 20 km south of the township of Moss Vale on the Southern Highlands of NSW (Figure 3.1). The site had a very slight slope to the south and was reasonably well-protected from the wind, being in a valley surrounded by woodland and forest (Plate 3.2). The site had been principally pasture that had been used for grazing, although it had, in earlier years, been used for growing potatoes. The site was limed before planting, at 5 t/ha, and cultivated. The trees were planted in July 1996, in rows with a north–south orientation.

The experiment comprised 4 replicates of 12 cultivars in a randomised block design, with 2 trees per treatment; both were used to obtain yield data. A row of buffer trees was planted at each end of the site with buffer trees also being planted at the end of each row. The layout of the individual trees is shown in Appendix B. An Environdata automatic weather station was located on the northern side of the site.

Plate 3.2 The Moss Vale site in November, 1996, the first year of leaf. The hazelnut plants are protected by polythene bags to reduce damage from rabbits and hares. The tree rows had been treated with the herbicide Roundup®, the strips between the tree rows were sown to a mix of clovers and ryegrass.

The site was fenced with rabbit netting and additionally had an electric fence to exclude kangaroos, wallabies and deer that roamed the bushland and forest of the area. The soil was a red podsol (Tables 3.2 and 3.3). The site had a supply of irrigation water from a nearby small, spring-fed dam. A sprinkler system was installed in the year of planting with a micro-sprinkler adjacent to each tree. The site was managed by the owners of the property, using an annual calendar of operations for site management worked out as part of the experimental protocols but with some adjustments for special circumstances such as pest infestations.

Myrtleford (146.71°E, 36 56°S, 260 m ASL*)*

The site was on land at the Ovens Research Station, owned and operated by the Victorian Department of Agriculture, 5 km south of the township of Myrtleford in the Ovens Valley of North-eastern Victoria. It was on the flood plain of the Ovens River (Plate 3.3). The valley, which was about 1.5 km wide at this point, ran in a north-west to south-easterly direction between 2 ranges of hills. The site was level and reasonably protected from wind, with a poplar plantation on the south-western side and some large gum trees to the south, along an anabranch of the Ovens River. The site had been planted to a block of Paulonia trees (*Paulonia fortunei*) for timber. These were removed in the year prior to planting; some timber had been harvested and the remaining trees were bulldozed and burnt. The site was limed at 7 t/ha, cultivated before planting and treated with the insecticide Lorsban ® (active ingredient chlorpyriphos) to control cockchafer grubs. The trees were planted in rows, with a north-west to south-east orientation, in July 1996. The experiment comprised 4 replicates of 24 cultivars in a randomised block design, with 2 trees per treatment; both were used to obtain yield data. A row of buffer trees was planted on each side of the outer rows with 2 buffer trees also being planted at the ends of each row. The layout of the individual trees is shown in Appendix B. An Environdata automatic weather station was located on the eastern side of the site.

The site was fenced to exclude cattle, which occasionally grazed the adjoining land. The soil was a deep alluvium on the valley floor (Tables 3.2 and 3.3). The site had a supply of irrigation water from the Ovens River. A sprinkler system was installed in the year of planting with a micro-sprinkler adjacent to each tree. The overall management of the site was the responsibility of the research station manager. Initially, day-to-day operations were supervised by the local horticulturalist, Dan Ridley, and subsequently by Dr Audrey Gerber. An annual calendar of operations was prepared for site management, based on the standard used for all sites.

Plate 3.3 Trees in their first growing season, November 1996, at the Myrtleford site. This site was on the floor of the Ovens Valley.

Toolangi (145.50°E, 37 57°S, 610 m ASL*)*

This site was on land at the Toolangi Potato Research Station that was owned by the Victorian Department of Agriculture. It was about 2 km south of the settlement of Toolangi at 1015 Myers Creek Road. The closest township was Healesville, about 10 km to the south. The research station is on the south-western side of the Yarra Ranges, which lie to the south of the Great Dividing Range. The site was on the lower slopes of Mount St Leonard (1010 m) to the east. The climate was strongly influenced by altitude and proximity to Port Phillip Bay and Bass Strait, 60-70 km to the southwest (Figure 3.1).

The site had been under pasture for many years. It sloped gently to the west (Plate 3.4) and was protected by wet sclerophyll eucalypt forest on the northern and western sides and most of the lower part of the south side. However, the top south-eastern corner of the site was exposed to southerly winds, which occurred generally following the passage of a cold front and were most persistent in the winter and spring.

The soil type was a deep krasnozem, forest soil with a high organic content and friable structure (Tables 3.2 and 3.3). The site was fenced on all sides to limit intrusion by wallabies and kangaroos, but it was visited by wombats that pushed under the fences and did some damage to trees on the southern side.

Plate 3.4 The Toolangi research site in November 1996 in the second growing season, looking down-slope to the west

The trees were planted in rows with an east-west orientation. The experimental design was similar to that at Orange, with 4 replicates of 16 cultivars in a randomised block design, with 4 trees per treatment; only the centre 2 trees were used to obtain yield data. A row of buffer trees was planted on each side of the outer rows with a buffer tree also being planted at the end of each row. The layout of the individual trees is shown in Appendix B. An Environdata automatic weather station was located on the southern side of the site.

Irrigation water was available from dams on the research station. A micro-sprinkler irrigation system was used with 1 micro-sprinkler per tree. The overall management of the site was the responsibility of the research station manager. An annual calendar of operations was prepared for site management, in the same manner as for all sites, with variations to address any particular site needs.

Kettering (147.26°E, 43.11°S, 50 m ASL*)*

This site was not selected until 1998, later than the other sites, due to operational reasons. It was in a small, recently-planted hazelnut orchard owned by John and Connie Zito on Saddle Road, about 1 km west of Kettering, which is in the Channel District, 34 km south of Hobart. The site was in the valley of the Little Oyster Cove Rivulet and about 1 km from Oyster Bay in the D'Entrecasteaux Channel (Figure 3.1 and Plate 3.5). The land sloped gently to the east, with wooded hills to the north, a vineyard to the west and wooded hills to the south. The climate was maritime, being close to the sea. It was affected at times by strong, gusty south-westerly winds.

Plate 3.5 The Kettering research site in February 2003, trees are in their fourth season of growth. This was the most maritime site being about 1 km from the D'Entrecasteaux Channel to the east.

Prior to the establishment of the existing hazelnut orchard, the site had at some time in the past been an apple orchard. Young hazelnut trees were removed in the centre of the orchard to make way for the research site. Twelve rows of trees were planted in 1999. These were planted in an east-west direction, the same as the orchard trees. Due to limited space, only 20 cultivars were planted with 2 trees per replicate and 3 replicates in a randomised block design. The layout of the individual trees is shown in Appendix B. An Environdata automatic weather station was located on the northern side of the site.

The soil was a yellow podsol with a grey-brown fine sandy loam surface soil overlying a cracking clay with impeded drainage. A description of the soil profile is given in Tables 3.2 and 3.3. The description of this soil type is in general agreement with that given by Nicolls and Dimmock (1965). A drip irrigation system was installed in the year of planting, with 1 4 L/hr dripper adjacent to each tree. Water was supplied from a dam on the property. The site was fenced in the year 2000 to exclude rabbits and wallabies, the latter having caused some damage to young trees. The site was managed by the landowner, John Zito, using an annual calendar of operations for site management. This was, as far as possible, the same for all sites, but some variations were required with fertiliser usage due to poor soil drainage.

3.3 Soils of the field sites

The soil profile at each site was described from soil samples taken with a 100 mm diameter auger down to 600 mm depth, from 4 sampling points within each site. A description of the profiles at each site is given in Table 3.2.

Table 3.2 General description of soil profiles at the 5 field sites. Soil pH values were measured prior to liming

	Orange	**Moss Vale**	**Myrtleford**	**Toolangi**	**Kettering**
Soil type	Krasnozem	Red podsol	Alluvial	Krasnozem	Yellow podsol
A horizon	0–300 mm, light brown clay loam, pH 5.5; well-structured	0–200 mm, dark reddish brown sandy loam, pH 4.5–5.0	Brown sandy loam, no significant texture or colour changes down the soil profile, pH 4.5–5.0; well-drained.	0–300 mm, brown clay loam and pH 5.0; friable and well-structured	0–250 mm, grey brown fine sandy loam, pH 5.0; weak structure
B horizon	Red light clay, pH 6.0, well-structured, some mottling.	Reddish brown sandy clay loam, pH 5.5		Red brown light clay, pH 5.5, well-structured.	Yellow-brown clay, pH 5.5-6.0, poorly drained

Notes: pH was measured with an Innoculo Soil pH Test Kit® (CSIRO developed) results equivalent to pH_w

The soils at both Orange and Toolangi were volcanic in origin, having been developed from basaltic lava flows. The basaltic rock had been weathered over millions of years to form deep, red krasnozem soils, Table 3.2. The texture of the A horizon at these sites was a clay loam overlying a light clay. The soil at Toolangi had a high organic carbon content with a more friable structure than at Orange.

The Moss Vale site was on a relatively well-drained red podsol derived from sedimentary rock (Plate 3.6), whereas the Kettering site was on a yellow podsol, which was poorly drained. Podsolic soils typically have a duplex profile with a heavier-textured, more clayey subsoil, or B horizon, which can have poor drainage characteristics. An example of the profiles for Moss Vale and Myrtleford are shown in Plate 3.6.

Plate 3.6 Examples of soil profiles extracted from top 600 mm of soil with a 100 mm diameter auger. The Moss Vale soil (left) was classified as a red podsol. The Myrtleford soil (right) was an undifferentiated alluvial sandy loam.

The soil at Myrtleford was alluvial, on the floodplain of the Ovens River. The soil was a deep sandy loam but with some variation in texture down the profile, due to the changing deposits of material that had been spread across the floor of the Ovens Valley, over time. Generally, this alluvial soil had a coarser texture than the krasnozem soils (Table 3.2).

3.3.1 Soil sampling and analysis

Prior to planting, 25 soil samples were taken across each of the sites from the top 10 cm of soil and combined to produce a composite sample of about 500 g for each site. The composite soil samples from each site were analysed for their level of available nutrients (Table 3.3). The soil pH and nutrient data was used to determine lime and fertiliser requirements for the sites. All sites were limed before planting to reduce any potential adverse effects of soil acidity. Olsen (1995) considered that pH_w 5.0 (1:10 soil: water) is the minimum that is suitable for hazelnut growing in Oregon. In Australia, pH is generally measured in a 1:10 calcium chloride solution (pH_{Ca}). Values for pH_{Ca} are generally 1.0-0.5 units lower than those for water. The pH_{Ca} values indicated that the soils at all the sites were moderately acid and would be likely to benefit from the application of lime to raise their pH to the minimum desirable. Five tonnes/ha of ground limestone were applied before planting at all sites, except Myrtleford, where 7 tonnes/ha was applied and incorporated into the soil by cultivation. A further 7 tonnes/ha of lime was applied at Orange in 2001 with an additional 2 tonnes/ha being applied in 2004, as manganese toxicity was suspected to be a problem at that site. These later broadcast applications were not incorporated.

Table 3.3 Soil analysis data for the field sites, prior to liming and planting

	Orange	**Moss Vale**	**Myrtleford**	**Toolangi**	**Kettering**	**Minimum Desirable Levels ^{1}**
pH_{Ca} (1:5 soil $CaCl_2$)	5.7	4.3	4.5	4.5	5.5	pH_w 5.0
Phosphorus (P) Bray test (mg/kg)	21.0	9.0	7.0	3.0	141.0	N/A (3)
Total carbon (%)	2.0	3.8	3.3	6.6	3.5	N/A
Potassium (K) meq/100g	0.6	0.3	0.6	0.5	1.0	0.2
Calcium (Ca) meq/100g	6.8	3.9	5.6	3.8	12.6	5.0
Magnesium (Mg) meq/100g	0.7	1.4	2.3	0.8	2.7	0.5
Sodium (Na) meq/100g	<0.1	0.2	<0.1	0.1	0.11	<5
Aluminium meq/100g	<0.1	0.6	0.2	1.4	<0.1	<5 (2)
Total exch. cations (mg/kg)^2	8.1	6.4	8.8	6.6	4	N/A
Ca/Mg ratio	9.7	2.8	2.4	4.8	4.7	>2.0
Boron (B) (mg/kg)	<2	<2	<2	<2	<2	N/A

Desirable levels for hazelnuts; Source: (1) Olsen, 1995, (2) Aluminium sensitive crops. Peverill et al., 1999. (3) Pastures 8mg/kg (Abbott and Vimpany, 1986). N/A Not available

The available phosphorus level varied considerably from low levels, less than 10 mg/kg, as recorded at Toolangi, Myrtleford and Moss Vale, to a very high level of 141 mg/kg at Kettering. This very high level was possibly due to previous applications of chicken manure to the site when it was an apple orchard. The desirable minimum level of phosphorus for hazelnuts is unclear. Olsen (1995) recorded no response to phosphorus fertilisers in Oregon, possibly because Oregon soils were already relatively high in this element. In Australia, temperate pasture species generally respond to applied phosphorus, when soil levels are below 8 mg/kg (Abbott and Vimpany, 1986). No data was available on desirable level of soil boron; it is most readily available in soils that are high in organic matter, medium- heavy texture grade and a pH range 5.0-7.0 (Glendinning, 1999).

Potassium and calcium levels were generally considered adequate, with an appropriate Ca/Mg ratio. Sodium levels were low, indicating that soils were neither sodic nor saline. Available aluminium was extremely high at Toolangi and relatively high at Moss Vale, being 20% and 9%, respectively, of the total exchangeable cations. No data has been found on the sensitivity of hazelnuts to aluminium. However, when soil pH_{Ca} levels are above 5.0, aluminium toxicity is not usually considered to be a problem (Abbott and Vimpany, 1986). As the growth of hazelnuts is favoured by soils that are not very acid, it is possible that hazelnut trees could be sensitive to aluminium, hence the recommendation to apply lime before planting (Olsen, 2001). As nutrient levels were considered to be satisfactory at the time of planting, based on current knowledge, no fertiliser was added at planting. However, fertilisers were applied in later years, as discussed in Section 3.7.

3.4 Experimental design and cultivars

A total of 26 hazelnut cultivars (*i.e.* main treatments, Table 3.4) were evaluated for tree growth, floral phenology, nut yields and some aspects of kernel quality, within a randomised block design which was used across the 5 sites. There were 4 replicates at each field site, except at Kettering where there were only 3 replicates. The trees were planted in rows 5 m apart with 3 m between trees within the rows, giving a planting density of 660 trees per hectare.

Table 3.4 Cultivars planted at the hazelnut field sites for yield assessment

Cultivar	Potential use	Country of origin	Original source of material[1]	Site planted and supplier of planting material[2]				
				OR	**MV**	**MY**	**TL**	**KT**
‘American White’	Kernel/ In-shell	Australia/ Turkey	I. Tokolyi			OK		
‘Atlas’	Kernel/ In-shell	Australia	NSW Ag, Orange	MP	MP	MP	MP	
‘Barcelona’	Kernel/ In-shell	USA	Oregon, USA	RS	RS	RS	RS	MP
‘Butler’	Polliniser /In-shell	USA	Oregon, USA	RS & MP	RS	RS	MP	MP
‘Casina’	Kernel	Spain	Oregon, USA	CO	CO	CO	CO	MP
‘Daviana’	Polliniser	England	Oregon, USA			RS		
‘Eclipse’	Kernel	Australia	Milan Paskas, Victoria	MP		MP	MP	MP
‘Ennis’	In-shell	USA	Oregon, USA	RS	RS	RS	RS	MP
‘Hall’s Giant’	Late polleniser	Germany	Oregon USA	RS	RS	RS & MP	RS	
‘Hammond #17’	Kernel/ In-shell	Australia	S. Hammond, Orange, NSW			SH		SH
‘Lewis’	Kernel	USA	Oregon, USA	BW		BW		MP
‘Merveille de Bollwilller’	Late polleniser	France	Knoxfield, Victoria			MP		MP
‘Montebello’	Kernel	Italy	Knoxfield, Victoria			MP		MP
‘Negret’	Kernel	Spain	Knoxfield, Victoria	RS		RS	RS	
‘Royal’	In-shell	USA	Oregon, USA			RS		MP
‘Segorbe’	Kernel	France	Knoxfield, Victoria	MP	MP	MP	MP	MP
‘Square Shield’	Kernel	Australia	Milan Paskas, Victoria	MP		MP	MP	MP
‘TGDL’	Kernel	Italy	Knoxfield, Victoria	MP		MP	MP	MP
‘TBC’	Kernel	Australia	I. Tokolyi/ J. Brown, Victoria	JBr	JBr	JBr	JBr	MP
Tonda di Giffoni	Kernel	Italy	Italy	JBe	JBe	JBe	JBe	JBe
‘Tonda Romana’	Kernel	Italy	Knoxfield, Victoria	MP	MP	MP	MP	MP
‘Tonollo’	Kernel/ In-shell	Australia	NSW Agriculture			NSW Ag		
‘Victoria’	In-shell	Australia	T. Baxter, Knoxfield, Victoria	MP	MP	MP	MP	MP
‘Wanliss Pride’	Kernel/ In-shell	Australia/ Turkey	T. Cerra, Victoria	JG & MP	JG	JG	JG	MP
‘Whiteheart’	Kernel	New Zealand	New Zealand					MP
‘Willamette’	Kernel	USA	Oregon, USA	BW		RS & MP		MP

Footnotes:

1. As most cultivars were imported, an attempt was made to identify the source of the original imports or, where this was unknown, the main importer or point of entry into Australia.

2. Key to suppliers of planting material: MP – Milan Paskas, RS – Richard Salt, BW – Bruce West, CO – Chris Offner, OK - Ollie Kroll, SH – Simon Hammond, JBr – Janet Brown, JBe – Jim Beattie, JG – Jim Gleeson, NSW Agriculture (subsequently NSW Department of Primary Industry).

The cultivar supplied as ‘Tonda Romana’ was found not to be true to type and has been called “Sicilian type”.

Additional data, on floral phenology only, was obtained from 4 additional cultivars (Table 3.5) that were included in the buffer rows of trees surrounding the treatment plots. It was considered that floral phenology would not be influenced by being in a border row, but nut yields could be.

Table 3.5 Cultivars planted in buffer rows, to obtain data on floral phenology

Cultivar	**Main use**	**Country of origin**	**Source of planting material**
Jemtegaard 5	Polleniser	Oregon, USA	Milan Paskas
Kentish Cob	Polleniser, green nut harvest	England	Milan Paskas
White Avelline	Polleniser, gardens for nut production	Europe	Milan Paskas
Woodnut	Polleniser	Australia	Milan Paskas

The cultivars evaluated were mainly those suited to the kernel market but included those suited to the in-shell trade and others whose main role was as pollinisers. A key objective of the study was to try and source as many cultivars as possible, particularly those imported into Australia in recent years, which are of significance in Europe and the USA. To facilitate the collection of cultivars for these studies, a presentation was made at the Australian Hazelnut Growers' annual conference in 1994 to explain the research project and to seek co-operation from propagators and importers of hazelnut plants in order to source material for the proposed research.

The cultivars included in the field experiments were mainly those of European and North American origin but included some Australian selections that have been given names such as 'Atlas', 'Tonollo' and 'Tokolyi/Brownfield Cosford' ('TBC'). The planting material was obtained chiefly from specialist hazelnut propagators but some material was obtained from growers. Most plants were available as bare-rooted whips (Plate 3.7) but a few had been grafted onto rootstocks of other cultivars of the European hazelnut (*Corylus avellana* L.). These grafted plants had a metal tie around the stem of the trees just above the graft and were planted with the graft below the ground to encourage them to be self-rooting, that is, to form roots on the scion wood.

Plate 3.7 A typical whip at planting. Roots were carefully spread before covering with about 50 mm of topsoil.

As not all cultivars were available at the beginning of the research and there was limited space at some sites, not all of the key 26 cultivars were planted at all sites. Moss Vale had only the core set of 12 cultivars. These 12 cultivars were common to all sites. At Orange and Toolangi, an additional 4 cultivars were planted with a further 8 added at Myrtleford. There were 20 cultivars planted at Kettering (12 core and 8 additional). The 4 mainland sites were planted first, as initially it had not been possible to find a suitable site in Tasmania. Each of the mainland sites comprised 4 replicates of the cultivar treatments in a randomised block design (Appendix B). At Orange and Toolangi there were 4 trees of each cultivar in each replicate, whereas at Moss Vale and Myrtleford there were only 2 trees per cultivar per replicate, Table 3.6. Planting at the Orange and Toolangi sites was commenced in July 1995 while planting commenced at Myrtleford and Moss Vale in July 1996. Planting did not commence at Kettering until 1999. At Kettering, it was decided to use only 3 replicates of 20 cultivars with 2 trees per replicate, due to limited space.

Table 3.6 Summary of the experimental design at each site and tree orientation

Design features	Orange	Moss Vale	Myrtleford	Toolangi	Kettering
Year of planting	1995	1996	1996	1995	1999
Number of replicates	4	4	4	4	3
Number of cultivar treatments	16	12	24	16	20
Number of trees per test plot	4	2	2	4	2
Number of in-row buffer trees	2	0	0	2	0
Number of trees used for yield assessment	2	2	2	2	2
Orientation of tree rows	NE-SW	N-S	NW-SE	E-W	E-W

Note: At ALL sites, only 2 trees per plot were used for growth and yield assessments. Where there were 4 trees per treatment plot, only the 2 central trees were used for these assessments.

The initial objective was to plant 4 trees per cultivar plot but at some sites it was only possible to plant 2 trees, with no buffer trees within the rows, due to the difficulty of obtaining sufficient planting material as well as limitations of space. As all sites were planted at a common tree density it was considered that the border effects within the experimental rows would be minimal. Only 2 trees per plot were sampled for yield data at all sites. At the Oregon State University, an experimental design was used for the evaluation of cultivars and new selections in which single tree treatments were used with 8 replicates (McCluskey et al., 1997).

At least 1 buffer row was used to surround the treatment trees at all sites, except at Kettering where the experimental site was within an existing orchard of hazelnut trees. These buffer rows included a range of hazelnut pollinating cultivars. This design was used to reduce any edge effects on the treatment trees and to maximise the period and diversity of pollen shed throughout the block, in an attempt to minimise yield limitations from inadequate pollination.

It was not possible to plant all cultivar treatments in the main year of planting due to the unavailability of some cultivars. This applied particularly to the cultivars ‘Willamette’ and ‘Lewis’ at Orange and Myrtleford as, at that time, these cultivars were relatively new releases from the breeding program at Oregon State University and had only recently been imported into Australia. At Kettering, it was possible to plant these 2 cultivars in the same year as the others. All sites were planted with rows 5 metres apart and trees 3 metres apart down the rows (Plate 3.2); at a semi-dense planting of 660 trees per hectare. This density was used to minimise the area of land required for the research yet provide sufficient space for tree development without overcrowding. Trees were planted in July or August when they were dormant.

3.5 Measurements

3.5.1 Cultivar characteristics

Cultivar names were based on the information provided by those who provided the planting material. However, observations on a range of genetically determined characteristics were used to assess whether the cultivars were true to type. The characters selected were based on those proposed by Thompson et al. (1978) and subsequently Bioversity, FAO, CIHEAM (2008). Fifteen key descriptors (Table 3.7) were selected for this validation. The United States Department of Agriculture (USDA) has a comprehensive collection of hazelnut cultivars at Corvallis in Oregon. The characteristics of many of these cultivars have been documented and are available from the USDA, Agricultural Research Service at, www.ars.usda.gov/cor/catalogs/corcult.html. The characteristics listed in Table 3.7 were noted for all the cultivars studied in this research and compared with those for the same cultivars in the hazelnut germplasm repository at Corvallis. These comparisons are tabled in Appendix A of this thesis.

Nut samples were sent to Oregon State University to obtain the opinion of Professor Mehlenbacher on whether the imported, named cultivars were true to type. Based on these comparisons of characteristics and the opinion of Professor Mehlenbacher, the only cultivar that it was considered to be incorrectly named was that provided as ‘Tonda Romana’. It was not possible to provide the specific identity of this genotype but it showed the characteristics of Sicilian types and was probably closely related to ‘Montebello’. In this thesis it has been referred to as “Sicilian-type”. In 1998, trees of ‘Tonda Romana’ were imported into Australia by Ferrero Australia and planted at Orange; during their growth and subsequent development they exhibited the typical characteristics of ‘Tonda Romana’.

Table 3.7 Fifteen plant descriptors adopted from Bioversity, FAO and CIHEAM (2008) to describe and identify the cultivars used in the study.

Descriptor type	Score range	Reference cultivars
Growth descriptor		
Tree vigour	1 (Low) 9 (Very high)	'Imperial de Trebizonde' 'Segorbe'
Tree growth habit	1 (Very erect) 5 (Drooping)	'Daviana' 'Imperial de Trebizonde'
Bud descriptors		
Bud colour	1 (Green) 3 (Reddish)	'Segorbe' 'Merveille de Bollwiller'
Bud shape	1 (Conical/pointed) 3 (Globular)	 'Segorbe'
Date of vegetative bud break	Date when 50% buds are enlarged	
Nut and kernel		
Involucre (husk) length compared to nut length	3 (Shorter) 7 (Longer)	'Jemtegaard 5' 'Du Chilly'
Predominant nut number per cluster	1 (one nut) 4 (Three to four)	'Daviana' 'Negret', 'Segorbe'
100-nut weight (g)	Actual weight	
Nut shape	1 (Oblate) 6 (Long sub-cylindrical)	'Imperial de Trebizonde' 'Du Chilly'
Nut shell colour	3 (Light brown) 5 (Dark brown)	'Ennis' 'Negret'
Shell stripping	0 (Absent) 7 (Many)	'Fertile de Coutard' 'Ennis'
Size of nut basal scar in relation to nut size	3 (Small) 5 (Medium) 7 (Large)	'Segorbe' 'Ennis' 'Merveille de Bollwiller'
100-kernel weight (g)	Actual weight	
Kernel fibre texture	3 (Lightly corky) 5 (Medium corky)	'Segorbe' 'Fertile de Coutard'
Kernel blanching	0 (None) 9 (Very good)	'Ennis' 'Negret'

It was not possible to use DNA 'bar-coding' to identify cultivars.

3.5.2 Tree growth

A key question identified (Section 2.4.4) in relation to tree growth was:

> How vigorously will the cultivars grow and how will their growth rates vary between sites and seasons?

General observations of tree growth were made throughout the period of the experiment. In April of each year, the butt circumferences of all treatment trees were measured 10-15 cm above the ground. These measurements were used to make comparisons of tree growth between years and between cultivars, as well as to determine yield efficiency. Yield efficiency was determined from the accumulated nut yields (kg) 7 years from planting, divided by the trunk cross-sectional area (TCSA) measured in cm^2 in April of that seventh year, i.e. just after harvest. A similar technique was used by McCluskey et al. (2005) although the number of years over which nut yields were accumulated varied in their experiments.

3.5.3 Bud break

The dates when the vegetative buds had enlarged and the scales had started to open, showing the green of the leaves inside (Figure 3.8), were recorded on a weekly basis at all sites in all seasons.

Plate 3.8 Buds of 'Barcelona' at the bud break stage

3.5.4 Floral phenology

The key questions (Section 2.4.4) in relation to floral phenology were:

3. When will the cultivars come into anthesis and how will the floral phenology differ between cultivars and across sites and seasons?
4. How will environmental conditions influence floral phenology?

The following phases of floral phenology were systematically recorded.

Pollen shed

Periods of pollen shed and female anthesis were recorded at weekly intervals each year at all sites. These periods were first recorded for most trees, in the second winter after planting. Pollen shed involves the phases of catkin extension, leading to extended catkins shedding pollen and eventually complete dehiscence with dry catkins. These phases do not occur simultaneously with all catkins (Plate 3.10) nor are there sharp changes in development, so that identifying the phases involves some degree of judgment rather than absolute precision.

As flowering varied across cultivars, study sites and seasons and because phenological developments occurred over a period of about 10 weeks, it was necessary to develop a standardised system that could be used by those involved in recording these changes at all sites and for all years. Although pollen shed could be considered to have commenced when a few catkins were shedding pollen, the commencement of pollen shed was recorded as the date when about 10% of the catkins had started to shed pollen. Bergoughoux et al (1978) described this as the Fm 1 stage of individual catkin development, the beginning of discharge of pollen. The end of pollen shed is harder to define than the beginning, as the catkins slowly lose their pollen, making it difficult to be precise when they have finished shedding. To try and overcome this problem, it was decided to consider that the end of pollen shed was when only about 10% of the catkins were still shedding, the remainder having shed all their pollen, the Fm 2 stage as described by Bergoughoux et al (1978). The period of pollen shed was between the dates of commencement and completion.

The stage of pollen shed was assessed weekly for all cultivars. A similar system of weekly monitoring of pollen shed was used by Santos and Silva (1994), although, in their case, they considered pollen shed had started when 5% of the catkins were shedding pollen. They also noted the issue of staggered or asynchronous development in flowering on a given tree.

Plate 3.9 Clusters of catkins, upper right to lower left, unopened, extending and fully open. The catkins on the far left on a further branch have begun to dry out at the completion of pollen shed.

Female anthesis

Records were kept of the development of female flowers. There was a difficulty in defining the commencement of female anthesis, as potential female flowers are indistinguishable from vegetative buds. The date when several (3-4 per branch) female flowers with extended stigmas were first observed on the trees was considered to be the beginning of female anthesis. This was described by Bergoughoux et al. (1978) as the Ef 2 stage. It was not possible to describe this in percentage terms of receptive flowers as female flowers are not visible before they exert their stigmas. The end of female anthesis was recorded as the date when the stigmas of most flowers were desiccated and there were few flowers remaining with exerted stigmas. This end point tended to be unclear as, towards the end of anthesis, stigmas had a withered, dark purple appearance. Similar problems were reported by Bergoughoux et al. (1978). The recorded dates provided an estimate of the commencement and duration of female anthesis.

These methods were used at all sites in all seasons. The method of data collection was explained to the field staff and collaborating growers, who monitored developments in floral phenology and bud break. Occasional visits were made to the sites in winter to validate the methods being used. The author collected all the data at the Orange site. As observations were made weekly, this system was found to be relatively reliable across sites, observers and seasons.

Catkin abundance

The relative number of catkins per cultivar gives some indication of the potential of that cultivar as a polleniser. A relative score 1 (low) – 5 (high) was used with 5 being the rating for the cultivar that appeared to have the greatest number of catkins at the site, in the year of recording. Unfortunately, the relative number of catkins does not give any indication of pollen viability or pollen numbers, which are also important considerations, nor does it give any indication of compatibility of pollen. A similar scoring system of 1-7 for catkin abundance was recommended in Bioversity, FAO and CIHEAM, (2008), with 1 as sparse and 7 as dense.

3.5.5 Nut yields and yield efficiency

The key questions (Section 2.4.4) in relation to nut yields were:

3. When will the cultivars commence bearing nuts, what will be the development of yield over years from planting and what will be their yield potential?
4. What will be the variation in nut yields between cultivars and the environments in which they are grown?

Nut yields were obtained by collecting all of the fallen nuts from under the pair of treatment trees for each cultivar in each replicate during late summer to early autumn, March – April. The nuts were dried at 30-35°C for 3 days and then cleaned; any husks were removed before weighing and recording.

In the early years of nut production, nuts at the Orange and Myrtleford sites that had fallen were gathered from the ground at weekly intervals during the period of nut fall, starting in late February in the years 2000, 2001 and 2002 at Orange and 2001 and 2002 at Myrtleford. The nuts from each cultivar for each date of collection were dried at 30-35°C, counted and weighed. A random sample of 50 nuts was taken from each of the weekly collection of nuts from the higher-yielding cultivars. These were cracked out to determine the proportion of blank nuts. This data was used to determine the periods of peak nut fall for each cultivar, the proportion of blank nuts and when the blank nuts fell.

Yield efficiency was assessed from the cumulative nut yield for the tree of each cultivar, seven years after planting, divided by the trunk cross-sectional area (cm^2) of the tree in the autumn of that seventh year.

3.5.6 Kernel assessments

The key question (Section 2.4.4) in relation to kernel quality was:

> How will kernel attributes vary between cultivars and how will these attributes be influenced by environmental conditions?

Nut samples were taken for kernel assessments. For the higher-yielding cultivars, a composite random sample of at least 100 nuts was taken from the total yield of nuts from each replicate for the assessment of kernel quality. For lower-yielding cultivars, it was often only possible to take 1 composite sample from the trees across all replicates.

Two cracking boards were made from 10 mm thick plywood boards (Plate 3.10). Fifty holes that were 24 mm in diameter were drilled in one of these at 40 mm centres in 5 rows of 10 holes. In the second board, holes were 32 mm in diameter and were at 60 mm centres; this board was for large nuts. A small handful of nuts was placed on the boards and spread until all the holes were filled. The nuts in each hole were cracked using a sharp blow with a small hammer. After cracking the 2 samples of 50 nuts, 100 nuts in total, the number of holes, in which there were no kernels, were counted to obtain a measure of the number of blank nuts. All the well-filled kernels were counted and weighed to obtain an average kernel weight. The remaining kernels were assessed for any defects, these included shrivelled or poorly-filled, those with black tips, mould, brown stain and twin kernels. The numbers of defective kernels in each category were counted and recorded. Kernel percentage was calculated from the weight of well-filled kernels divided by the weight of 100 nuts.

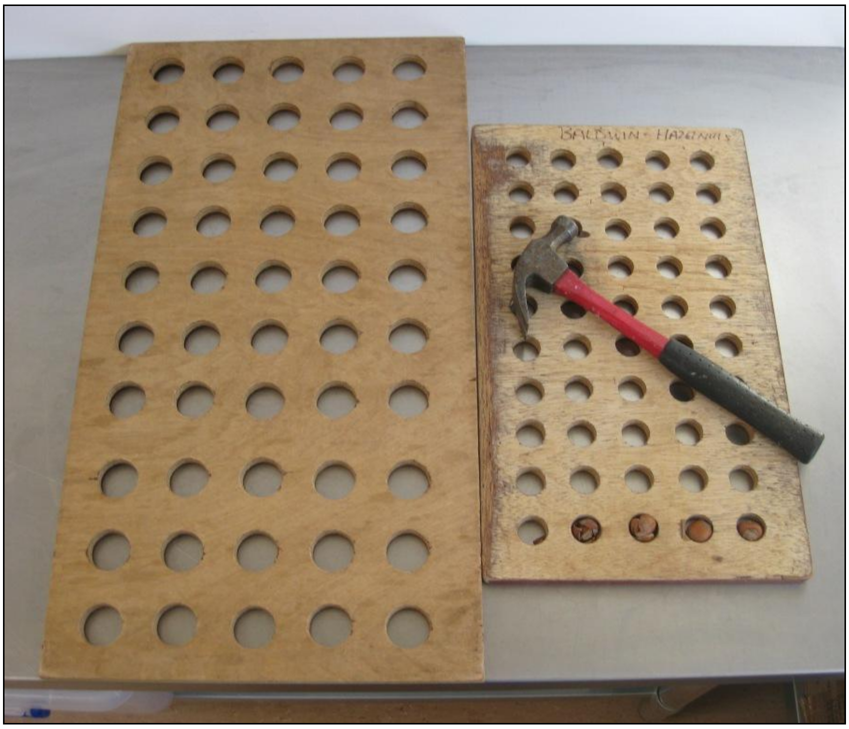


Plate 3.10 Plywood boards with holes drilled to hold individual nuts. The small hammer was used to crack nuts. The board on the left was used for large nuts.

Blanching characteristics were assessed by heating samples of whole kernels in an oven at a temperature of 140–150°C for 15 minutes, followed by rubbing the blanched kernels in a cloth to remove any loose skin or pellicle. Ratings of the degree of blanching were made using the 1–7 rating scale that has been used in the Oregon State University cultivar evaluation programme (McCluskey et al, 2001), where 1 = 100% removal and 7 = nil removal of the pellicle.

Some kernel samples were sent to the NSW Agriculture laboratories in Wagga Wagga (subsequently Department of Primary Industry NSW) for determination of their chemical composition, particularly their fatty acid composition, oil content and levels of α tocopherol, to provide some indication of variation between cultivars and seasons as well as a comparison with overseas data. These samples were not replicated. The methods used were:

- Fatty Acid Profile WWA1 Method 2-1702
- Free Fatty Acids Method OACS AC 5 -41
- A Tocopherols (Vitamin E) Method OACS Ce 8-89

3.6 Weather records and climate data

Five automatic weather recording stations from Environdata Australia Pty. Ltd., (Percy St, Warwick, Queensland) were installed, at 1 per site. The weather stations measured air temperature, relative humidity, wind run, wind direction, solar radiation and rainfall. There were 3 memories; 1 was for recording mean data from the instruments on an hourly basis. A second memory recorded the maximum and minimum temperature, maximum and minimum relative humidity, the total wind run, average wind direction, total solar radiation and total rainfall on a daily basis. It also calculated total evaporation based on the Penman formula, the total chilling hours, *i.e.* the hours when the temperature was in the range 0–7°C. The third memory recorded the intensity of rainfall by recording the frequency the tipping buckets emptied; each tip was equivalent to 0.2 mm of rain.

The instruments were calibrated by Environdata before installation, but were checked for accuracy twice yearly, with a complete clean of the weather stations and instruments annually. The memories were downloaded monthly, which provided an opportunity to ensure the instruments were working correctly. Occasionally the weather stations failed to record, mainly as a result of battery failures. They were promptly repaired and put back into service. Any missing data was obtained from other sources, such as records maintained at research stations or from the closest weather station operated by the Australian Bureau of Meteorology. The instrument that proved least reliable was the relative humidity sensor; all other instruments were generally found to be reliable and operated well with few faults.

The weather data recorded was used principally to describe the climate of the sites, how this varied between sites and seasons and how climate affected crop phenology, development and some aspects of production.

3.7 Leaf analysis, soil samples and fertiliser treatments

During February of each year, from the second growing season after planting, composite leaf samples of at least 100 fully expanded leaves were obtained from each site. These samples were collected at random across each site and analysed for the total content of selected elements. This data was compared with desirable levels for hazelnuts as reported by Olsen (2001) and used to assess the general nutrient status of the experimental trees and to determine fertiliser requirements at each site.

Samples from the top 0–100 mm of soil were collected, in March 2003 and again in March 2006, for the mainland sites, and in March 2008 for the Kettering site, to assess the available nutrients in those years and to compare them with the nutrient status of soil samples taken at the commencement of the experiments.

No fertiliser was applied to young trees in the year of planting at any of the sites, as the roots of young hazelnut trees are considered to be very sensitive to fertiliser at this early stage. In subsequent years, Nitram ® (ammonium nitrate; 34% N) was sprinkled around the trees in the spring, at the rates shown in Table 3.8. As trees came into production, an NPK mix of Pivot 400 ® was used to boost levels of phosphorus (P) and potassium (K) which may have been removed in harvested nuts. Nitrogen fertilisers are the main fertilisers recommended for young developing hazelnut trees (Olsen, 2001).

Table 3.8 Typical rates of fertiliser elements applied per tree at the field sites. The actual fertiliser used varied slightly with sites and circumstances.

Year from planting	**Rate of element (g/tree)**			
	Nitrogen (N)	**Phosphorus (P)**	**Potassium (K)**	**Sulphur (S)**
3	10	-	-	-
4	15	-	-	-
5	20	-	-	-
6	25	-	-	-
7 onwards	30	5	8	9

The level of nutrients measured in the leaf samples was used as a basis for determining fertiliser applications to meet the nutrient requirements of the trees. No nutrient deficiencies were observed, although high levels of manganese were recorded at Orange and it was possible these might have had a detrimental effect on tree growth at that site. In Tasmania, a slow-release fertiliser was used from 2001 onwards, providing the same rate of nutrients as at other sites (Table 3.8). The slow-release fertiliser was used on that site because it was suspected that damage from nitrogen fertiliser had occurred following very high rainfall which saturated soils in September and October, 2000.

3.8 Irrigation

Micro-sprinkler irrigation systems were installed at all sites except Orange and Kettering, where drip irrigation was initially used. In the spring of 2002, the irrigation system at

Orange, that had comprised two 4L/hour drippers per tree, was changed to a system of a single 30L/hour micro-sprinkler per tree in order to provide a greater distribution of water within the tree rows. This change was made to match the irrigation systems of all the other mainland sites. Drip irrigation was used throughout the commercial orchard at Kettering, necessitating the use of drip irrigation on that study site.

The amount of irrigation water applied during the irrigation season was recorded weekly. The frequency and rates applied were influenced by rainfall and the amount of water available for irrigation. In the months of December–February inclusive, the equivalent of about 25 mm of rain was applied per week, when less than 10 mm of rain had fallen. The aim was to try and maintain available soil moisture levels in the top 600 mm of soil above 50% of field capacity. The approximate quantities of irrigation water applied per tree, in the growing season, the months of August- February over the years 2000/01–2007/08, are shown in Table 3.9.

Table 3.9 Total rainfall (mm) August –February and approximate quantities of irrigation water applied as litres (L) per tree at the 5 sites, on a per season basis.

	Orange		**Moss Vale**		**Myrtleford**		**Toolangi**		**Kettering**	
Seasons	Rain mm	L/tree	Rain mm	L/tree	Rain mm	L/tree	Rain mm	L/tree	Rain mm	L/tree
2000/01	633	240	655	200	775	840	767	200	634	90
2001/02	521	1100	816	200	538	300	703	0	858	0
2002/03	328	1700	354	1050	219	2160	313	0	538	200
2003/04	552	1050	566	500	834	960	N/A	N/A	638	140
2004/05	672	300	621	600	766	480	N/A	N/A	592	60
2005/06	781	500	N/A	N/A	587	1440	N/A	N/A	576	240
2006/07	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	514	160
2007/08	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	427	190

Note: N/A - Not applicable as site no longer being used for research

At the Orange, Moss Vale and Myrtleford sites, relatively high rates of water were applied in 2002/03 to try to compensate for the severe rainfall deficits in that season. The low rainfall at Moss Vale limited water supplies in the dam used for irrigation and, as a consequence, the amount of irrigation applied was less than desirable, in that very dry season. The effects of this are discussed in the chapters on tree growth and nut yields. At Toolangi, the water supplies were limited and were in greater demand for other research programs, making it impossible to irrigate the hazelnut research site in the very dry season of 2002/03. The summer of 2006 was very dry at Kettering, hence the high level of irrigation applied; it was also dry in the summer of 2008. However, water supplies were limited in that year with little being available for irrigation.

At a tree density of 660 trees per hectare, irrigation levels of 1600 L/tree are equivalent to 1 megalitre of water per hectare. It can be seen that, at Myrtleford, water use was 2160 L/tree in the very dry season of 2002/03, i.e. 1.4 ML/ha. More detailed records of rainfall during the period of the experiment are presented in the chapters on tree growth, nut yields and kernel characteristics.

3.9 Orchard management

After planting, the young trees were mulched to minimise moisture loss from the soil around the trees. Straw and old hay of low nutrient status were used for this purpose. The stems of the trees were painted with a dilute mixture of white acrylic paint to minimise sunburn. The weeds in the tree rows were sprayed with Roundup ® (glyphosate) and hand-weeded as necessary. The strips between the trees were mown to encourage a short grass and clover sward.

Suckers were removed from the base of each tree by hand in the first 2 to 3 years to maintain a single stem. In subsequent years, Sprayseed ®, a paraquat plus diquat contact herbicide mixture, was used at regular intervals to kill young suckers in the spring and early summer. This was supplemented by hand-cutting, as required.

Pruning of trees was undertaken from about the third year of planting to shape trees into an open-vase form on a single stem and to remove any limbs that affected orchard operations. At Myrtleford, it was necessary to do significant pruning each winter from the seventh year from planting, to minimise limbs crossing within the rows between cultivars and across the rows (Plate 3.11). This was necessary to minimise the mixing of nuts from adjacent cultivars at nut fall and to facilitate mechanical harvesting.

Plate 3.11 Trees were pruned at Myrtleford in July 2003, 7 years after planting, to remove cross-over branches and to reduce spread across the rows.

3.10 Pests and diseases

Site managers made observations of pests and diseases throughout the experimental period and took action to manage any pest and disease problems.

3.10.1 Pests

A number of pests were recorded from the study sites over the period of the research. Collected specimens were identified by the Australian Scientific Collections Unit, Orange Agricultural Institute, DPI NSW. These observations were then incorporated into BioLink, an Australian database. Nearly all of the accessions in that collection relating to hazelnuts were sourced over the duration of the research project.

Recorded pests included:

- painted apple moth (*Teia anartoides*);
- fruit tree borer (*Marogo melanostigma*);
- green peach aphid (*Myzus persicae*);
- hazelnut aphid (*Myzocallias coryli*).

Infestations of aphids were controlled at some sites with the insecticide Pirimor ®. This insecticide was only used when aphids were considered to be at damaging levels. The hazelnut aphid (*Myzocallias coryli*) was of greatest concern at Kettering, where it seemed more difficult to control than at other sites and caused black sooty mould on the leaves of trees in autumn.

Borers generally affected unhealthy trees. The Orange site, where the trees had made relatively poor growth, had relatively high borer counts. No borers were recorded at Myrtleford, Toolangi or Kettering, with only a few at Moss Vale. Borers are a serious pest, as the larvae can kill whole trees by girdling or ring-barking the branches or trunks. Ring-barking of branches occurred on a few trees at Orange. No preventative insecticide treatments were available for use. The pest was controlled manually by poking a piece of wire down the hole when evidence of the insect was found.

Big bud mite (*Phytoptus avellanae* Nal.), a serious pest of hazelnuts in Europe and some cultivars in North America, (AliNiazee, 1997; Ozman and Toros, 1997), was observed by the author on old collections of hazelnut trees in Tasmania in 1998. Infected trees were found in the Hobart Botanic Gardens, an old arboretum at Perth in the Northern Midlands where a plant nursery was once located, and at a site adjacent to the North Esk River at Hadspen. It appears this pest is relatively widespread in Tasmania in older plantations and was seen in 1 plant nursery. It was not initially present at the study site at Kettering but by 2005 some infected trees were found in the commercial orchard adjacent to the research site and subsequently were found in the study site. It is suspected the pest was introduced in hazelnut stock in the early years of plant introduction into Tasmania. In 1998 and 1999, a number of bud and leaf samples were collected from the research sites in Tasmania and on the mainland. Big bud mite was only found on samples from Tasmania (Snare and Knihinicki, 2000).

3.10.2 Diseases

The major disease recorded from the study sites was the bacterial disease, hazelnut blight (*Xanthomonas arboricloa pv. corylina*). This was most prevalent at Orange, with some minor occurrence at other sites. Copper oxychloride as either Kocide ® or Cuprox ® was applied at Orange annually in May from 2004 at 50% leaf-fall to try to protect the young developing trees. It seems that damage to stems caused by hail can present opportunities for bacterial spores to enter the plant and cause infection, the effects of which may not be seen until the following season.

3.10.3 Other pests

Other pests included hares, deer and wallabies that damaged young plants from time to time. An electric fence was erected around the Moss Vale site to supplement the existing rabbit and stock-proof fence, as deer and wallabies were pests at that site, which abutted a State Forest. Rabbit netting and electric fencing was erected around the Kettering site, where rabbits and wallabies were a problem. Wombats caused some minor damage at Toolangi.

Sulphur crested cockatoos (*Cacatua galerita*) were a major pest at harvest time, causing large losses of nuts at Orange, Toolangi and eventually at Myrtleford in 2006, as discussed under nut yields. This pest was managed at Moss Vale through the use of bird-scaring tactics. Sulphur crested cockatoos seem to be less common in Tasmania.

Additional experiments

As well as the main field experiments, some additional investigations examined in greater depth some of the phenomena observed in the field. This included the use of growth cabinets to investigate the effects of temperature on floral phenology and a nutrient culture experiment to study the effects of manganese on the growth of young trees. Details on these additional studies are presented in the appropriate chapters.

Data and statistical analyses

All data was entered into spreadsheets and checked for errors and consistency. Data analyses were mainly done using GenStat Release 12.1, with some regression analyses using Microsoft Excel 2003. The main procedures used were analysis of variance (ANOVA) for comparisons between cultivars and sites on data collected on tree growth, time of flowering, nut yields and kernel quality. Regression analyses were used to assess the effects of environmental conditions, mainly temperature and rainfall effects on floral phenology, tree growth, nut yields and kernel quality.

CHAPTER 4 - TREE GROWTH

4.1 Introduction

Hazelnut cultivars vary markedly in their relative vigour, growth habit and tendency to produce suckers at the base of the trunk (Mehlenbacher, 1991b). Vigour is a relative term and is often based on observations and comparisons with reference cultivars (Bioversity, FAO and CIHEAM, 2008) rather than objective measurements. Although measurements of trunk circumference are relatively easy to obtain and give an indication of relative tree vigour, they do not provide a measure of overall tree size. Santos et al (1994) found that the crown volume and the total stem mean area of 11 hazelnut cultivars grown as multi-stem trees in Portugal were not highly correlated. Despite these limitations, measurements of trunk cross-sectional area (TCSA) are commonly used to assess tree growth and yield efficiency (Westwood, 1993) and (McCluskey, et al., 1997).

Cultivars that are considered to be of high vigour include ‘Barcelona’ and ‘Hall’s Giant’ (Mehlenbacher 1991b). ‘Ennis’ and ‘TGDL’ are considered to be of intermediate vigour and ‘Imperial de Trebizonde’ (syn ‘Wanliss Pride’) is of low vigour (Bioversity, FAO and CIHEAM, 2008). However, there are reports of cultivars performing differently under different pedoclimatic conditions. For example, Grau and Bastias (2005) reported high vigour of growth of ‘TGDL’ at Los Robles in Chile on a “low stress” site, whereas in more “stressful” situations it was of low vigour.

Although some parts of Australia have similar climates to hazelnut growing regions of Europe and Oregon, Australian soils are generally very different. Most Australian soils are ancient and have been developed in situ from the parent material; many are highly leached and have duplex profiles, with heavier-textured sub-soils (Charman and Murphy, 1991). The growth of cultivars in Australia may be considerably different from their growth overseas and may differ between regions in Australia, due to either differences in soil type or climate.

This chapter investigates the growth of hazelnut cultivars under varying seasonal conditions and the different soil types on the 5 field sites as described in Chapter 3, Methods. It aims to answer the question:

- How vigorously will the cultivars grow and how will this vary between sites and seasons?

4.2 Methods

There were 3 main factors that were likely to influence tree growth at the study sites:

- Genetics (Cultivars)
- Time (Development of trees over years from planting)
- Environmental conditions (Soils and climates of the study sites)

In order to assess the potential effects of these 3 variables, the trunk circumferences of all trees in the experimental blocks were measured annually, 10-15 cm above the ground, as stated in Chapter 3, Methods, (3.5.2 Tree growth). This was converted to trunk cross-sectional area (TCSA), and used as an indication of tree growth. Although TCSA has some limitations as an estimate of tree growth, it is a commonly used, simple method. In addition to these measurements, observations and ratings of relative tree growth were made.

A combined analysis of variance of the annual TCSA measurements obtained over 7 years for 8 cultivars that were common to all 5 sites was conducted. The 8 cultivars were ‘Barcelona’, ‘Ennis’, ‘Hall’s Giant’, ‘Segorbe’, the “Sicilian type”, ‘Tonda di Giffoni’, ‘TBC’ and ‘Victoria’. The main factors were cultivars, sites and years from planting, with years from planting considered as a split plot for analysis.

Separate analyses of variance were also conducted on annual measurements of TCSA for all cultivars at each site. Years from planting were again treated as split plots.

4.3 Results and Discussion

The analysis of variance of the annual measurements of TCSA of 8 cultivars at the 5 sites over 7 years showed that there were highly significant differences (P=<0.001) in the mean TCSA of the cultivars with years from planting (Figure 4.1). However, there was a significant (P<0.001) interaction between cultivars and sites, indicating that some cultivars grew better than others at some sites. Although the interaction effects were statistically significant, they were minor compared with the effects of time, cultivars and sites.

The mean annual TCSA of all the cultivars increased each year from planting over the 7 years, Figure 4.1. Quadratic and linear functions accounted for 99% and 98%, respectively, of the variation for all 8 cultivars.

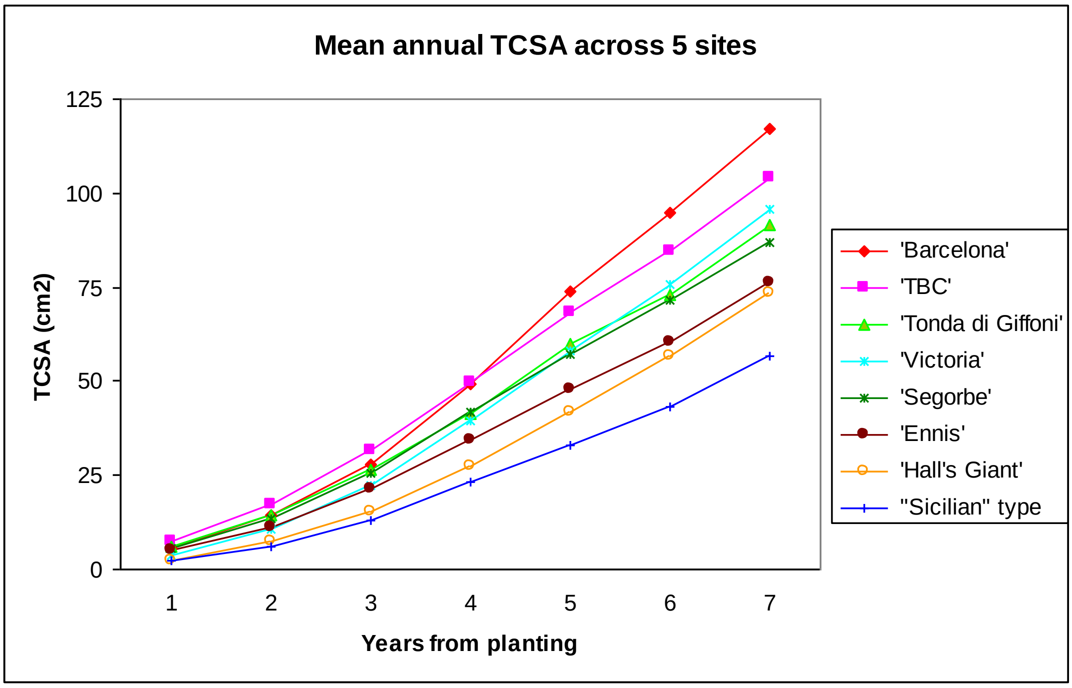


Figure 4.1 Mean increase in TCSA for 8 cultivars across the 5 study sites over 7 years from planting.

On average, 'Barcelona' had the highest growth rate of the 8 cultivars and the "Sicilian type" the lowest. Examples of growth rate differences between cultivars and sites and the interaction effects between these are shown in Figure 4.2.

4.3.1 Cultivar comparisons

There was a significant (P<0.001) cultivar x site interaction effect in relation to the growth of the cultivars, with no single cultivar having the highest growth rate at every site.

At Orange ‘Barcelona’ had a similar TCSA to ‘TBC’, with both cultivars being greater than the others. However, at Moss Vale, the mean TCSA of ‘TBC’ and ‘Tonda di Giffoni’ were significantly greater than ‘Barcelona’. At Myrtleford, ‘Barcelona’, ‘TBC’, ‘Tonda di Giffoni’ and ‘Victoria’ had the highest mean TCSA. ‘Barcelona’ had the highest mean TCSA at Toolangi.

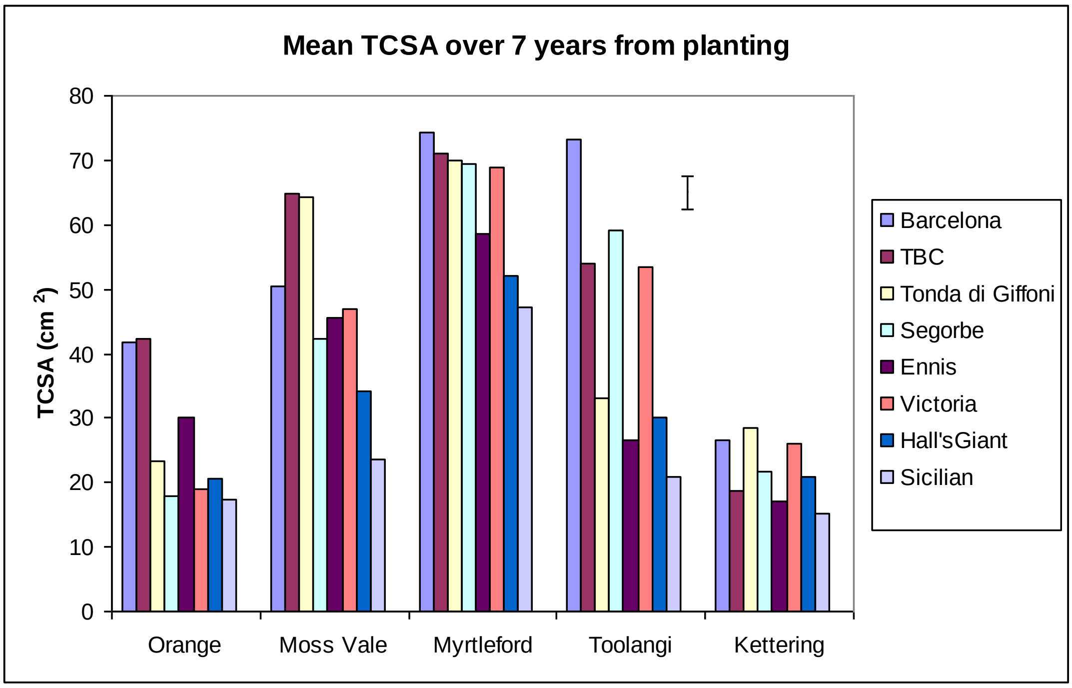
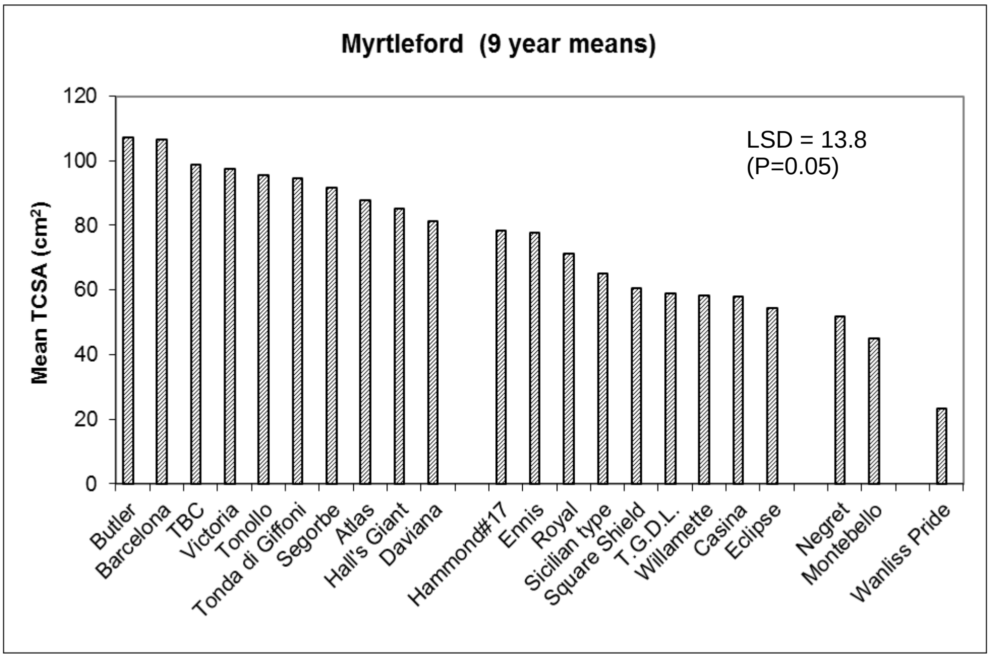


Figure 4.2 Mean TCSA of 8 cultivars grown at each of the 5 study sites over a period of 7 years from planting.

It is difficult to hypothesise on the reasons for these differences. However, the climates and soil types at the 5 sites were different, indicating that environmental conditions could influence the growth and subsequent productivity of cultivars.

Generally, the vigour of growth of the cultivars, as assessed by TCSA, lay on a continuum, ranging from those with high growth rates, such as ‘Barcelona’, to those with low growth rates, such as ‘Wanliss Pride’ (Figure 4.3).



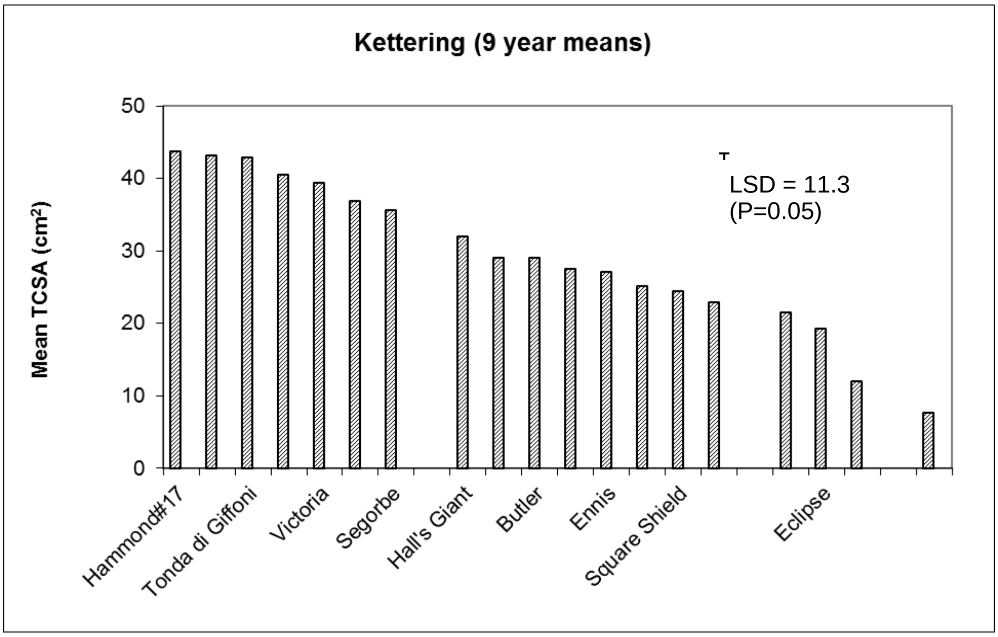


Figure 4.3 Mean trunk cross-sectional area (cm^2) of cultivars at Myrtleford and Kettering, over 9 years from planting.

Reference cultivars recommended for relative tree vigour include ‘Fertile de Coutarde’ syn. ‘Barcelona’ and ‘Merveille de Bollwiller’ syn ‘Hall’s Giant’ for high vigour, ‘Ennis’ (intermediate), ‘Negret’ and ‘TGDL’ (low) with ‘Impérial de Trébizonde’ syn ‘Wanliss Pride’ as very low (Bioversity, FAO and CIHEAM, 2008).

Although cultivars could be placed in groups based on their relative growth rates, these seem rather arbitrary, based on the interaction effects between sites and tree growth, along with the observations that within sites there is general grading in cultivar vigour from high to low. However, the data on mean TCSA values can be separated into high growth rates, intermediate (75% of the highest cultivar), low (50% of the highest cultivar) and very low (25% of the highest cultivar). On this basis, ‘Barcelona’ and ‘Tonda di Giffoni’ are in the high growth category and ‘Ennis’ is in the intermediate category at both sites. However, ‘Negret’, ‘TGDL’ and ‘Wanliss Pride’ varied between sites but were generally of low vigour with low growth rates at both Myrtleford and Kettering. These cultivars are generally considered to be of low vigour (Mehlenbacher (1991b).

‘Barcelona’ grew consistently well at all sites. Other cultivars that generally had high growth rates included ‘Atlas’, ‘Butler’, ‘TBC’, ‘Segorbe’, ‘Tonda di Giffoni’, ‘Tonollo’, and ‘Victoria’, although their relative growth rates varied between sites, illustrating the interaction effect between cultivars and sites. The cultivar ‘Hammond#17’ grew well at Myrtleford, where it had a similar growth habit to ‘Butler’. ‘Hammond#17’ grew very vigorously at Kettering (Figure 4.3).

The cultivar ‘Wanliss Pride’ made poor growth at all sites, particularly at Orange, where many plants died in the first and second years. Replacement plants of ‘Wanliss Pride’ also died with none of the original trees remaining at the end of the experiment.

The “Sicilian type” was of intermediate vigour, resulting in a small compact tree. It produced high nut yields for its size with a high yield efficiency, as discussed in Chapter 7. ‘Willamette’ was a relatively small, compact tree as described by Mehlenbacher et al. (1991).

Habit of growth

Observations of relative tree height and spread were made at all sites in the early years of growth. The relative shape or spread of the cultivars did not vary greatly between sites and was considered to be principally a genetic characteristic, although modified by environmental conditions. The typical form of growth of the cultivars is given in Table 4.1 for trees in their fourth growing season at Myrtleford. This was at a stage when it was considered that trees were able to express their individual habit of growth, prior to them meeting down the rows (Plate 4.1) when competition between trees might have influenced their growth form.

Table 4.1 Relative vigour and growth habit of cultivars at Myrtleford in their fourth growing season (14 December, 2000)

Cultivars	TCSA (cm^2)	Relative height 1 (low) – 5 (high)	Relative spread 1 (erect) – 5 (spreading)	Growth habit
‘Butler’	74	5	4	Very vigorous, semi dense
‘Segorbe’	71	5	4	Vigorous, dense foliage
‘TBC’	68	4.5	4	Dense, large leaves
‘Barcelona’	68	5	3	Relatively open
‘Tonda di Giffoni’	67	4.5	4	Semi-dense foliage
‘Victoria’	64	4.5	3	High vigour, dense foliage
‘Atlas’	60	4.5	4	Relatively dense foliage
‘Tonollo’	59	3.5	4	Open
‘Ennis’	58	4.5	4	Dense foliage
‘Daviana’	49	3.5	3	Relatively dense
“Sicilian type”	47	3.5	4	Relatively open
‘Hall's Giant’	47	4.5	3	Relatively open
‘Hammond#17’	45	4.5	3	Semi dense
‘Royal’	44	3.5	3	Compact, dense
‘TGDL’	41	3.5	3	Erect, open
‘Eclipse’	41	2.5	4	Spreading open habit
‘Casina’	38	3.5	3	Compact
‘Negret’	33	2.5	2	Relatively low vigour, dense
‘Square Shield’	33	3	1	Erect, open
‘Wanliss Pride’	17	2	5	Relatively open, spreading

This data showed a good relationship between TCSA and height ($R^2 = 0.77$), with an increase of 0.05 relative units per cm^2 increase in TCSA (Figure 4.4).

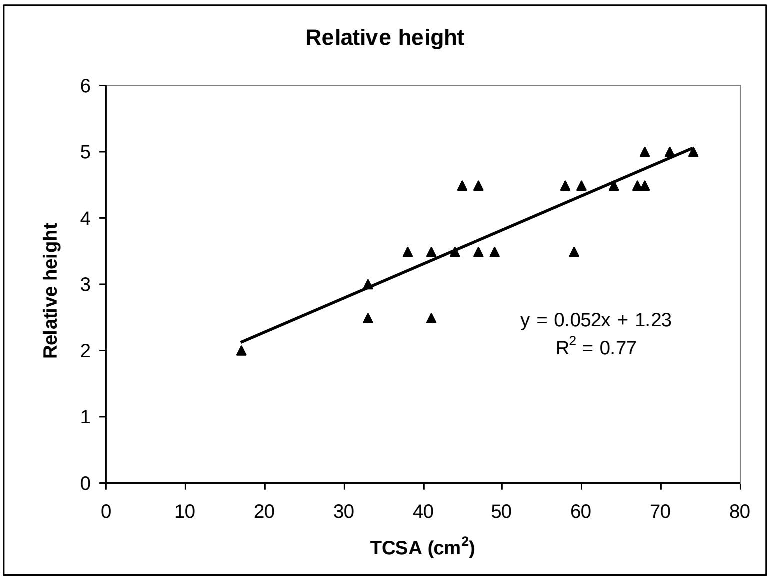


Figure 4.4 Relationship between relative tree height (1 low – 6 high) and TCSA.

There was no relationship between TCSA and the spread of the crown, which is in agreement with the studies of Santos et al (1994). However, tree shape and an approximation of tree volume can be obtained by multiplying relative height by relative spread. Relative volume was found to be related to TCSA ($R^2 = 0.69$), it increased at 0.25 relative units per cm^2 increase in TCSA (Figure 4.5).

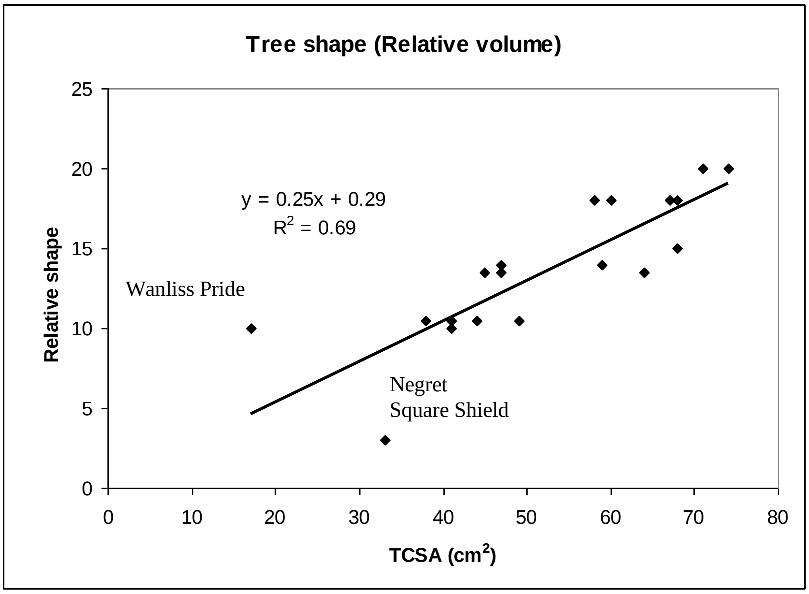


Figure 4.5 Relationship between relative tree volume (height x spread) and TCSA.

Although ‘Wanliss Pride’ had a low TCSA, it had a relatively high tree volume, due to its spreading habit of growth. In comparison, ‘Negret’ and ‘Square Shield’ both had a very low tree volume, due to their short stature and erect habit of growth. The implications of high vigour, high values of TCSA and tree shape on nut yields will be discussed in Chapter 7, Nut Yields.

The cultivars ‘Lewis’, ‘Montebello’ and ‘Willamette’ were not included in the initial year of planting at Myrtleford. As a result, their growth was very erect due to competition with the earlier-planted trees. Ratings of their relative growth and descriptions of their habit of growth have not, therefore, been included in Table 4.1.

4.3.2 Site effects on growth

There were highly significant differences ($P<0.001$) between the sites in the increase in the mean TCSA (cm^2) for the 8 cultivars over the 7 years from planting, Figure 4.6. There was a linear relationship for increase in TCSA for all sites ($R^2 \geq 0.98$). The highest average annual increase in TCSA for the cultivars was 20.6 cm^2 at Myrtleford; the lowest was 9.1 cm^2 at Orange.

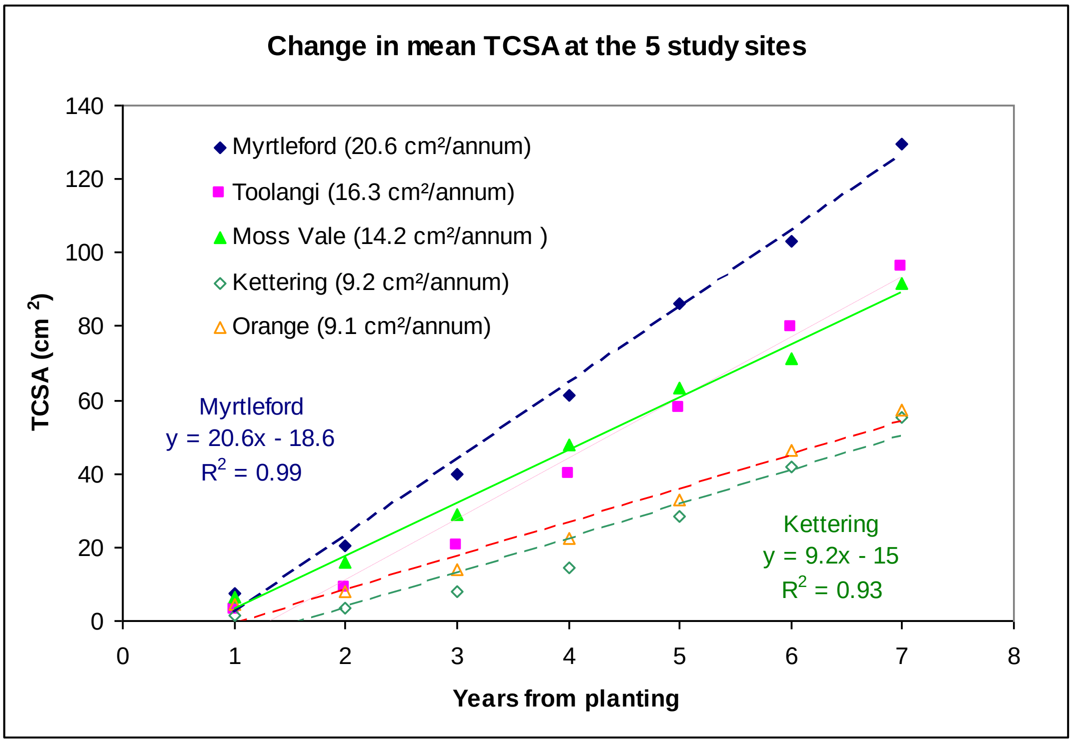


Figure 4.6 Annual increase in mean trunk cross-sectional area (cm^2) of 8 cultivars over 7 years from planting at the 5 study sites

At Myrtleford, the high rate of growth resulted in the canopies of most cultivars meeting within the tree rows in the fifth growing season (Plate 4.1). As the TCSA of woody plants increases, the relative growth rate decreases as the relative proportion of the trunk mass increases faster than the photosynthetic area. Thus the trees at Myrtleford with their highest increase in TCSA become relatively woodier at an earlier age and it would be expected they would reach full canopy and maximum nut yields at an earlier age, as discussed in the next chapter.

Plate 4.1 Trees at Myrtleford in the summer of their fifth growing season. At this stage most cultivars were just meeting down the tree rows.

There are 3 factors that could account for the differences between the sites:

- Site management
- Climate
- Soils

It is likely there would be interactions between these; however, their effects are initially discussed separately.

Site management

As discussed in the methods, common management plans were developed for the sites to try to minimise differences between sites in tree growth and productivity. However, there were some differences in irrigation practices with Toolangi and Kettering using drip irrigation systems whereas Myrtleford and Moss Vale used micro sprinklers throughout the period of research. At Orange a drip system was used initially on the young trees changing to a micro-sprinkler system after 4 years. Availability of water supplies also affected levels of irrigation as discussed in this chapter and those on nut yields and kernel quality. Thus methods and levels of irrigation confounded differences between sites in management, rainfall and the availability of soil moisture.

4.3.3 Climate effects on tree growth

Key climatic factors that affect the growth of plants are temperature, moisture supply and solar radiation (Westwood, 1991). Strong winds may also have an adverse effect on the growth of hazelnuts as reported by Bergoughoux et al. (1978). Major differences between the sites in these climate characteristics might account for the differences in tree growth between the sites. Records from the weather stations at each site were used to obtain mean values for temperature, growing degree days (GDD >10°C), solar radiation, evaporation, rainfall and wind run for the months of October – February each year (Table 4.2). These months are considered as being the main months for the growth of hazelnut trees in Australia.

Table 4.2 Mean monthly air temperature (°C), solar radiation (MJ/m^2), evaporation (mm), rainfall (mm) and wind run (km) over the months of October – February.

	Orange	**Moss Vale**	**Myrtleford**	**Toolangi**	**Kettering**
Mean temperature (°C)	14.8	17.2	18.7	14.6	14.5
Mean GDD >10°C	722	1081	1317	701	679
Solar radiation (MJ/m^2)	22.7	21.1	22.1	18.7	16.4
Evaporation (mm)	122	104	110	119	107
Mean rainfall (mm)	71	85	68	85	77
Wind run (km)	2530	2510	2406	2710	2325

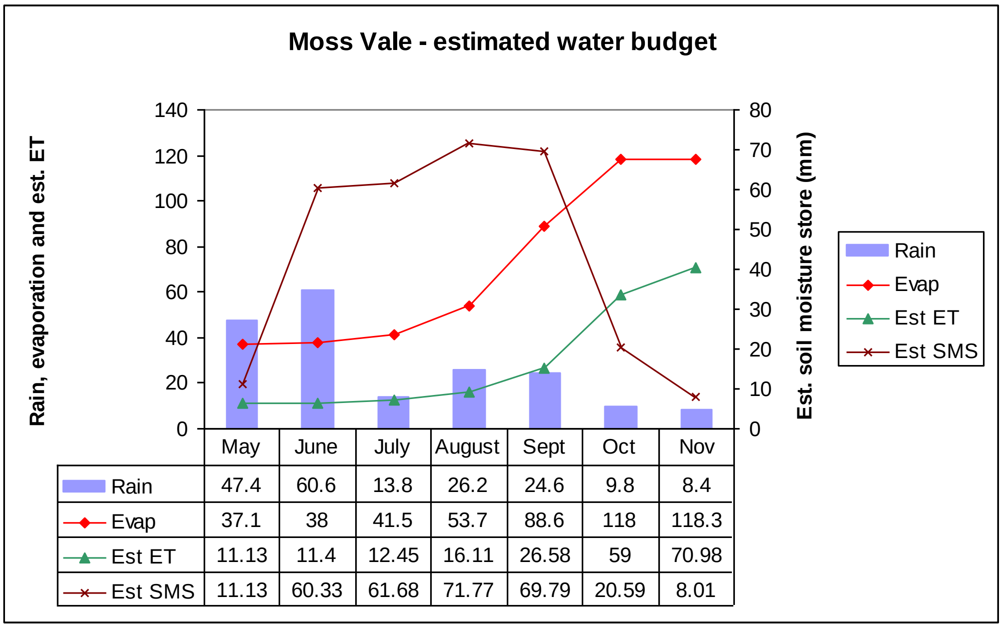
The highest mean increase in TCSA was obtained at Myrtleford, followed by Toolangi and Moss Vale, which were very similar. The mean monthly temperatures at Moss Vale were considerably higher than those at Toolangi, which was very similar to Orange and Kettering, yet tree growth was considerably higher at Toolangi than those centres, Figure 4.6. Analyses were done to assess if there was any correlation between the increase in TCSA at the study sites and any of the climatic variables shown in Table 4.2. No significant relationships were found between these climatic variables and tree growth, although it is recognised that temperature and rainfall in the growing season can affect tree growth. It is possible that within the temperature range of the sites, the differences in the mean temperatures between the sites were not having a limiting effect on growth.

Mean monthly evaporation rates were similar across all sites. They were higher than mean monthly rainfall at all sites. Wind run was high at all sites; this is discussed later in this section.

Rainfall effects on tree growth

Although the mean growing season rainfall, October – February, was similar across sites (Table 4.2) and was not correlated with increase in TCSA, there were large differences between months and seasons.

Very low rainfall was recorded in the winter and spring of 2002 in South-eastern Australia. It was particularly dry that year at Moss Vale in the 5 months of July - November (Figure 4.7). This is a period when the available soil moisture store should be increasing prior to trees making active shoot and trunk growth, following bud break in September - October. The estimated soil moisture was calculated from rainfall and evaporation recorded on the site, with a crop factor of 0.3 until bud break in September. Values of 0.5 and 0.6 were used for the months of October and November, based on the work of Mingeau and Rousseau (1994). Irrigation was applied in November, equivalent to approximately 50 mm of rainfall. Evaporation rates rose rapidly in October and November, with the estimated quantity of available soil moisture store (SMS) declining to very low levels in the months of October and November (Figure 4.7).



	May	June	July	August	Sept	Oct	Nov
Rain	47.4	60.6	13.8	26.2	24.6	9.8	8.4
Evap	37.1	38	41.5	53.7	88.6	118	118.3
Est ET	11.13	11.4	12.45	16.11	26.58	59	70.98
Est SMS	11.13	60.33	61.68	71.77	69.79	20.59	8.01

Figure 4.7 Estimated available soil moisture for the months of May – November, 2002

Due to the low winter and spring rainfall at Moss Vale, the spring that fed the irrigation dam did not flow and there was limited irrigation water available to make up for the low rainfall during the critical period of growth and nut development from October - February. Irrigation usage was a total of 2820 L/tree, Table 3.9, Chapter 3.

The relative rate of increase in the TCSA of the 11 cultivars grown at Moss Vale shows a decline over the 8 years following planting in 1996 (Figure 4.8). A decline in the relative rate of increase in TCSA is common in woody plants (Tromp et al., 2005), as the proportion of actively growing tissue declines in proportion to the woody material produced in earlier years. In the dry spring of 2002, the trees were subjected to considerable moisture stress, particularly in November, with relatively little new shoot growth. The rate of increase in TCSA declined to a greater extent than expected, based on the trend line, Figure 4.8. Lower increments in the increase of TCSA of hazelnut trees in Italy due to low rainfall (161mm) during the growing season, in their case April – September, were reported by Bignami and Natali (1997).

In the following year at Moss Vale, the September – November rainfall was 334 mm which appeared to favour tree growth, resulting in a greater relative increase in TCSA, suggesting some compensatory growth.

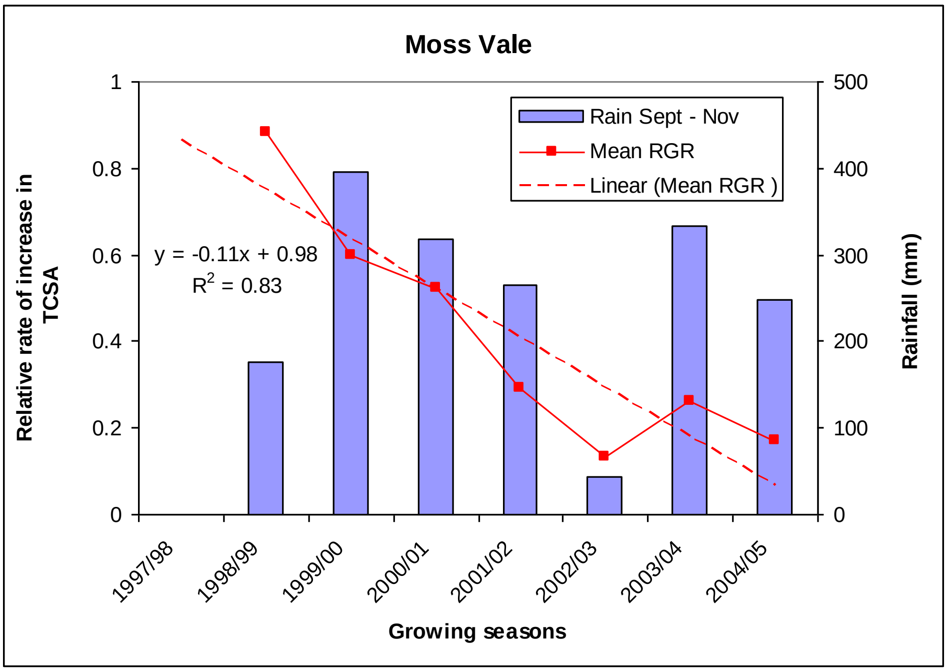


Figure 4.8 Relative rate of increase in TCSA (cm²) of 11 cultivars at Moss Vale planted in 1996, compared with total rainfall (mm) in the months of September – November

At Myrtleford, the rainfall was also below average in the 2002 growing season, only 198 mm in the 4 months of August to November, compared with the mean of 445 mm. However, at that site, more water was available for irrigation with a total of 4240 L/tree being used through that growing season (Chapter 3, Table 3.9). The combination of slightly more rainfall and a higher level of supplementary irrigation at Myrtleford had less adverse effect on tree growth than at Moss Vale. At the other sites, the rainfall deficits in that season were less severe with little impact on tree growth.

Excessive soil moisture

In contrast to dry seasonal conditions, some young trees died at Kettering, as the result of abnormally high rainfall in the spring of 2001. A total of 267 mm of rain was recorded for the months of June, July and August with a further 342 mm of rainfall being recorded in September and October of that year. This caused the poorly-drained soil to become saturated. The damaging effect of rainfall in this period was most likely due to the poor drainage of the clay sub-soil at that site (Table 4.4). Under conditions of high rainfall, poor soil drainage leads to low levels of oxygen in the soils, which can inhibit or stop root growth and the up-take of nutrients (Russell, 1961) and (Westwood, 1993). These observations are in agreement with those of Thompson (1981) and Germain and Sarraquigne (2004), who reported that hazelnut trees do not tolerate poorly-drained soils.

The wet conditions experienced in September 2000 at the Myrtleford site, which was flooded for approximately 2 days with the trees standing in about 500 mm of water, did not appear to have any adverse effect on tree growth and neither did the 628 mm of rainfall at Moss Vale in August 1998. It appears that damage is more likely to occur when poorly-structured clay soils are saturated for an extended period in the spring, when the trees are making active growth.

Frost effects

In October 2003, severe damage to the buds and young leaves of the trees was observed at the Orange site, probably due to a late spring frost. A minimum temperature of -4.7°C was recorded at the site on 29 September 2003. Ratings of the severity (0 nil – 5 severe) of the damage were noted for 18 cultivars in all 4 replicates. The effects ranged from very severe, major damage to newly-developed leaves for the cultivars ‘TGDL’, ‘Tonda di Giffoni’ and ‘Lewis’, to none for the late-leafing cultivars, ‘Hall’s Giant’ and ‘Ennis’. The level and causes of the damage are discussed in the next chapter, in Part B, Section 5.6, ‘Bud Break’.

Despite the severe level of damage on some cultivars, such as ‘Barcelona’ and ‘Tonda di Giffoni’, this did not appear to have affected overall seasonal growth, as reflected in the TCSA of these cultivars in the following autumn, May 2004, 9 years after planting.

However, many growing points had been killed by the frost in the badly-affected cultivars, resulting in the production of many side shoots.

Wind

Hazelnut trees can be adversely affected by strong and persistent winds, particularly in the spring (Bergoughoux et al., 1978). This was very obvious at Toolangi, with trees in the top south-western corner of the site being considerably smaller and more bent than those further down the slope, where there was greater wind protection. Another factor causing poor growth at Orange could be attributed to wind effects, as initially that site had very little shelter from wind. At the time of planting, the Orange site was far windier than the Myrtleford site (Figure 4.9). However, 8 years after planting, total annual wind run at Orange had been reduced by over 60% (Figure 4.9), due to the combined effects of the casuarina trees (*Casuarina cunninghamiana)* that had been planted as a wind break and the developing hazelnut trees themselves.

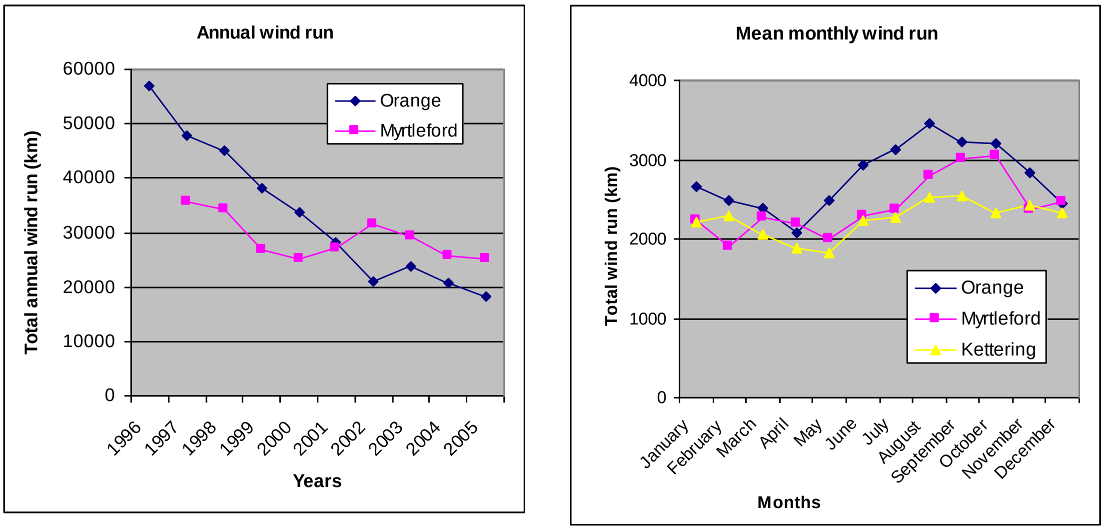


Figure 4.9 Total annual wind run at the Orange and Myrtleford sites and mean monthly wind at the Orange, Myrtleford and Kettering sites (km)

At most sites, strong winds in spring and summer caused damage to both leaves and developing shoots of young trees, with some leaf scorch being observed in summer, associated with hot dry winds. At most sites, the windiest period of the year was in the spring (Figure 4.9).

The hazelnut trees at the Kettering site were planted in a young orchard and received some protection from the surrounding orchard trees. As a result, the mean monthly wind run at Kettering was, on average, less than that at Orange (Figure 4.9), yet the trees at that site made poor growth. Although strong winds were observed to cause some reduction in tree growth in the top south-western corner of the site at Toolangi, it was concluded that winds at Orange were not likely to be a major factor contributing to the poor growth at that site.

4.3.4 Conclusions on climate

It was concluded that the main climatic factor influencing tree growth across the sites was related to inadequate rainfall or soil moisture in early spring when trees were making active shoot growth. Excessively wet conditions in the spring, associated with poorly drained soils, also impaired tree growth.

The frost at Orange, in 2004, demonstrated that a severe frost in spring at early leafing can be very damaging to young trees. The recommendation of Germain and Sarraquigne (2004), to avoid locations where the minimum temperature after leafing out should be no less than -3°C, is considered to be valid.

Strong winds were observed to adversely affect tree growth, but were not considered to be a major factor influencing differences in tree growth between the sites. Differences in mean temperatures, solar radiation and wind run between sites did not appear to be major factors affecting tree growth. However, availability of soil moisture was significant, particularly on a seasonal basis.

4.3.5 Soil effects

As the significant differences observed in tree growth between sites did not seem to be related to differences in mean temperatures, solar radiation, and wind run between sites, the question arises, did soil type have a significant effect?

Soil type was reported as having a very significant effect on the growth and production of *Corylus avellana* L. by Woodroof (1967), Lagerstedt (1981), Thompson (1981), Mehlenbacher (1994), Botu and Tucu (2001), and Germain and Sarraquigne (2004b). Desirable soil attributes are considered to be: deep (at least 1.2 m), loam texture (sand – clay loams), well-drained, fertile, with pH 6-7. Heavy clay soils should be avoided, particularly if poorly-drained (Woodroof, 1967 and Thompson, 1981). Using these characteristics, parameters for suitable soil attributes were developed for site assessment, Table 4.3. A limitation of these soil attributes is that they are developed from studies conducted on soils in Europe and North America with no mention of the effects of soils with duplex profiles. As the bulk of hazelnut roots are in the surface 0.6 m (Thompson, 1981) and (Germain and Sarraquigne, 2004), soils that have a duplex profile with an A horizon that is 250-300 mm deep overlaying a clay B horizon, may have limitations in their suitability. A point score was given for each attribute based on the emphasis given in the literature. The physical attributes of texture, depth and drainage seem to be the attributes most emphasised; they are also the attributes that are the most difficult to change. Soil pH can be amended with liming and fertility with the addition of fertilisers.

Table 4.3 Key parameters to assess the suitability of soils for hazelnut production

Key attribute	**Comments**	**Max points**
Texture	Loam, range sandy – clay loams	4
Deep>1.0 m	Majority of roots in top 0.6 m going down to at least 1.2 m. A duplex profile with clay B horizon is probably a major limitation	4
Good drainage and aeration	Positive indicators are red colour (good aeration), no mottling, stable structured (little dispersion or slaking of soil crumbs)	4
Fertility	Desirable levels for hazelnuts see Table 4.5 (Olsen, 1995)	1
pH 6.0-7.0	Slightly acid to neutral	1

Soils of the study sites

The characteristics of the soils at the study sites and the levels of elements in the surface 100 mm were assessed, as described in Chapter 3, Methods. There were large differences between the soils of the field sites with an alluvial soil at Myrtleford, krasnozem soils developed from basalt at Orange and Toolangi and podsolic soils at Moss Vale and Kettering, Table 4.4. All sites, except Myrtleford, had duplex soils.

Table 4.4 General description of soil profiles at the 5 field sites. Soil pH values were prior to liming.

	Study sites				
	Orange	**Moss Vale**	**Myrtleford**	**Toolangi**	**Kettering**
Soil type	Krasnozem	Red podsol	Alluvial	Krasnozem	Yellow podsol
A horizon	0–300 mm, red brown clay loam, pH 5.5; well structured	0–250 mm, dark reddish brown sandy loam, pH 4.5–5.0	Brown sandy loam, without separate soil horizons down the profile, pH 4.5–5.0; well drained.	0–300 mm, brown clay loam and pH 5.0; friable and well structured	0–250 mm, grey brown fine sandy loam, pH 5.0; weak structure
B horizon	Red light clay, pH 6.0, well structured, some mottling.	Reddish brown sandy clay loam, pH 5.5		Red brown light clay, pH 5.5, good structured.	Yellow-brown clay, pH 5.5-6.0, poorly drained

A subjective assessment of the suitability of the soils for growing hazelnuts was made, using the parameters developed in Table 4.3. It was very difficult to make an objective assessment on the characteristics of texture and depth in the duplex soils.

Table 4.5 Assessment of the suitability of the soils at the study sites based on 5 key attributes.

Key attribute	**Orange**	**Moss Vale**	**Myrtleford**	**Toolangi**	**Kettering**
Texture	Clay loam - clay	Sandy loam – clay loam	Sandy loam	Clay loam – light clay	Sandy loam - clay
Deep>1.0 m	Duplex - B clay	Duplex – B clay loam	Deep alluvial	Duplex – B light clay	Duplex,- B clay
Drainage and aeration	B horizon mottled (some limitation)	Reddish clay loam (acceptable)	Sandy loam well drained	Well structured (acceptable)	Poor drainage
Fertility	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
pH 6.0-7.0	5.5-6.0	4.5-5.5	4.5-5.0	5.0-5.5	5.0-6.0
General limitations	Heavy texture, depth and poor aeration	Depth, less than desirable pH	Less than desirable pH	Less than desirable pH	Texture, depth, drainage and aeration
Overall score (Max 14)	8	11	13.5	10.5	7.5

The overall assessments of the suitability of the soils were in approximate alignment with the relative growth of the trees at the sites, with the best growth occurring at Myrtleford, intermediate growth at Moss Vale and Toolangi and the poorest growth at Orange and Kettering, Figure 4.6.

At Orange, the cultivars ‘Wanliss Pride’, ‘TGDL’ and ‘Negret’ made very poor growth with many young plants dying and requiring replacement. At Myrtleford (Figure 4.3), the growth of these cultivars was better but they were generally of low vigour. In general, the trees at Orange and Kettering made poor growth (Figure 4.6). It was considered this could have been related to either the clay texture of the B horizon at those sites (Table 4.5) impeding the growth of the tree roots or associated with nutrition.

The soil at the Orange site was a clay loam in the A horizon, overlying a light clay (Table 4.4). It was generally well-structured. At the time of planting, the topsoil pH_w was 5.5, it was one of the least acidic of the study sites; the subsoil (B horizon) was pH_w 6.0. The mottling of the sub-soil was indicative of poor drainage and aeration in a wet season. In a pit dug on the site, nodules of manganese were observed in the B horizon which was indicative of high levels of manganese which can become readily available under anaerobic conditions during periods of waterlogging. Manganese can become toxic to some plants, inhibiting their root growth (Glendinning, 1999).

Soil nutrients

As explained in Chapter 3, Methods, soil samples were taken at all sites in March, in the year prior to planting, to obtain initial levels of available nutrients, Table 4.6. These were used to determine lime and fertilizer requirements. Soils were subsequently sampled again at the completion of the studies at each site to obtain final nutrient levels.

As soil pH levels were considered to be marginal at all sites prior to planting, all sites were top-dressed with ground limestone prior to planting. The levels of pH appeared to rise from the initial to the final figures at all sites in response to liming (Table 4.6). There is limited information on desirable levels of soil phosphorus (P) for hazelnuts, with few responses being reported from applications of this element (Tous et al, 1994). Levels of available P appeared to increase during the study period (Table 4.6), presumably due to applications of this element in the fertiliser treatments. Levels of phosphorus were assumed to be adequate.

The levels of available potassium (K), calcium (Ca) and magnesium (Mg) in the soil were generally above the desired minimum level (Olsen, 1995). The levels of calcium increased from the initial measurement over the period of the study, presumably due to the applications of ground limestone. The levels of the elements K and Mg appeared to be relatively stable, indicating that either the draw-down of nutrients was low or the fertiliser applications matched or exceeded nutrient removal.

Aluminium (Al) levels were below the level considered harmful to some sensitive crops (Peverill et al., 1999). The Ca/Mg ratio was greater than 2.0, indicating a stable surface soil structure. Apart from soil pH, it was considered that the available nutrient levels were suitable for hazelnut production, as stated in the site suitability assessment (Table 4.5). It was considered that any differences between sites in fertility were unlikely to have contributed to the difference in growth between the sites.

Table 4.6 Estimated levels of available nutrients in soil samples collected from a depth of 0-100mm across the sites prior to planting (initial) and in the last year of study at each site.

	Study sites										
	Orange		**Moss Vale**		**Myrtleford**		**Toolangi**		**Kettering**		**Desirable levels**
Elements	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	
pH_{Ca}	5.7	7.3	4.3	5.2	4.5	5.2	4.5	5.2	5.5	5.8	pH_w 5.0
Total C (%)	2	1.8	3.8	3.2	3.3	3.5	6.6	6.1	3.5	3.7	N/A
P (mg/kg)	21	76	9	18	7	12	3	4	141	120	N/A (1) 8 (3)
K meq/100g	0.6	0.78	0.3	0.35	0.6	0.5	0.5	1.8	1.03	1.2	0.2 (1)
Ca meq/100g	6.8	12	3.9	8.4	5.6	9.8	3.8	11	12.6	13	5.0 (1)
Mg meq/100g	0.7	0.95	1.4	1	2.3	2.5	0.8	1.8	2.65	3.1	0.5 (1)
Al meq/100g	<0.1	<0.1	0.6	0.12	0.2	<0.1	1.4	0.31	<0.1	<0.1	<5 (2)
Ca/Mg ratio	9.7	12.2	2.8	8.4	2.4	4	4.8	6.1	5	4.2	2.0 (3)

Source: Desirable levels are for hazelnuts. (1) Olsen, 1995 (2) Aluminium sensitive crops. Peverill et al., 1999. (3) Phosphorus (P) Bray (mg/kg) for pastures 8mg/kg (Abbott and Vimpany, 1986),
N/A Not available, pH_{Ca} *(1:5 soil:*$CaCl_2$ *solution)*

Soil carbon, which reflects organic matter content, appeared to have remained fairly steady, even with the use of the herbicides down the tree rows to suppress weed growth, which is where the soil samples were collected for the final test.

Leaf analyses

In order to monitor the nutrient status of the plants at each site, composite samples of at least 100 leaves were collected annually in February, as explained in Chapter 3, Methods. These were analysed to determine their chemical composition. The results obtained were compared with levels that were considered to be desirable, based on the studies of Weir and Cresswell, (1993) and Olsen (2001). The major nutrients were generally within or close to the desired levels, Table 4.7, suggesting that there were no major nutrient deficiencies affecting plant growth.

Table 4.7 Range of levels (lowest – highest) of key elements in leaves taken annually (mid summer) from the 5 hazelnut study sites, compared with desirable levels; levels outside the desirable range are highlighted in red.

Elements	Sites					Desirable Range(1)
	Orange	Moss Vale	Myrtleford	Toolangi	Kettering	
	Site ranges, lowest–highest					
Nitrogen %	2.4-3.17	2.3-2.92	2.5-2.9	2.7-3.1	2.2-3.49	2.2–2.5
Phosphorus %	0.12-0.17	0.12-0.19	0.12-0.38	0.13-0.29	0.31-0.45	0.14–0.45
Potassium %	0.65-1.3	0.43-1.2	0.55-1.3	0.63-1.5	0.72-1.32	0.8–2.0
Calcium %	1.25-1.9	1.04-1.60	0.94-2.1	1.15-1.8	1.17-2.0	1.0–2.5
Magnesium %	0.13-0.22	0.16-0.33	0.14-0.6	0.12-0.23	0.21-0.3	0.25–0.5
Sodium %	0.01-0.05	0.05-0.17	0.01-0.24	0.02-0.13	0.04-0.12	<0 0.1 (2)
Sulphur %	0.1-0.2	0.15-0.21	0.1-0.23	0.1-0.22	0.13-0.23	0.12 - 0.2
Boron ppm	38-67	25-68	20-57	44-69	20-53	30-75
Copper ppm	7.3-11	5-10	3-11	6.7-17	4.8-9.9	0.8–2.0
Zinc ppm	19-32	20-40	16-49	17-45	21-47	15 - 60
Manganese ppm	490-1900	484-1050	162-530	230-550	46-327	26–650

(1) Desirable range for hazelnuts, Olsen, 2001. (2) Weir and Cresswell, 1993.

It is difficult to properly define ideal levels of soil nutrients for plants. Often only limited work has been done to define response curves, hence ‘desirable levels’ are only a guide. Comparison of values obtained and desirable ranges show that most nutrients were at an appropriate level. The exception was manganese which was high at Orange and Moss Vale. This nutrient is known to be toxic to plants (Glendinning, 1999).

Phosphorus levels in the leaf samples were at the lower end of the desirable range, reflecting the low levels of available soil phosphorus identified in the soil tests. An exception to this was Kettering which had high levels of phosphorus in both the soil and the leaves, Table 4.6. Potassium and magnesium were also at the lower end of the desirable range at most sites, as was calcium, despite the moderately high levels of lime application.

The levels of manganese varied considerably across sites and years within sites. Some very high readings were obtained at both Orange (1900 ppm) and Moss Vale (1050 ppm) in the second year after planting. These levels subsequently declined, presumably as a response to soil applications of lime prior to planting and subsequently at Orange. However, it is possible that some initial damage was done to trees at those sites.

The data on the nutrient content of the leaves (Table 4.7), coupled with that for available nutrients in the soil (Table 4.6), indicates that the level of nutrients was generally adequate for healthy growth of the plants at all sites and that inadequate nutrition was unlikely to account for the poorer growth of trees at Kettering and Orange compared with Myrtleford.

The leaf analyses were performed on a composite collection of leaves from the sites so did not show any differences between cultivars. However, in 2006, leaf samples were collected and analysed from ‘Wanliss Pride’ as well as the composite sample for the Orange site. The ‘Wanliss Pride’ sample showed far higher levels of manganese, 1200 ppm compared with the site sample that year of 490 ppm. The ‘Wanliss Pride’ sample was lower in potassium, 0.53% compared with the site mean of 0.88%. Other elements were similar. Although this sampling was not replicated or repeated in subsequent years, it indicated that there could be differences between cultivars in their up-take of nutrients. It is recognised that, in other deciduous tree crops, rootstocks can influence the up-take of minerals (Westwood, 1993); therefore, it is possible that the low growth rates of ‘Wanliss Pride’ may have been due to either that cultivar being less effective in extracting potassium from the soil or it may have been related to an excessive uptake of manganese, which may have affected root growth. It is uncertain if any damage to hazelnut roots might then enable some fungal pathogens in those roots, reducing their function.

The effect of manganese on hazelnuts does not appear to be well-documented in the literature. However, Grau et al. (2001) considered that poor growth of hazelnuts in Chile on some sites may have been due to high levels of manganese. They found higher levels of foliar manganese in ‘TGDL’ than in ‘Barcelona’. In some situations ‘TGDL’ had over 1200 ppm, with more than 6000 ppm in some other cultivars. Grau et al. observed visual symptoms of manganese toxicity in some situations but these did not seem to be directly related to foliar levels of manganese.

Annual crops and pastures can vary in their tolerance to manganese, with lucerne, canola and phalaris being particularly sensitive (Glendinning, 1999). Differential cultivar tolerance to soil manganese has also been reported for some agricultural plants, such as lucerne (Sale et al., 1993) and tropical beans (Gonzalez and Lynch, 1999). It seems possible that some hazelnut cultivars, such as ‘Barcelona’, ‘TBC’ and ‘Tonda di Giffoni’, could be more tolerant of high levels of soil manganese than are cultivars such as ‘Wanliss Pride’, ‘Negret’ and ‘TGDL’.

Manganese availability is influenced by soil type. Krasnozem soils developed on basalt are commonly high in manganese (Peverill et al, 1999). When these soils are saturated with water and oxygen levels are low, manganese compounds are reduced and become soluble. On drying, the manganese is oxidised, becomes insoluble and forms deposits and nodules in the soil (Charman and Murphy, 1991). The availability of manganese is affected by soil pH, with manganese becoming less available as soil pH is increased (Uren, 1999). The lime applied pre-planting at all sites raised soil pH by 0.5 to 1 unit (Table 4.6). The general decline in the levels of manganese in leaves, particularly at Orange (Figure 4.6), was probably due to the effects of liming and the consequent rise in soil pH. At that site, 5 tonnes of ground limestone were applied pre-planting, with a further 7 tonnes being applied in 2001 and 2 tonnes in 2004.

Fluctuating manganese levels between seasons are possibly due to winter-spring rainfall, with higher levels of available manganese occurring as a result of relatively high winter-spring rainfall, such as at Orange in 2000.

There is the possibility that the high levels of manganese (Mn) in the first 7 years at Orange (Figure 4.10) might have caused a deleterious effect on the growth of the hazelnut trees in the early years of growth. Foliar levels of manganese at that site were above the desirable range of 26 – 650 ppm reported for hazelnuts by Olsen (2001), although there was a general trend of declining levels during the study period. As high levels of manganese at Orange may have had a deleterious effect on tree growth, it was decided to do a sand culture experiment with varying levels of manganese to investigate the effects of manganese on young hazelnut plants.

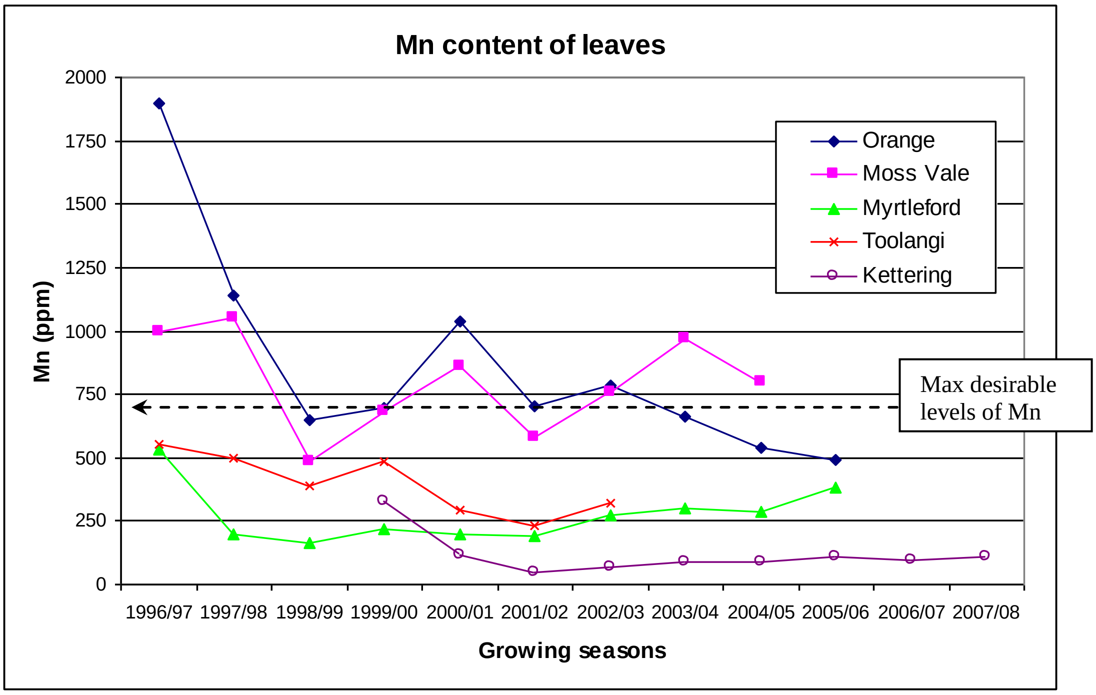


Figure 4.10 Levels of manganese in leaf samples collected annually in February from all sites.

4.3.6 Manganese toxicity - sand culture experiment

Sand culture experiments have been used to assess the tolerance of crops to manganese and the visual symptoms of toxicity. A wide range of crop plants were reported by Hewitt (1966) to be tolerant of 0.5 ppm of manganese in sand culture experiments with some tolerating up to 5 ppm. Levels above this were toxic to many crops. It was decided to conduct a sand culture experiment with rates up to 50 ppm. The aim of the experiment was to ascertain the response of young hazelnut trees to levels of manganese in the range 0-50 ppm.

Methods – sand culture experiment

A small factorial sand culture experiment was conducted at Orange, which comprised 2 cultivars (‘Barcelona’ and ‘Wanliss Pride’) and 6 levels of manganese (0, 0.5, 2, 5, 20 and 50ppm). There were 2 replications in a randomised block layout. Twenty four (24) plastic tubs with a capacity of 40 L had 4 holes drilled in their base for drainage and were filled with coarse, washed river sand (Plate 4.2). Dormant hazelnut whips of the cultivars ‘Barcelona’ and ‘Wanliss Pride’ were placed in these tubs on 13 September, 2004. Further details of the methods used are given in Appendix C.

Plate 4.2 Young trees of 'Barcelona' and 'Wanliss Pride' grown in a sand culture medium with a range of levels of manganese applied weekly to ascertain their effects on tree growth.

On 5 October, when the trees were at the early leafing stage, 2 L of a Manutec ® hydroponic solution mix formulated for vegetables was applied to each of the tubs as a base nutrient treatment; this was repeated at weekly intervals for the duration of the experiment.

The Manutec ® formulation was close in analysis to the standard solution used for sand and water studies for fruit trees at the Long Ashton Research Centre in the UK (Hewitt, E.J., 1966), (Appendix C).

Applications of the manganese treatments were commenced in early November, when it was considered the trees had become established. The manganese treatment solutions were made from manganese sulphate, providing a series of solutions containing 0, 0.5, 2.0, 5.0, 20 and 50 ppm of manganese, as per Appendix C. These solutions were applied weekly at 1 L per tub. The manganese treatments were in addition to the 1 ppm of manganese in the Manutec® solution. The 2 cultivars used were selected to try to assess any possible differences in cultivar tolerance. Although the manganese sulphate increased the sulphur levels at the same time as the manganese, these increased levels of sulphur were minor, apart from the 20 and 50 ppm levels of manganese, compared with the levels of sulphur provided by the Manutec® solution.

The tubs were located in a sheltered garden. In addition to the Manutec® and manganese solutions, they were supplied with water on a needs basis depending on weather conditions. Observations of tree growth were made on a monthly basis. No adverse effects were recorded on any trees during the growing period. The trees were removed from the pots on 17 March 2005 and thoroughly washed to remove the sand from the roots. The whole plants were weighed. The roots were cut from the tops at the level of the sand surface and weighed, to give separate weights for tops and roots. Regression analyses of levels of manganese (6) were conducted on shoot and root weights (Figure 4.11).

Results and Discussion

Neither the linear or quadratic regressions of shoot or root weights to the levels of applied manganese were significant with either 'Barcelona' or 'Wanliss Pride'. The level of variation within the samples was relatively high, with low R^2 values, Figure 4.11.

Both the root and shoot biomass of the 'Barcelona' was significantly greater ($P=0.05$) than that of the 'Wanliss Pride' (Figure 4.11). Root biomass was greater than that of the shoots for both cultivars. The ratio of shoots:roots was significantly greater ($P=0.05$) for 'Barcelona' at 0.66 compared with 0.45 for 'Wanliss Pride'. The total plant biomass was an average of 781 g/plant for the 'Barcelona' compared with 408 g for the 'Wanliss Pride', reflecting the growth of these 2 cultivars in the field experiments.

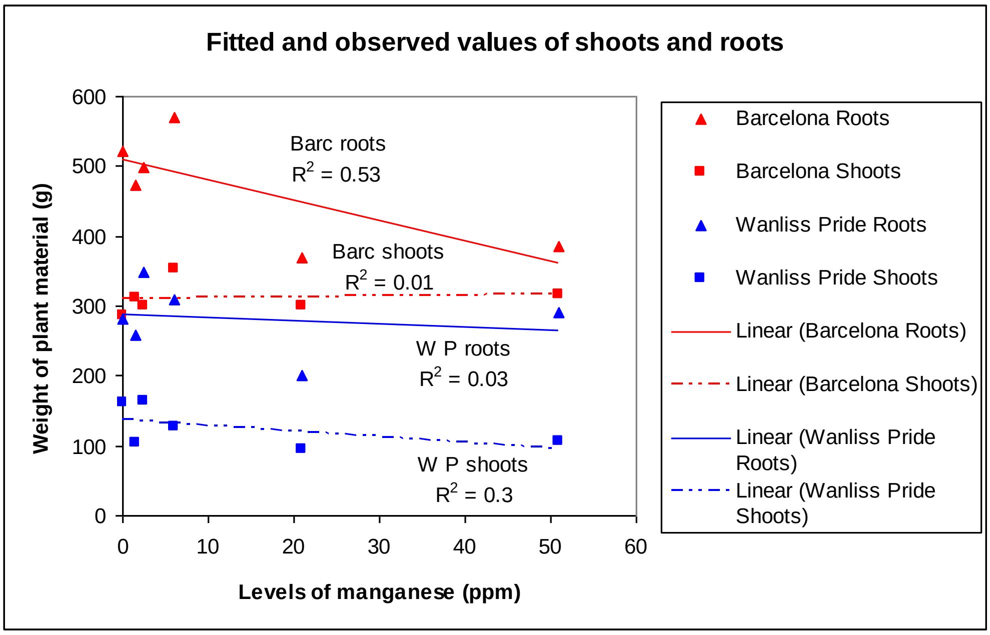


Figure 4.11 Relationship between levels of manganese and the mean weights of shoots and roots for the cultivars 'Barcelona' and 'Wanliss Pride'

There could be a number of reasons why there did not appear to be any response to the manganese treatments, viz:

- There was insufficient replication of the treatments;
- The rates of manganese were too low, although 50 ppm is quite high;
- The manganese treatments were not applied from planting. They were applied when the plants were established in early November, possibly hazelnut plants are most sensitive to manganese when they are developing their new roots immediately after planting;
- The sand was well drained and consequently well aerated; poor aeration and poor root growth might increase the adverse effects of manganese;
- Manganese may damage roots and enhance fungal infections that reduce root function. In a well-aerated soil, like coarse sand, pathogenic fungi may not be active.

Although the results of the experiment were considered inconclusive, they indicated that hazelnut trees do not appear to be highly sensitive to manganese, which is contrary to the initial hypothesis. Future work needs to look at the interactions of manganese, aeration, temperatures and levels at planting, plus possible pathogens, to see what effects occur.

An aspect of interest from this experiment was the huge amount of fibrous root growth from both cultivars in all of the treatments, Plate 4.3, indicating the nature of root growth in a light-textured soil.

Plate 4.3 Mass of fibrous roots produced by plants grown in sand with a nutrient solution 6 months after planting

Physical soil factors

If high levels of manganese were not the reason for the poor growth of ‘Wanliss Pride’ at Orange and no other nutritional effects were apparent, could the poor growth be attributed to physical soil factors?

‘TGDL’ and ‘Negret’ grew poorly at Orange and ‘TGDL’ and ‘Wanliss Pride’ also showed low vigour at Kettering, where foliar levels of manganese were the lowest of all 5 sites, Figure 4.10. Negret’ was not grown at Kettering. ‘TGDL’ is the main cultivar grown in the Langhe region of Italy, where the soils are mainly composed of marine sediments of Tertiary origin, such as marls, silts and sands (Tropeano, 1984). Variable growth of this cultivar was reported by Grau et al (2001) in Chile. In Oregon, ‘TGDL’ was reported to be of much lower vigour than ‘Barcelona’ but was similar to ‘Negret’ (McCluskey et al 1997). ‘Negret’ is the main cultivar grown in Spain, where it grows as a relatively small bushy tree. However, when grafted onto rootstocks of more vigorous genotypes, such as the non-suckering hybrid rootstock of ‘Dundee’, its vigour was increased markedly (Tous et al, 2009). It seems that these cultivars are generally of relatively low vigour. Even at Myrtleford, the site with the highest average growth rates, ‘TGDL’ and ‘Negret’ lacked vigour compared with other cultivars. It appears highly likely that the poor growth of ‘Negret’, ‘TGDL’ and ‘Wanliss Pride’ at Orange and the latter 2 cultivars at Kettering, was due to some physical soil factor, such as the relatively high clay texture of the B horizon at those sites (Table 4.5) and poor drainage in wet years, but this might have been accentuated by a poor up-take of some nutrients.

4.4 General discussion and conclusions

Cultivars

There were significant differences between the hazelnut cultivars in their growth rates. These differences were primarily genetically influenced, as rankings did not change much with climate, soil type or other variations in growing conditions. TCSA was found to be a useful measure of tree growth, correlating with semi-quantitative measures of whole tree growth. Tree growth rates varied between sites, but similar rankings among cultivars occurred across sites. The growth rates of cultivars generally lay on a continuum. Those with high growth rates (high vigour) included ‘Barcelona’, ‘Butler’, ‘Hall’s Giant’ and ‘Segorbe’, which were also reported as being of high vigour by Lagerstedt (1975), Thompson et al, (1978) and Mehlenbacher (1991). In contrast, cultivars with low growth rates (low vigour) included ‘TGDL’, ‘Negret’ and ‘Wanliss Pride’.

The reasons for the variation in rates of growth between cultivars were not evident. While significant differences in tree growth were found, this did not mean that those differences translated into nut yields, as will be investigated in subsequent chapters.

Sites

Sites had a large and significant effect on tree growth. Growth rates varied two-fold, the highest being 20.6 cm^2/annum, the lowest being 9.1 cm^2/annum (Figure 4.6). The reasons for this are unclear. Differences between the sites in temperature and rainfall patterns were considered not to be significant factors. However, there were individual season differences. At 1 site, high moisture stress from very low soil moisture during the period of active shoot growth in October and November resulted in lower growth rates. Excessive moisture in early spring had an adverse effect on growth on the poorly drained soil at Kettering.

The frost damage to trees at Orange indicated the importance of avoiding locations where late frost can occur. It is considered the climatic parameter for the minimum air temperature in October should be -3°C, as recommended by Germain and Sarraquigne (2004). This is discussed further in the next chapter.

Although strong winds were observed to cause some damage to developing shoots and young leaves, wind was not considered to be a major factor contributing to differences in tree growth between sites.

Site differences were considered to be related principally to soil type. It was hypothesised that manganese toxicity may have been a factor influencing tree growth. However a sand culture experiment failed to demonstrate any effect.

The influence of soil texture, soil depth and aeration were not scientifically evaluated, although soil profiles in the top 600 mm of soil were described, including the characteristics of texture, colour, structure, drainage and pH.

The deep, well drained, sandy loam of Myrtleford appeared to be the most suitable soil type for root growth. In contrast, the yellow podzolic soil at Kettering, with the yellow brown clay of its B horizon, was far less suitable, due to poor aeration and drainage. Although the sub-soil at the Orange site was probably better drained than at Kettering, as indicated by its red colour, its heavy texture may have impeded active root growth of the developing hazelnut trees. However, the mottling and manganese nodules indicated poor aeration and waterlogging in some seasons. Average rates of tree growth at this site were similarly low to the Kettering site.

The ratio of top growth to root growth is considered to be relatively constant for a tree species (Westwood, 1993); therefore if a soil is unfavourable to root growth due to poor drainage, poor aeration or heavy texture, the top growth is likely to be restricted, such as occurred at Orange and Kettering, with potential impacts on productivity as discussed in Chapter 7.

There appear to be few specific studies on the growth of hazelnut roots and the effects of soil texture and drainage on root and tree development. It is considered there is a need for such studies in relation to soil type and the influence of root development on tree growth. There is also a need for studies on the uptake of water from the soil under conditions of high temperatures, low humidity and high evaporation.

It is considered that parameters to assess the suitability of soils for hazelnut production, such as those listed in Table 4.3, should be evaluated. There is a need for scientific studies to ascertain the effects of soil texture, structure, root impedance, drainage and aeration on growth rates, particularly in relation to duplex soils.

The relationship between tree growth and nut yields is examined in Chapter 7, Nut yields, yield development and yield efficiency.

CHAPTER 5 - CULTIVAR FLORAL PHENOLOGY

Introduction

The pollination of hazelnuts (*Corylus avellana* L.) occurs during the winter. The plant is monoecious, with separate male and female flowers on the same plant. In winter, the catkins (male flowers) shed their pollen which is carried by the wind. The stigmas of the female flowers (glomerules) become elongated and develop into structures that resemble small red spiders. Pollen landing on these stigmas can pollinate the female flowers.

Bud break, the time when the vegetative buds start to open, occurs in early spring following anthesis (flowering) and marks the beginning of the plant's growing season.

Both the processes of flowering and bud break occur after a period of chilling. This probably causes growth inhibitors in the catkins, the staminate (female) flowers and the vegetative buds to decline to low levels, when other plant regulating compounds can stimulate their development. This chapter examines the development of these plant organs and how they vary with cultivar, time and seasons. The chapter has been written in 2 parts; Part A examines the flowering process and Part B the timing of bud break.

Part A Floral phenology

5.1 Introduction

Hazelnuts are grown for their nuts; an understanding of the processes of reproduction in hazelnut and how these are influenced by environmental conditions is important in evaluating genetic material. The production of female flowers, their successful pollination, subsequent fertilisation and their development are keys to nut yields and productivity, as discussed in Chapter 2, Section 2.2.4 'Reproduction in Hazelnuts' and illustrated in Figure 2.4.

Corylus avellana L. is an anemophilous species with pollen grains being dispersed through the air by light winds and then captured by receptive stigmas. Stigmas can be receptive for up to 2 months (Germain 1994). Only a small percentage of the pollen grains that land on the stigmas produce pollen tubes that reach the base of the style, resulting in pollination.

Flowering generally occurs in winter after a period of chilling to break the dormancy of the catkins and staminate flowers. It is considered that the chill requirements of catkins are generally lower than those for female flowers, (Kavardzhikov 1982, Mehlenbacher, 1991a and Germain 1994). The need for post-chill warmth to stimulate flowering was reported by Barbeau (1972), Kavardzhikov (1980), Mehlenbacher (1991a), Turcu et al (2001) and Tiyaynon (2008). This post-chill warmth was generally considered to be greater for catkins than for female inflorescences.

In a Mediterranean climate, such as SW France and Italy, most cultivars behave in a protandrous manner, (Bergoughoux et al. 1978) and (Manzo and Taponi 1982); that is, catkins shed pollen before female anthesis. However, in more continental climates with colder winters, the degree of dichogamy, that is the period between pollen shed and female anthesis, is less, with many cultivars behaving in a homogamous manner (Germain 1994). Under very cold winter conditions, some cultivars become protogynous, that is female anthesis occurs before catkins shed pollen (Turcu et al. 2001).

Hazelnuts are generally self-incompatible with incompatibility occurring between some cultivars (Germain 1994). Incompatibility is determined sporophytically and depends on a series of alleles at a single locus, S, as discussed in Chapter 2, Section 2.2.4, ‘Reproduction in Hazelnuts’. The incompatibility alleles have been identified and published for a very wide range of cultivars (Mehlenbacher, 1997).

Cultivars vary widely in the number of catkins they form, the amount of pollen they produce and the viability of the pollen (Mehlenbacher 1991b). For a given cultivar, catkin abundance varies from year to year, due to fluctuations in shoot growth and crop load. Cultivars that generally produce many catkins include ‘Hall’s Giant’ and ‘Casina’ whilst ‘TGDL’ and ‘Kentish Cob’ produce few catkins. Some cultivars, such as ‘Daviana’, drop their catkins in autumn or early winter. Other cultivars, such as ‘Negret’, produce little pollen, whilst ‘Barcelona’, ‘Ennis’ and ‘TGDL’ can produce defective pollen (Mehlenbacher, 1991b).

For successful pollination to occur in a cultivar, pollen from a compatible cultivar needs to be shed at the time when the stigmas of the recipient cultivar are exerted and receptive. Therefore, it is important to select genetically compatible cultivars with synchronous flowering to ensure pollination in commercial orchards. As the timing of pollen shed and female anthesis, for any given cultivar, varies with climatic conditions, it is essential to ascertain the floral phenology of cultivars in new regions of production, such as Australia.

This part of the chapter focuses on floral phenology, including observations on the relative abundance of catkins and how this varies between cultivars. The timing and duration of pollen shed and female anthesis is assessed and how this varies between cultivars and seasons. This chapter does not attempt to assess how climate, particularly temperature, might affect these phenomena; these effects are examined in the next chapter, Chapter 6, 'The effect of temperature on floral phenology'.

The key questions to be answered in this chapter are:

- What will be the phenological response of the cultivars being evaluated?
- How will this response vary between seasons and sites?

5.2 Methods

5.2.1 Catkin abundance

The relative number of catkins per cultivar may give some indication of the potential of that cultivar as a pollinator. However, it does not give any indication of pollen viability, numbers, or compatibility. Despite these limitations, an estimate was made of the relative number of catkins per cultivar by giving a relative score 1 (few) to 5 (many), with 5 being the rating for the cultivar that appeared to have the greatest number of catkins at a site in the year of recording, as suggested by Thompson et al., (1978). Relative catkin abundance was estimated for all cultivars at all sites in early winter, before catkin extension. In most cases, ratings of relative catkin abundance were undertaken from the second winter after planting.

5.2.2 Pollen shed

The dates of commencement of pollen shed and female anthesis were recorded at weekly intervals for each cultivar in each year at all 5 study sites. They were first recorded, for most trees, in the second winter after planting. As flowering varied between cultivars, study sites and seasons, and these phenological developments occurred over a period of at least 10 weeks, it was necessary to develop a system that could be used at all sites by the people who were involved in recording these developments. Although pollen shed could be considered to have commenced when a few catkins were shedding pollen, the commencement of pollen shed was recorded as the date when about 10% of the catkins, for a given cultivar, had started to shed pollen.

Plate 5.1 Extended catkins at pollen shed. To the left of the catkins is a female flower with fully exerted red stigmas. Female inflorescences are compound buds, with a lower vegetative part.

The end of pollen shed was harder to define than the beginning, as catkins slowly lose their pollen, making it difficult to be precise as to when they have finished shedding pollen. To try to overcome this problem, it was decided to record the end of pollen shed as the date when it was estimated that less than 10% of the catkins were still shedding; the remainder having shed all their pollen. The duration of pollen shed was between the dates of commencement and completion.

5.2.3 Female anthesis

Records were kept of the development of female flowers. As with catkins, there was a similar problem in defining the start of female anthesis; that is when female flowering had commenced, as potential female flowers are indistinguishable from vegetative buds. The date when several female flowers were visible, with fully-extended stigmas as in Plate 5.1, was considered to be the beginning of female anthesis. It was not possible to describe this in percentage terms of receptive flowers as female flowers are not visible before they exert their stigmas. The end of anthesis was recorded as the date when the stigmas of most flowers were desiccated and there were few flowers remaining with exerted stigmas. This end point tended to be unclear as, towards the end of anthesis, stigmas had a withered, dark purple appearance. The recorded dates provided an estimate of the commencement and duration of female anthesis. The difference in dates for the commencement of pollen shed and female anthesis were used to determine the relative degree of protandry, measured in days.

5.3 Results

5.3.1 Catkin abundance

The mean relative number of catkins for each cultivar was calculated for each study site, based on 4 years of records. An overall mean for all sites was determined, Table 5.1. Cultivars that consistently had a very high number of catkins across sites and seasons included ‘Hall’s Giant’ (‘Merveille de Bollwiller’ syn.), ‘TBC’ (‘Tokolyi/Brownfield Cosford’), ‘Victoria’, ‘Woodnut’ and ‘Square Shield’. These scored an average of more than 4 points (maximum of 5 points). However, there were many other cultivars that scored an average of greater than 3 out of 5. There was generally little difference in the relative number of catkins for a given cultivar between sites.

At the other end of the scale, ‘Wanliss Pride’, ‘Tonollo’ and ‘TGDL’ produced few catkins. Data was only available for ‘Kentish Cob’ from the Kettering site, where it had regularly produced a high number of catkins, although Mehlenbacher (1991b) reported this cultivar as a poor producer of catkins. ‘Jemtegaard 5’ was only grown at 1 site, Orange, but produced many catkins late in the season with an average rating of 3.6. Seven cultivars scored an average of more than 3.5 out of the maximum score of 5, Table 5.1.

Table 5.1 Mean values for relative catkin abundance (1=few - 5=many) produced by cultivars over a period of 4 years at all sites.

Cultivars	**Overall Mean (Max 5)**	**Orange**	**Moss Vale**	**Myrtleford**	**Toolangi**	**Kettering**
Cultivars with data from all 5 sites						
‘TBC’	4.5	4.0	4.8	4.0	4.8	4.8
‘Hall’s Giant’ (1)	4.2	4.2	4.3	3.6	4.5	4.7
‘Victoria’	4.2	4.3	3.3	4.3	4.5	4.8
‘Square Shield’	4.0	3.9	2.5	4.1	4.8	4.7
“Sicilian-type”	3.8	3.6	4.0	2.5	4.3	4.5
‘Willamette’	3.4	3.2	4.3	3.3	0.0	2.8
‘Eclipse’	3.4	3.8	1.5	3.4	3.8	4.5
‘Ennis’	3.1	4.1	4.0	2.8	1.5	3.3
‘Lewis’	3.1	3.7	2.7	3.0	0.0	3.2
‘Tonda di Giffoni’	3.0	3.3	3.0	2.5	3.5	2.7
‘Segorbe’	2.9	3.8	3.5	3.8	1.8	1.5
‘Barcelona’	2.6	3.0	3.8	2.1	1.8	2.2
‘TGDL’	2.1	2.0	1.3	1.0	3.8	2.3
‘Wanliss Pride’	2.0	1.4	3.5	1.0	2.3	1.8
Cultivars with limited data						
‘Woodnut’	*4.0*	*3.1*	-	-	-	*5*
‘Royal’	*3.6*	*3.7*	-	*3.0*	-	*4.2*
‘Montebello’	*3.4*	-	-	*2.6*	-	
‘Casina’	*3.2*	*3.4*	*4.3*	*3.1*	*2.0*	
‘Hammond#17’	*2.8*	*2.5*	-	*1.5*	-	*4.3*
‘Atlas’	*2.7*	*3.0*	*1.8*	*1.8*	*4.3*	-
‘Daviana’	*2.5*	*4.0*	-	*1.0*	-	-
‘Negret’	*2.4*	*2.3*	-	*2.6*	*2.3*	-
‘Butler’	*2.3*	*2.9*	*2.8*	*1.2*	*2.5*	-
‘Whiteheart’	*2.2*	*1.7*	-	-	-	*2.8*
‘Tonollo’	*2.0*	*2.5*	-	*1.5*	-	-

Note: (1) ‘Hall’s Giant’ is synonymous with ‘Merveille de Bollwiller’; there was very little difference between the 2 clones in catkin abundance

‘Daviana’ dropped some of its catkins in autumn in some seasons; this loss seemed to be greater when the autumn was warm and dry. ‘Hall’s Giant’ also dropped catkins in the dry autumn of 2005. Mehlenbacher (1991b) reported that warm temperatures in early winter can cause catkin drop in some cultivars, such as ‘Daviana’ and ‘TGDL’, but did not report it for ‘Hall’s Giant’.

The scores of the relative number of catkins only provide an estimate of the apparent potential pollen-producing qualities of cultivars; they do not give information on the total production of pollen or pollen viability. Differences in the appearance of catkins were observed; ‘TBC’, ‘Segorbe’ and ‘Lewis’ had large catkins and appeared to produce large quantities of pollen, whereas ‘Tonda di Giffoni’ had relatively small, thin catkins.

5.3.2 Floral phenology at the Orange site

The 2 main factors influencing floral phenology at the Orange site were cultivars and the years in which the data was collected. The years represented varying seasonal conditions, most likely representing different temperature patterns. Analyses of variance were conducted on dates expressed as the day of the year (DOY) to the commencement of pollen shed and female anthesis, along with the duration of flowering (days) for 16 cultivars over 7 years at the Orange site. The degree of protandry was calculated annually from the difference in the dates between the commencement of pollen shed and female anthesis. Significant differences ($P<0.001$) were found between the cultivars in the number of days to the commencement of both pollen shed and female anthesis, the duration of flowering and the degree of protandry (Table 5.2). There was a significant difference between years (seasons) in the mean dates to the start of pollen shed and female anthesis for the cultivars and the duration of flowering. There were no significant interaction effects between cultivars and years.

Table 5.2 *F* values from an analysis of variance on floral phenology of 16 cultivars over 7 years (1999-2005) at the Orange site

	Start of pollen shed	**Duration of pollen shed**	**Start of female anthesis**	**Duration of female anthesis**	**Degree of protandry**
Cultivars	<0.001	<0.001	<0.001	<0.001	<0.001
Years	<0.001	<0.001	<0.001	<0.001	<0.001
Cultivars x years	N.S.	N.S.	N.S.	N.S.	N.S.

Note: N.S. Not significant P> 0.05

Cultivar effects on flowering

Pollen shed

The mean day of the year (DOY) to the commencement of pollen shed for the 16 cultivars, for which there was 7 years of data, ranged over a period of nearly 10 weeks. The earliest was ‘Tonda Gentile delle Langhe’ (‘TGDL’), commencing on 6 June (DOY 157) to the latest, ‘Hall’s Giant’ commencing on 14 August (DOY 226), Figure 5.1. All of the other cultivars appeared to lie on a continuum of dates between these 2 cultivars.

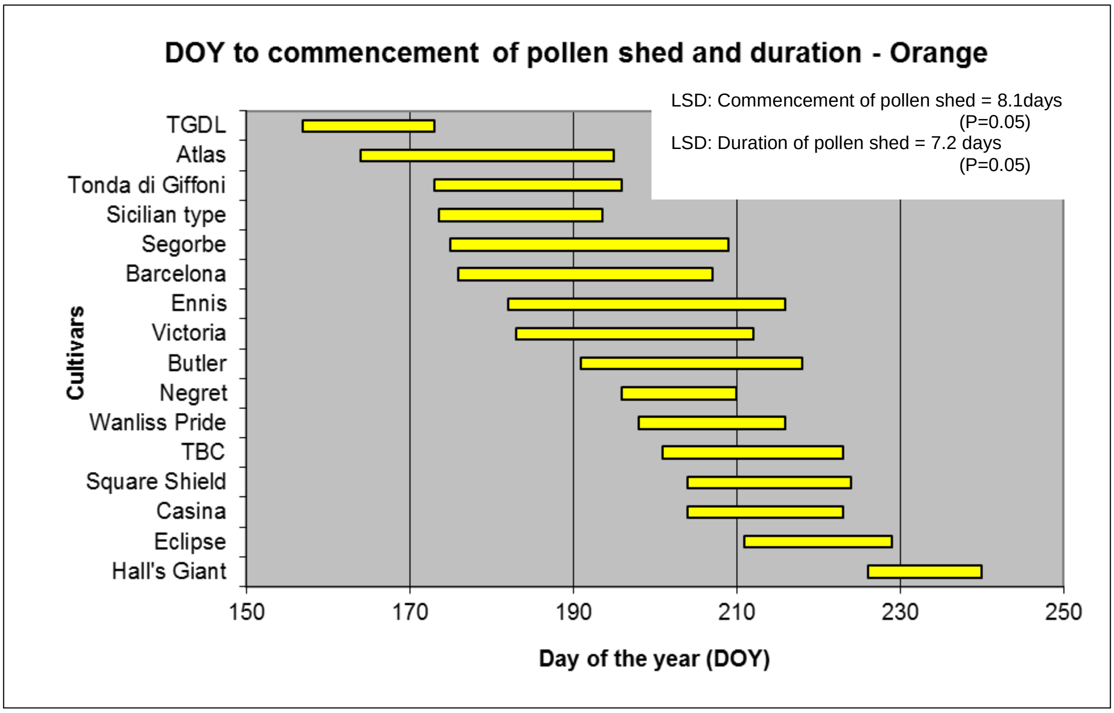


Figure 5.1 Average day of the year (DOY) to the commencement of pollen shed for 16 hazelnut cultivars grown at Orange over the period 1999–2005
Note: The left hand end of the yellow bars indicates the commencement of pollen shed and the length indicates the duration. The day of the year is the number of days from 1st January ie, May 31st = Day of the Year (DOY) 151

As there was no interaction effect between cultivars and years, the sequence of pollen shed was consistent between the cultivars across the 7 different seasons. This is very important for the selection of pollinisers, as it provides a high level of predictability of the relative date, compared with other cultivars, when pollen will be shed for a given cultivar.

Female anthesis

The commencement of female anthesis for the 16 cultivars ranged from the earliest, DOY 185 (4 July), for ‘Atlas’, through to the latest DOY 240 (28 August) for ‘Ennis’ and ‘Hall’s Giant’, Figure 5.2. These latest cultivars were 55 days later than ‘Atlas’. The date of commencement of female anthesis of ‘Square Shield’ was not significantly different from ‘Ennis’ and ‘Hall’s Giant’ (P = 0.05). The dates for the commencement of female anthesis seemed to lie on a continuum (Figure 5.2) as they did for the commencement of pollen shed, but the order was different.

The earliest cultivar to commence female anthesis, ‘Atlas’, was significantly earlier than the next earliest cultivars ‘Tonda di Giffoni’ and ‘Wanliss Pride’, Figure 5.2.

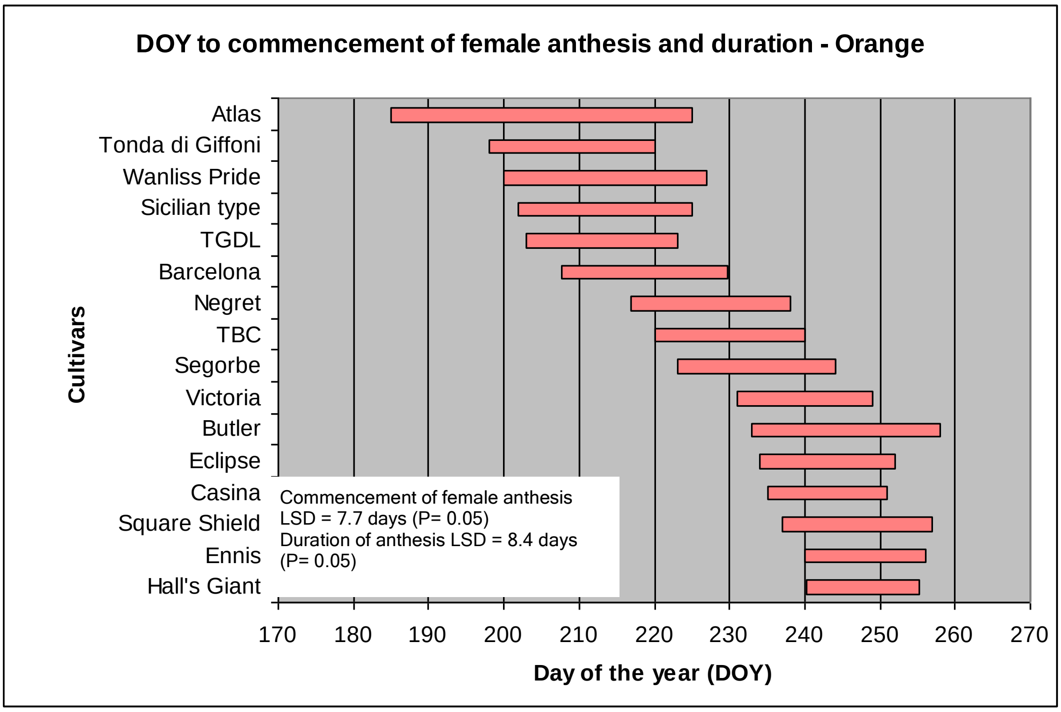


Figure 5.2 Average day of the year to the commencement of female anthesis for 16 cultivars grown at Orange over the years 1999 – 2005.
Note: The left hand end of the bars indicates the commencement of female anthesis and the length, its duration

There were significant differences (P=0.01) between cultivars in the duration of female anthesis. The longest mean period was 40 days for the cultivar ‘Atlas’; the shortest was on average only 20 days for the cultivars ‘Hall’s Giant’, ‘Casina’ and ‘Ennis’, Figure 5.2.

As there appeared to be a relationship between the date of commencement of female anthesis and its duration in Figure 5.2, a regression analysis was conducted on these 2 variables. The linear relationship was highly significant (P=0.01) accounting for 73% of the variation, Figure 5.3.

It was found that the later the date that cultivars commenced female anthesis, the shorter the period of time the stigmas were exerted. It is considered this was possibly an environmental effect related to the degree of chilling received by the cultivars that were late into female anthesis. The later the cultivars commenced flowering, the greater the chilling they would have received, which might have stimulated a more synchronous development of their female flowers.

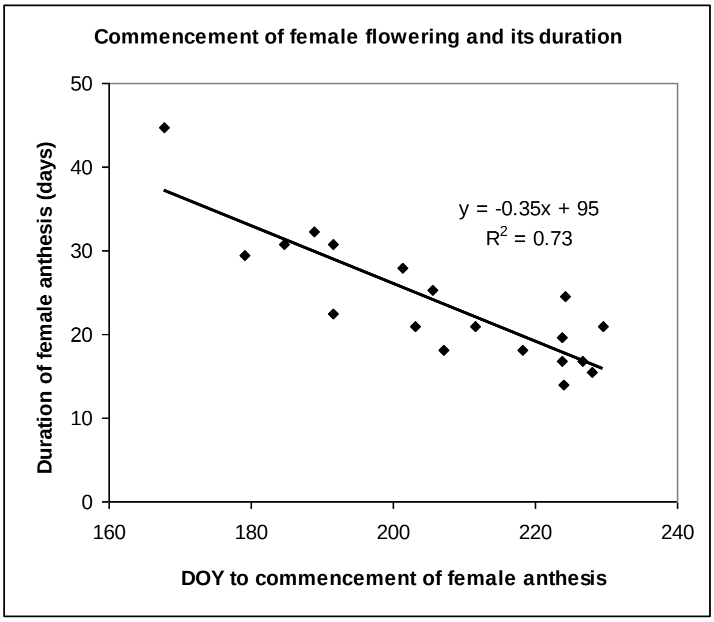


Figure 5.3 Relationship between the duration of female anthesis (days) and the day of the year anthesis commences

Regression analyses were conducted on the relationship between the date of commencement of pollen shed and its duration. In this case, no significant linear or quadratic relationships were obtained.

Protandry

At Orange, on average, all the cultivars behaved in a protandrous manner; that is the catkins commenced pollen shed before the stigmas were exerted from the female inflorescences. 'Ennis' exhibited the highest degree of protandry with pollen shed commencing, on average, 59 days before female anthesis. 'Wanliss Pride' was the least protandrous, with pollen shed commencing, on average, just before female anthesis (Figure 5.4), it was almost homogamous.

As with other floral characteristics, the cultivars appeared to lie on a continuum ranging from highly protandrous to almost homogamous. This data indicates that the onset of anthesis for catkins and female flowers operates independently suggesting different requirements for these organs. Mehlenbacher (1991a) reported no relationship between the dates of commencement of pollen shed and female anthesis for a wide range of cultivars in Oregon, supporting this hypothesis. The chill and post-chill heat requirements of catkins and female flowers are discussed in the next chapter, Chapter 6.

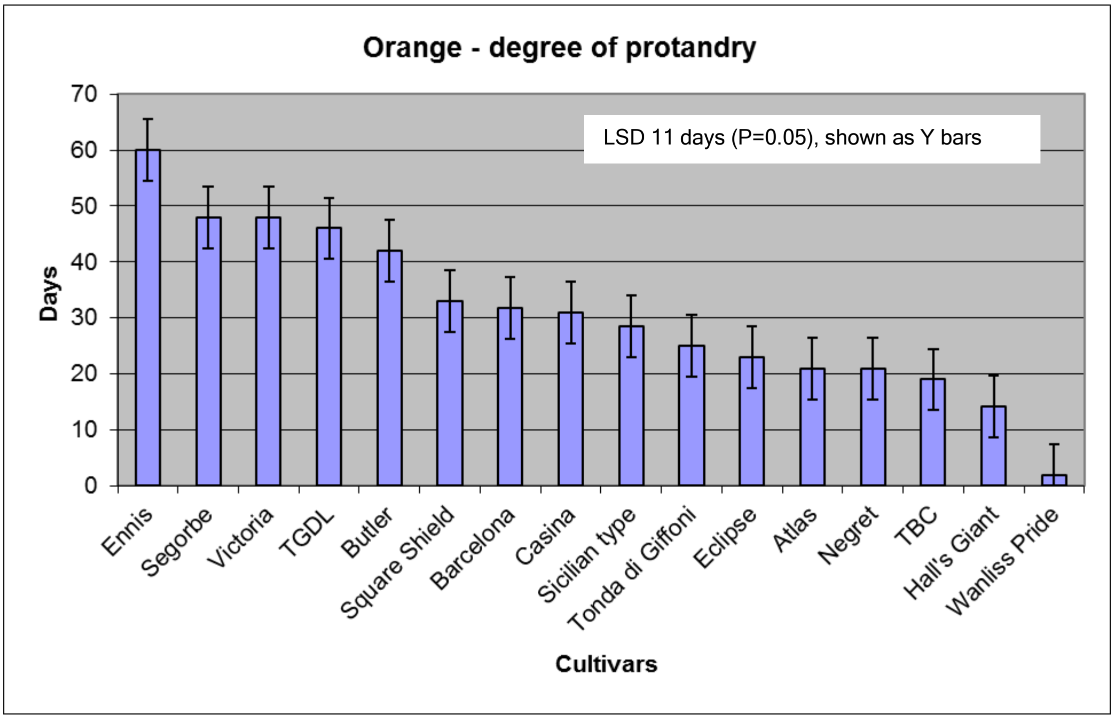


Figure 5.4 Average number of days that catkins commenced pollen shed before the commencement of female anthesis, protandry

Although Figures 5.1 and 5.2 show the days when pollen shed and female anthesis commenced and Figure 5.4 shows the degree of protandry, they do not show how these processes are integrated. The combination of days when both pollen shed and female anthesis commenced and the duration of these processes are shown in Figure 5.5. Graphs, such as Figure 5.5, are very valuable in the selection of polliniser cultivars for main crop nut-bearing cultivars in a commercial orchard, when combined with information on their incompatibility, S-alleles. This is discussed in the final chapter after the presentation of yield data and kernel quality in Chapters 7 and 8, respectively.

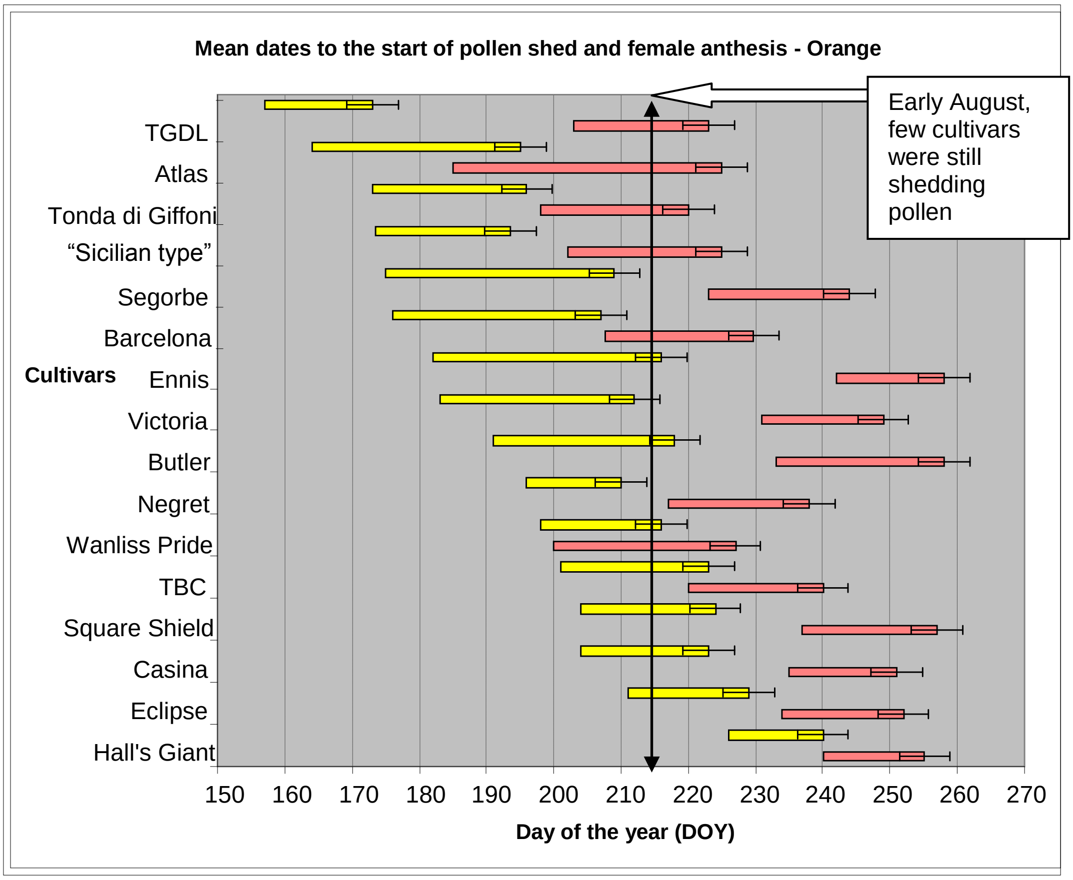


Figure 5.5 Mean day of the year when pollen shed and female anthesis commenced, for 16 cultivars grown at Orange over the years 1999-2005, along with the degree of protandry
Note: The length of the T-bars indicates the standard errors for both the duration of pollen shed and female anthesis.
Pollen shed 🟨 *Female anthesis, exerted stigmas* 🟧

Many of the cultivars studied had shed most of their pollen by the beginning of August, DOY 213, yet there were several cultivars that did not have many flowers with exerted stigmas before that date, such as ‘Segorbe’, ‘Butler’ and ‘TBC’, Figure 5.5.

Several cultivars that were late shedding pollen, such as ‘Jemtegaard 5’ and ‘Kentish Cob’, were not available in the initial year of planting but were planted later in the surrounding border rows at the Orange site. Data on the floral phenology for these later-planted cultivars was collected in the years 2003–2005 and is presented in Figure 5.6, along with ‘Barcelona’ and ‘Hall’s Giant’, as comparisons of early and late pollen-shedding cultivars.

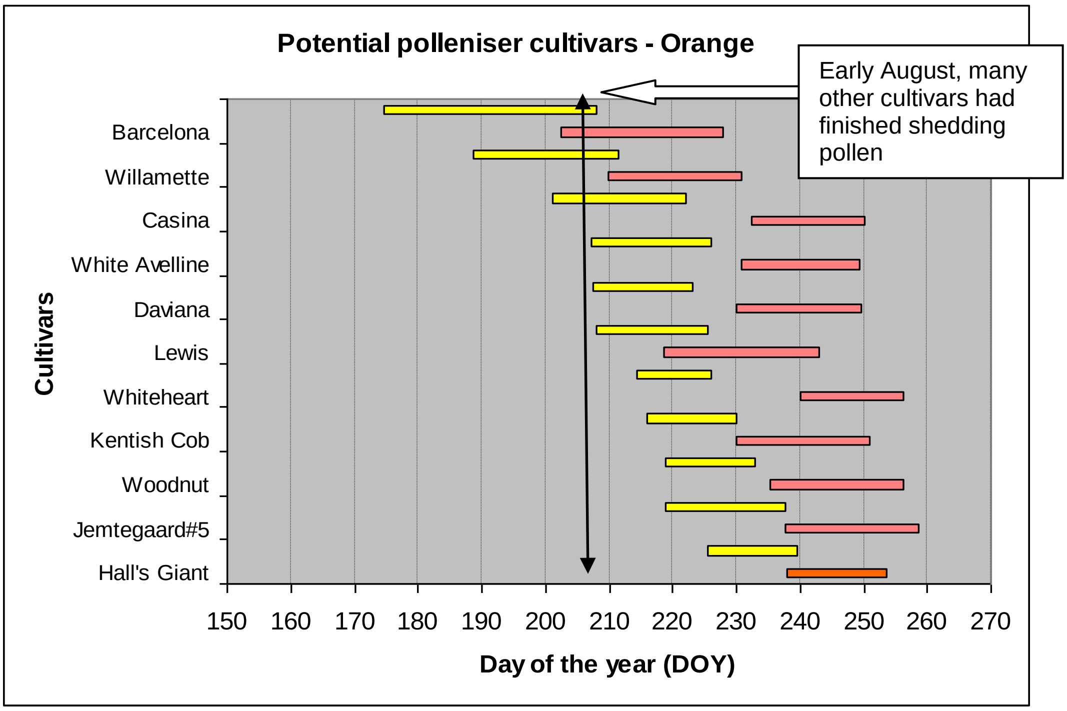


Figure 5.6 Mean day of the year when pollen shed and female anthesis commenced, for some potential polliniser cultivars grown at Orange, over the years 2003-2005, along with the duration of pollen shed and female anthesis. This is compared with 'Barcelona' which commences female anthesis in mid-season.

Mehlenbacher (1991a) reported dates for the start of pollen shed and when stigmas were first noted to be exerted, for a range of cultivars in Oregon, including 11 of the cultivars in this study. His results were similar to those reported herein; 'Tonda di Giffoni' was early into female anthesis with 'Casina' and 'Hall's Giant' being late in both locations. Tiyayon (2008) reported similar results, in Oregon, to these where 'TGDL' was very early in pollen shed, 'Barcelona' was mid-season and 'Hall's Giant' was late.

Seasonal effects on flowering

The analysis of variance (Table 5.2) conducted on the dates to the commencement of pollen shed and female anthesis and their duration (days) for 16 cultivars at Orange over the period (1999-2005) showed significant differences (P<0.001) between years in all these characteristics. However, there were no significant interactions. The earliest mean date for pollen shed was DOY 162 in 2003, the latest was some 40 days later in 2004 (Table 5.3).

Table 5.3 Seasonal differences in the mean day of the year for the commencement of pollen shed and female anthesis for 16 cultivars grown at Orange, over the years 1999 – 2005.

	Earliest year		**Latest year**		**Range**	**LSD**
	Year	DOY	Year	DOY	**(days)**	**(P=0.05)**
Start pollen shed	2003	162	2004	202	40	5.4
Start female anthesis	2003	208	2005	231	23	5.1

Note: LSD for the comparison between years derived from the ANOVA, Table 5.2

There was a greater range in the mean day to the commencement of pollen shed (40 days) than the commencement of female anthesis (23 days), over the 7 years of observations, Table 5.3. The factors causing these differences in the dates to the commencement of pollen shed and female anthesis are not readily apparent; it is likely they are related to differences in temperature patterns relating to chilling and post-chill warmth between the seasons. The effects of temperature on the floral phenology of hazelnuts are discussed in Chapter 6.

5.4 Floral phenology across four sites

An analysis of variance was done on the mean dates for the commencement of pollen shed and female anthesis of the 9 cultivars that were common to 4 sites, Orange, Moss Vale, Myrtleford and Toolangi, over 4 years (1999-2002), Table 5.4. Kettering was excluded as this site was planted later than other sites.

Table 5.4 Analysis of variance on floral phenology of 9 cultivars over 4 years (1999-2002) at the Orange, Moss Vale, Myrtleford and Toolangi sites, with levels of significance

	Start of pollen shed	**Duration of pollen shed**	**Start of female anthesis**	**Duration of female anthesis**
Cultivars	<0.001	<0.001	<0.001	<0.001
Sites	<0.001	<0.001	<0.001	<0.001
Cultivars x sites	<0.001	N.S.	N.S.	N.S.

Note: N.S Not significant

The only significant interaction was between cultivars and sites for the DOY to the commencement of pollen shed. Over the 4 years, the sequence in which the 9 cultivars commenced pollen shed was very similar for all the sites, Fig 5.7. The “Sicilian type” and ‘Tonda di Giffoni’ were the earliest to commence pollen shed at all sites and ‘Hall’s Giant’ was the latest. However, at Moss Vale and Toolangi, ‘Segorbe’ was recorded as commencing pollen shed at a significantly later date than ‘Barcelona’, whereas at Orange there was no significant difference between them.

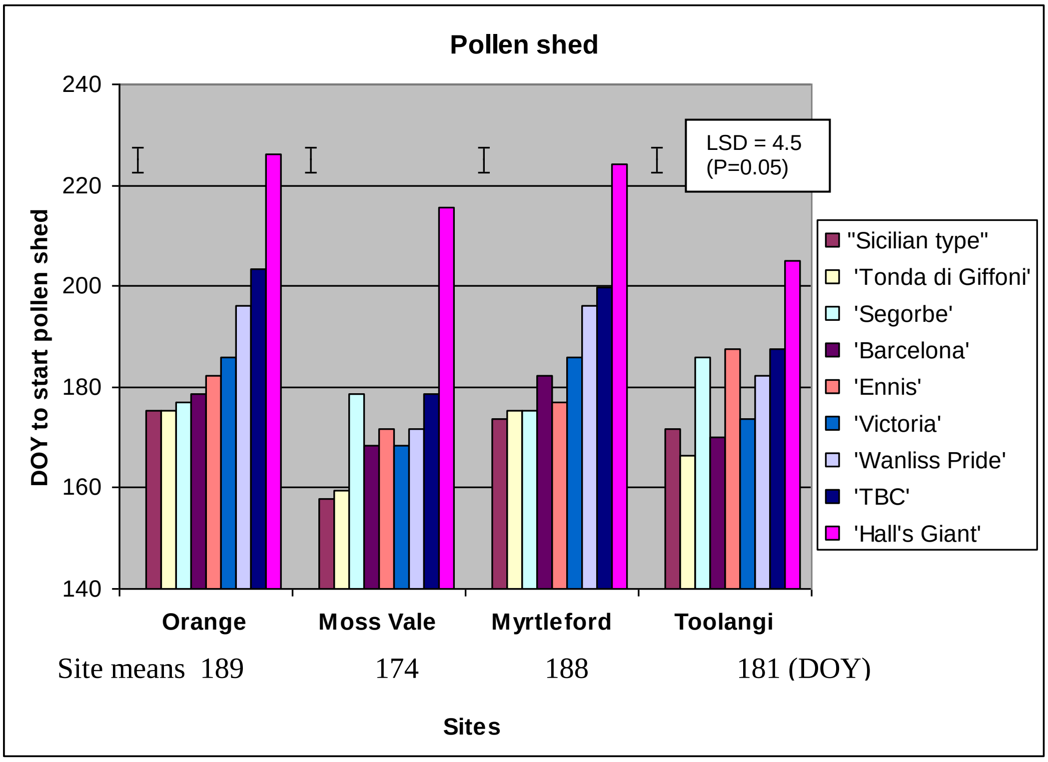


Figure 5.7 Mean dates (DOY) to the commencement of pollen shed for 9 cultivars at the Orange, Moss Vale, Myrtleford and Toolangi sites in the years 1999-2002.

At Toolangi, ‘Ennis’ was recorded as commencing pollen shed significantly later than ‘Victoria’, whereas at the other 3 sites, there was no significant difference between them. As these discrepancies in the order of pollen shed were minor, less than the 7-day period between making observations of development, it is possible that they were due to differences in observer interpretation of the stages of floral phenology, rather than a true effect.

On average, pollen shed occurred 10-14 days earlier at Moss Vale than at the other 3 sites. Female anthesis commenced 20 days earlier at Moss Vale than Orange and Myrtleford, but was not significantly different from Toolangi. It is likely these differences were associated with different temperature patterns between the sites rather than effects from other factors, as discussed in the next chapter.

5.5 Cultivar summary – floral phenology

The main factors that influenced the commencement of pollen shed and female anthesis and the duration of these processes were related to cultivars and seasonal conditions. Differences between cultivars are considered to be related to their differing chill requirements to terminate dormancy and commence flower development (Kavardzhikov 1982, Mehlenbacher 1991 and Germain 1994) and to their post-dormancy heat unit requirements for the further development of these floral structures (Barbeau 1972, Kavardzhikov 1982, Mehlenbacher 1991, Turcu et al 2001 and Tiyaynon 2008).

There was a relatively predictable sequence of dates in which cultivars commenced both pollen shed and female anthesis across sites and seasons. The order in which cultivars commenced pollen shed ranged from ‘TGDL’ (the earliest) to ‘Barcelona’, (early) ‘Casina’ (late) with ‘Hall’s Giant’ being the latest. Similar sequences in flowering were reported by Bergoughoux et al. (1978) in France, Santos and Silva (1994) in Portugal and Mehlenbacher (1991a) in Oregon. The order in which cultivars commenced female anthesis was highly predictable, ‘Tonda di Giffoni’ was early and ‘Hall’s Giant’ was late.

As the relative dates that pollen shed and female anthesis commenced is cultivar-related, this data was used as an aid in cultivar identification (Appendix A).
The cultivars generally behaved in a protandrous manner. Protandry was also reported in areas with relatively mild winter temperatures, similar to the study sites, such as southern France (Germain, 1994), Italy (Manzo and Taponi, 1982) and Oregon (Mehlenbacher, 1991a). There was a continuum in the degree that the cultivars were protandrous under the climatic conditions experienced, ranging from highly protandrous cultivars to those that were almost homogamous. Variation in protandry was interpreted as an indication that the onset of anthesis, for catkins and female flowers, operates independently with different levels of chilling and post-chill warmth for these organs. Mehlenbacher (1991a) considered that, within cultivars, the staminate and pistillate flowers had different chill requirements.

The dates for the commencement of flowering were affected by seasons and locations, but the flowering sequence did not seem to vary between seasons and study sites. Seasonal conditions, particularly temperature, were reported by Bergoughoux et al. (1978) and Germain (1994) to influence the commencement of pollen shed and stigma exertion. The differences in the commencement of flowering between the locations were probably a reflection of differing temperatures rather than other environmental differences, such as soil type. The chill and post-chill heat requirements of catkins and female flowers are discussed in Chapter 6.

Many of the cultivars studied had shed most of their pollen by the beginning of August (DOY 213) yet several cultivars did not have many flowers with exerted stigmas before that date. This could have implications for pollination and nut production, as discussed in Chapter 7, ‘Nut Yields’. The diversity in times of pollen shed and female anthesis would probably have been beneficial to the species in the wild by producing a range of ecotypes that fitted into a diverse range of winter climatic niches. Some ecotypes may have had flowering patterns that avoided periods when staminate and pistillate flowers could have been damaged by frost, enabling these ecotypes to be fruitful.

As the sequence that cultivars commenced flowering was relatively predictable across sites and seasons, the data obtained on floral phenology, combined with published information on the S-alleles (Mehlenbacher, 1997) should make it possible to select cultivars for effective cross-pollination for cultivars selected for nut production. This is discussed in the final chapter (Chapter 9, ‘Conclusions’) which integrates aspects of growth, nut yield, kernel quality and floral phenology.

Part B Bud break

5.6 Introduction

Bud break and leafing out closely follow flowering in hazelnuts. This marks the beginning of active growth. Dates of bud break vary between cultivars and seasons. For example, in Oregon, bud break occurs from late February to early April for hazelnuts, depending on the cultivar (Mehlenbacher, 1991).

As newly-developing leaves on hazelnut trees can be affected by late spring frosts, (Mehlenbacher 1991b, Cakirmelikoğlu and Caliskan, 1997) knowledge of dates of bud break is important, particularly for new regions of production.

5.7 Methods

Bud break was recorded at all sites in all seasons when bud scales were just beginning to expand or open, showing the green of the enclosed leaves, Plate 5.2. This method of data collection was explained to the field staff and collaborating growers, who monitored developments in floral phenology and bud break of the cultivars. Occasional visits were made to the sites in winter to validate the methods being used. The author collected all of the data at the Orange site.

Plate 5.2 Hazelnut bud at the bud break stage in spring

5.8 Results

An analysis of variance was conducted on the recorded day of bud break for 9 cultivars grown at 4 sites, Orange, Moss Vale, Myrtleford and Kettering, over a period of 5 years (2000-2004). There were significant differences between cultivars, sites and years, with a significant (P=0.01) interaction between sites and years (Table 5.5). It is considered that the site x year interaction effect was associated with different temperature patterns between sites and seasons influencing the commencement of bud break. Although this interaction was significant, the main effects of cultivars and seasonal conditions (sites and seasons) were considered to be the most important.

Table 5.5 Analysis of variance on the day of the year to bud break for 9 cultivars at 4 experimental sites over 5 years (2000-2004)

Factors	**Level of significance**
Cultivars	<0.001
Sites	<0.001
Years	<0.001
Cultivar x sites	(N.S)
Cultivar x years	(N.S)
Sites x years	0.01

Note: N.S., Not significant F value > P = 0.05

5.8.1 Cultivar effects

There were significant differences between the cultivars in the mean dates of bud break. The cultivars that were earliest into bud break were ‘Tonda di Giffoni’, followed by ‘Wanliss Pride’ and the “Sicilian type” (Figure 5.8); the latest were ‘Ennis’ and ‘Hall’s Giant’.

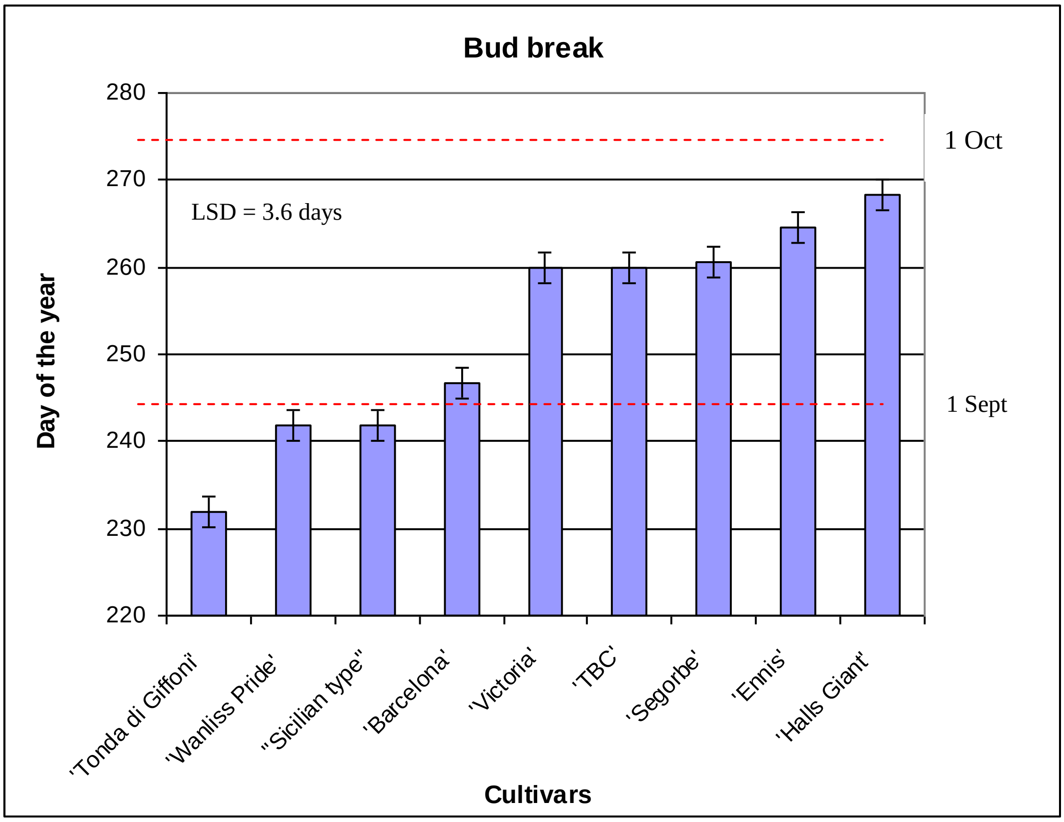


Figure 5.8 Mean day of the year of bud break for 9 cultivars at 4 sites (Orange, Moss Vale, Myrtleford and Kettering) over 5 years (2000-2004)

On average, across all sites and seasons, bud break for the cultivar ‘Tonda di Giffoni’ occurred on 20 August (DOY 232). In contrast, ‘Hall’s Giant’, the latest cultivar into bud break, was on 22 September (DOY 268), about 1 month later than ‘Tonda di Giffoni’. The sequence of dates that the cultivars came into bud break was similar to those reported by Thompson et al. (1978) in Oregon.

Plate 5.3 Phenological differences in the time of bud break are quite marked between the earliest and latest cultivars. The early leafing cultivar 'Lewis' (left) is well into leaf in early October compared with 'Hall's Giant' (right).

5.8.2 Years and sites

The variation between years in the mean day to bud break was small, a range of only 6 days, whereas there was a greater variation between sites. On average, bud break was earliest at Kettering (DOY 247) compared with Orange (DOY 262), Table 5.6.

Table 5.6 Mean day of the year (DOY) and date of bud break for 9 cultivars at 4 sites over a period of 5 years (2000-2004)

	Sites				**LSD P=0.05**
	Orange	**Moss Vale**	**Myrtleford**	**Kettering**	
Mean DOY to bud break	262	254	249	247	2.4
Mean date of bud break	19 Sept	11 Sept	6 Sept	4 Sept	

The cause of the difference between sites is unclear; it could be a response to temperature or daylength or a combination of the 2 as discussed in the next chapter.

As the main differences in dates of bud break were between cultivars and sites with no significant interactions between cultivars and years or cultivars and sites, the data on cultivars was combined for 3 sites, Orange, Myrtleford and Kettering. This provided mean dates of bud break across these sites for a total of 27 cultivars, which was used as an aid in cultivar identification, Appendix A.

5.8.3 Frost effects

In locations with mild spring environments, early-leafing cultivars might have an advantage with a longer growing season. However, newly-developing leaves on hazelnut trees can be damaged by late spring frosts (Bergoughoux et al., 1978, Mehlenbacher, 1991a and Cakirmelikoğlu and Caliskan, 1997).

In October 2003, severe damage to the buds and young leaves of the trees was observed at the Orange site. Descriptions of these effects and ratings of the severity of the damage (0 nil – 5 severe) were noted for 18 cultivars in all 4 replicates. The effects ranged from none, for the cultivar 'Hall's Giant', to very severe, major damage to newly-developed leaves for the cultivars 'TGDL', 'Tonda di Giffoni' and 'Lewis'. A regression analysis showed the mean ratings of the severity of damage to be negatively correlated with the date of bud break (P> 0.001) in that year. That is, the earlier the date the cultivars were at bud break, the higher the rating of damage (Figure 5.9).

It was considered the damage was related to late frost, as a minimum air temperature of -4.7°C had been recorded at the site on 29 September, when the latest cultivars 'Hall's Giant' and 'Ennis' were observed to be at the bud break stage. Bergoughoux et al. (1978) reported that critical temperatures for frost damage after bud break are in the range -3 to -4°C.

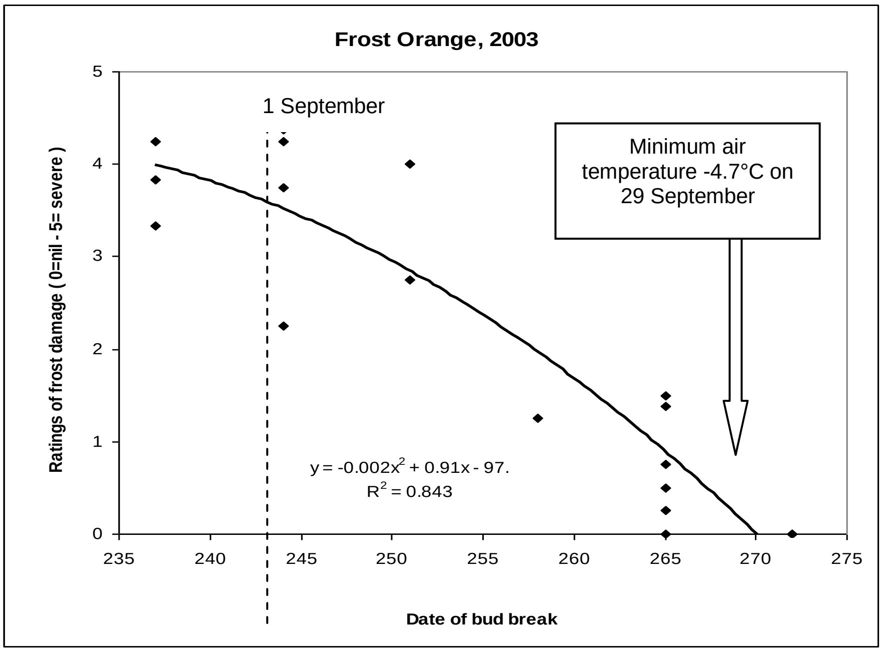


Figure 5.9 Relationship between the degree of frost damage noted at the Orange site in November 2003 and the date of bud break of 18 cultivars.

To obtain further insights into the effects of frost after bud break, a comparison was made of minimum temperatures lower than -3°C after bud break for the early-leafing cultivar ‘Tonda di Giffoni’ at the Orange site over the years 1999-2004, Table 5.7. It appears there were 2 factors that affected frost damage. These were the relative date of the frost after bud break and the severity of the frost. A minimum temperature of -3.5°C, recorded 30 days after bud break of ‘Tonda di Giffoni’ in 2002, did not cause damage, nor did a minimum temperature of -4.1°C, 14 days after bud break in 1999, Table 5.7.

Table 5.7 Latest date that minimum temperatures were recorded below -3°C in the period 1999 – 2004 at the Orange site, compared with the date of bud break for the cultivar ‘Tonda di Giffoni’

	Years					
	1999	**2000**	**2001**	**2002**	**2003**	**2004**
Date of bud break	30 Aug	30 Aug	27 Aug	2 Sept	25 Aug	3 Sept
Latest date temp < -3°C	13 Sept	5 Sept	26 Aug	2 Oct	29 Sept	6 Sept
Temp recorded	-4.1°C	-3.1°C	-4.1°C	-3.5°C	-4.7°C	-4.5°C
Days after bud break	14	6	-1	30	35	3

However, damage was recorded in 2003, when a minimum air temperature of -4.7°C was recorded 35 days after the bud break of the early-leafing cultivar ‘Tonda di Giffoni’. It appears that the critical temperature for frost damage after bud break is about -4°C, as reported by Bergoughoux et al. (1978). The data on the mean dates of bud break can be used as an aid to cultivar selection in areas where late frosts might occur.

Frost damage was not reported at any of the other sites, but none of them recorded temperatures below -2°C after the end of August.

5.8.4 Cultivar summary – bud break

The date of bud break varied between cultivars from late August for ‘Tonda di Giffoni’ to late September for ‘Hall’s Giant’. The date of bud break varied between years and sites but the order in which the cultivars commenced bud break was similar across seasons and sites. The sequence in which cultivars commenced leafing out was similar to that reported by Thompson et al, (1978).

It was considered the dates of bud break were associated with the chill requirements to break dormancy and post-chill warmth to stimulate leaf development. This is discussed further in the next chapter.

Based on observed frost damage at Orange, it is concluded that a climate parameter of a minimum temperature of -3°C following bud break, as recommended by Bergoughoux et al. (1978), is an appropriate critical value for the selection of sites for hazelnut production, as discussed in Chapter 2 (Table 2.1). As in these studies, bud break of most cultivars occurred from the end of August, a minimum temperature of -3°C is recommended as a critical climate parameter for the months of September and October in South-eastern Australia.

The data on the mean dates of bud break can be used as an aid to cultivar selection in areas where late frosts might occur.

5.9 Overall Conclusions

There were quite large differences between the cultivars in the relative number of catkins they produced. About half of the cultivars received a rating of more than 3 out of a maximum of 5 for catkin abundance. This data, along with the results obtained on floral phenology and the literature on genetic compatibility, is valuable in the selection of cultivars as pollinisers.

The data gathered across sites and seasons on the mean number of days to both pollen shed and female anthesis, along with the duration of pollen shed and genetic compatibility, can be used to select appropriate pollinisers for nut-bearing cultivars. This is discussed further in the final chapter of this thesis.

The data on frost effects at Orange and other sites supports the view that a climate parameter of a minimum temperature of -3°C following bud break is an appropriate critical value for hazelnuts that can be used in site selection, as proposed by Bergoughoux et al. (1978).

The effects of chilling and post-chill warmth on the flowering and bud break of hazelnuts are examined further in the next chapter.

CHAPTER 6 - THE EFFECT OF TEMPERATURE ON FLORAL PHENOLOGY AND BUD BREAK

6.1 Introduction

In this chapter, there is some reiteration of the literature on factors affecting floral phenology, from the Literature review, Chapter 2. This short review leads to the development of a hypothesis on the factors affecting flowering in hazelnuts. This hypothesis is subsequently tested, as discussed in this chapter.

6.1.1 Floral development

In the previous chapter it was found that the sequence in which cultivars commenced pollen shed and female anthesis was very similar across seasons and sites. However, there were marked differences between seasons in the date of commencement of anthesis of catkins and female inflorescences for any given cultivar.

Hazelnuts are monoecious, with separate male and female flowers which have different temperature requirements for their development. The main factor influencing the onset of anthesis appears to be related to the particular chill requirements of cultivars to break the dormancy of the catkins and female flowers (Mehlenbacher, 1991). There is also a need for post-chill warmth to stimulate flowering. Barbeau (1972), Kavardzhikov (1982), Mehlenbacher (1991a) and Turcu et al. (2001) considered catkins had lower chill requirements but greater post-chill warmth requirements than female inflorescences. These differences in the chill and post-chill warmth requirements of catkins and female inflorescences could explain why a cultivar can behave in a protandrous manner in mild winter climates and in a protogynous manner where winters are colder, as discussed in Chapter 2, Section 2.2.5. For example, most European cultivars behave in a protandrous manner in maritime climates with relatively mild winters, such as southern France (Germain, 1994), Italy (Manzo and Taponi, 1982) and Oregon (Mehlenbacher, 1991a). However, these cultivars are more commonly protogynous in locations with very cold winter climates, such as Romania (Turcu et al, 2001).

Seasonal differences in the timing of anthesis for a given location are also reported. Bergoughoux et al, (1978) reported that, in the Gironde region of France, the cultivar

‘TGDL’ normally commences pollen shed in the second week of December, but, if the autumn is very mild, pollen shed occurs a little after mid-November. These seasonal differences in the commencement of anthesis of catkins and female inflorescences are presumably due to the same effects of temperatures on anthesis as those temperature differences that occur between various locations.

The differences between seasons and locations could possibly be explained by the following hypothesis. If catkins have low chill requirements and higher post-chill warmth requirements, then, in cold winter environments, pollen shed might be delayed due to a slow accumulation of post-chill warmth. In contrast, if female flowers have higher chill requirements but require little accumulated post-chill warmth to stimulate their development, then in a cold winter environment, their development will be delayed to a lesser extent due to the slow accumulation of post-chill warmth. That is, their stigmas would be exerted before the catkins are extended and shed pollen. Thus, they would be protogynous in the colder winter climate but protandrous in the milder climate.

As endodormancy is controlled by plant growth regulators inside the bud and different types of buds, such as flower and vegetative buds, can be at different stages of dormancy (Tromp, 2005) at the same date, it seems feasible that catkins and female flowers could have different temperature requirements for their phenological development.

In other deciduous fruit and nut trees, there is widespread agreement that a period of chilling is required to break the dormancy of buds, as reported by Richardson et al (1974) on peach, Coullivon and Erez (1985) on apple, cherry, peach and pear, Fekler and Robitaille (1985) on sour cherry, Smith et al (1992) on pecan, Barone and Zappila (1993) on walnut and Rattigan and Hill (1986) and Egea et al (2003) on almond. Post-chill warmth is then required for flowers to develop but the thermal sums for this process vary between species, cultivars and seasons. For example, minimum threshold temperatures for peach and almond are reported to be 2.5°C and 4.5°C respectively (Sedgley, 1990). However, these may be estimates as it is likely that there is a sigmoid response to temperatures with a gradual decline to “threshold” temperatures.
Under conditions where there was prolonged exposure to chilling, the post-dormancy heat requirements were reduced in apple, cherry, peach and pear (Couvillon and Erez, 1985) and (Herter el al., 2000). Studies by Garcia et al (1999) on apricot in 2 differing climatic environments, 1 in Spain, the other in Italy, found that more heat could partially

compensate for a low amount of chilling They found considerable differences between seasons, that were not predicted by models, using a specific number of chill units and growing degree hours for the cultivars.

6.1.2 Dormancy of buds and dormancy release

It is known that in most deciduous woody species, growth ceases in the latter part of summer and terminal buds subsequently form; growth of these buds will not be triggered until some appropriate climatic signal is obtained, typically through winter as chilling (Westwood, 1988). The cessation of growth and development is in response to shortening day-length and a decline in temperature. Tanino (2004) described the process of endodormancy induction as being complex with the path to endodormancy being a continuum, which starts early in autumn. Endodormancy increases during the late autumn and winter, in association with an increase in the level of growth inhibitors such as abscisic acid (ABA). Chilling is required to break or terminate endodormancy, with chill requirements varying depending on species and genotypes. Temperatures in the range 0-7°C appear to favour enzymic reactions that lead to a reduction in the inhibitory systems that influence endodormancy (Westwood, 1988). At the termination of endodormancy, there is a rise in growth promoters relative to inhibitors and a sharp increase in respiration indicating that growth rates are increasing. Endodormancy is commonly followed by ecodormancy, a period when temperatures may be too low for growth or development.

In *Corylus avellana* L., female inflorescences are compound buds, the lower part being vegetative (Germain, 1994). The chill requirements to initiate the development of vegetative buds were reported by Mehlenbacher (1991) to be greater than those of female inflorescences. However, there was a correlation between the chill requirements of the vegetative buds and female inflorescences (ibid, 1991).

Prolonged chilling was reported by Couvillon and Erez (1985) and Heide (1993) to decrease the post-chill warmth required for vegetative bud break in several deciduous species. The base line temperature for post-chill warmth for vegetative bud break of a range of deciduous species was found by Heide (1993) to vary between species but a base value of 0°C was suggested for calculations. All the species studied responded to long days, including *Corylus avellana* L.

Key questions in relation to dormancy are:

- when does endodormancy commence in hazelnut trees?
- what starting date should be used for the calculation of accumulated chill hours to terminate dormancy?

In a study of microsporogenesis in hazelnuts, Tiyayon and Azarenko (2005) found the reproductive developmental process of catkins occurred earlier in those cultivars that were early to shed pollen compared with cultivars that were late to shed pollen. However, all cultivars had produced microspores by 26 September in Oregon (close to the autumn equinox) when catkins were 23-40 mm in length and were considered to be dormant, that is, the catkins were fully developed but required the appropriate stimuli to expand and shed pollen. In the studies in this thesis, calculations for the accumulation of chill were taken from 1 April (close to the autumn equinox), which is equivalent to 1 October in the northern hemisphere. In general, there were few chill hours in March and leaf fall was not significant until the latter part of April. Alonso et al. (2005) used chill units to determine chill requirements of almond and used a starting date when chill units were no longer negative.

Rodriguez and Sanches-Támés (1986) monitored monthly levels of the growth regulating substances indole-3-acetic acid (IAA), abscisic acid (ABA) and total phenolic compounds, in *Corylus avellana* L. buds in Spain. The highest levels of the growth retardant ABA occurred approximately at the onset of dormancy, with the lowest levels just before bud burst. The opposite result was obtained for the growth stimulant IAA, being lowest in autumn, with a sharp increase just before bud break. The proportion of IAA to ABA steadily increased from late autumn (November), with a very rapid increase in IAA in early spring (March).

6.1.3 Hypothesis

It is hypothesised that a similar mechanism controlling the development of vegetative buds influences the development of catkins and female inflorescences. That is, there is a critical balance between two principal growth-regulating substances:

- an *inhibiting* substance – which declines over time due to the effects of chilling.
- a *stimulating* substance – which appears to increase as temperatures rise. It causes catkin extension and the exertion of stigmas, once chilling requirements have been satisfied.

When the levels of the stimulating substances exceed those of the inhibiting ones, pollen shed or female anthesis will commence, Figure 6.1.

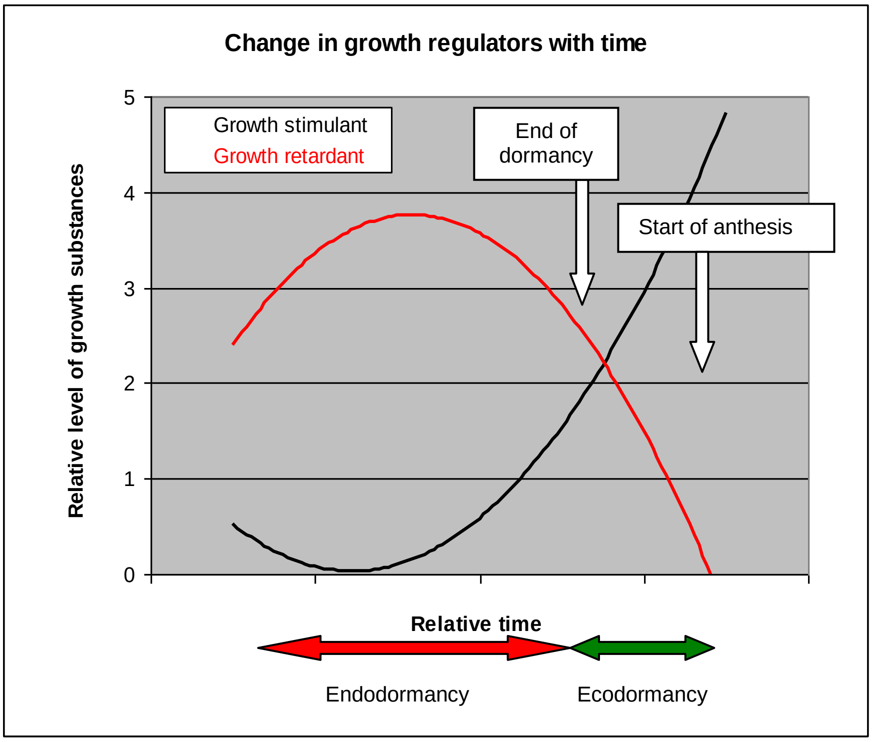


Figure 6.1 Concept of levels of growth regulators influencing flowering in hazelnuts and periods of endodormancy and ecodormancy

If a cultivar requires a certain level of chilling followed by a certain accumulation of post-chill warmth before catkin extension can occur, then, under cold winter conditions, the rate of development of the stimulating substance may be prolonged due to low temperatures and slow accumulation of warmth. Under such conditions, further chilling could lead to further decline in the level of the restraining substance; the amount of the stimulating substance required to overcome dormancy may then be less. That is, less heat units may be required to produce a sufficient level of the stimulant to overcome the lessened effects of the retardant, due to the prolonged chilling, as reported by Couvillon and Erez (1985) for flowering in several fruit species.

Under low winter temperatures, such as in Poland, once hazelnut flowers had received sufficient chill to overcome endodormancy, it was considered they had became ecodormant (Piskornick et al., 2001). That is, they were awaiting suitable temperature conditions or accumulation of warmth for development, as proposed by Fuchigami et al (1982) and Alonso (2005) for almond.

In general, it has been considered that temperatures in the range 0-7°C are required for the chilling requirements of hazelnut. However, Tiyayon (2008) reported chilling occurred in the range 5-15°C, with chill unit (CU) values similar to those developed by Richardson et al. (1974). In seasons or locations where the winter is relatively mild, but sufficiently cool to meet the required minimum amount of chilling, the mild winter temperatures may produce sufficient of the stimulant to lead to pollen shed. This appeared to be the situation at Moss Vale, where winter temperatures were relatively mild compared with the lower winter temperatures of Orange, due to its higher altitude. Pollen shed for a given cultivar generally occurred earlier at Moss Vale than at Orange, as stated in Chapter 5, Section 5.4 ‘Floral phenology across four sites’. Thus, the variation in autumn and winter temperatures between years, with the consequent different levels of chilling and post-chill warmth, could account for differences in dates when pollen shed commenced for a given cultivar or set of cultivars. The relatively cold winter days in Orange were likely to produce a longer period of ecodormancy than at Moss Vale.

As female flowers are borne in vegetative buds, which are distinctly different and separate from catkins, it is considered feasible that the female inflorescences could behave differently from the catkins, although a similar mechanism might apply. As catkins are relatively large organs compared with female flowers, it seems feasible that a greater amount of warmth (thermal time) might be required for the catkins to extend, whereas the stigmas, being quite small, may need relatively less warmth to cause exertion. Tiyayon (2008) considered the optimum temperature for catkin development was 15°C.
Meeting the basic chilling requirements of cultivars appears to be the key factor in releasing them from dormancy. This appears to be genetically determined, thus the

relative sequence of pollen shed and female anthesis, as shown in Chapter 5, Table 5.4 for the cultivars in this study, is predictable over a wide range of sites and seasonal conditions.

The aim of this chapter is to determine how autumn and winter temperatures influence the onset of anthesis of catkins and female inflorescences, by comparing phenological development in temperature-controlled growth cabinets with that in the field.

6.2 Methods

Two experiments were conducted in which temperature-controlled growth cabinets were used to try to determine the chill and post-chill heat requirements for the flowering of 8 cultivars. The experiments were performed using excised shoots from plants grown at the Orange research site. The floral phenology of the cultivars in the growth cabinets was compared with that of the plants in the field. The first experiment was conducted in 2002 using a single Conviron® plant growth chamber operating at a constant temperature of 15°C and then again in 2005 using the same growth cabinet, also at 15°C. The timing of experiments related to when sufficient plant material could be obtained from the field and the availability of the growth cabinets.

In 2002, single shoots that were 300-400 mm long were cut at weekly intervals from 27 May until 29 July from each of 8 cultivars. The cultivars selected (Table 6.1) covered a range of dates when pollen shed and female anthesis commenced; these included the cultivars ‘Atlas’ and ‘Tonda di Giffoni’, that were early into pollen shed, ranging through to the late-shedding cultivar ‘Hall’s Giant’. The shoots were placed in buckets with water to a depth of about 100 mm. The buckets with shoots were placed in the Conviron® plant growth cabinet (Plate 6.1) set at a constant temperature of 15°C (+/-1°C). The day length was set at 10 hours light and 14 hours dark, similar to the photoperiod occurring in the field. A temperature of 15°C was chosen, as it was considered the shoots would be unlikely to receive any further chilling and the minimum chill requirements could be determined from those received in the field prior to cutting. The temperature of 15°C was equivalent to the maximum which could occur on a warm winter’s day, though the average daily temperature at Orange in winter is 5°C. Tiyaynon (2008) considered 15°C was the optimum temperature for catkin extension.

The number of catkins was counted at the time of placement in the growth cabinet. Each week, the number of both the extended catkins and the female inflorescences with exerted stigmas were counted. The water was changed weekly. The cut branches were retained in the cabinet for a period of 5 weeks. It was considered that chill requirements of the flowers had been met when 50% of the catkins had extended or when there were at least 4 female inflorescences with exerted stigmas. Once flowering had occurred in the field, for a given cultivar, shoot cutting was terminated. Although the primary aim of this experiment was related to floral development, some observations were also made on the dates that vegetative bud swell first occurred in the growth cabinet.

Plate 6.1 Cut shoots of hazelnut cultivars in buckets of water in a Conviron® growth cabinet. Some catkins are still closed whilst others are extended and shedding pollen.

Observations of floral development were made in the field at the Orange site to ascertain the dates when 50% of the catkins were shedding pollen and when there were inflorescences with exerted stigmas. This experimental technique was similar to that used by Mehlenbacher (1991a) to determine the chill requirements of hazelnut cultivars in Oregon.

The second experiment was conducted in 2005, in a similar manner to the first. Its purpose was to ascertain whether the results achieved in the first experiment were reproducible. However, in this experiment, 2 shoots of each of the 8 cultivars that were used in the 2002 experiment were cut at weekly intervals from 3 May–16 August. The shoots were 400-500 mm long and 5 mm in diameter. They were placed in buckets of water in the Conviron® growth cabinet, with the same settings as used in 2002.

In both years, the accumulated chill hours (0-7°C), from 1 April to the cutting date when 50% pollen shed was first observed in the growth cabinets, were obtained from the weather station at the Orange site. These chill hours were considered to be the minimum chill requirement to break dormancy. There were very few chill hours recorded before April in either of the years.

Post-chill warmth, thermal time, was calculated in the growth cabinet and in the field from the cutting date when it was considered the chill requirements of the flowers had been achieved. A base temperature of 0°C, as suggested by Heide (1993) for *Corylus* spp, was used to calculate units of "growing degree days" (GDD). In the field, the GDD units were calculated from mean daily temperatures, using a base temperature of 0°C.

6.3 Results and discussion

6.3.1 Pollen shed

The mean minimum number of chill hours to the first cutting date when more than 50% of the catkins shed pollen, that is the break of catkin dormancy of the 8 cultivars, was 565 hours in 2002 and 460 hours in 2005 (Table 6.1). This was a difference of 105 chill hours between the 2 years in the mean dates to the commencement of pollen shed, which were 10 days apart.

The mean day of the year to the commencement of pollen shed for all 8 cultivars occurred earlier for excised shoots in the growth cabinets than for shoots in the field. This date was, on average, 38 days earlier in the growth cabinet compared with that in the field in 2002 and 23 days earlier in 2005 (Table 6.1). Pollen shed commenced earlier in both the cabinets and in the field in 2005, than it did in 2002.

In both years, 'Atlas' and 'Tonda di Giffoni' were the earliest to shed pollen, with the least number of chill hours, and 'Hall's Giant' was the latest, with the greatest number of chill hours (Table 6.1).

Table 6.1 Day of the year (DOY) to the end of dormancy of catkins with recorded chill hours to that date and the DOY to the commencement of pollen shed in the field, along with post-chill heat units for the years 2002 and 2005.

2002 **Cultivars**	**Earliest cutting date (DOY) to 50% of catkins shedding pollen in the cabinet**	**Total chill hours from 1April to initial cutting date of 50% of catkins shedding in the cabinet**	**DOY to 50% of catkins shedding pollen in the field**	**Post chill heat units GDD in cabinet**	**Post chill heat units GDD in field**
'Atlas'	140	365	168	280	216
'Tonda di Giffoni'	147	472	182	420	206
'Barcelona'	154	565	189	315	200
'Segorbe'	154	565	182	420	175
'Casina'	161	619	217	420	284
'Ennis'	161	619	196	210	166
'TBC'	161	619	210	420	235
'Hall's Giant'	168	693	224	420	285
Means	*158*	*565*	*196*	*363*	*221*
2005 **Cultivars**					
'Atlas'	130	258	171	420	335
'Tonda di Giffoni'	137	338	178	420	331
'Barcelona'	144	404	185	525	347
'Segorbe'	144	417	185	525	284
'Ennis'	151	499	192	525	274
'Casina'	158	569	213	525	344
'TBC'	158	569	213	420	354
'Hall's Giant'	165	623	234	630	391
Means	*148*	*460*	*171*	*499*	*336*

The mean level of post-chill warmth required in the cabinet to stimulate at least 50% of the catkins to shed pollen, once endodormancy had been terminated, was greater in 2005 (499 GDD), the year of lower accumulated chill hours, compared with 2002 (363 GDD) (Table 6.1). This compared with an average of 336 GDD in the field in 2005 from the day when minimum chill to break dormancy was achieved until the day when 50% pollen shed commenced, compared with 221 GDD in the field in 2002. It was considered that the lower heat requirements in the field, compared with the growth cabinets, and differences between the years could have been due to the extra chilling received in the field. A reduction in the post-chill heat units following prolonged chilling was reported by Couvillon and Erez (1985) for a number of deciduous tree fruits and Herter et al. (2000)

for peach, with a decrease in total growing degree hours (GDH) for hazelnut (Tiyaynon, 2008).

As cutting dates progressed beyond the end of endodormancy, the amount of post-chill warmth required in the growth cabinets to stimulate pollen shed in the excised shoots decreased to zero, when pollen shed was occurring in the field (Figure 6.1).

Regression analyses were used to investigate the relationship between the DOY when the branches were cut and the estimated post-chill heat requirements in the growth cabinets for the cultivars for each year and for the 2 years combined. There were significant differences (P<0.001) in the linear regressions for the DOY when the shoots were cut and for the cultivars (Table 6.2). In 2002, the slopes of the regression lines of the cultivars were not significantly different from one another, with a mean value of
-8.7. That is, on average, for each day that cutting the shoots was delayed after the minimum chill requirements had been met, the post-chill heat requirements for pollen shed were reduced by 8.7 GDD.

Table 6.2 Levels of significance for variables influencing the post-chill heat unit requirements of pollen shed for 8 cultivars in 2002 and 2005
.

	Years		
Variables	**2002**	**2005**	**Combined**
Cutting dates (DOY)	<0.001	<0.001	<0.001
Cultivars	<0.001	<0.001	<0.001
DOY x Cultivars	N.S. (0.09)	0.01	0.002
Years	N.A.	N.A.	<0.001
DOY x Years	N.A.	N.A.	<0.001
Years x Cultivar	N.A.	N.A.	<0.001
DOY x Years x Cultivars	N.A.	N.A.	N.S. (0.27)
Percentage variation	91%	95%	94.5%
Slope of line	-8.7	-9.5	

In 2005, there were small but significant differences (P = 0.01) between cultivars and the dates of cutting, Table 6.2. There were highly significant differences (P<0.001) in the regressions for the cutting dates and for the cultivars, as occurred in 2002. In 2005, the average slope of the regression equations was -9.5.

A combined regression analysis for both years was undertaken, Table 6.2. All the two-way interaction effects were highly significant (P<0.001). The two-way interactions between the date of cutting and the cultivars showed the slopes of the regression lines were significantly different (P = 0.002) between the cultivars. A small but significant difference in the gradient of regression lines between the cultivars in 2005 can be seen in Figure 6.2 for the cultivars ‘Tonda di Giffoni’ and ‘Casina’ compared with the other cultivars. In 2002, the gradients of the regression lines for cultivars were not found to be significantly different.

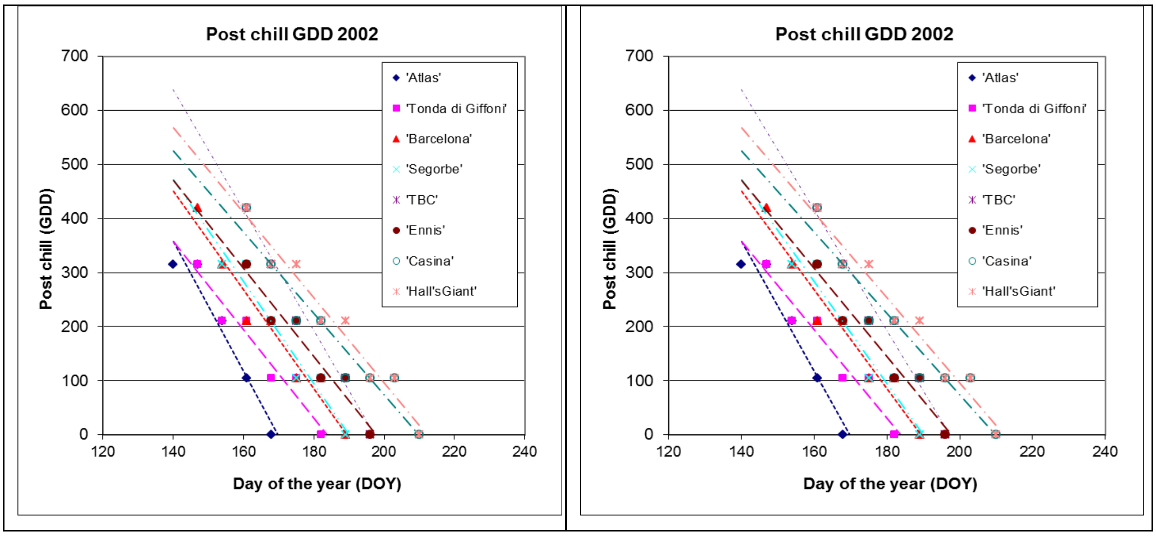


Figure 6.2 Effect of date of shoot cutting (DOY) on the post-chill heat requirements (GDD) in growth cabinets at 15°C for 50% pollen shed of 8 cultivars of hazelnut.

It is considered that the small differences between the gradients of the regression of the cultivars in 2005 could be attributed to greater variation that year. In general, the analyses indicate that the post-chill heat requirements for catkin extension were not different between the cultivars; however, there were significant differences between the years (P<0.001).

Using similar cutting techniques on hazelnut twigs and providing post-chill heat in growth chambers, Tiyaynon (2008) found no difference between several hazelnut genotypes in their post-chill heat requirements. However, Turcu et al, (2001) reported that, in Romania, there were differences between cultivars in the post-chill GDD requirements for pollen shed, their mean values were 126 GDD, with a range of 50 GDD for their cultivars. These values are far less than those required for pollen shed (Table 6.1) in these experiments. This may reflect the lower winter temperatures of Romania, possibly with prolonged chilling and consequently lower GDD requirements.

6.3.2 Female inflorescences

Female anthesis occurred after pollen shed for all 8 cultivars in both the growth cabinets and the field (Tables 6.1 and 6.3).

The initial cutting dates for the commencement of stigma exertion in the growth cabinets were less clearly defined than those for the commencement of pollen shed. However, as with the start of pollen shed, the mean day of the year to the commencement of stigma exertion for all 8 cultivars occurred earlier for cut shoots in the growth cabinets than for shoots in the field. This occurred 16 days ahead in 2002, compared with 29 days in 2005 (Table 6.3). Stigma exertion commenced 18 days earlier in the growth cabinet in 2005 than in 2002, but only 5 days earlier in the field.

Table 6.3 Day of the year (DOY) to the end of dormancy and commencement of stigma exertion with recorded chill hours to that date in 2002 and 2005 and the DOY to the commencement of stigma exertion in the field, along with post-chill heat units.

2002 **Cultivars**	**Earliest cutting date (DOY) to start of stigma exertion in the cabinet**	**Chill hours from 1 April to DOY to start of stigma exertion in the cabinet**	**DOY to start of stigma exertion in the field**	**GDD in cabinet from DOY to start of stigma exertion in cabinet**	**GDD in field from DOY to start of stigma exertion in the field**
‘Atlas’	189	994	196	105	31
‘Tonda di Giffoni’	189	994	217	210	149
‘Barcelona’	203	1123	217	105	93
‘TBC’	210	1179	231	105	147
‘Segorbe’	217	1254	224	105	57
‘Casina’	224	1326	231	105	49
‘Ennis’	224	1326	245	105	141
‘Hall’s Giant’	224	1326	245	105	141
Means	*210*	*1190*	*226*	*118*	*101*
2005 **Cultivars**					
‘Atlas’	165	632	199	210	201
‘Tonda di Giffoni’	165	716	206	315	234
‘Barcelona’	186	936	213	210	159
‘TBC’	193	1041	213	210	157
‘Segorbe’	200	1194	220	210	163
‘Casina’	200	1194	234	210	229
‘Ennis’	200	1194	241	210	116
‘Hall’s Giant’	221	1375	241	210	116
Means	*192*	*1035*	*221*	*223*	*172*

The mean minimum number of chill hours to break the dormancy of the female inflorescences was 1190 hours in 2002, the earlier year to the completion of dormancy, and1035 hours in 2005, a difference of 155 chill hours. The mean post-chill heat requirements in the growth cabinet were 118 GDD in 2002, the year with more chill hours, and 223 GDD in 2005. These were much less than the mean post-chill heat requirements for pollen shed, which were 363 GDD in 2002 and 499 GDD in 2005.

It was unclear whether there were differences between the cultivars in their post-chill GDD requirements. The number of GDD required in the cabinet to stimulate stigma exertion did not appear to differ between cultivars in either year. However, there was more variation between cultivars in the field in the calculated GDD in both years compared with the growth cabinets, suggesting there might be cultivar differences.

6.3.3 Chill hour requirements to overcome dormancy

In these controlled temperature experiments, the chill requirements of the cultivars varied between years and cultivars; they were less in 2005 than in 2002. The chill requirements appeared to be the main factor influencing the relative timing of both male and female anthesis of the cultivars. The chill requirements of the catkins were less than the female flowers, as reported by Bergamini and Ramina (1968), Fontanazza and Salleo (1968) and Mehlenbacher (1991a).

Chill requirements of a range of cultivars were estimated by Mehlenbacher (1991a) using a similar technique to that used in these studies. There were similarities in the relative chill requirements of the cultivars that were common to both this experiment and that of Mehlenbacher (1991a), Table 6.4.

In both situations, ‘Tonda di Giffoni’ had relatively low chill requirements for catkins and female inflorescences compared with the other cultivars, and ‘Hall’s Giant’ had relatively high chill requirements (Table 6.4). There were similarities in the sequence that the other cultivars fitted in between these 2 cultivars for both pollen shed and female anthesis. However, on average, the estimated minimum chill hours recorded at Orange for all cultivars were greater than those estimated in Oregon, particularly for pollen shed.

Table 6.4 Estimated minimum chill hours required to break dormancy of catkins and female inflorescences in 2002 and 2005, compared with published figures for Oregon (Mehlenbacher, 1991a).

Cultivars	**Orange**		**Chill hours, Oregon (Mehlenbacher, 1991)**
Pollen shed	**Chill hours 2002**	**Chill hours 2005**	
‘Tonda di Giffoni’	472	338	170-240
‘Barcelona’	565	404	240-290
‘Segorbe’	565	417	240-290

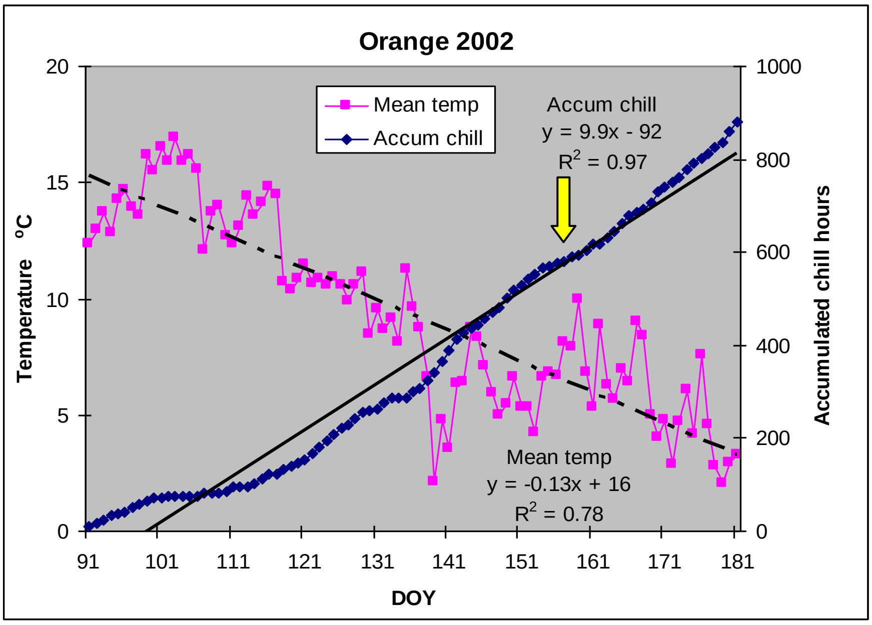
‘Casina’	619	569	290-365
‘Ennis’	619	499	240-290
‘Hall’s Giant’	693	623	290-365
Female anthesis			
‘Tonda di Giffoni’	994	716	600-680
‘Barcelona’	1123	936	600-680
‘Segorbe’	1254	1194	1170-1255
‘Casina’	1326	1194	1395-1550
‘Ennis’	1326	1194	1040-1170
‘Hall’s Giant’	1326	1375	990-1040

6.3.4 Seasonal differences in flowering

Seasonal differences

The difference in the chill hour requirements estimated for the 2002 and 2005 seasons at Orange and those estimated by Mehlenbacher (1991a) for one season in Oregon indicate there is seasonal variation. It raises the question, what are the minimum chill requirements and why do these vary between seasons?

The method of calculating chill hours was similar. Mehlenbacher (1991a) calculated accumulated chill requirements from the date that chilling commenced in autumn. At Orange, the chill hours were accumulated from 1 April, as there were very few chill hours before that date. The rates of accumulation of chill hours in 2002 and 2005 were very similar, at an average of 9.8 chill hours per day, over the period 1 April–30 June, Figure 6.3. The total chill hour accumulation by 30 June was just over 800 hours in each year. In both years, there was a highly positive correlation (P=0.001) between the number of accumulated chill hours per day and the day of the year (DOY) over the period 1 April–30 June, Figure 6.3. Thus, the later the date of anthesis, the more chill the flowers received.



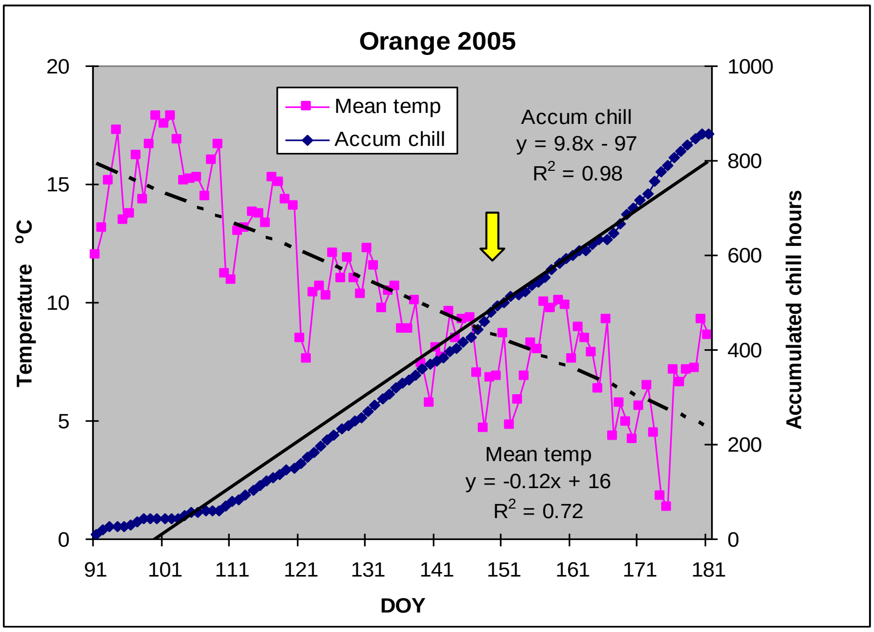


Figure 6.3 Mean daily temperatures °C and accumulated chill hours (0-7°C) recorded at the Orange site over the period 1 April–30 June, 2002 and 2005. The arrows show the earliest mean cutting dates for the commencement of pollen shed in the cabinet, indicating the mean minimum chill requirements.

All cultivars were later into flowering in 2002 than in 2005 and hence had greater chilling in 2002. However, the mean temperature for the same period, 1 April–30 June, was slightly higher in 2005 (10.3°C) and declined more slowly at 0.12°C per day, compared with a mean of 9.3°C and a decline of 0.13°C per day in 2002, the year when flowering commenced at a later date. Thus, there were, on average, more heat units per day from 1 April to 30 June in 2005 compared with the same period in 2002. The cultivars were earlier into anthesis in 2005, the year with the greater number of heat units per day.

Site differences

The DOY when flowering occurred varied between sites as well as seasons, as reported in the previous chapter, Chapter 5, ‘Cultivar Floral Phenology’. On average, pollen shed and female anthesis occurred earlier at Moss Vale than at Orange. Mean temperatures and the accumulation of chilling hours over the months of April, May and June were very different between the 2 sites. For example, in 2002, the accumulated chill hours in the period 1 April–30 June (DOY 91-181) were 470 hours at Moss Vale, compared with 880 hours for Orange, Figures 6.3 and 6.4. The mean temperature at Moss Vale for that period was 11.3°C compared with 9.3°C for Orange. In that year, 2002, the average date for the commencement of pollen shed in the field for 8 cultivars, common to both sites, was DOY 177 at Moss Vale compared with DOY 195 at Orange. Pollen shed occurred 18 days earlier at Moss Vale.

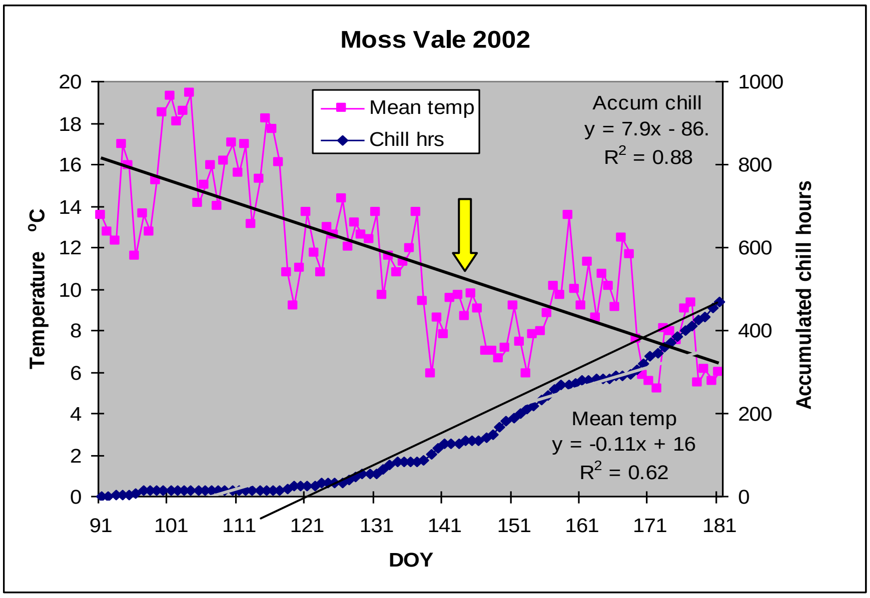


Figure 6.4 Mean daily temperatures °C, and accumulated chill hours (0-7°C) recorded at the Moss Vale site over the period 1 April–30 June, 2002.

The earliest cutting dates for pollen shed at Orange were about 35 days earlier than for pollen shed in the field. Based on this, it is estimated that at Moss Vale the average minimum chill hours for pollen shed for the 8 cultivars was 100-150 chill hours. This figure is lower than that estimated for the earliest cultivar, ‘Tonda di Giffoni’, in Oregon by Mehlenbacher, (1991a), Table 6.4.

It is concluded that, at Orange, there was ample chilling to break dormancy with less warmth to stimulate the development of the catkins, which delayed their development.

However, at Moss Vale, there was far less chilling, but presumably sufficient to break dormancy, with ample warmth to promote the production of the growth stimulant that led to the development of the catkins.

In their studies on peach, Richardson et al (1974) found that temperatures in the range 2.1-9.1°C were more effective in meeting the chill requirements. Some temperatures outside this range were less effective and were assigned a lower weighting value of 0.5. Temperatures below 1.5°C were given a value of zero. When temperatures rose above 15°C there was a negation of chilling. This chill unit (CU) system became known as the "Utah" model for calculating chill requirements of crops and was considered to be superior to the chill hours (0-7°C) for some crops. However, Norvell and Moore (1982) considered this model required modification for high-bush blueberries (*Vaccinium corymbosum* L.). Tiyaynon (2008) assessed this model for hazelnut and considered it slightly superior to the conventional chill hour model. Temperatures of 15°C were not found to have a negative effect on the accumulation of chill hours in *Corylus avellana* L. This temperature was reported as being the optimum for catkin development (ibid, 2008).

Calculations of "chill units" as described by Richardson et al (1974), were calculated for both years, 2002 and 2005, at Orange, to assess whether there were better correlations between the break of dormancy and these chill units, compared with the chill hour calculations (0-7°C). The correlations were not found to be significantly different from the more conventional chill hours.

6.3.5 Conclusions on floral phenology

It is concluded that difficulties in estimating the chilling requirements of hazelnut flowers are related to:

- the method of calculating chilling hours (chill hours vs. chill units);
- determining the starting date for calculation;
- determining the date when endodormancy is complete; and
- the lack of visual signs of changes from endodormancy to ecodormancy.

Similarly, difficulties in estimating the heat unit requirements are related to:

- determining the base temperature for calculations; and
- knowing when to commence the calculation of the thermal sums.

Several authors have reported difficulty in accurately predicting the flowering date of deciduous fruit trees using simple temperature models. Garcia et al (1999), reported differences between years in the timing of flowering of apricot in Spain and Italy and concluded that forecasting flowering date, on the basis of chill and heat units, was unreliable. Felker and Robitaille (1985) considered there was an overlap between chilling and heat unit accumulation influencing the flowering of sour cherry. Chuine, Cour and Rousseau (1999) evaluated the effectiveness of a range of models to predict the flowering of temperate trees. They concluded that the selection of the most appropriate model depended on the tree species and that there was no universal model that could be used for all species.

It seems likely that, in hazelnut, the sequential model of chilling followed by post-chill warmth has limitations and that heat units prior to the completion of dormancy may have an effect on the commencement of flowering, as suggested by Tiyaynon (2008). Such a concurrent model would be in line with the notion that the level and effect of a restricting chemical, such as ABA, declines with time due to chilling, whilst the level and effect of a stimulating chemical, such as IAA, is influenced by warmth with the level of that hormone slowly rising during winter (Figure 6.1). These processes run concurrently, with an overlap point being reached when the effect of the stimulating chemical exceeds that of the restricting hormone, as shown by Rodriguez and Sanches-Támés (1986), and flowering subsequently commences. As there are no obvious visual phenological signs of this point, it is not possible to determine it in the field.

It is considered that more studies using growth cabinets operating at different temperatures could provide valuable data in gaining an understanding of the effects of temperature and temperature accumulation on post-chill thermal requirements. This should be coupled with anatomical studies similar to those done by Tiyaynon (2008).

6.4 Bud break

Very limited data was obtained on the chill requirements for bud break. However, in 2002, observations were obtained on the cutting dates when bud swell was first observed in 4 cultivars, Table 6.5. In all cultivars, bud break was later than the exertion of stigmas. The first cutting date to bud break in the growth cabinet was on average 40-45 days earlier in the cabinet than in the field. In that year, 2002, the calculated accumulated chill hours to terminate endodormancy ranged from 1050 hours with the early-leafing cultivar ‘Tonda di Giffoni’ to 1482 hours for the late-leafing cultivar ‘Hall’s Giant’. These chill hours were far higher than those estimated by Mehlenbacher (1991a) which ranged from 680 for ‘Tonda di Giffoni’ to 1040 for ‘Hall’s Giant’. However, they are in agreement with reports that differences between cultivars in dates of bud break are related to the relative chill hour requirements of the cultivars to overcome dormancy. These vary between seasons for any cultivar but the sequence the cultivars break into leaf is genetically determined (Tromp 2005).

Table 6.5 Day of the year (DOY) to the end of dormancy and commencement of bud break with recorded chill hours to that date in 2002 and the DOY to the commencement of bud break in the field

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Cultivars	**Cutting date for first observations in cabinet**	**DOY cabinet**	**Chill hours to cutting date in cabinet**	**Date of bud break in field**	**DOY Bud break in field**
‘Tonda di Giffoni’	15 July	196	1050	2 September	245
‘Wanliss Pride’	5 August	210	1179	9 September	252
‘Barcelona’	5 August	217	1254	14 September	257
‘Hall’s Giant’	30 August	242	1482	7 October	280

As ‘Hall’s Giant’ was one of the latest cultivars into leaf (Chapter 5, Section 5.5.1 ‘Cultivar effects’), the date that endodormancy was complete gives an indication of the minimum chill hour requirements for a wide range of hazelnut cultivars. In 2002, endodormancy had terminated by 30 August in Orange. As the variation between years was found to be small (Chapter 5, Section 5.5.2 ‘Years and sites’) it is considered likely that the endodormancy of vegetative buds for the latest-leafing cultivars (e.g. ‘Hall’s Giant’) was complete at all sites by 30 August. However, based on that assumption, the chill hours to that date vary considerably between sites, with the lowest at Kettering, 1088 hours, as shown in Table 6.6.

Table 6.6 Mean dates of bud break at the study sites along with the mean accumulated chill hours over the months of April – August, inclusive.

	Orange	**Moss Vale**	**Myrtleford**	**Kettering**
Mean date of bud break	19 Sept	11 Sept	6 Sept	4 Sept
Accumulated chill hours April - August	1606	1085	1370	1088

Source: Table 5.6

Orange had lower mean winter temperatures than Kettering, Figure 6.5. The accumulation of chill hours (0-7°C) was higher at Orange, based on its cooler temperatures; hence Orange has a higher level of accumulated chill hours by the end of August. However, as mean temperatures in August and September were higher at Kettering, it seems likely that thermal sums post-dormancy would be higher at Kettering and might account for the earlier bud break at that site.

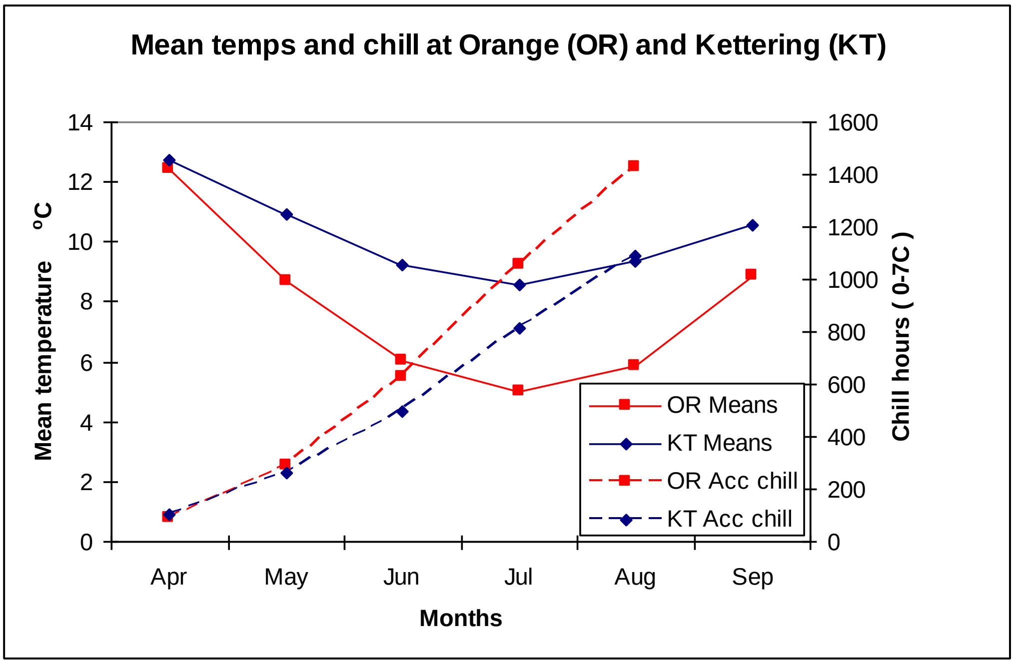


Figure 6.5 Mean monthly temperatures (°C) and accumulated chill hours (0-7°C) recorded at the Orange and Kettering sites during the months of April – August.

The determination of accumulated chill units (CU) using a modified Utah chill model, as suggested by Tiyaynon (2008), may be a better technique for assessing the degree of chilling in hazelnuts over the range of temperatures experienced at the sites. However, more information is also required on base temperatures for post-chill heat units and dates when endodormancy is complete. The issues relating to the prediction of bud break across sites and seasons are very similar to those for floral phenology.

Conclusion

Despite the limitations of the data obtained on bud break, it is concluded that the minimum amount of chill required to ensure bud break of the highest-chill cultivars is in the range 1100 – 1600 accumulated chill hours, over the months of April – August. This figure is a useful guide to include in climatic parameters when selecting suitable sites for hazelnut production, as discussed in Chapter 2. The range of 1100-1600 chill hours is similar to that suggested by Mehlenbacher (1991a) of 1500 hours, as presented in Table 2.1.

6.5 Overall Conclusions

Flowering

The chilling requirements of cultivars for flowering varied considerably (Table 6.3). These requirements appeared to be the main factor influencing the timing of pollen shed and female anthesis and the sequence in which cultivars commenced flowering, as reported in the previous chapter, Chapter 5, ‘Cultivar Floral Phenology’, Figures 5.1, 5.2 and 5.4. Similar findings were reported for hazelnut cultivars by Mehlenbacher (1991a) and for almond cultivars by Egea, et al. (2003).

It was concluded that the heat units (post-chill) for female flowers were considerably less than those required for catkins, which is in agreement with the published findings of Barbeau (1976), Kavardzhikov (1980), Mehlenbacher (1991) and Turcu et al (2001). Both catkins and female flowers require warmth to stimulate their development, once dormancy is terminated. However, it is postulated that the effects of accumulated chilling on the decline in chemicals that maintain endodormancy and the effects of warmth that stimulates the levels of chemicals that stimulate flowering may overlap in a parallel model for the development of flowering. There is a need for further studies to test this hypothesis and develop a more sophisticated model for predicting flowering in hazelnut. Such work should include studies of floral phenology coupled with biochemical monitoring of the chemicals that control dormancy and stimulate floral development, in conjunction with monitoring climatic conditions.

Bud break

The variation in dates of bud break between cultivars was considered to be strongly influenced by their chill requirements. Differences between sites in accumulated chill hours to bud break ranged from 1100 to 1600 chill hours for the latest-leafing cultivar, ‘Hall’s Giant’, in 2002. Although only limited data was obtained on chill requirements of hazelnut in this research, it is considered that the climatic parameter of 1500 accumulated chill hours in April–August, as suggested in Chapter 2, Table 2.1, is a valid but probably very conservative figure when evaluating sites for their suitability to grow hazelnuts. It could be as low as 1000 chill hours, based on estimates from Moss Vale, however, until further data is obtained, a range of 1200-1500 chill hours is the recommended amoun

CHAPTER 7 – NUT YIELDS, YIELD DEVELOPMENT AND YIELD EFFICIENCY

7.1 Introduction

Nut yields are a key measure of the productivity of hazelnuts, particularly when assessing cultivars for the in-shell market. However, as the kernel of the hazelnut is the edible and marketable part of the plant, growers seek high yields of good quality kernels per hectare, of a type that meets market requirements, in order to maximise their financial returns. Nut and kernel yields per tree are influenced by the number of female inflorescences produced, the proportion that become pollinated and subsequently fertilised to produce nuts, and the proportion of these that produce good quality kernels. The factors influencing the number of female inflorescences produced, pollination, fertilisation and kernel development were discussed in the literature review, Section 2.2.4 ‘Reproduction in Hazelnuts’, Figure 2.1. The pathway from flowering to nut and kernel development is presented again in Figure 7.1.

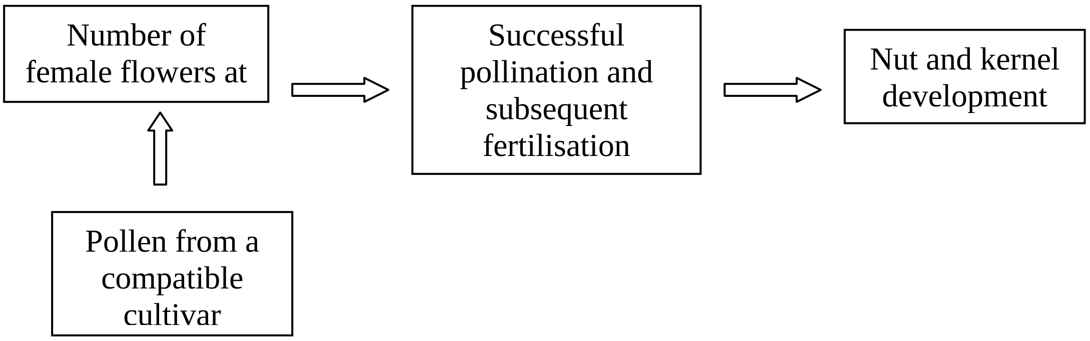


Figure 7.1 Pathway of kernel development from flowering to final kernel fill

Generally, nut yields are assessed by collecting and weighing the mature nuts that fall from the trees in late summer. The harvested nuts are cleaned and dried to approximately 8% moisture content (McCluskey et al., 2005) before weighing. The data obtained from the annual harvest of nuts is used to assess the development of yield, over time, as trees grow and develop. In addition, cumulative yield assessments can be made after a certain number of years. In Oregon, this was commonly assessed over a total of 3 to 5 years of production (McCluskey et al. 2005). However, in Portugal, (Santos and Silva 2001) nut yield was measured annually for 14 years from the first year of nut production in order to obtain cumulative yields.

Another important measure used to evaluate the performance of cultivars is the yield efficiency of the cultivars. This measurement can be carried out annually, but a common method is to divide the cumulative yield of a tree by its trunk cross-sectional area (cm^2) in the last year of harvest (Westwood, 1993) to obtain the cumulative yield efficiency (∑YE). Yield efficiency provides an estimate of the efficiency of the bearing surface of a tree or cultivar:

$$\sum YE = \text{cumulative yield per tree (kg)/TCSA (cm}^2\text{) in the last year of harvest}$$

Although high yields of good quality kernels are a key objective for most commercial producers, particularly those wishing to supply product into the kernel market, the starting point in assessing cultivars or crosses from breeding programs is nut yields and the development of nut yield as trees grow and mature. Cracking nuts and assessing kernel percentage and quality is time-consuming. In the early years of tree growth there may be relatively few nuts to crack. Also, differences in nut yields between cultivars at the same stage of growth and development may be so great that even if low-yielding cultivars have high quality kernels, they may be discarded due to their low yields.

Following the chapters on tree growth and floral phenology, this chapter investigates the effects of cultivars, sites and seasons on nut yields; the next chapter evaluates the time of nut fall, nut weights, kernel yields and kernel quality.

7.2 Methods

The annual nut yields of the cultivars at all sites were measured, as described in Chapter 3, ‘Methods’, Section 3.6.4 ‘Nut yields and yield efficiency’. The data was used to assess differences between cultivars in their annual nut yields and the interaction effects between cultivars and sites, as well as cumulative yields and yield efficiency. Analyses of variance were carried out using the statistical package, Genstat.

Nuts were collected by hand from the orchard floor from individual treatment trees at all sites in the early years of production. The exception was at Myrtleford, from 2004, where nuts were harvested with a Tonutti suction harvester. After sucking up the nuts from an individual tree, the machine was emptied before moving on to the next tree. The machine had the capacity to suck up the crop from the orchard floor and separate the nuts from leaves, husks and soil. Nuts were harvested at Kettering in a similar manner, using a FACMA suction harvester, in 2006 and 2007.

Plate 7.1 Tonutti vacuum harvester used for collecting nuts at Myrtleford in March 2005; All trees were harvested separately to obtain nut yields.

Sulphur-crested cockatoos (*Cacatua galerita*) caused problems at several sites, as the birds developed a liking for hazelnuts. At Myrtleford, some yield losses to these birds occurred in 2006 and 2007, despite the use of gas guns to deter them. Yield losses due to cockatoos were substantial at Toolangi in 2003 and high at Orange in 2002. From 2003 to 2006, immature nuts were hand-picked at Orange, to minimise loss from birds.

The nut yields were estimated from the numbers of green nuts which were picked in January, multiplied by average nut weights from mature nuts collected later in that season, from trees that had been protected with bird netting. One of the problems with this technique was that it was assumed that green nuts would develop into mature nuts, which is not necessarily the case. It is therefore possible that there was a slight over-estimation of yield using this technique, particularly with the cultivar ‘Ennis’, as that cultivar had many clusters of two nuts, in which one nut was large and the other was smaller; there was some doubt as to whether the smaller nuts would develop to maturity. However, any small nuts that appeared yellow or slightly shrivelled were excluded from the nut count and estimated nut yield.

7.3 Results and Discussion

7.3.1 Comparisons between cultivars and sites

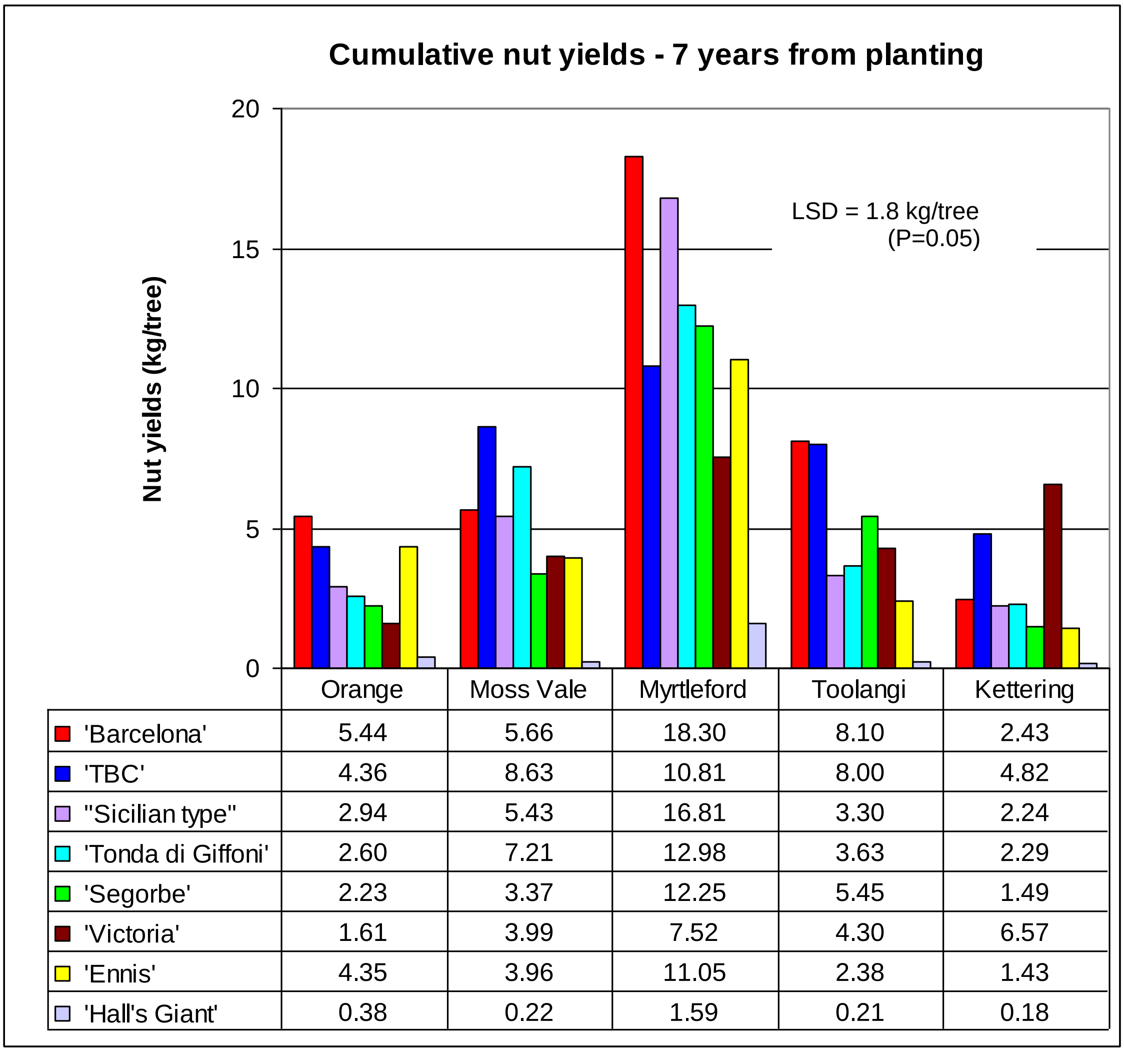
Although, initially, there had been a core of 12 cultivars planted at all 5 sites, a full set of yield data was obtained for only 8 of these cultivars over 7 years from planting. This was because, at some sites, trees failed to grow, such as 'Wanliss Pride' at Orange; there were also some errors with tree planting and at most sites sulphur-crested cockatoos caused a loss of nuts in later years.

An analysis of variance was conducted on the cumulative nut yields, 7 years after planting, and on the yield efficiency of 8 cultivars that were common to all 5 study sites. There were significant interactions in the mean cumulative yields and the yield efficiency between cultivars and sites (P<0.001) (Table 7.1).

Table 7.1 Levels of probability (F-values) from an analysis of variance of the effects of 2 factors, cultivars (8) and study sites (5) on cumulative nut yields and the yield efficiency of trees 7 years from planting.

Source of variation	Cumulative yield	Yield efficiency
Cultivars	<0.001	<0.001
Sites	<0.001	<0.001
Sites x cultivars	<0.001	<0.001

The significant differences in cumulative nut yields between the 8 cultivars and the interactions between cultivars and sites are illustrated in Figure 7.2. No single cultivar produced the highest cumulative yield or the greatest yield efficiency at all sites. 'Barcelona' was one of the highest yielding cultivars at Orange, Moss Vale, Myrtleford and Toolangi but not at Kettering. 'TBC' produced the highest yield at Moss Vale and was one of the highest yielding cultivars at all other sites, except Myrtleford. 'Hall's Giant' produced low yields at all sites.



	Orange	Moss Vale	Myrtleford	Toolangi	Kettering
🟥 'Barcelona'	5.44	5.66	18.30	8.10	2.43
🟦 'TBC'	4.36	8.63	10.81	8.00	4.82
🟪 "Sicilian type"	2.94	5.43	16.81	3.30	2.24
■ 'Tonda di Giffoni'	2.60	7.21	12.98	3.63	2.29
🟩 'Segorbe'	2.23	3.37	12.25	5.45	1.49
🟫 'Victoria'	1.61	3.99	7.52	4.30	6.57
🟨 'Ennis'	4.35	3.96	11.05	2.38	1.43
⬜ 'Hall's Giant'	0.38	0.22	1.59	0.21	0.18

Figure 7.2 Cumulative nut yields (kg/tree) 7 years from planting for 8 cultivars at the 5 study sites.

On average, the 7-year cumulative nut yields for the 8 cultivars were highest at Myrtleford, Figures 7.2 and 7.3. The second highest cumulative nut yields were obtained at both the Moss Vale and Toolangi sites. There were no significant differences in the mean yields between these two sites (P=0.05), Figure 7.3. The lowest cumulative yields were obtained from both Orange and Kettering, with no significant difference (P=0.05) between these sites. This was similar to the growth pattern of the cultivars at these sites, with the highest growth rates being achieved at Myrtleford and the lowest at Orange and Kettering, as discussed in Chapter 4, ‘Tree Growth’, Section 4.3.3 ‘Site effects on growth’. The relationship between nut yields and tree growth are discussed later in this chapter.

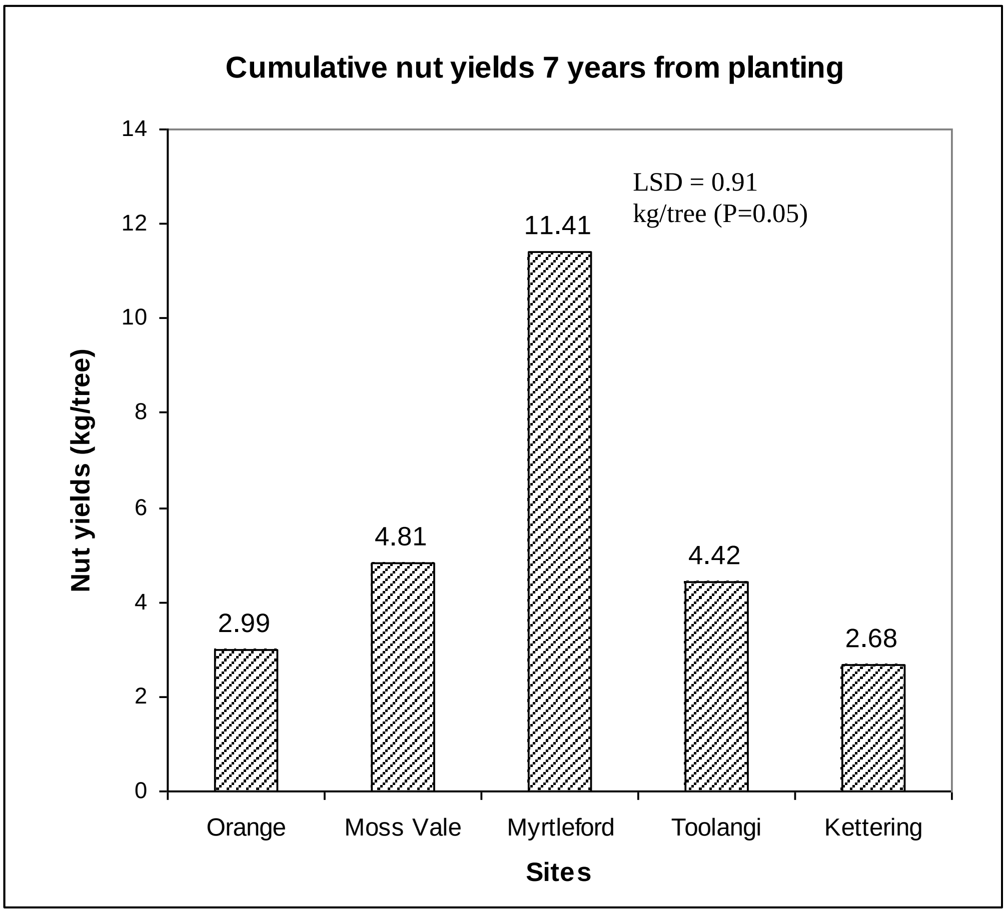


Figure 7.3 Mean cumulative nut yields, 7 years from planting, for 8 cultivars grown at each of the 5 study sites.

The production at each site is discussed in the order of north to south locations, as are all site comparisons throughout this thesis. Separate analyses of variance on annual and cumulative nut yields and yield efficiency were conducted for each site, where there were additional cultivars to the 8 cultivars common to all sites. These analyses provided additional data on cultivar performance.

7.3.2 Orange

Although nut yields to the eighth year from planting were used to compare cumulative yields across sites and to determine yield efficiencies, a further 3 years of data for nut production was obtained at Orange for 13 cultivars from which cumulative nut yields and yield efficiency data was obtained (Table 7.2). This included the 8 cultivars that were included in the analysis for all sites, plus ‘Atlas’, ‘Butler’, ‘Casina’, ‘Eclipse’ and ‘Square Shield’.

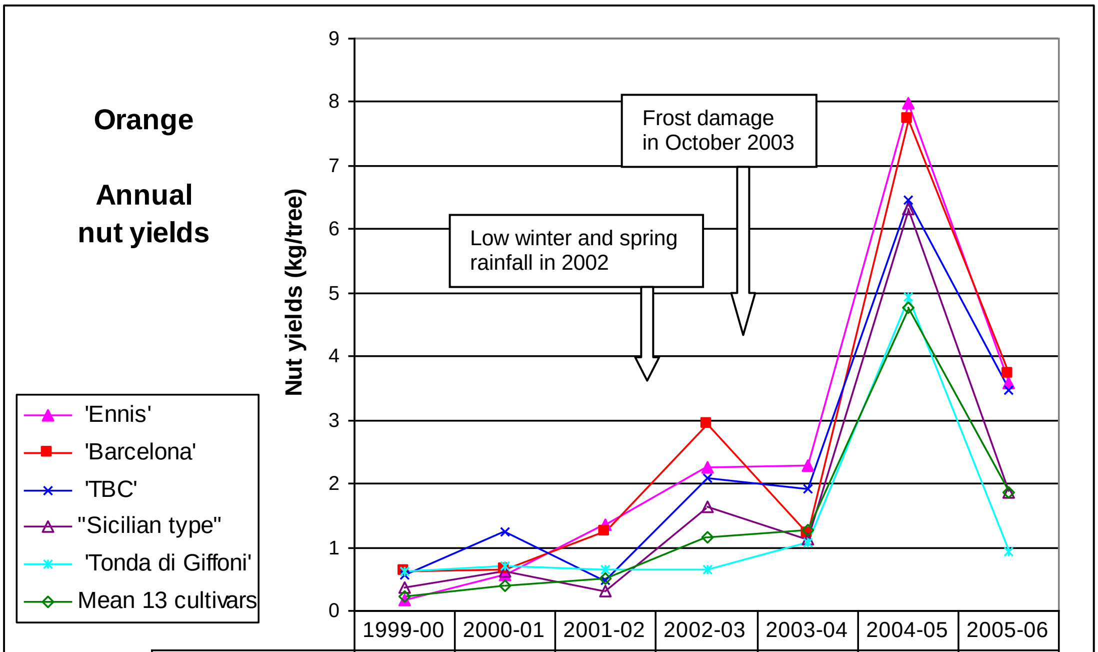
The trees at Orange grew relatively slowly, as discussed in Chapter 4 (Section 4.3.2 ‘Site effects on growth’) and had relatively low cumulative nut yields 10 years from planting. ‘Barcelona’, and ‘Ennis’ produced higher cumulative yields than any other cultivar except ‘TBC’ (P=0.05), Table 7.2. The lowest-yielding cultivars included ‘Casina’, ‘Hall’s Giant’, ‘Eclipse’ and ‘Square Shield’. There was a high degree of variation within cultivars in growth and nut yield, resulting in relatively high values for least significant differences between cultivars for yield, tree growth (TSCA) and yield efficiency (Table 7.2), making it difficult to assess small differences between cultivars.

Table 7.2 Estimates of annual and cumulative nut yields (kg/tree) recorded at Orange (2000–2006) along with trunk cross-sectional area (TCSA) (cm^2) at the end of the growing season in 2006 and yield efficiency (YE) kg/cm^2

Growing seasons	Years							Cum yield kg/tree	TCSA cm^2	YE kg/cm^2
	99/00	00-01	01-02	02-03	03-04	04-05	05-06			
Years from planting	4	5	6	7	8	9	10			
‘Ennis’	0.17	0.58	1.36	2.24	2.29	7.98	3.57	18.2	107.6	0.17
‘Barcelona’	0.62	0.64	1.25	2.93	1.21	7.73	3.73	18.1	147.7	0.12
‘TBC’	0.57	1.23	0.48	2.08	1.93	6.47	3.47	16.2	136.5	0.12
“Sicilian type”	0.37	0.62	0.32	1.62	1.12	6.31	1.87	12.2	74.8	0.16
‘Atlas’	0.18	0.40	0.54	1.87	1.01	5.21	2.20	11.4	162.2	0.07
‘Segorbe’	0.17	0.30	0.57	1.20	1.63	4.13	2.21	10.2	64.7	0.16
‘Tonda di Giffoni’	0.61	0.71	0.64	0.64	1.07	4.94	0.93	9.5	92.0	0.10
‘Victoria’	0.12	0.29	0.42	0.90	1.18	6.11	0.30	9.3	87.7	0.11
‘Butler’	0.02	0.06	0.28	0.49	1.65	2.81	2.72	8.0	93.1	0.09
‘Casina’	0.07	0.03	0.09	0.27	0.93	3.15	1.21	5.8	73.4	0.08
‘Hall's Giant’	0.01	0.04	0.23	0.13	0.33	4.04	0.51	5.3	100.9	0.05
‘Eclipse’	0.16	0.18	0.46	0.37	1.79	1.24	1.00	5.2	47.3	0.11
‘Square Shield’	0.00	0.02	0.07	0.11	0.21	1.76	0.66	2.8	62.9	0.05
LSD P =0.05	0.21	0.32	0.40	0.80	0.81	2.3	0.81	4.8	37.5	0.037

‘Ennis’ and the “Sicilian type” produced the highest yield efficiency at 0.17 and 0.16 kg/cm^2 respectively (Table 7.2). The yield efficiency of ‘Barcelona’ was 0.12 kg/cm^2; a similar yield assessment experiment in Oregon with ‘Barcelona’ produced 4-year cumulative nut yields of 9.8 kg/tree and a yield efficiency of 0.13 kg/cm^2 (McCluskey et al., 1997). This is indicative of the relatively poor growth of the ‘Barcelona’ trees at Orange compared with Oregon.

The development of nut yield up to the tenth year from planting, the 2006 harvest, is presented in Figure 7.4 for 5 of the highest-yielding cultivars at that site and the mean yield of the 13 cultivars.



Frost damage in October 2003

Low winter and spring rainfall in 2002

	1999-00	2000-01	2001-02	2002-03	2003-04	2004-05	2005-06
Years from planting	4	5	6	7	8	9	10
'Ennis'	0.17	0.58	1.36	2.24	2.29	7.98	3.57
'Barcelona'	0.62	0.64	1.25	2.93	1.21	7.73	3.73
'TBC'	0.57	1.23	0.48	2.08	1.93	6.47	3.47
"Sicilian type"	0.37	0.62	0.32	1.62	1.12	6.31	1.87
'Tonda di Giffoni'	0.61	0.71	0.64	0.64	1.07	4.94	0.93
Mean 13 cultivars	0.24	0.39	0.51	1.14	1.26	4.76	1.87
LSD P=0.05	0.21	0.32	0.40	0.80	0.81	2.33	0.81
Aug-Nov rain (mm)	563	557	306	102	369	357	496

Seasons

Figure 7.4 Development of nut yield (kg/tree) for the 5 highest yielding cultivars and the mean of the 13 cultivars.

Up to the seventh year from planting, nut yields increased annually. In the seventh year from planting, the 2002-03 season, nut yields either declined or were similar to the previous season. There were 2 possible reasons for this, either frost damage in the spring of that season or low rainfall in the previous spring, Figure 7.5.

There was a frost, in October 2003, which affected many cultivars at Orange, particularly those that were earlier into leaf, such as ‘Barcelona’, as discussed in Chapter 4, Section 4.3.3, ‘Climate effects on tree growth’. The leaf and shoot damage caused by frost in October is likely to have caused a loss of some developing fruits. The decline in nut yields from the 2002-03 season appeared to be greater for the earlier-leafing cultivars, such as ‘Barcelona’ and the “Sicilian type”, which were more affected by frost than the later-leafing cultivar, ‘Ennis’, Table 7.2 and Figure 7.5. A regression analysis of the difference or decline in nut yields from the 2002-03 season to the 2003- 04 season compared with the scores for frost damage showed that the greater the frost damage, the greater the yield decline, Figure 7.5. This accounted for 75% of variation in nut yield.

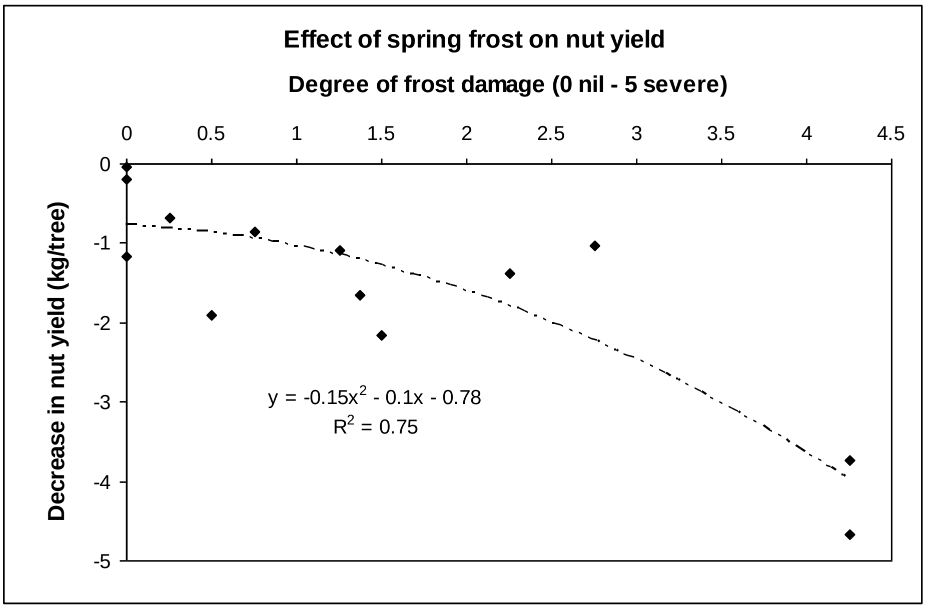


Figure 7.5 Relationship between decrease in nut yield in the 2003-04 season compared with 2002-03 and the score for severity of frost damage in October 2003 for 13 cultivars at Orange.

The very low rainfall in winter and spring of 2002 was associated with very little new shoot growth, which was considered to be another factor that might have caused low nut yields the following season, 2003-04 (Figure 7.4). The months of October and November are a critical period of the growing season when hazelnut trees are producing new shoot growth and initiating female inflorescences for the following year's crop. A stress at this stage of growth can adversely affect nut yields the following season Bergoughoux et al. (1978), Mingeau et al. (1994) and Bignami and Natali (1997).

The strong relationship between frost damage and the decline in yield was considered to be the main factor contributing to the decline in nut yields in the 2003-04 season.

The frost did not appear to have had any effect on nut yields in the following year, 2004-05, when nut yields increased markedly, Figure 7.4. Nut production in the subsequent year, 2005-06, was considerably lower than in 2004-05, Figure 7.4. This was despite 357 mm of rainfall in the months of August to November 2004, plus supplementary irrigation. It is postulated that this decrease in yield could have been due to intra-plant competition for assimilates, between shoot growth and developing nuts, during the spring of 2004, with the trees utilising most of the assimilates from photosynthesis for nut production. The phenomenon of partitioning limited assimilates to either shoot growth or fruit production often marks the beginning of biennial-bearing (Westwood, 1993). The nut yields at Orange seemed to follow a biennial-bearing pattern from the eighth year from planting. Biennial-bearing is common in hazelnuts, particularly with the cultivar 'Barcelona' in Oregon (Olsen and Goodwin, 2005).

The trees lacked vigour at Orange (Plate 7.2) and nut yields were poor until the ninth year from planting.

Plate 7.2 Growth of trees at Orange in March 2005, 9 years from planting, the trees generally lacked vigour and at this stage were just meeting within the rows.

7.3.3 Moss Vale

At Moss Vale, annual nut yields were obtained from 10 cultivars for 7 years from planting; these included the 8 cultivars that were common to the 5 study site plus 'Atlas' and 'Wanliss Pride'.

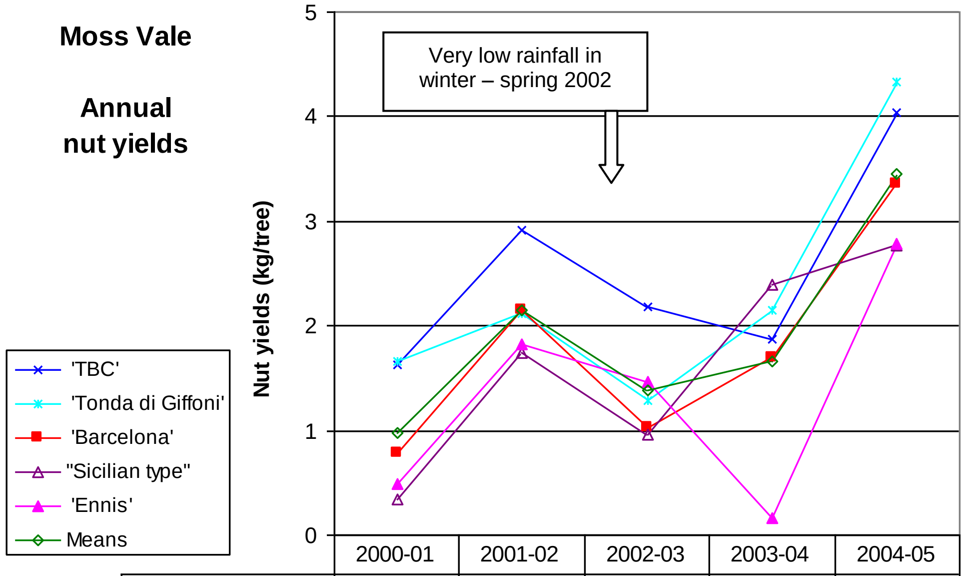
‘TBC’ produced the highest cumulative yield (P=0.05) over the 7 years. ‘Tonda di Giffoni’ produced the next highest yield (P=0.05) followed by ‘Barcelona’ and the “Sicilian-type”, which were not significantly different from one another, Table 7.3. The lowest-yielding cultivars were ‘Hall’s Giant’ ‘Atlas’ and ‘Wanliss Pride’. The highest yield efficiency was from the “Sicilian-type” at 0.11 kg/cm^2, which was higher than that achieved at the Orange site.

Table 7.3 Annual and cumulative nut yields (kg/tree) recorded at Moss Vale (2001–2004) along with TCSA (cm^2) in 2004 and yield efficiency (YE) kg/cm^2.

	Year of leaf and harvest				**Cum Yield (kg)**	**TCSA (cm^2)**	**YE kg/cm^2**
Years from planting	**4**	**5**	**6**	**7**			
Growing seasons	**2000-01**	**2001-02**	**2002-03**	**2003-04**			
‘TBC’	1.64	2.92	2.19	1.88	8.63	123.8	0.07
‘Tonda di Giffoni’	1.66	2.12	1.28	2.15	7.21	118.9	0.06
‘Barcelona’	0.79	2.15	1.03	1.70	5.66	106.4	0.06
“Sicilian-type”	0.34	1.74	0.96	2.39	5.43	50.8	0.11
‘Victoria’	0.90	1.53	1.30	0.25	3.99	93.6	0.04
‘Ennis’	0.49	1.83	1.47	0.17	3.96	86.1	0.05
‘Segorbe’	0.47	2.08	0.64	0.18	3.37	76	0.04
‘Wanliss Pride’	0.37	0.47	0.27	1.13	1.79	21.7	0.08
‘Atlas’	0.29	0.48	0.15	0.17	1.09	86.5	0.01
‘Hall's Giant’	0.03	0.10	0.06	0.03	0.22	72.9	0.00
LSD (P=0.05)	0.43	0.57	0.37	0.55	1.36	22.4	0.02

Due to limited funding, yield data was obtained for only 5 of the cultivars in 2004-05, the eighth year from planting, when the trees had finally recovered from the drought of 2002-03. By the end of that season, their canopies were meeting down the tree rows, Plate 7.3. Some very valuable yield data was obtained from these 5 cultivars, with a noticeable increase in nut yields that year. Yields of more than 4 kg/tree were obtained from both ‘TBC’ and ‘Tonda di Giffoni’, which were significantly higher (P=0.05) than from ‘Barcelona’ (3.36 kg/tree), Figure 7.6. These 3 cultivars produced significantly more than ‘Ennis’ (2.78 kg/tree).

The general decline in nut yield in the seventh year from planting, the 2002-03 growing season, was almost certainly due to the extremely low rainfall in that season. There was a total of only 69 mm of rain in the period August to November 2002 (Figure 7.6), with the dry conditions continuing into the next 2 months. There was a shortage of water for irrigation in that growing season, as the winter rainfall had also been low and the spring that fed the irrigation dam did not flow. However, it was possible to apply a total of 2120 L/tree during that growing season (Table 3.9 in Chapter 3, ‘Methods’). Despite this supplementary irrigation, the trees appeared moisture-stressed in late spring and throughout summer, with shoot growth, nut yields (Figure 7.6) and kernel quality seeming to be adversely affected by the moisture stress.



	2000-01	2001-02	2002-03	2003-04	2004-05
Years from planting	4	5	6	7	8
'TBC'	1.64	2.92	2.19	1.88	4.05
'Tonda di Giffoni'	1.66	2.12	1.28	2.15	4.33
'Barcelona'	0.79	2.15	1.03	1.70	3.36
"Sicilian type"	0.34	1.74	0.96	2.39	2.76
'Ennis'	0.49	1.83	1.47	0.17	2.78
Means	0.98	2.15	1.39	1.66	3.46
LSD P=0.05	0.43	0.57	0.37	0.55	0.79
Aug - Nov rain (mm)	351	423	69	378	278

Growing seasons

Figure 7.6 Development of nut yield for 5 key cultivars at Moss Vale

The dry conditions during the spring and early summer in the 2002-03 season occurred during a period of growth that was identified by Bergoughoux et al. (1978) and Mingeau et al. (1994) as being particularly sensitive to moisture stress. The dry conditions limited shoot growth and consequently the initiation of female inflorescences for the next season's crop, as well as adversely affecting the current season's crop. The trees at Moss Vale appeared to be under greater moisture stress than those at Orange, due to the lower rainfall and limited supplies of irrigation water. An estimate of the monthly soil moisture store was given in Chapter 4, 'Tree Growth', Table 4.7. It was estimated that by the end of October, when trees would normally be making active growth, the available soil moisture store was only about 20 mm, with 50 mm of irrigation being applied in November to maintain some available soil moisture.

Although nut yields were relatively low in the following season (2003-04), moderately high rainfall in the period August to November of that spring produced good new shoot growth which resulted in the highest yields for the site of 3-4 kg/tree in the following season (2004-05), the ninth year from planting (Figure 7.6). It is unclear why the yield of ‘Ennis’ was so poor in 2003-04, compared with ‘Barcelona’, ‘TBC’ and ‘Tonda di Giffoni’ (Figure 7.6).

Plate 7.3 The Moss Vale site, where most cultivars were meeting in the rows by the final harvest in 2005, their ninth season of growth. Karilyn Gilchrist, Technical Assistant (left) and Jim Gleeson (right) at the final visit to the site in April 2005.

7.3.4 Myrtleford

The largest number of cultivars were evaluated at Myrtleford, where growth rates were the highest, trees came into production earliest and, in general, produced the highest cumulative yields 7 years after planting, across all sites, Figure 7.3.

There was a further year of growth and nut production, providing data for 8 years from planting. The 3 cultivars, ‘Barcelona’, ‘Butler’, and the “Sicilian-type” produced higher cumulative yields (P=0.05) than any other cultivars, Table 7.4. ‘Tonollo’ and ‘Segorbe’ produced the next highest cumulative yields (P=0.05). Of these 5 higher-yielding cultivars, the smaller, more compact-growing “Sicilian-type” had the highest yield efficiency at 0.19 kg/cm² (P=0.05).

Table 7.4 Annual and cumulative nut yields to the eighth year from planting (kg/tree) recorded at Myrtleford along with trunk cross-sectional area (TCSA) (cm^2) at the end of the eighth growing season and yield efficiency (YE) kg/cm^2.

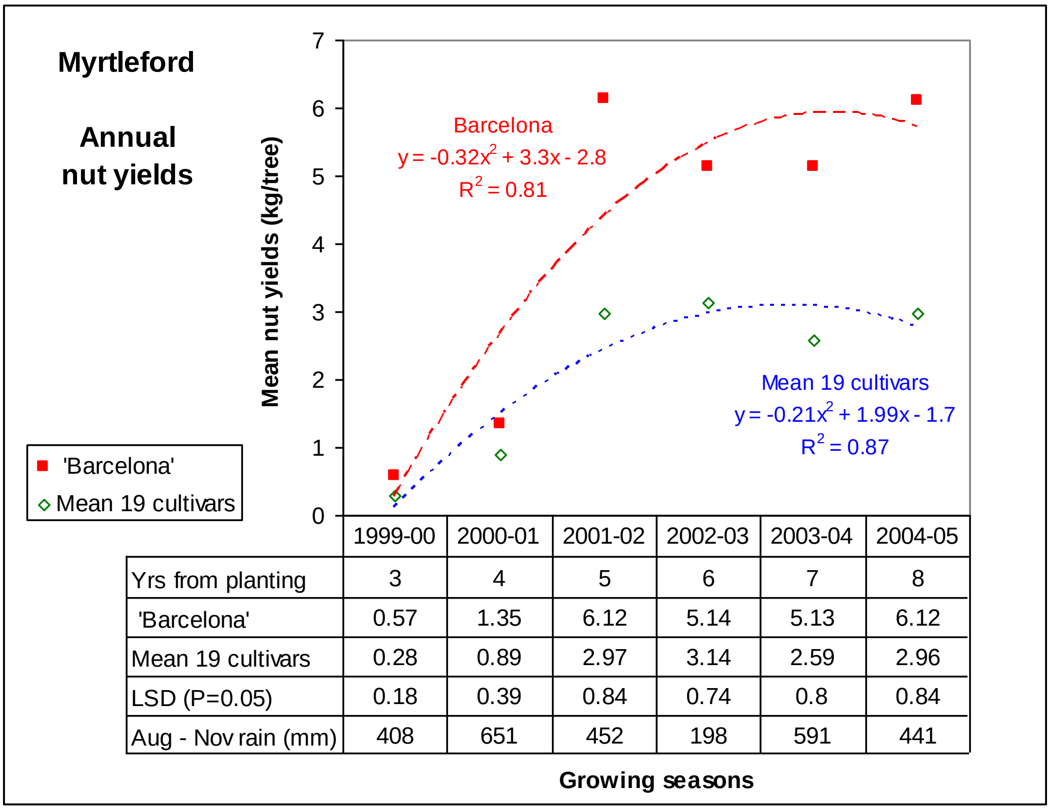
Growing season	1999-00	2000-01	2001-02	2002-03	2003-04	2004-05	2005 Cum. yield (kg)	Mean TCSA (cm^2) 2005	YE (kg/cm^2)
Yrs from planting	3	4	5	6	7	8			
‘Barcelona’	0.57	1.35	6.12	5.14	5.13	6.12	24.43	198	0.12
‘Butler’	0.42	1.11	5.59	5.46	5.72	5.59	23.89	197	0.12
“Sicilian type”	0.43	2.15	5.31	4.1	4.82	5.31	22.12	117	0.19
‘Tonollo’	0.19	0.92	4.87	4.68	4.15	4.87	19.68	178	0.11
‘Segorbe’	0.41	1.02	4.67	3.73	2.43	4.67	16.93	156	0.11
‘Tonda di Giffoni’	0.59	2.25	2.92	4.86	2.37	2.92	15.91	165	0.10
‘Ennis’	0.24	0.89	3.54	3.66	2.73	3.54	14.60	134	0.11
‘TBC’	0.66	1.8	3.01	3.54	1.8	3.01	13.82	177	0.08
‘Atlas’	0.51	1.53	2.36	4.29	2.02	2.36	13.07	158	0.08
‘Hammond#17’	0.1	0.22	2.18	3.05	3.8	2.18	11.53	158	0.07
‘Eclipse’	0.2	0.41	2.5	2.31	2.78	2.50	10.70	94	0.11
‘Negret’	0.19	0.48	2.33	2.01	3.11	2.33	10.45	93	0.11
‘Victoria’	0.06	0.89	2.59	2.77	1.21	2.59	10.11	176	0.06
‘Casina’	0.18	0.37	2.37	2.39	1.42	2.37	9.10	110	0.08
‘Royal’	0.29	0.62	1.9	2.38	1.64	1.90	8.73	134	0.06
‘T.G.D.L.’	0.13	0.57	1.6	2.28	1.67	1.60	7.85	106	0.07
‘Square Shield’	0.09	0.14	1.1	1.86	1.11	1.10	5.40	118	0.05
‘Daviana’	0.08	0.18	0.74	0.79	0.87	0.74	3.40	152	0.02
‘Merveille de Bollwiller’	0.03	0.07	0.66	0.44	0.4	0.66	2.26	140	0.02
‘Hall's Giant’	0.01	0.03	0.36	0.39	0.26	0.36	1.41	166	0.01
LSD (P=0.05)	0.18	0.39	0.84	0.74	0.8	0.84	3.28	23	0.03

The plants of ‘Hall’s Giant’ and ‘Merveille de Bollwiller’, which are considered to be the same cultivar, gave the lowest cumulative yields. The plants from these 2 sources of planting material appeared to be the same. Other low-yielding cultivars were ‘Daviana’ and the Australian selection, ‘Square Shield’.

The trees at Myrtleford made very good early growth and were producing nuts by their third year from planting. ‘Barcelona’, ‘Butler’ and the “Sicilian type” produced more than 5 kg of nuts per tree by the fifth year from planting, Table 7.4. The mean nut yields for the cultivars reached a peak 7 years from planting, Figure 7.6.

By the end of the seventh year from planting, when the ‘Barcelona’ trees had reached peak yields, they had an average TCSA of 161 cm^2/tree which, at the density of the planting

(667 trees/ha), is equivalent to a total TCSA of 106 000 cm^2/ha. This is close to the total of 91 800 cm^2/ha that Lagerstedt (as reported in Westwood, 1993) estimated to be the maximum bearing surface for an orchard. Although not stated, this was probably for 'Barcelona'. The "Sicilian type" achieved peak yields at a lower TCSA (99 cm²/tree or 65 000 cm²/ha).



	1999-00	2000-01	2001-02	2002-03	2003-04	2004-05
Yrs from planting	3	4	5	6	7	8
'Barcelona'	0.57	1.35	6.12	5.14	5.13	6.12
Mean 19 cultivars	0.28	0.89	2.97	3.14	2.59	2.96
LSD (P=0.05)	0.18	0.39	0.84	0.74	0.8	0.84
Aug - Nov rain (mm)	408	651	452	198	591	441

Figure 7.7 Development of nut yield (kg/tree) at Myrtleford, observed and fitted data

Rainfall in the period August to November, 2002, the sixth year from planting, was low, 198 mm. However, it was higher than Moss Vale, which had only 69 mm for the same period. At Myrtleford, there was good access to irrigation water and the trees were well-watered to minimise any soil moisture stress. A total of 2160 L/tree of irrigation water were applied through the growing season. As a result, tree growth and crop yields were relatively unaffected by the below average rainfall and the trees did not seem to go into a biennial-bearing pattern.

Pruning had been carried out annually to remove some limbs in order to maintain vigour and maximise an open tree structure (Plate 7.4). The trees had been planted at a high density of 3 m within the rows and 5 m between rows (667 trees/ha), as they had been at all sites.

Plate 7.4 Pruning to remove low branches and crossing limbs, to aid access, harvesting and light penetration at Myrtleford in August 2005

At Myrtleford, the trees had developed a full canopy by the seventh year from planting and probably should have been thinned, a common practice with high-density plantings of ‘Barcelona’ in Oregon. Pruning had not been done to shorten branches or to reduce the height of the trees. It was realised that there was probably a need for severe pruning to reduce the competition for light, either by cutting back the limbs of the trees or removing alternate trees in the row. It was considered that such treatments would be very time-consuming, relatively expensive and would probably cause a short-term reduction in yield, as reported by Me et al. (1994) and Roversi and Mozzone (2005). As there was little to gain from a research point of view, with the experiment nearing completion, such actions were not undertaken. Despite the very vigorous tree growth and high density planting, some light was still reaching the orchard floor at the end of the eighth growing season and the final year of the research, Plate 7.5. It appeared that peak nut yields were starting to decline in the final year of growth, but there was more loss of nuts from cockatoos that season, which may have accounted for the yield decline.

Plate 7.5 The Myrtleford site in March 2005, the ninth year from planting; although there was a full canopy, some light was still reaching the floor of the orchard. Yields had reached a plateau at this stage of tree growth.

The cultivars ‘Casina’ and ‘Montebello’ were not planted at Myrtleford until 1998; 2 years after the initial cultivars were planted. Half of the ‘Willamette’ trees were planted in 1998 with the remainder being planted in 1999. ‘Lewis’ trees were not available for planting until 2001, 5 years after the initial planting. These later-planted cultivars initially appeared to benefit from the wind shelter created by the earlier-planted trees, but, in time, competition for light seemed to limit the growth of these trees, particularly those of ‘Lewis’. It was, therefore, not possible to make a fair assessment of their yield.

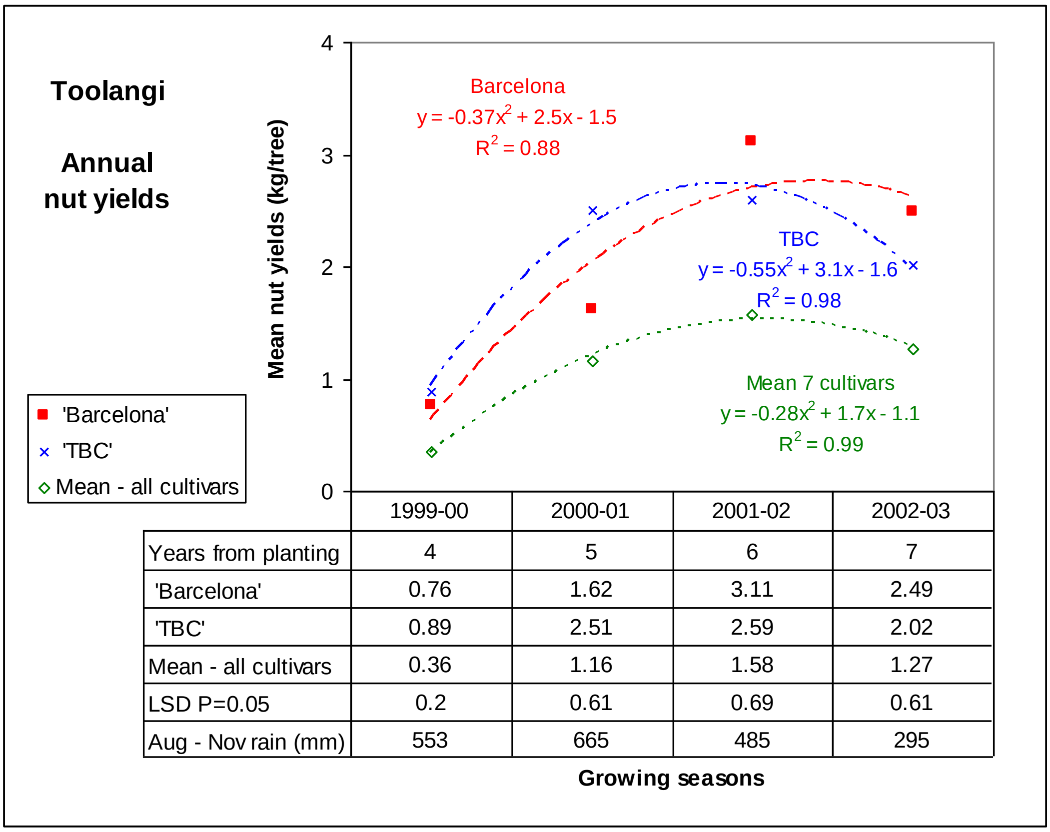
7.3.5 Toolangi

At Toolangi, ‘Barcelona’ and ‘TBC’ had the highest cumulative yields over the first 8 years from planting. However, in the sixth year from planting, ‘TBC’ yielded more than ‘Barcelona’ (Table 7.5). ‘Segorbe’ and ‘Victoria’ had the next highest cumulative yield (P=0.05); the cumulative yields of ‘Tonda di Giffoni’, the “Sicilian-type” and ‘Ennis’ were not significantly different from one another. ‘Hall’s Giant’ had the lowest cumulative yield of all the cultivars. Although ‘Wanliss Pride’ did not grow strongly, as reflected by its low TCSA, it had the highest yield efficiency.

Table 7.5 Annual and cumulative nut yields 7 years from planting (kg/tree) recorded at Toolangi along with TCSA (cm^2) at the end of the growing season in 2003 and yield efficiency (YE) kg/cm^2.

Cultivars	Growing seasons and years from planting 1999-00 4	 2000-01 5	 2001-02 6	 2002-03 7	Cum. Yield (kg)	TCSA (cm^2)	YE kg/cm^2
'Barcelona'	0.76	1.62	3.11	2.61	8.10	127.2	0.06
'TBC'	0.89	2.51	2.59	2.02	8.00	95.6	0.08
'Segorbe'	0.34	1.22	2.06	1.83	5.45	97.5	0.06
'Victoria'	0.33	1.15	1.52	1.30	4.30	127.6	0.03
'Tonda di Giffoni'	0.29	1.22	0.91	1.21	3.63	65.5	0.06
"Sicilian-type"	0.10	0.53	1.28	1.40	3.30	36.4	0.10
'Ennis'	0.09	0.54	0.82	0.94	2.38	49.1	0.05
'Wanliss Pride'	0.25	0.65	1.02	0.38	2.27	16.9	0.17
'Hall's Giant'	0.02	0.04	0.05	0.10	0.21	69.7	<0.01
LSD (P=0.5)	0.20	0.61	0.69	0.61	1.50	14.34	0.06

At Toolangi, there was an increase in nut yield to the sixth year from planting for all the cultivars, Figure 7.8. In the seventh year from planting, the tree canopies were just meeting within the rows and had achieved a mean TCSA of 70 cm^2. It appeared that peak yields had been achieved by this stage (Figure 7.8), when the mean TCSA of Barcelona was 150 cm^2, which was similar to the Myrtleford site.



	1999-00	2000-01	2001-02	2002-03
Years from planting	4	5	6	7
'Barcelona'	0.76	1.62	3.11	2.49
'TBC'	0.89	2.51	2.59	2.02
Mean - all cultivars	0.36	1.16	1.58	1.27
LSD P=0.05	0.2	0.61	0.69	0.61
Aug - Nov rain (mm)	553	665	485	295

Figure 7.8 Development of nut yield (kg/tree) at Toolangi, observed and fitted data

Although rainfall in 2002 was below the 8-year average in the months of August to November, the amount of rain recorded was greater than at the other mainland sites and did not seem to be detrimental to growth and production, although yields in that year were slightly lower for ‘Barcelona’ and ‘TBC’. No irrigation was applied in that year (Chapter 3, ‘Methods’, Table 3.9), as the limited water supplies were allocated to higher priority projects at the Research Station. The apparent decline in nut yields in the seventh year from planting was attributed mainly to damage from sulphur crested cockatoos that caused losses in nut production that year.

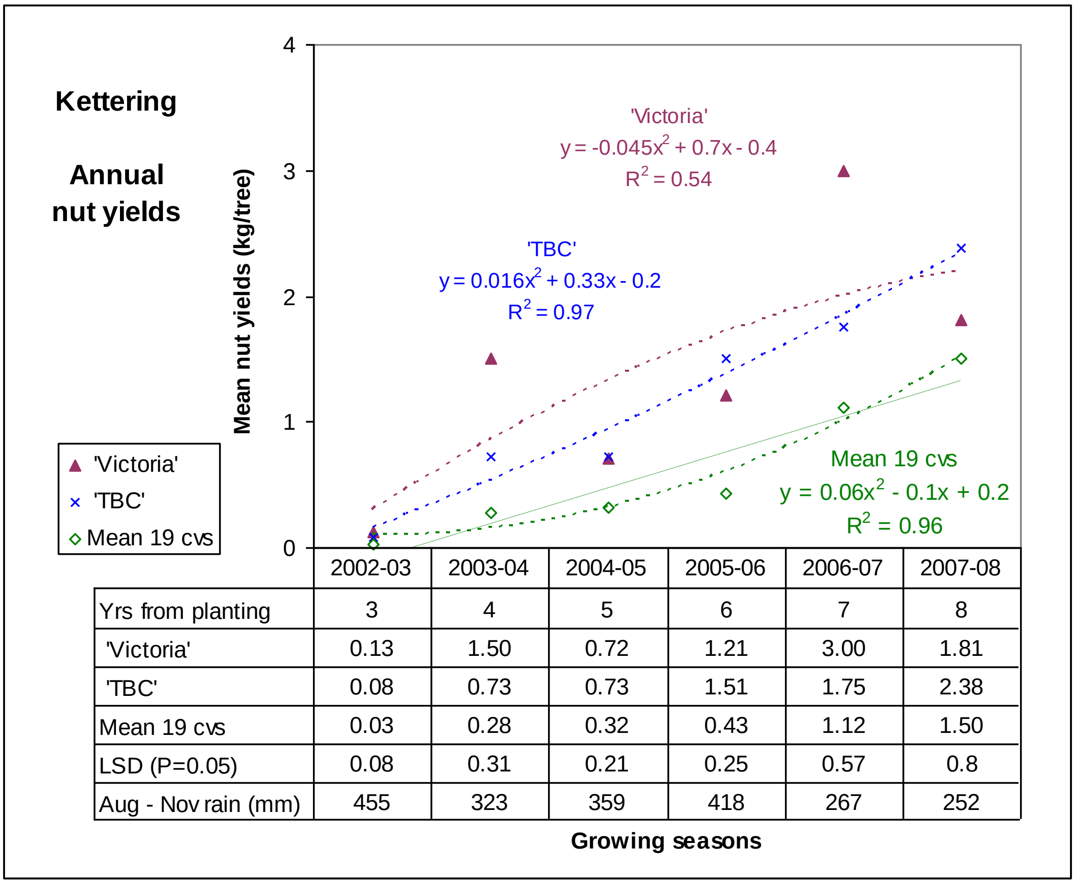
7.3.6 Kettering

At Kettering, the cultivar ‘Victoria’ produced the highest cumulative nut yield 8 years from planting (P=0.05), Table 7.6. ‘TBC’ and ‘Hammond#17’ produced the next highest cumulative nut yield (P=0.05). ‘Ennis’, ‘Whiteheart’, ‘TGDL’ and ‘Hall’s Giant’ had the lowest cumulative yields.

Table 7.6 Annual and cumulative nut yields at the eighth year of leaf (kg/tree) recorded at Kettering (2003–2007) along with trunk cross-sectional area (TCSA) (cm^2) at the end of the growing season in 2007 and yield efficiency (YE) kg/cm^2.

Cultivars	**Growing seasons and years from planting**						**Cum. yield (kg)**	**TCSA (cm^2)**	**YE (kg/cm^2)**
	2002-03	**2003-04**	**2004-05**	**2005-06**	**2006-07**	**2007-08**			
	3	**4**	**5**	**6**	**7**	**8**			
‘Victoria’	0.14	0.53	0.72	1.21	3.00	1.81	7.41	95.9	0.08
‘TBC’	0	0.01	0.75	1.51	1.75	2.38	6.39	73.4	0.09
‘Hammond#17’	0	0.02	0.46	0.75	2.03	2.83	6.08	103.8	0.06
‘Butler’	0.01	0.06	0.58	0.79	1.16	1.90	4.50	65.7	0.07
‘Tonda di Giffoni’	0.08	0.73	0.39	0.32	0.91	1.91	4.33	114.4	0.04
‘Barcelona’	0.09	0.34	0.29	0.38	1.34	1.79	4.22	103.6	0.04
‘Wanliss Pride’	0.13	1.51	0.33	0.47	0.78	0.93	4.15	80.6	0.05
“Sicilian type”	0.00	0.10	0.37	0.22	1.17	2.03	3.89	51.3	0.08
‘Eclipse’	0.00	0.00	0.42	0.47	0.99	1.74	3.62	61.4	0.06
‘Square Shield’	0.03	0.46	0.24	0.35	0.95	1.57	3.60	63.6	0.06
‘Royal’	0.03	0.23	0.59	0.58	1.01	1.01	3.45	99.7	0.03
‘Montebello’	0.00	0.04	0.32	0.13	0.86	2.07	3.42	94.6	0.04
‘Segorbe’	0.01	0.13	0.24	0.42	0.74	1.76	3.30	59	0.06
‘Willamette’	0.01	0.42	0.25	0.11	0.63	1.84	3.26	29.1	0.11
‘Lewis’	0.02	0.04	0.09	0.19	1.76	0.91	3.01	58	0.05
‘Ennis’	0.00	0.16	0.06	0.10	1.25	0.91	2.47	56.9	0.04
‘Whiteheart’	0.03	0.24	0.03	0.04	0.83	0.58	1.74	57.7	0.03
‘T.G.D.L’	0.01	0.26	0.00	0.08	0.08	0.27	0.70	23	0.03
‘Hall’s Giant’	0.00	0.00	0.05	0.07	0.02	0.22	0.36	79.2	>0.01
LSD P= 0.05	0.08	0.31	0.21	0.25	0.57	0.81	1.7	29.1	0.02

The growth of the trees and the development of nut yield over time were very slow at Kettering (Figure 7.9 and Plate 7.6), with the highest-yielding cultivars, ‘Victoria’ and ‘TBC’ producing cumulative nut yields of 7.41 and 6.39 kg/tree respectively at the end of the eighth year from planting, in contrast to their production at Myrtleford, where these cultivars produced cumulative yields of 10.1 and 13.8 kg/tree respectively over the same period of time. At the end of the eighth year from planting, the trees of the fastest growing cultivars were just meeting down the rows; none of the cultivars appeared to have achieved peak yields (Figure 7.8). ‘Willamette’ had the highest yield efficiency (P=0.05) at an average of 0.11 kg/cm^2. The yield efficiency of ‘TBC’ was 0.09 kg/cm^2, which compared favourably with its yield efficiency at Myrtleford of 0.08 kg/cm^2.



	2002-03	2003-04	2004-05	2005-06	2006-07	2007-08
Yrs from planting	3	4	5	6	7	8
'Victoria'	0.13	1.50	0.72	1.21	3.00	1.81
'TBC'	0.08	0.73	0.73	1.51	1.75	2.38
Mean 19 cvs	0.03	0.28	0.32	0.43	1.12	1.50
LSD (P=0.05)	0.08	0.31	0.21	0.25	0.57	0.8
Aug - Nov rain (mm)	455	323	359	418	267	252

Figure 7.9 Development of nut yields (kg/tree) at Kettering, observed and fitted data

At Kettering, the cultivars ‘Barcelona’ and ‘Tonda di Giffoni’ produced relatively low nut yields compared with their performance on the mainland sites. Although ‘Barcelona’ produced good shoot growth, it appeared to have relatively fewer female flowers than ‘TBC’. To try and ascertain whether the Barcelona trees had less flowers and a poorer nut set than TBC, some flower counts were undertaken on tagged branches; a branch of a single tree of the cultivars ‘Barcelona’, ‘Lewis’ and ‘TBC’ was selected at random in each of the 3 replicates for this study. On 20 July, 2006, the numbers of female flowers on each branch were counted. These branches, which were about 500 mm in length, were tagged and the number of nut clusters subsequently produced were counted in the following January, Table 7.7.

Table 7.7 Average number of female flowers on branches of 3 cultivars at Kettering in July 2006, and the number and proportion of fruitful flowers

Cultivars	Female flowers	Nut clusters	Fruitful flowers
'Barcelona'	4.7	3.7	79%
'Lewis'	11.7	11.3	97%
'TBC'	8.7	5.3	62%

The number of flowers on the cultivar 'Barcelona' was low compared with 'TBC' and 'Lewis'. However, pollination did not seem to be an issue, with a high percentage of flowers on the tagged branches producing nut clusters, particularly with the cultivar 'Lewis'. There was a wide range of compatible polliniser cultivars at this site, as there was at all sites, so pollination was unlikely to be an issue for most cultivars, except for those that were very late into female flowering, such as 'Hall's Giant'. This cultivar was one of the latest at all sites to come into female anthesis and gave low yields at all sites. 'Whiteheart' and 'Ennis' were also cultivars that were very late commencing female anthesis, which might account for their low yields, although 'Whiteheart' was also of low vigour.

Plate 7.6 The Kettering site in April, 2008; John Zito used a FACMA suction machine for harvesting. Although healthy, the trees grew relatively slowly, just meeting within the rows 8 years from planting.

The mean monthly temperatures in the period November to March were lower at Kettering than at the mainland sites. This may possibly have affected the development of floral buds. It is possible that ‘Barcelona’ requires more warmth in this period than ‘TBC’ for floral bud initiation or for fertilisation to occur.

7.4 The productivity of cultivars

In the initial analysis of variance, which examined the variable factors of cultivars and sites, (Table 7.1) a significant interaction ($P<0.001$) between cultivars and sites was found for the cumulative yields of cultivars and their yield efficiency. In the context of this interaction, the yields of the cultivars and their yield efficiencies are discussed.

The cultivars ‘Barcelona’ and ‘TBC’ were commonly the cultivars with the highest cumulative 7-year nut yields; however, there were exceptions. ‘Barcelona’ had the highest cumulative yield at Myrtleford, along with ‘Butler’ (Table 7.4), whilst ‘Barcelona’ and ‘TBC’ had the highest cumulative yields at Orange and Toolangi (Figure 7.9). At Moss Vale, ‘Barcelona’ was the third highest-yielding cultivar along with the “Sicilian type”. The results for ‘Barcelona’ are in general agreement with those reported for this cultivar, that being a cultivar of high vigour over a wide range of conditions with generally high nut yields, as reported by Baratta et al. (1994), Miljković and Prgomet (1994), McCluskey et al. (1997), Santos and Silva (2001) and Grau and Bastias (2005).

The Australian cultivar ‘TBC’ also had a high growth rate and was a high-yielding cultivar, with the highest cumulative yields at Moss Vale (Figure 7.9), equal highest to ‘Barcelona’ at Orange and Toolangi and the second highest-yielding at Kettering (Figure 7.9), where ‘Victoria’ was the highest-yielding cultivar.

The “Sicilian-type” demonstrated a high yield potential (Figure 7.9). It produced nut yields that were not significantly different ($P=0.05$) from the highest-yielding cultivar, ‘Barcelona’ at Myrtleford. At Moss Vale, the “Sicilian-type” also had a similar yield to ‘Barcelona’, whilst at Orange its yields were not significantly different from ‘TBC’ and ‘Ennis’. At Toolangi and Kettering, yields of the “Sicilian-type” were similar to ‘Tonda di Giffoni’. The “Sicilian-type” grew as a relatively small, bushy tree with the highest yield-efficiency of all cultivars at Myrtleford, Orange and Moss Vale.

‘Tonda di Giffoni’ yielded well at Myrtleford and Moss Vale, where the nut yield was not significantly different from ‘TBC’ (P=0.05). However, ‘Tonda di Giffoni’ was not as productive at Orange, Toolangi or Kettering. It is possible that this cultivar, that has low chill requirements for catkins, female flowers and vegetative buds, is better adapted to warmer climates.

‘Ennis’ produced the highest cumulative yield at Orange, along with ‘Barcelona’ and ‘TBC’ (Table 7.2). ‘Ennis’ produced yields equivalent to ‘TBC’ at Myrtleford; however, it did not yield well at Toolangi and Kettering. As Kettering and Toolangi were sites with cooler summer temperatures, these results suggest that possibly ‘Ennis’ prefers a warmer summer climate. McCluskey et al (1997) reported high yields and a high yield-efficiency in Oregon for ‘Ennis’. In northern Portugal, Santos and Silva (2001) found ‘Ennis’ to be high-yielding and precocious.

‘Segorbe’ grew well at all sites, but only produced mediocre cumulative yields at Orange, Moss Vale and Kettering. However, at Myrtleford and Toolangi, it produced well with cumulative nut yields that were not significantly different from those of ‘TBC’. This cultivar is grown in France, principally as a polliniser, but also for its relatively small, round kernels which have a smooth pellicle (Germain and Sarraquigne, 2004).

The Australian selection ‘Victoria’ was the highest-yielding cultivar at Kettering. Yields of ‘Victoria’ were mediocre at Orange, Myrtleford and Toolangi (Figure 7.9).

‘Hall’s Giant’ (‘Merveille de Bollwiller’ syn.) grew well at all sites but produced very low nut yields. In the Oltenia region of Romania, where the winters are very cold, ‘Merveille de Bollwiller’ showed good adaptability and yield (Parnia and Botu 1994).

Overall Cultivar rankings

In order to obtain an overall assessment of the yield potential of the 8 cultivars, a scoring system was used with a ranking score for each site. This was obtained by dividing the cumulative yield of each cultivar by the cumulative yield of the highest yielding cultivar at that site. The highest yielding cultivar gained a score of 1 with the others being a fraction. These site scores were used to obtain a mean score for each cultivar across the 5 sites. Based on this scoring system, the cultivars ‘Barcelona’ and ‘TBC’ were ranked as the highest scoring cultivars across all sites for nut yields (Table 7.8), indicating wide adaptation with high yield potential across all sites. They were followed by the "Sicilian type" and 'Tonda di Giffoni', with 'Hall's Giant' being ranked the least productive.

Table 7.8 Relative nut yield scores and total cumulative yields 7 years from planting for 8 cultivars across the 5 sites.

Cultivars	Relative yield score (Max. score = 1.0)	Cumulative nut yield (kg/tree)
'TBC'	0.82	7.32
'Barcelona'	0.81	7.99
"Sicilian type"	0.57	6.15
'Tonda di Giffoni'	0.56	5.74
'Victoria'	0.54	4.80
'Segorbe'	0.47	4.96
'Ennis'	0.47	4.63
'Hall's Giant'	0.05	0.52

There was a highly significant (P<0.01) correlation between the relative mean scores and the mean cumulative nut yields across the 5 sites (Figure 7.10), accounting for 97% of the variation between the scores and the cumulative yields.

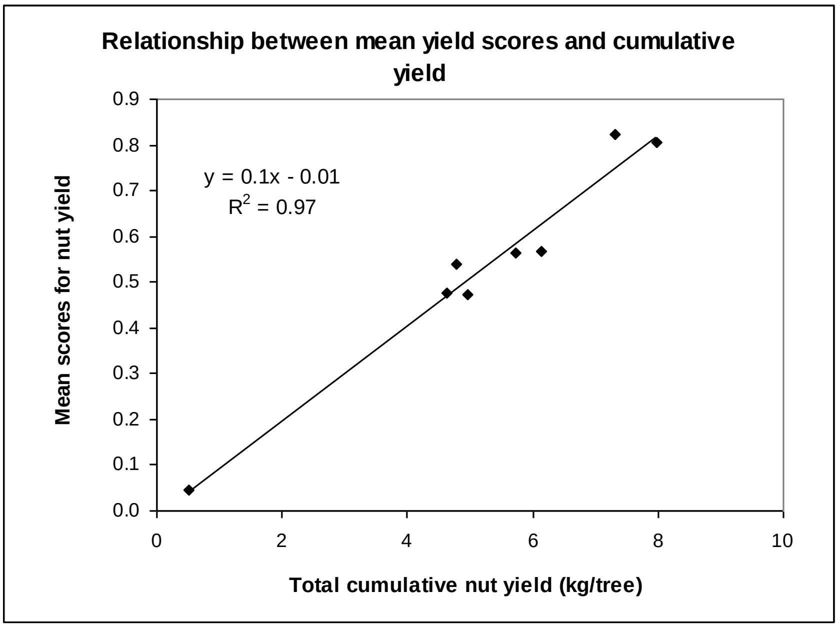


Figure 7.10 Relationship between mean scores for relative yields at each site and total cumulative nut yield, 7 years from planting at the 5 sites for 8 cultivars.

Other cultivars

‘Butler’ and ‘Tonollo’ yielded very well at Myrtleford (Table 7.4) but ‘Tonollo’ was not included for yield comparisons at the other sites. ‘Tonollo’ was reported as the highest-yielding cultivar in the field evaluation of hazelnut genotypes at Glen Innes in 1937 (Trimmer, 1965). Snare (1982) also reported good yields for ‘Tonollo’ in the cultivar collection at Orange. The origin of ‘Tonollo’ is unknown, but it seems likely that it is related to ‘Barcelona’, as it has many similar characteristics to that cultivar.

‘Atlas’ only produced mediocre yields and did not yield as well as had been reported in previous studies. High yields had been recorded for this cultivar at Orange (Department of Agriculture NSW, 1982) and were later recorded at Myrtleford by Sample (1993).

‘Negret’ was only planted at Myrtleford and Orange. At Myrtleford, it grew as a small tree with relatively low nut yields, whilst at Orange, growth and production were very poor. In Oregon, ‘Negret’ trees were of low vigour and produced relatively low nut yields, McCluskey et al. (1997). However, ‘Negret’ was reported to grow well and produce high yields in Chile (Grau et al., 2001). It is the main cultivar grown in Spain (Tous, 2005).

‘Lewis’ and ‘Willamette’ were planted at Kettering at the same time as the other cultivars, whereas these 2 cultivars were planted later than the other cultivars at all the other sites. At Kettering, yields of ‘Lewis’ and ‘Willamette’ were not significantly different from ‘Barcelona’, but were significantly lower (P=0.05) than the highest-yielding cultivars, ‘Victoria’ and ‘TBC’. In Oregon, both ‘Lewis’ and ‘Willamette’ produced higher yields than ‘Barcelona’ (McCluskey et al, 2001).

‘TGDL’ was planted at Orange, Myrtleford and Kettering. It struggled to grow at Orange and grew relatively slowly at the other 2 sites, producing low yields. In Oregon, McCluskey et al (1997) also reported ‘TGDL’ to be of low vigour with low nut yields. In Chile, however, growth and yield of ‘TGDL’ varied considerably with sites, (Grau and Bastias, 2005). Parnia and Botu (1994) obtained good yields from ‘TGDL’ in Romania.

‘Wanliss Pride’ yielded best at Kettering, with yields not significantly different from ‘Barcelona’, although significantly lower than the highest-yielding cultivars, ‘Victoria’ and ‘TBC’. At Toolangi, the cumulative yield of ‘Wanliss Pride’ was not significantly different from ‘Ennis’, ‘Tonda di Giffoni ‘or the “Sicilian type”. Production at the other 3 sites was poor in comparison with other cultivars, especially at Orange, where ‘Wanliss Pride’ made very poor growth. This cultivar had been the most widely-grown cultivar in Australia until the early 1990s. At that time, ‘Wanliss Pride’ was viewed as the industry standard or benchmark cultivar in Australia. Very variable results have been observed in the performance of this cultivar in growers’ orchards. An example of good growth and nut yields was reported at Kallista, in the Dandenong area of Victoria, where ‘Wanliss Pride’ trees that were at least 40 years old and were at a spacing of 8 m x 6 m, were reported to have given yields of 20 kg/tree, equivalent to 4 tonnes/ha. (Merry, Anthony, HGA field visit, 19 October, 2008). The Kallista site had a krasnozem soil, which appeared similar to the Toolangi site and had high annual rainfall of about 1000 mm per annum. ‘Wanliss Pride’ seems to perform better in more maritime climates, such as Kettering and in the hills east of Melbourne.

‘Wanliss Pride’ has a spreading habit of growth and may grow better as a multi-stemmed tree. In Portugal, Santos and Silva (2001), found that multi-stemmed trees produced higher cumulative yields than single trunk trees in their early years of production. It is possible that, had ‘Wanliss Pride’ been grown with 4-5 stems, it might have given higher nut yields.

7.5 Some factors influencing nut yields

In general, nut yields appear to have been strongly influenced by tree growth. A significant relationship (P=0.01) was found between the vigour of growth of 8 cultivars and their cumulative nut yields 7 years from planting (Figure 7.11) across the 5 study sites. However, this only accounts for 50% of the variation in nut yields.

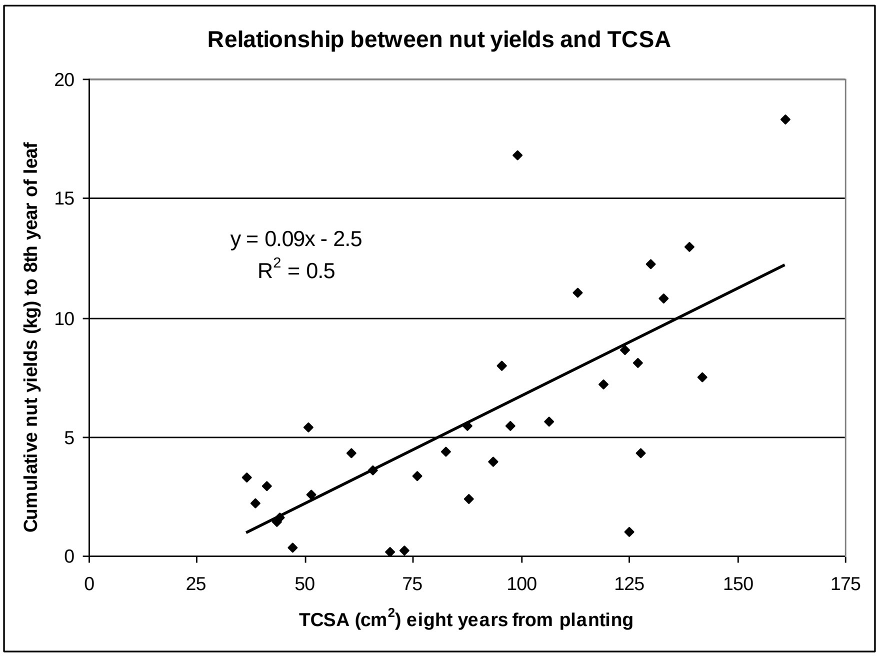


Figure 7.11 Relationship between cumulative nut yield (kg/tree) and TCSA, 7 years from planting for 8 cultivars common to the 5 sites.

This relationship suggests that, in order to obtain good early production under Australian conditions that might not be ideal for hazelnut production due to unfavourable soil type, an important cultivar characteristic is high vigour of growth. Some weaker-growing cultivars, such as ‘Whiteheart’ and ‘Wanliss Pride’, might perform well over a very much longer time-frame, possibly as long as 20 years. Planting these less vigorous cultivars at a relatively high density might help achieve higher early production per hectare. However, with the relatively high cost of orchard establishment and income foregone from low yields in the early years of establishment, the economics of such slow-growing cultivars are questionable.

Some vigorous cultivars such as ‘Hall’s Giant’ and ‘Segorbe’ were low-yielding. Another factor influencing the productivity of cultivars could be related to the availability of pollen at the time of female anthesis, as discussed in Chapter 5, Section 5.3.2 ‘Floral phenology at the Orange site’.

Cultivars that were late into female anthesis included ‘Eclipse’, ‘Casina’, ‘Square Shield’ and ‘Hall’s Giant’. These cultivars generally had low yields and, on average, their stigmas were not exerted before the beginning of August, when many cultivars had completed pollen shed and therefore there were limited supplies of pollen for pollination. However, ‘Ennis’ and ‘Butler’ were cultivars that were late into female anthesis, yet produced good yields at some sites, for example ‘Ennis’ at Orange and ‘Butler’ at Myrtleford. There was a significant relationship between the cumulative nut yields of the 8 cultivars that were grown across the 5 sites and their mean dates for the commencement of female anthesis. However, this accounted for only 19% of the variation in yield (Figure 7.12). The data shows that, after DOY 213, nut yields were low. Before DOY 213 there was a large spread in the data points for nut yields indicating that before that date the DOY that female anthesis commenced was not a major factor influencing nut yields.

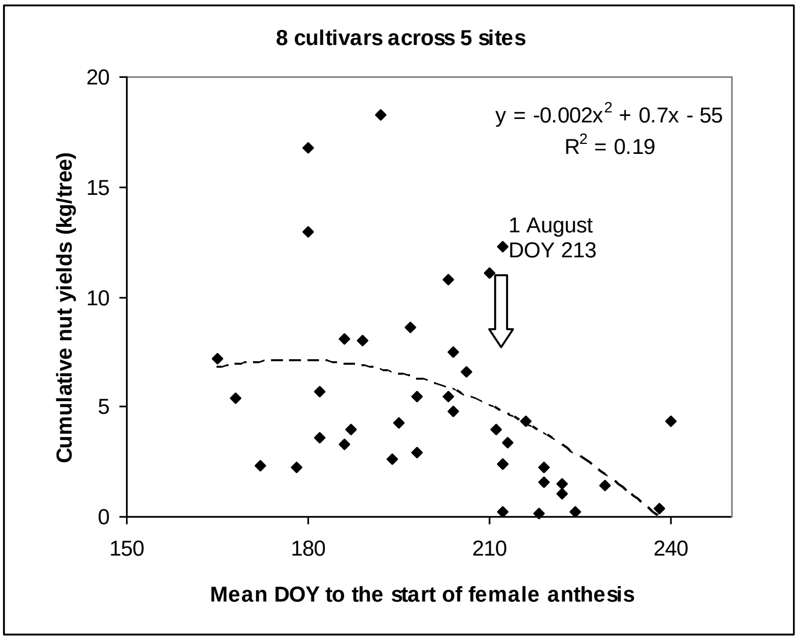


Figure 7.12 Relationship between cumulative nut yield (kg/tree) and the mean day of the year to the start of female anthesis for 8 cultivars common to the 5 sites.

7.6 Conclusions

Tree growth and nut yields were found to vary between sites. There were significant differences in nut yields between cultivars, with a significant interaction with site, depending on the environments in which they were grown. There was no single cultivar that yielded best at all sites. In general, ‘Barcelona’ and ‘TBC’ produced the highest nut yields across all sites. Nut yields from many cultivars were highly variable across sites, for example the cultivars ‘Ennis’, ‘Tonda di Giffoni’ and ‘Victoria’ performed well at some sites but less well at others.

There was a positive correlation between vigour of growth and nut yields. However, time of female flowering appeared to be another factor affecting the nut yields. Several cultivars, that did not commence female bloom until early August, were low-yielding. At that time, most of the cultivars evaluated in these studies had completed pollen shed. As a result, a cultivar such as ‘Hall’s Giant’ and to a lesser extent ‘Segorbe’, both of which grew well but were late in female bloom, produced low nut yields.

The pathway of nut production, Figure 7.1, identified that the number of female flowers produced by a cultivar was a factor influencing nut yields. Apart from the very limited observations of a few trees at Kettering in 2006, no data was collected on this yield component. The data from Kettering indicated that there could have been large differences between cultivars in the number of female inflorescences produced as well as the proportion of flowers producing nut clusters, with a variation between sites and seasonal conditions.

Although some factors influencing nut yields were identified, as discussed above, there is a need for further studies to ascertain how the production of female inflorescences and the development of the flowers from pollination to nut production, varies between seasons.

Overall, it was concluded that, of the cultivars studied, 2 attributes that were associated with relatively high nut yields were relatively vigorous growth coupled with early to mid-season stigma exertion.

The next chapter examines kernel yields and the characteristics of kernels, with the final chapter integrating the characteristics of floral phenology, pollination requirements, nut yields, kernel attributes and market requirements in the final assessment of the cultivars.

CHAPTER 8 - NUT FALL AND THE CHARACTERISTICS OF NUTS AND KERNELS

8.1 Introduction

The bulk of hazelnuts are grown for their kernels. The value of a cultivar therefore depends on its nut yield, kernel percentage and the market acceptance of its kernels. Kernel size, flavour and chemical composition are also considerations.

In Australia, hazelnuts generally commence nut fall in late February or early March, the main period being throughout March. For most cultivars, nut fall has been observed to take place over a period of 3 to 5 weeks. It is advantageous to have hazelnut cultivars that mature quickly, with nuts falling over a short period of time, so that the crop is at least risk to pests and wet weather and can be harvested efficiently in 1 operation. Studies were undertaken at the Orange and Myrtleford sites to ascertain whether there were differences between cultivars in the period of peak nut fall and how this varied between seasons.

This chapter examines:

- The pattern of nut fall and how this varies with cultivars and environmental conditions;
- The characteristics of the nuts and kernels of the key cultivars evaluated;
- The effects of environmental conditions on nuts and kernels; and
- The chemical composition of kernels.

8.2 The pattern of nut fall

8.2.1 Introduction

In Australia, hazelnuts start to fall to the ground in late February, depending on the season, and continue throughout March. As Australian labour costs are high, there is a need to harvest the crop mechanically after the nuts have fallen. As temperatures and evaporation rates decline in March and April, and nuts are best harvested when it is warm and dry, it is advantageous to have cultivars that shed nuts early and over a short period of time, to facilitate efficient mechanical harvesting and minimise drying costs. This section examines the period of nut fall and how this varied with cultivars and seasonal conditions.

8.2.2 Methods

In the early stages of growth and production, when the trees were relatively small, fallen nuts were collected from the ground at weekly intervals at the Orange site in 2000, 2001 and 2002, and at the Myrtleford site in 2001 and 2002. The collected nuts from each tree were kept in net bags that were suspended from the tree from which they had been collected, (Plate 8.1). There were a total of 8 trees for each cultivar, comprising 2 trees per replicate with 4 replicates at each of the 2 sites. A tie was placed around the bag after each week of collection, with the collection from the following week being placed in the same bag and also being tied off. By the end of harvest, each bag had 8 or more segments, each segment representing a harvest date, as in Plate 8.1.

Plate 8.1 Nuts from weekly collections were placed in net bags with a string tied to separate each week of collection. The bags were suspended from the harvested tree until the final harvest. The bag on the left was from the first 6 weeks, with those in the lowest segment being from the first collection; those at the top in the right bag were from the last week of collection.

In some situations more than 1 bag was required for the whole harvest. At the completion of harvest, the bags of nuts were dried at 35°C for 3 days. The dry nuts from each tree, for each date of collection, were counted and weighed. In 2001, the nuts from the Myrtleford site were cracked for each date of harvest for 6 of the higher yielding cultivars, Table 8.1. The number of blank nuts and the number of well-filled kernels were recorded for each week. The period over which the blank nuts fell is shown in Figure 8.3.

8.2.3 Results and discussion

Dates of peak nut fall

The dates of peak nut fall, that being the week when the greatest number of nuts fell to the ground, were determined for 6 of the highest yielding cultivars at Orange and Myrtleford, Table 8.1. The date of peak nut fall varied little between cultivars, although 'Tonda di Giffoni' and the "Sicilian type" were generally the earliest, whilst 'Ennis' and 'Segorbe' were the latest, (Table 8.1). However, there appeared to be a greater difference between sites and seasons. At Myrtleford, the period of peak nut fall occurred nearly 2 weeks earlier in 2001 compared with 2002, for nearly all cultivars, Table 8.1. Nut maturity is reported to be a genetically inherited trait (Mehlenbacher, 1991). 'Tonda Gentile delle Langhe' was rated as an early-maturing, free-husking cultivar, 'Barcelona' and 'Tonda di Giffoni' were rated as being a little later maturing with 'Ennis' being later still (ibid, 1981). The work reported here (Table 8.1) is in agreement with the relative dates of maturity recorded for these cultivars.

Table 8.1 Dates when the highest number of nuts had fallen, peak nut fall, for 6 cultivars harvested at the Orange and Myrtleford sites.

	Sites and years					
	Orange			**Myrtleford**		**Cultivar means**
Cultivars	**2000**	**2001**	**2002**	**2001**	**2002**	
'Barcelona'	21 Mar	5 Mar	17 Mar	5 Mar	19 Mar	14 Mar
'Ennis'	31 Mar	19 Mar	17 Mar	26 Feb	12 Mar	22 Mar
'Segorbe'	31 Mar	19 Mar	17 Mar	5 Mar	19 Mar	22 Mar
"Sicilian type"	21 Mar	5 Mar	17 Mar	26 Feb	12 Mar	14 Mar
'TBC'	21 Mar	12 Mar	17 Mar	26 Feb	5Mar	17 Mar
'Tonda di Giffoni'	21 Mar	5 Mar	17 Mar	26 Feb	5Mar	14 Mar
Mean dates	24-Mar	11-Mar	17-Mar	28-Feb	12-Mar	

There was a relatively distinct peak of nut fall for most cultivars in most seasons, with about 80% of nuts of most cultivars falling in a 3 to 4 week period, (Figure 8.1). 'Tonda di Giffoni' appeared to have a more distinct period of nut fall than 'Barcelona' and 'TBC'.

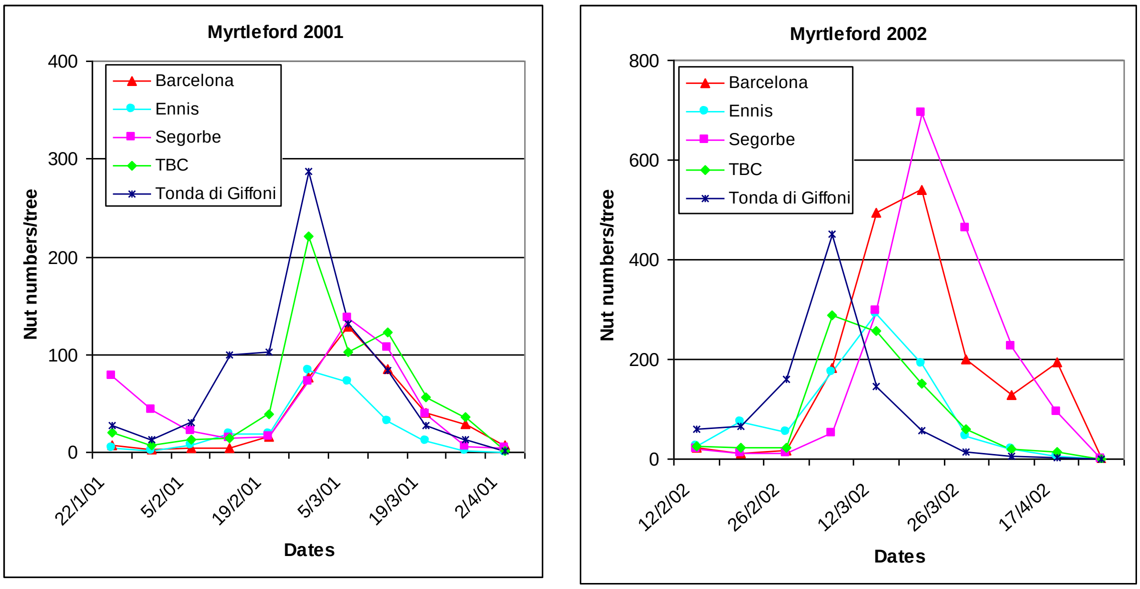


Figure 8.1 Mean number of nuts falling per week at Myrtleford in the seasons 2001 and 2002 for 5 cultivars.

The effect of temperature on the date to peak nut fall

The mean daily temperature recorded at each site was used to estimate the daily heat units as the number of Growing Degree Days (GDD). The daily GDD were calculated for base temperatures of 5°C, 7°C and 10°C, over the period from 1 September, when most cultivars were at bud break, until the mean day of peak nut fall for the cultivars ‘Barcelona’, ‘Ennis’, ‘Segorbe’, the “Sicilian type”, ‘TBC’ and ‘Tonda di Giffoni’. Accumulated GDD were determined for the periods from 1 September, 1 October, 1 November, 1 December and 1 January to the dates of nut fall for the 6 cultivars at Orange in 2000, 2001 and 2002 and at Myrtleford for 2001 and 2002. Correlation analyses were undertaken to identify relationships between the accumulated GDD for the above periods of time that extended from leafing out through nut and kernel development to peak nut fall (Table 8.2).

Correlation analyses were conducted on the number of days to peak nut fall and the accumulated GDD above base temperatures of 5°C, 7°C and 10°C. These relationships were significant (P= 0.05) for all periods of time. The correlation coefficients for the period from 1 November to peak nut fall had the highest levels of significance (P=0.01) for the base temperature calculations of 10°C. It was, therefore, considered that the accumulation of GDD above a base temperature of 10°C over this period is the best predictor for the day of peak nut fall.

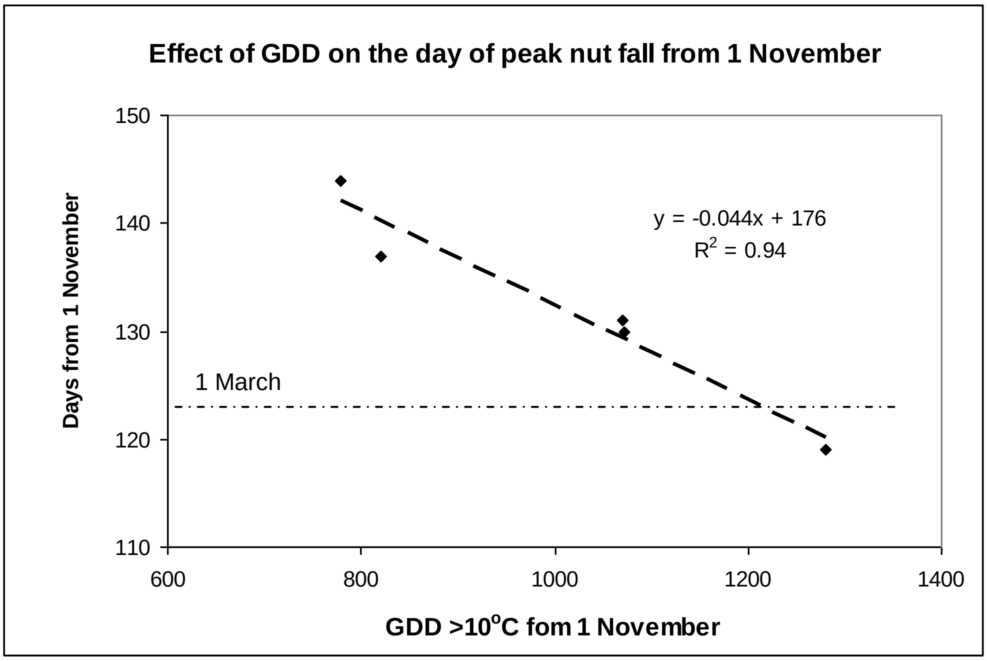


Figure 8.2 Relationship between the number of accumulated Growing Degree Days (GDD>10°C) from 1 November and the number of days to peak nut fall. (Fitted vs. observed data, based on 5 years of observations from Orange and Myrtleford)

The linear relationship for the total number of GDD from 1 November to the day of peak nut fall at a base temperature of 10°C was calculated to be:

$$y = -0.04x + 176$$

where y is the days from 1 November to peak nut fall and x is GDD in this period.

This linear regression accounted for 94% of the variance (Figure 8.2). The equation showed that, on average, for the 6 cultivars used in the analysis, the more heat units (GDD above a base of 10°C) that occurred after 1 November, the earlier the nuts matured and fell from the trees. That is, for every increase of 159 GDD in the range 700-1300 GDD, from 1 November, peak nut fall occurs 7 days earlier.

As automatic weather stations and on-line temperature data are becoming increasingly available, it is possible for growers to monitor GDD and gain better insights into the timing of nut fall. This may be of assistance in planning the logistics of harvesting operations.

Biologically, the period from 1 November to nut fall extends from fertilisation and the start of fruit development through nut growth and kernel fill to maturity, for most cultivars. In areas that have higher summer temperatures than Orange and Myrtleford, this data indicates nut fall would be earlier. There might be implications for kernel fill or kernel quality if the period of kernel filling is hastened by higher temperatures. Conversely, locations with cooler summer temperatures are likely to have delayed nut fall and may not have sufficient heat units for kernel fill, if summer temperatures are too low. Hazelnut trees in the cooler mountainous areas of Spain were reported by Tous et al (2001) to ripen later than those on the plain areas, supporting these results on the effects of GDD on nut maturity.

In these studies, the number of GDD from 1 November to peak nut fall ranged from about 800–1350. An extrapolation of the graph to 150 days from 1 November, that is to the end of March, indicates that minimum heat unit requirements for commercial hazelnut production from fertilisation to nut maturity may be about 600 GDD >10°C. This could be included as a climate parameter for hazelnut production. However, more data is required to test this hypothesis over a wider range of temperature and environmental conditions. A total value of 1250 GDD >10°C was considered by MacDaniels (1977) to be desirable for nut trees in the Northeast of the USA.

Blank nuts

Data on blank or seedless nuts was obtained. Samples from the weekly collections of 6 higher-yielding cultivars were cracked out to determine the proportion of blank nuts at Myrtleford in 2001, Figure 8.3.

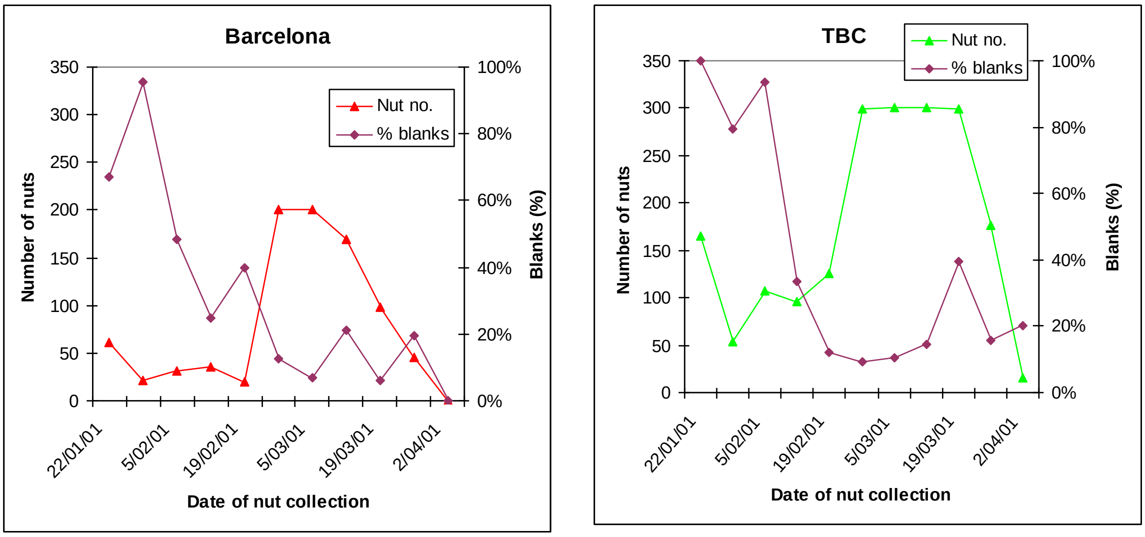


Figure 8.3 Pattern of nut fall, shown as nut numbers collected weekly per tree and the proportion of blank nuts, for the cultivars 'Barcelona' and 'TBC' at Myrtleford in 2001.

Most blank nuts fell in the 3-4 weeks leading up to the peak period of nut fall, although some blank nuts fell through the whole period of nut fall.

As cracking nuts on a weekly basis to determine the proportion of blanks is very time consuming, this process was only carried out on the weekly collections at Myrtleford in 2001.

Conclusions

The main period of nut fall for most cultivars was over a period of about 5 weeks, with most blank nuts falling at the beginning of this period. The peak date of nut fall varied slightly between cultivars and seasons. It was influenced by the accumulated GDD above a base temperature of 10°C from 1 November. It was considered that 600 GDD in the period 1 November to 31 March could be the minimum for commercial hazelnut production.

8.3 Nut and kernel characteristics

The size and weight of nuts, shell thickness and percentage kernel are considered to be highly heritable traits (Thompson et al. 1978 and Mehlenbacher 1991b), although nut and kernel weights are also influenced by environmental conditions (Mehlenbacher, 1991b), particularly moisture stress during nut and kernel fill development (Mingeau et al., 1994 and Bignami and Natali, 1997). Kernel percentage is an important factor influencing kernel yields per hectare and an important consideration when processing nuts for the kernel market. Cultivars with thick shells and a low kernel percentage produce a lower proportion of kernels per unit of processed nuts. Thick, heavy shells can be more difficult to separate from kernels when using air separation.

The ease of pellicle removal after roasting, known as blanching, is moderately heritable, as reported by Thompson et al. (1978) and Mehlenbacher (1991b). The flavour of kernels is principally a cultivar characteristic, as is nut shape. Some cultivars, such as ‘TGDL’, are favoured by the confectionery industry for their kernels, which are relatively small and round, blanch well and have a good “nutty” flavour (Mehlenbacher, 1991b and Tombesi and Limongelli, 2002). ‘TGDL,’ ‘Tombul’ and ‘Negret’ are considered to be reference cultivars for kernel quality (Mehlenbacher, 1991b). Some cultivars, such as ‘Ennis’, produce large nuts with attractive shells, which are highly suited to the in-shell market (Mehlenbacher and Olsen, 1997). Some cultivars, such as ‘Wanliss Pride’, have potential for more than 1 market sector. ‘Wanliss Pride’ has relatively large, shiny, attractive nuts, making it a suitable cultivar for the in-shell market, (Lagerstedt, 1988), but as the kernel has little fibre and blanches well, it is also suitable for some uses in the kernel market

8.3.1 Methods

Composite, random samples of 150–200 nuts from all the replicates were retained from all cultivars after harvest. A sub-sample of 100 nuts was weighed to obtain a mean nut weight. The nuts were cracked using the template boards and small hammer, as described in Chapter 3, ‘Methods’, Section 3.5.6, ‘Kernel assessments’. The number of good kernels was counted and weighed to obtain the mean kernel weight. The kernel percentage was derived from the weight of well-filled kernels divided by the weight of 100 nuts. Kernels that were shrivelled, not well-filled or which had some defects were counted but not included in the final kernel count and weight. This technique was similar to that used in Oregon for cultivar evaluation (McCluskey et al., 1997). Kernel yields per hectare are the product of nut yields per tree, kernel percentage and the number of trees per hectare.

In the early years of production, these assessments were only done on the higher-yielding cultivars, as there were insufficient nuts of the lower-yielding cultivars.

Kernels were assessed for their blanching characteristics by heating them in an oven at 130-150°C for 15 minutes, followed by rubbing them in a cloth to remove any loose skins. The blanched kernels were scored for their degree of blanching on a 1 - 7 scale, as recommended by Thompson et al. (1978). A score of 1 equated to all skin being removed, with a score of 7 for all skin being retained.

The size of good kernels for 13 cultivars, harvested from the Myrtleford crop in 2002, was measured. Samples of 50 nuts from each cultivar were cracked to obtain the kernels. The diameter of the individual kernels was measured by passing them through a plastic gauge that had a range of hole sizes, to see which was the closest fit. The mean size was determined, as was the degree of variation between the sizes of the kernels.

Uniformity of nut size was assessed on the nuts from the 2008 harvest at Kettering that were from cultivars with large nuts, with potential for the in-shell market. The nuts were passed through a rotating drum, size grader with hole sizes varying by 1 mm from 16-21 mm, to assess size grades. As several cultivars had nuts that were more than 21 mm in diameter (Table 8.4), it was not possible to obtain the proportion of nuts in each 1 mm size grade above 21 mm. For example, more than 90% of the nuts of the cultivars ‘Ennis’ and ‘Royal’ were over 21 mm in diameter.

The length and width of 10 nuts from each cultivar collected at Orange in 2006 were measured to determine the shape of the nuts to assess their relative roundness and as an aid to identification, Table 8.3 and Appendix A ‘Cultivar characteristics and identification’.

8.3.2 Results and discussion

Cultivar and site effects on nuts and kernels

An analysis of variance was conducted on the mean nut and kernel weights of 13 cultivars that were common to 3 sites, Orange, Myrtleford and Kettering, and for which there was 6 years of data at each site, Table 8.3.

The variables were:

- Cultivars (13)
- Sites (3)
- Years (Seasonal conditions 6)

Table 8.2 Effects of cultivars, sites and years on the mean nut and kernel weights and mean kernel/nut ratios for 13 cultivars grown at 3 sites, Orange, Myrtleford and Kettering, over 6 years.

Source of variation	Mean nut weight	Mean kernel weight	Mean kernel/nut ratio
Cultivar	<.001	<.001	<.001
Site	0.14 (NS)	<.001	<.005
Year	<.001	0.004	0.2 (N.S.)
Cultivar x site	<.001	0.002	0.02
Cultivar x year	0.3 (N.S.)	0.6 (NS)	0.8 (NS)

The mean nut and kernel weights varied between cultivars and were influenced by the conditions under which the nuts were grown, with a significant interaction between the cultivars and sites, Table 8.2. It is considered that site effects were likely to be a combination of differences in climate and soil conditions. Interactions between cultivars and sites occurred for tree growth and nut yields, as discussed in previous chapters. Although there were significant interactions between environmental conditions and nut and kernel weights, biologically these effects were small. However, as seasonal conditions had an effect on nut and kernel weights, the specific effects of temperature and rainfall during nut and kernel development at the 3 sites were examined, as discussed in Section, 8.3.

There were significant differences between cultivars in nut and kernel weights and the kernel to nut ratio (percentage kernel). The mean nut weights for the 13 cultivars ranged from ‘Segorbe’ at 2.4 g/nut through to ‘Ennis’ at 4 g/nut, Figure 8.4. The other cultivars lay more or less on a continuum of weights between these, with ‘Tonda di Giffoni’ (2.7 g) being at the lower end of those cultivars with a medium weight and ‘Barcelona’ (3.2 g) at the heavier end.

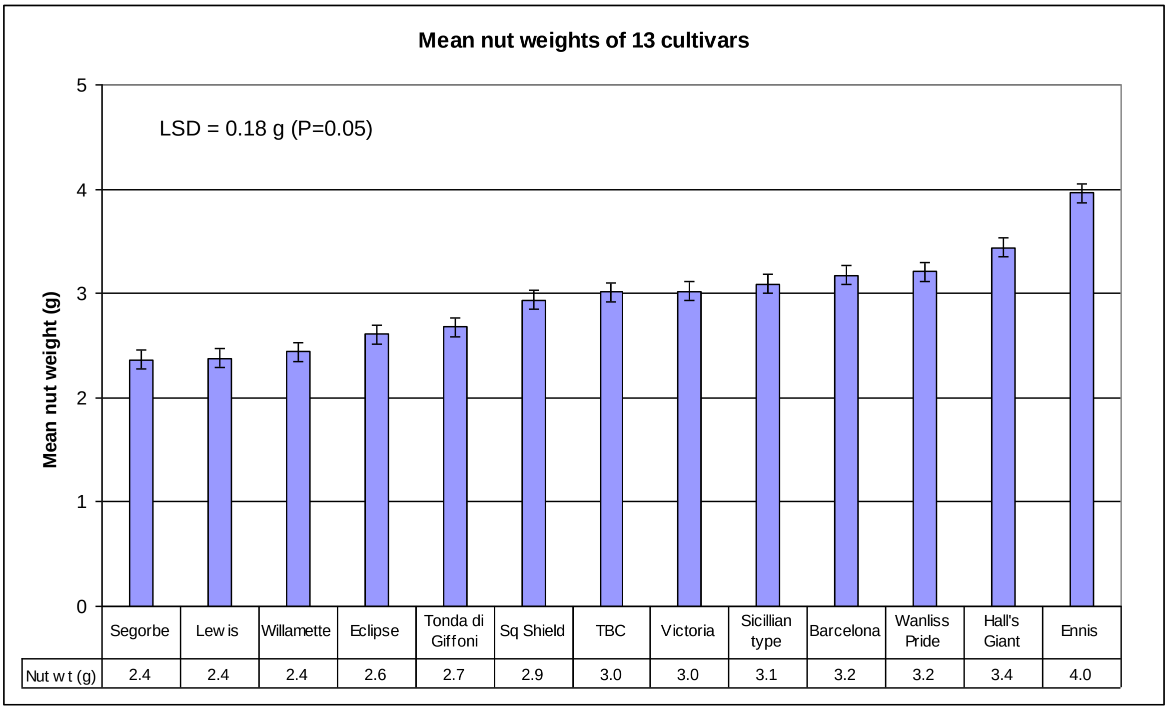
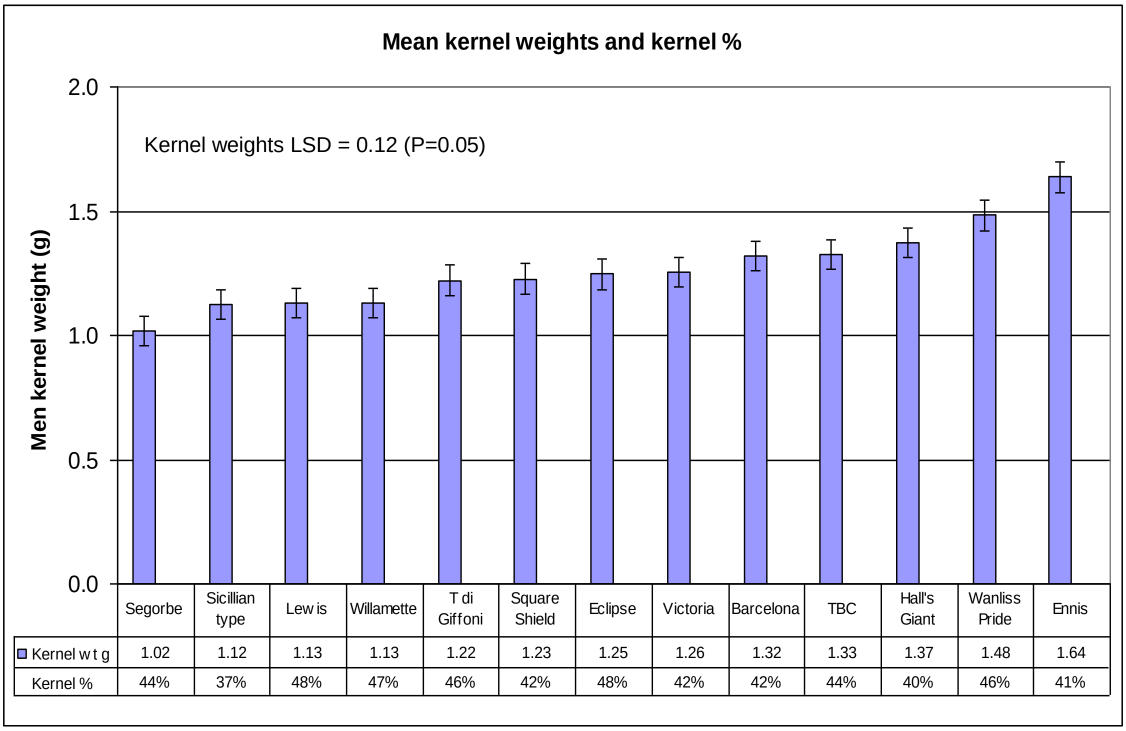


Figure 8.4 Mean nut weights for 13 cultivars grown at Orange, Myrtleford and Kettering, 6 years of data

Similar nut weights have been reported in the literature, ‘Segorbe’ at 2.6-3.1 g (Germain and Sarraquigne, 2004) ‘Tonda di Giffoni’ at 2.7-3.2 g, ‘Barcelona’ at 3.2-3.8 g (Mehlenbacher and Miller, 1989) and ‘Ennis’ at 3.1-4.6 g (Lagerstedt, 1980) and (McCluskey et al, 2001). The nut weights of cultivars are commonly expressed as a range of weights, reflecting the conditions under which they were grown.

The mean kernel weights and the percentage kernel for the 13 cultivars are given in Figure 8.5. In a similar manner to nut weights, kernel weights lay on a continuum from the smallest kernels of ‘Segorbe’ to the heaviest and largest of ‘Ennis’. ‘Tonda di Giffoni’ and ‘Barcelona’ were intermediate. Similar kernel weights and kernel percentages were reported by McCluskey (2001). There was no correlation between kernel weight and kernel percentage for the 13 cultivars. Thompson (1977) reported kernel percentage was associated with shell thickness and was a highly heritable characteristic. The highest percentage kernel or crack-out was for the cultivars ‘Lewis’ and ‘Eclipse, which were noted to have thin shells; whereas ‘Hall’s Giant’, the cultivar with the lowest kernel percentage, appeared to have thicker shells. It was noted that where sulphur crested cockatoos invaded sites with mature nuts, the birds seemed to have a preference for cultivars with small nuts and thin shells, such as ‘Lewis’ and ‘Casina’.



	Segorbe	Sicillian type	Lewis	Willamette	T di Giffoni	Square Shield	Eclipse	Victoria	Barcelona	TBC	Hall's Giant	Wanliss Pride	Ennis
▨ Kernel wt g	1.02	1.12	1.13	1.13	1.22	1.23	1.25	1.26	1.32	1.33	1.37	1.48	1.64
Kernel %	44%	37%	48%	47%	46%	42%	48%	42%	42%	44%	40%	46%	41%

Figure 8.5 Mean kernel weights (g), kernel percentage and kernel size (mm) for 13 cultivars grown at Orange, Myrtleford and Kettering, 6 years of data

Assessments of other cultivars

Mean nut and kernel weights, nut shape, kernel fibre and relative blanching assessments were obtained for a total of 24 cultivars from Orange, Moss Vale, Myrtleford and Kettering, Table 8.3. The number of years of data used to obtain these means varied between cultivars and years, depending on the amount of material available for assessment. Due to the variation in sample size, the means were not statistically analysed. The cultivars have been assigned to 4 main groups, according to the principal market sectors to which they are best suited, Table 8.4.

Table 8.3 Mean nut and kernel weights with nut shape and kernel characteristics allotted to main market sectors.

Cultivar	Nut wt (g)	Nut shape (length/width)	Kernel wt (g)	Kernel/nut wt (%)	Kernel fibre	Relative blanching
Cultivars with large nuts mainly for the in-shell trade						
‘Royal’	4.1	1.2	1.6	40%	1.7	4.8
‘Ennis’	3.9	1.12	1.6	41%	1.5	6.6
‘Hall’s Giant’ (1)	3.4	1.1	1.4	41%	1.3	3.4
‘Butler’ (1)	3.4	1.1	1.4	42%	2	6.3
‘Hammond#17’	3.3	1.1	1.4	41%	2	5.7
‘Daviana’ (1)	2.8	1.25	1.4	51%	2	5.4
Cultivars with kernels 15-17 mm size grade						
‘Barcelona’	3.3	0.97	1.3	40%	3	3.3
‘Tonollo’	3.3	0.98	1.4	43%	3	3.8
‘Wanliss Pride’	3.2	0.85	1.5	45%	2	2.4
‘Atlas’	3.1	0.92	1.3	41%	2.5	4.1
‘TBC’	3.0	1.01	1.3	43%	2.5	2.6
‘Square Shield’	3.0	0.96	1.2	40%	2	5.1
‘Victoria’	2.9	1.05	1.2	40%	1.3	5.5
Cultivars with round kernels 13-15 mm size grade that blanch						
“Sicilian type”	3.2	0.96	1.1	35%	2	3.1
‘Montebello’	3.0	0.92	1.1	36%	2.5	2.7
‘Eclipse’	2.7	0.92	1.3	46%	3.3	3.1
‘T. di Giffoni’	2.6	0.94	1.11	43%	2	3.1
‘Whiteheart’	2.5	1.00	1.3	47%	1	1.0
‘TGDL’	2.5	0.97	1.11	45%	2	2.8
‘Lewis’	2.4	0.97	1.2	48%	1.8	2.6
‘Willamette’	2.1	0.96	1.0	45%	2.5	2.8
‘Negret’	1.9	1.15	0.8	49%	2	1.7
Cultivars with round kernels 13-15 mm size grade that do not blanch						
‘Segorbe’	2.4	1.04	1.0	40%	1.7	4.1
‘Casina’	1.9	1.08	1.0	51%	1.5	5.7

Notes: Kernel fibre was rated on a 1(low) - 5 (high) scale. Relative blanching was rated on a 1(little pellicle remaining or excellent blanching) to 7 (most pellicle remaining, kernels did not blanch).

Cultivars for the in-shell market

The most important characteristics of cultivars for the in-shell market are size, preferably >21 mm, and appearance. ‘Royal’ and ‘Ennis’ both have large nuts with an attractive light brown colour (Table 8.5). More than 90% of nuts graded over 21 mm, placing them in the Australian “Very Large” category (Wilkinson, 1999). The kernels of both cultivars have relatively little fibre (Table 8.4), which also makes them attractive once cracked. Although ‘Ennis’ does not blanch, this is not of great significance if used as a table nut and consumed for the fresh market.

‘Wanliss Pride’ also had a large proportion of nuts that graded larger than 21 mm (Table 8.4). ‘Hall’s Giant’ is used mainly as a polliniser for ‘Ennis’, as is ‘Butler’, but these cultivars have bright shiny nuts suitable for the in-shell market. The cultivars ‘Barcelona’, ‘Victoria’ and ‘TBC’ have smaller nuts than ‘Ennis’ and ‘Royal’ and are less-suited to the in-shell market.

Table 8.4. Proportion of nuts in each size grade from 16mm to above 21mm for cultivars with potential for the in-shell market

	Size grade (mm)						
Cultivar	**16**	**17**	**18**	**19**	**20**	**21**	**21+**
‘Royal’					1%	3%	97%
‘Ennis’						6%	93%
‘Wanliss Pride’				2%	4%	11%	83%
‘Hall’s Giant’				1%	5%	18%	75%
‘Barcelona’				2%	7%	27%	64%
‘Victoria’			1%	3%	11%	29%	56%
‘Butler’			2%	7%	18%	27%	45%
‘TBC’				2%	14%	39%	44%

Cultivars for the kernel market

Assessments of kernel size for cultivars that had potential for the kernel market were undertaken in 2002. The mean size ranged from 13.4 mm for ‘Negret’ to 17.0 mm for ‘Wanliss Pride’, Table 8.5. The cultivars with the most even size, lowest coefficient of variation, were ‘Tonda di Giffoni’ and ‘Willamette’. The most variable in size were ‘TGDL’ and ‘Wanliss Pride’.

Cultivars with kernels in the 15-17 mm range are generally considered to be too large for the confectionery trade. If consumed raw, such as in snack foods, the kernels need to be attractive with relatively smooth, thin skins, such as ‘Wanliss Pride’, whereas kernels of ‘Barcelona’ and ‘Tonollo’ appear rough and fibrous. Blanching ability is considered to be important if kernels are to be roasted and used in bakery products or sold in snack foods. The low score for relative blanching (Table 8.3) indicates that the pellicle of ‘Wanliss Pride’ is readily removed after roasting, making it suitable for this market. ‘Barcelona’ and ‘TBC’ are also suitable, as can be seen in Plate 8.2. Flavour is also a consideration for this market, but was not assessed in these studies.

Table 8.5 Mean size of kernels from the Myrtleford site in 2002

Cultivar	**Mean kernel size (mm)**	**Co-efficient of variation %**
	Kernels 13-15mm	
‘Negret’	13.4	5.78
‘Casina’	13.5	5.70
‘Segorbe’	13.7	5.47
‘Montebello’	14.2	4.99
“Sicilian type”	14.4	5.75
‘TGDL’	14.4	6.79
‘Tonda di Giffoni’	14.6	4.34
	Kernels 15-17 mm	
‘Willamette’	15.1	4.37
‘Atlas’	15.3	5.58
‘TBC’	15.8	5.31
‘Barcelona’	15.7	5.96
‘Tonollo’	16.3	5.20
‘Wanliss Pride’	17.0	6.99

Kernels in the 13-15 mm size range, that are round and blanch well, are highly sought after in the confectionery market. Traditional cultivars sought after in this market are ‘TGDL’ and ‘Tonda di Giffoni’ in Italy (Tombesi, 2005) and ‘Negret’ in Spain (Tous, 2005). Apart from the “Sicilian type” and ‘Montebello’, which had low kernel/ nut weights, all the cultivars in this category (Table 8.5), appeared to be suitable for the confectionery market. The good blanching characteristics of ‘Lewis’ are evident in Plate 8.2, compared with virtually no blanching of the ‘Ennis’ kernels. The cultivar ‘Whiteheart’ appears to be almost perfect for this market category with its round shape, high crack-out, low kernel fibre and a blanching score of 1.0 (Table 8.3). The small kernels of the cultivars ‘Segorbe’ and ‘Casina’ did not blanch, limiting their use in the confectionery trade. ‘Segorbe’ has a low crack-out which is a further disadvantage.

Some cultivars, such as ‘Butler’ and ‘Daviana’, are grown principally as pollinisers. It is advantageous to have polliniser cultivars that have nut and kernel characteristics that suit the market sectors of the cultivars which they are pollinating as, when mechanically harvested, the nuts of the polliniser and main crop cultivars are mixed.

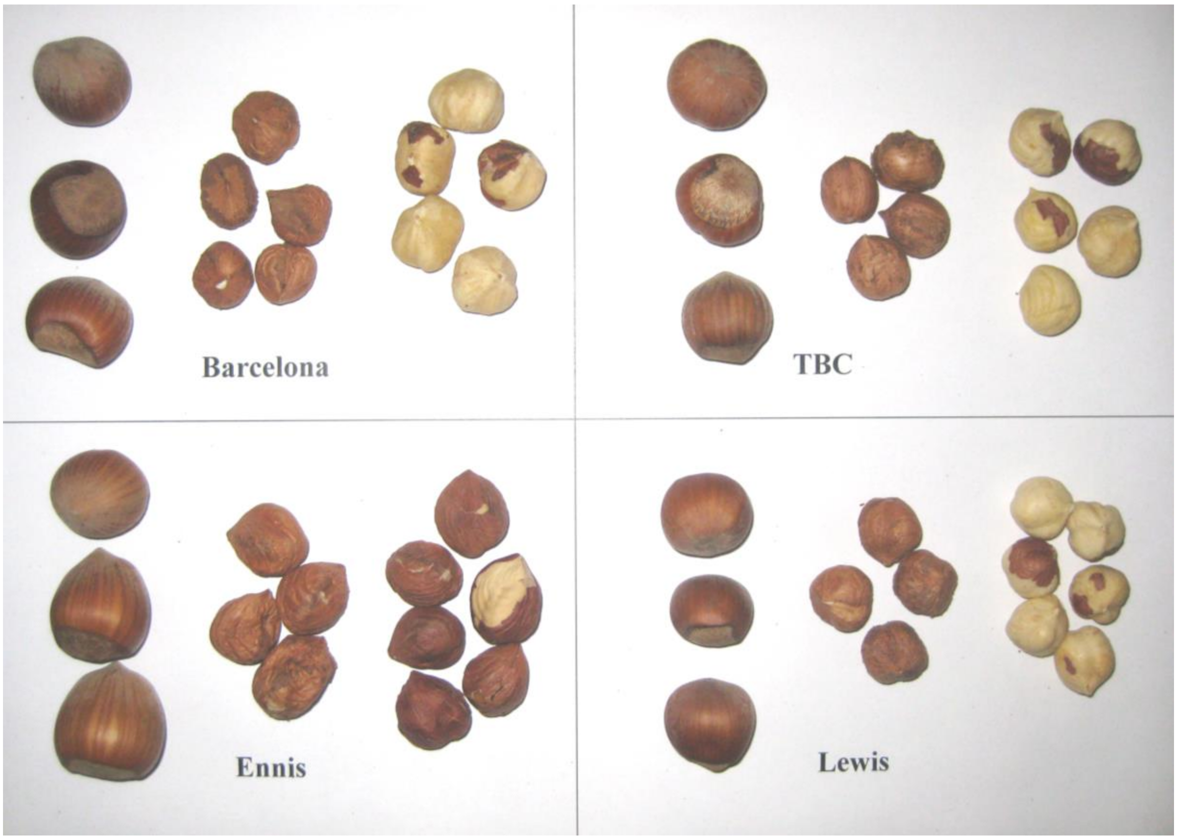


Plate 8.2 Nuts and kernels, unblanched and blanched, of the cultivars ‘Barcelona’, ‘TBC’, ‘Ennis’ and ‘Lewis’. ‘Ennis’ nuts were the largest and ‘Lewis’ the smallest. ‘Ennis’ kernels did not blanch whereas ‘Lewis’ kernels blanched well.

The length and width of nuts from a range of cultivars grown at Orange were measured to obtain an assessment of nut shape. A high index for length/width indicates the nuts are long, such as ‘Daviana’ (Table 8.3); a value less than 1.0 indicates they are rather squat, such as ‘Wanliss Pride’, whereas a value of 1.0 indicates they are round. Further details on nut and kernel characteristics can be found in Appendix A.

8.4 Environmental factors influencing kernel quality

8.4.1 Kernel defects

Data obtained from cracking 100 nut samples showed that the main defects were poorly-filled or shrivelled kernels, as illustrated in Plate 8.3. Generally, relatively few kernels showed defects from mould or black tips. Twin kernels are not a serious defect, although they look less attractive than full kernels. If well-filled, their taste is no different to full kernels. ‘Barcelona’ was found to have the highest proportion of twin kernels, which was also reported by Mehlenbacher (1991) for this cultivar. Kernels with black tips had an unpleasant flavour as did the poorly-filled kernels. The latter often had a slightly sweet taste; presumably the process of filling was incomplete with only sugars being formed in the kernel as a precursor to the synthesis of the oil content. Mouldy kernels were highly undesirable, but were at a very low level.

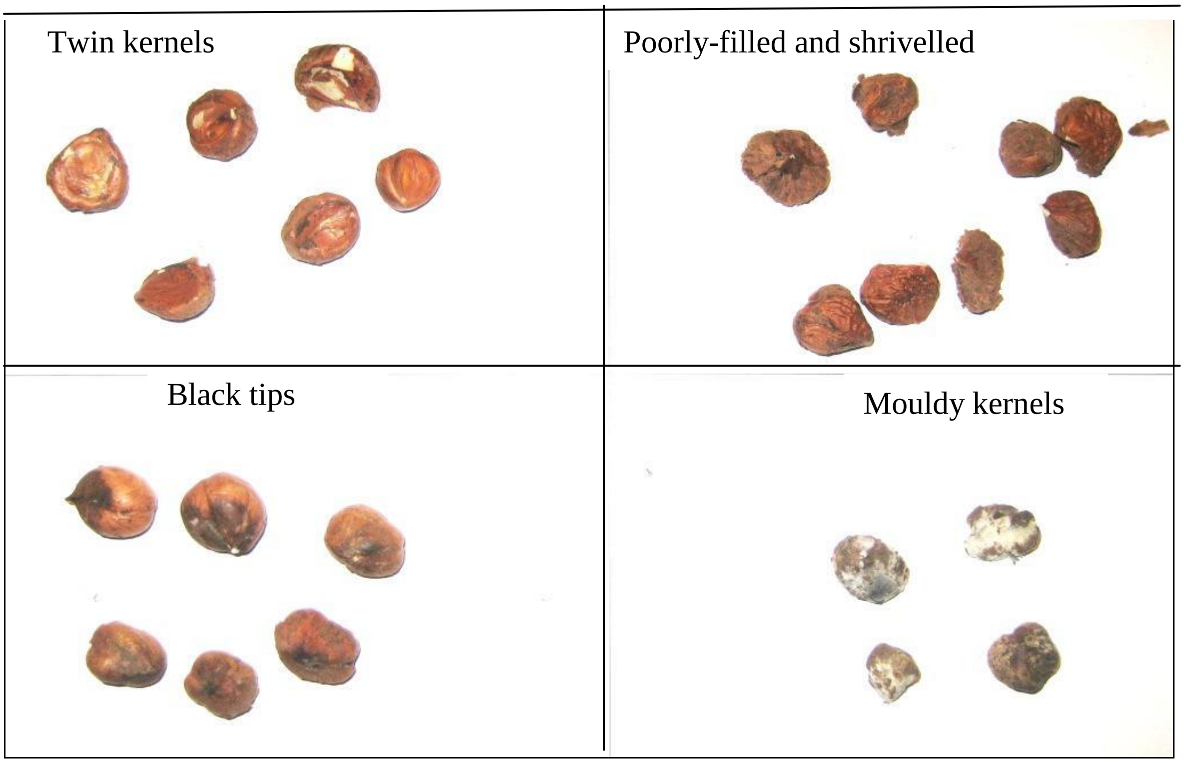


Plate 8.3 There were four main types of kernel defects; these included twin kernels, poorly-filled, black tips and mould.

8.4.2 Kernel weight and poor-fill

A regression analysis was conducted on the relationship between mean nut and mean kernel weights and the proportion of poorly-filled kernels for 13 cultivars across 3 sites, Orange, Myrtleford and Kettering, over 6 seasons. There was a significant correlation (P=0.01) between both nut weight and kernel weight and poor-fill. The linear relationship between nut weight and the proportion of poorly-filled kernels accounted for only 43% of the variation, whereas mean kernel weight accounted for 51% of the variation in poor-fill, Figure 8.6.

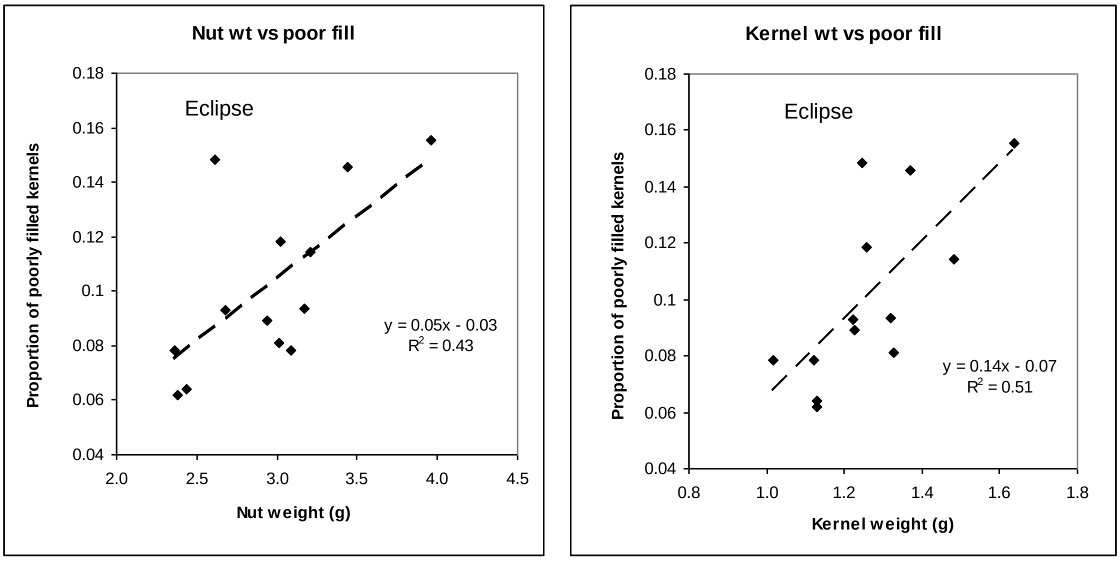


Figure 8.6 Relationship between mean nut weight and mean kernel weight and the proportion of poorly-filled kernels of 13 cultivars grown at 3 sites, Orange, Myrtleford and Kettering over 6 years.

It is hypothesised that small kernels fill more readily and hence are less subject to incomplete fill. However, it would be expected that total crop load on a tree would also be a factor in kernel fill; with cultivars that have a large number of nuts requiring more assimilates to fill their kernels. It is interesting to note that ‘Eclipse’ was a low-yielding cultivar, yet on average 15% of the kernels were poorly-filled, Figure 8.6. Mehlenbacher (1991) noted that cultivars that produced large nuts tended to have poor quality kernels, but poor fill was also associated with stress, caused by drought and high crop loads on trees (ibid, 1991, Mingeau et al., 1994 and Bignami and Natali, 1997).

8.4.3 Temperature and rainfall effects on kernel fill

Data on poorly-filled kernels for 13 cultivars across 3 sites over 6 years showed there was a significant correlation (P=0.001) between the mean maximum temperature in January, when kernels were developing, and the proportion of poorly-filled kernels. There was an increase of 0.08 (8%) in poor-fill for each 10°C rise in the mean maximum temperature, Figure 8.7. However, the regression only accounted for 15% of the variation.

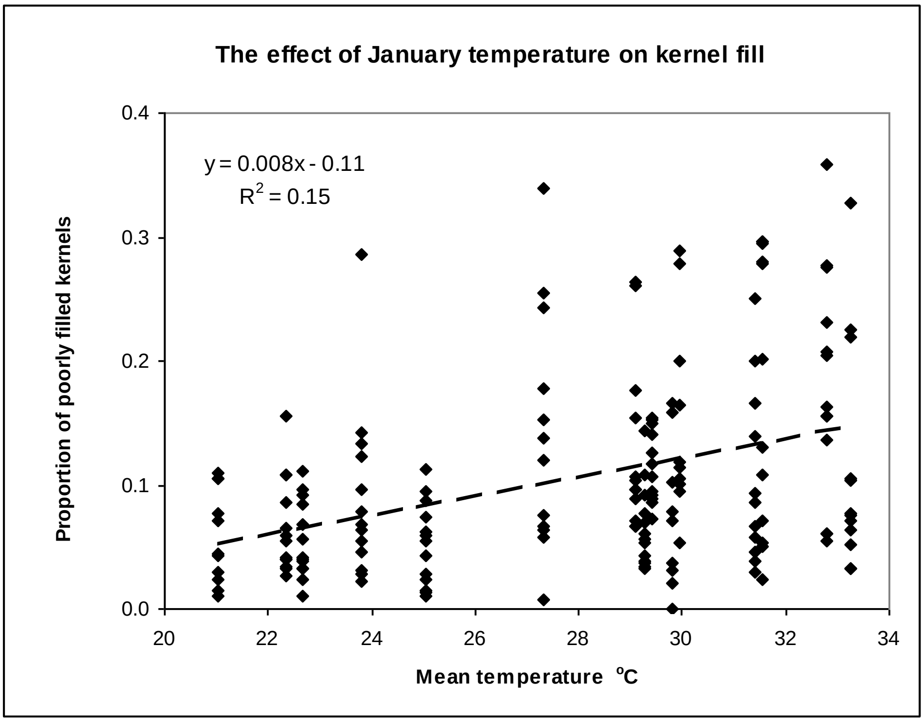


Figure 8.7 Relationship between mean temperature in January and the proportion of poorly-filled kernels of 13 cultivars grown at 3 sites, Orange, Myrtleford and Kettering, over 6 years.

There was no significant relationship between January rainfall and the proportion of poorly-filled kernels. As all sites received irrigation in January to minimise moisture stress, it appears that generally the trees were not under severe moisture stress during kernel fill in the years of this analysis.

However, a reduction in nut and kernel size can arise when trees are stressed during nut and kernel growth (Mingeau et al. 1994, Bignami and Natali 1997, Tombesi and Rosati 1997 and Lagerstedt 1988).

Hazelnuts appear to be sensitive to high temperatures and moisture stress during kernel fill. It is hypothesised that the rate of kernel development and the days to maturity are hastened by increasing temperatures, as was indicated by the data on the period to nut fall. If the weather is hot, it seems likely that the process of kernel fill may become too short for the kernels to adequately fill and hence they are shrivelled, with this being aggravated further, if coupled with moisture stress. This problem appears to be greater with cultivars that have large kernels, such as ‘Royal’ and ‘Ennis’, with small kernels being more readily-filled during this critical phase. The phenomena of poorly-filled nuts and seeds and lower oil contents, due to moisture stress and high temperatures, have been reported by several authors, such as Mingeau, (1994) and Bignami and Natali, (1997) for hazelnuts, Sistrunk et al. (1996) and Byford (2006) for pecans, Ramos et al. (1978) for walnuts and Pritchard et al. (1999) for canola.

8.5 Chemical composition of kernels

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8.5.1 Introduction

Hazelnut kernels have a relatively high lipid content, mainly comprising triglycerides. The lipid content varies from 50-70% for cultivars and is dependent on the environmental conditions under which they are grown (Mehlenbacher, 1991). Hazelnut kernels are also rich in protein (10-20%) and are an excellent source of Vitamin E (α-tocopherol). Although no detailed studies were undertaken on the fatty acid, protein, α-tocopherol, sugar or mineral composition of the cultivars in this study or the effects of environmental conditions on these, some data was obtained from samples in order to compare these with published levels overseas.

8.5.2 Methods

Samples of kernels (approximately 100g each) from the 2002, 2005, 2006, and 2008 harvests were sent to NSW DPI laboratories in Wagga Wagga for an analysis of their oil content, their fatty acid composition and α-tocopherol content. The methods used are shown in Table 8.6. There was no replication of these measurements, meaning that they could not be analysed statistically.

Table 8.6 Chemical extraction methods used by the NSW DPI laboratories.

Substances analysed	Method
Oil by solvent extraction	WWAI 2-1607
α-tocopherol	AOCS Ce 8-89
Water-soluble carbohydrate	AFIA Method 1.1
Nitrogen in meal	LECO AFIA Method 5R

8.5.3 Results and discussion

Although the data could not be statistically analysed, there appeared to be some differences between cultivars in their oil content (Tables 8.7 and 8.8). ‘Ennis’ appeared to have a lower oil content (52.6-59.4%) than most of the other cultivars, which averaged around 62%, Table 8.7.

Table 8.7 Oil content (%) of hazelnut cultivars from the study sites compared with Oregon (Ebrahem et al, 1994b, Richardson, 1997).

Locations	**Kettering**		**Moss Vale**	**Myrtleford**			**Oregon**	
Cultivars	**2006**	**2008**	**2005**	**2002**	**2005**	**2006**	**(1)**	**(2)**
‘Barcelona’	64.2	62.7	57.4	62.0	59.1	63.5	62.8	61.8
‘Butler’					56.3			
‘Ennis’		58.7	52.6		54.2	59.4		
‘Lewis’	62.4	64.8			61.0	64.7		
‘Segorbe’					56.6			
“Sicilian”			58.2	61.1	59.3			
‘TBC’	64.0	64	56.4	60.1	60.2	64.4		
‘Tonda di Giffoni’	61.9	64.9	57.3	63.6	63.0	62.5	62.9	63.1
‘Tonollo’				60.2	56.1			
‘Wanliss Pride’		62.2		57.5	55.5			
‘Whiteheart’		64.2						

Source of Oregon data: (1) Ebrahem et al, (1994b), (2) Richardson (1997).

There also appeared to be differences between seasons and sites. The oil content of the kernels from Moss Vale in 2005 was generally lower than those for the other sites and seasons (Table 8.7). It is presumed that oil content is related to the conditions during the period of kernel fill. Ebrahem et al. (1994a) showed that oil content steadily rose to a peak towards the end of kernel development. The oil content obtained under Australian conditions, for the cultivars ‘Barcelona’ and ‘Tonda di Giffoni’, do not seem to vary markedly from those obtained by Ebrahem et al. (1994b) and Richardson (1997) for these 2 cultivars.

The fatty acid profile and α-tocopherol (vitamin E) content of 5 cultivars was assessed. The proportion of mono-unsaturated fatty acids appeared to vary little between cultivars and situations; it was generally about 80% (Table 8.8). The main fatty acid was oleic acid with a proportion of about 85% of the mono-unsaturated fatty acids. The relative levels of poly-unsaturated fatty acids to mono-unsaturated fatty acids did not seem to vary between cultivars, but it did seem to vary between sites and years. Variation between situations was reported by Piskornik (1994), who found that the lower temperatures in Poland during kernel fill resulted in a slightly higher content of the longer-chained unsaturated fatty acid, linoleic acid (C18:2). The mean maximum temperatures at Myrtleford in January for both years of data at that site averaged 31.5°C, compared with those for Kettering which averaged 23.2°C. Mean minimums at the 2 sites for January were 13.9°C and 10.8°C respectively. Thus, the lower temperatures at Kettering might account for the higher mean values for polyunsaturated fatty acids at that site, Table 8.8.

Table 8.8 Oil content (%), α-tocopherol (µg/g) and the proportion of mono-unsaturated fatty acids for 5 hazelnut cultivars in 2 seasons and at 2 sites

		Cultivars					
Sites and seasons	**Kernel component**	**'Barcelona'**	**'Ennis'**	**'Lewis'**	**'TBC'**	**'Tonda di Giffoni'**	**Means**
Myrtleford	Total oil %	59.1	54.2	61	60.2	59.3	58.8
2005	Mono-unsat	80	80	81	81	82	80.8
	Poly-unsat	13	12	11	11	11	11.6
	α-tocopherol	388	293	387	419	396	377
Myrtleford	Total oil %	63.5	59.4	64.7	64.4	62.5	62.9
2006	Mono-unsat	83	82	84	83	82	82.8
	Poly-unsat	9	8	7	8	9	8.2
	α-tocopherol	295	224	262	274	351	281
Kettering	Total oil %	64.2	59.1	62.4	64	61.9	62.3
2006	Mono-unsat	76	76	79	79	80	78.0
	Poly-unsat	17	16	14	15	13	15.0
	α-tocopherol	400	364	378	475	383	400
Kettering	Total oil %	62.7	58.7	64.8	64	64.9	63.0
2008	Mono-unsat	77	74	79	79	80	77.8
	Poly-unsat	16	17	14	14	13	14.8
	α-tocopherol	526	428	430	525	474	477
Means	Total oil %	62.4	57.9	63.2	63.2	62.2	
	Mono-unsat	79.0	78.0	80.8	80.5	81.0	
	Poly-unsat	13.8	13.3	11.5	12.0	11.5	
	α-tocopherol	402	327	364	423	401	

The α-tocopherol content (vitamin E) seemed to vary between situations and cultivars. The mean levels for the cultivars tested were in the range 327-423 µg/g. Ebrahem et al. (1994) recorded a range of levels of α-tocopherol from 302-434 µg/g for 17 cultivars in Oregon. The levels of α-tocopherol appeared to be lower for 'Ennis', as was the oil content. There appeared to be some site differences, with higher α-tocopherol levels being recorded at Kettering, compared with Myrtleford. Although Savage et al. (1997) recorded very high levels of α-tocopherol in 'Whiteheart', the levels recorded at Kettering did not appear to be higher than for other cultivars (Table 8.9). There was no significant correlation between the oil content and α-tocopherol levels of the cultivars over the range of seasons and sites.

Other constituents

Kernels from 7 cultivars harvested at Kettering in 2008 were sent to NSW DPI for an analysis of their water-soluble carbohydrate (sugar) and nitrogen content (Table 8.9). ‘Wanliss Pride’ was found to have a high level of water-soluble carbohydrates which is consistent with previous analyses on sugar content, (Dawson and Halleday, 1993) and (Baldwin and Simpson, 2003). It appears that ‘Ennis’ also has a high level of water-soluble carbohydrates (sugars), which aligns with the sweet taste commonly associated with its kernels.

Table 8.9 Oil content (%), α-tocopherol (μg/g), water-soluble carbohydrates and nitrogen contents of kernels from 7 hazelnut cultivars from Kettering, 2008

Cultivars	Oil (%)	α-tocopherol (μg/g)	Water soluble carbohydrates (% meal)	Nitrogen (% meal)
‘Barcelona’	62.7	526	15.9	6.38
‘Ennis’	58.7	428	21.4	5.9
‘Lewis’	64.8	430	14.2	7.47
‘TBC’	64	525	15.7	5.87
‘Tonda di Giffoni’	64.9	474	17	6.11
‘Wanliss Pride’	62.2	599	19.5	5.82
‘Whiteheart’	64.2	544	16	6.81

Kernels from the same 7 cultivars harvested at Kettering in 2008 were analysed by NSW DPI for 3 key elements:- potassium, phosphorus and calcium. The analyses showed very high levels of potassium (average 8110 mg/kg), this was about twice the concentration of phosphorus (average 4069 mg/kg) and nearly 8 times the average levels of calcium (average 1231 mg/kg), Figure 8.8.

There appeared to be little difference between the cultivars in the concentration of the individual elements, except for potassium, where ‘Wanliss Pride’ appeared to have a higher concentration than any other cultivar.

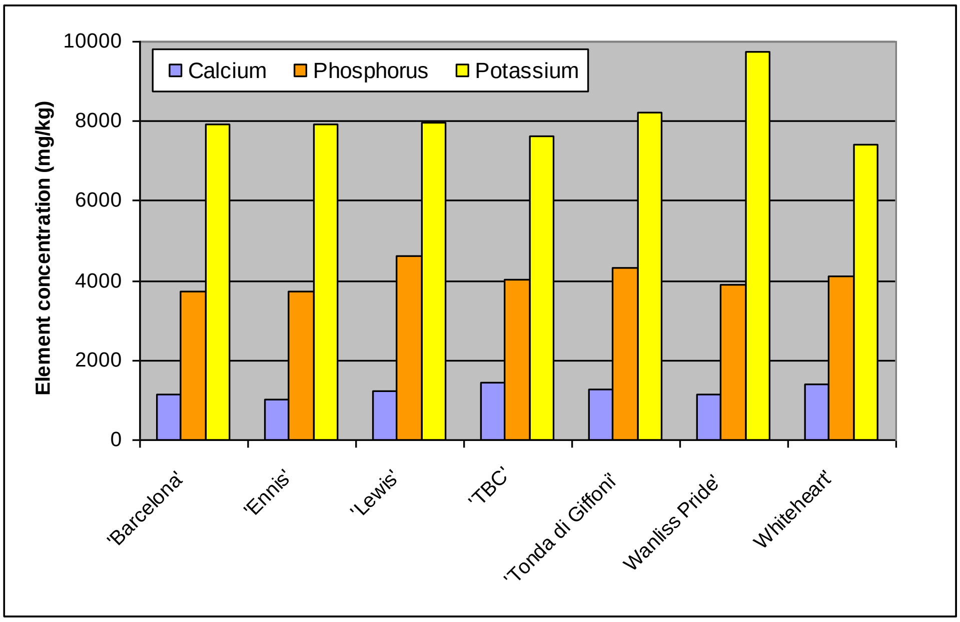


Figure 8.8 Concentration levels of some key elements in hazelnut kernels from 7 cultivars harvested at Kettering in 2008.

Due to a lack of replication, the data obtained on the lipid, α- tocopherol, nitrogen, sugar levels and mineral content must be considered to be only indicative and the conclusions drawn in the discussion only tentative. However, the results were generally consistent with those reported in the literature.

8.6 Overall conclusions

The date of peak nut fall varied between seasons. It was found to be related to thermal units, growing degree days from 1 November. It varied between cultivars; both ‘Barcelona’ and ‘Tonda di Giffoni’ were early into nut fall, on average 2 weeks before ‘Ennis’ and ‘Segorbe’. The majority of blank, seedless nuts fell before peak nut fall.

The size and weight of nuts and kernels and the kernel/nut ratio varied between cultivars and were mainly inherited characteristics. There were small differences between seasons. The characteristics of cultivars were evaluated on a market sector basis. The large, attractive nuts of ‘Ennis’ and ‘Royal’ made them suitable for the in-shell market. The kernels of ‘Barcelona’, ‘TBC’ and ‘Wanliss Pride’ were placed in the 15-17 mm category, kernels mainly for snack foods and general purposes, such as catering. These 3 cultivars had acceptable attributes of kernel/ nut ratio, skin thickness and blanching for this market.

In the small kernel size, 13-15mm, several cultivars had appropriate attributes of roundness, crack-out and blanching. These kernel attributes are considered in the next and final chapter, along with attributes of growth and nut yields, to develop cultivar recommendations.

The main kernel defects were related to incomplete nut fill and shrivel. There was a significant correlation between kernel size and nut fill. In general, cultivars with large kernels had a higher proportion of poorly-filled kernels.

High temperatures and moisture stress during kernel development appeared to have an adverse effect on kernel quality, producing a higher proportion of poorly-filled kernels. It was hypothesised that higher temperatures during kernel development hastened the process of maturity. If photosynthesis in this period was impaired by moisture stress, the likely outcome was poor kernel fill. The synthesis of the longer chain poly-unsaturated fatty acids, such as linoleic acid, may possibly also be impaired by the higher temperatures and moisture stress. Further research on the effects of environmental conditions on the process of kernel development and quality are considered desirable to assess the potential of regions in Australia for hazelnut production.

Although there was limited data on the chemical constituents of kernels, it appeared there were cultivar differences in oil content, α-tocopherol, water-soluble carbohydrates, nitrogen content in meal and levels of potassium.

CHAPTER 9 - CONCLUSIONS

9.1 Introduction

Although hazelnuts (*Corylus avellana* L.) were introduced into Australia in the Nineteenth Century by European settlers there has been minimal industry development compared with many other deciduous nut and tree crops. Some small orchards were established in the Ovens Valley of north-east of Victoria in the 1930s. There was a renewed interest in the crop in the 1980s, with many cultivars being introduced from overseas. However, there had been no systematic evaluation of this imported material or comparisons made with local selections. Why have hazelnuts remained a minor crop when Australia imports over 2000 tonnes of kernels annually with a value of at least A$20 million? Is this due to a lack of knowledge on the most appropriate cultivars to grow and the appropriate pollinisers for them or is it that hazelnuts are not well-adapted to the soils and climate of the temperate areas of south-eastern Australia and do not produce commercially viable yields? This thesis was designed to address these issues.

The general aims of the research were to answer the questions:

- What are the relative merits of the main hazelnut cultivars available for commercial production in Australia?
- How do environmental conditions affect the growth, phenology and productivity of hazelnut cultivars?
- What is the productive potential of hazelnuts (*Corylus avellana* L.) in Australia?

This final chapter summarises the research data presented in the previous chapters and how it relates to these questions.

9.2 Cultivar evaluation for commercial production

The first research question was:

- What are the relative merits of the main hazelnut cultivars available for commercial production in Australia?

In Australia there is the potential to grow hazelnuts for a range of markets; however, there are 3 main market sectors, each with its own specifications. The criteria used to evaluate the commercial potential of the cultivars in this study are based on those used by Mehlenbacher (1994) for the hazelnut breeding program at the Oregon State University (OSU), as discussed in Section 2.3.3 'Breeding Programs'. The key criteria used herein for cultivar evaluation are:

- High nut or kernel yield;
- High kernel percentage for the kernel market;
- Appropriate size, shape and appearance of nuts or kernels;
- Resistance to major pests and diseases.

9.2.1 Cultivars for the in-shell market

This market sector is relatively small compared to the kernel market (Chapter 1, Figure 1.1). The in-shell market seeks large nuts (>21 mm) that are attractive in appearance. The cultivar 'Ennis', with its large shiny, light brown nuts (Lagerstedt, 1980), sets the quality standard for this market. When assessments were made of nut sizes, in Chapter 8, it was found that there were only 4 cultivars that had 75% or more of nuts that were of the large size grade >21 mm (Table 8.4). These were 'Ennis', 'Royal', 'Wanliss Pride' and 'Hall's Giant', their cumulative nut yields are shown in Table 9.1.

Table 9.1 Cumulative nut yields 8 years from planting for potential cultivars for the in-shell market

Cultivars	Orange	Moss Vale	Myrtleford	Toolangi	Kettering
'Ennis'	4.35a	3.96a	11.05a	2.38a	1.43a
'Hall's Giant'	0.38b	0.22c	1.04c	0.2b	0.2c
'Royal'	N.D.	N.D.	6.84b	N.D.	2.33a
'Wanliss Pride'	Failed	1.79b	6.28b	2.27a	1.9a
LSD (P=0.05)	1.52	1.36	2.74	1.5	1.08

Source - Cumulative nut yields from Tables 7.3-7.7 in Chapter 7.
Note N.D. No data, not grown. Cultivars with the same letter are not significantly different (P = 0.05).

Of these 4 cultivars, the cumulative nut yields of ‘Ennis’, 8 years after planting, were either the highest or equal highest. At Orange, ‘Ennis’ was one of the highest yielding cultivars (Table 9.1). At Moss Vale and Myrtleford, ‘Ennis’ produced about 50% of the yield of the highest-yielding cultivar, whereas at Toolangi and Kettering its nut yields were low compared with the highest-yielding cultivar. Unfortunately, the cultivar ‘Royal’ was only grown at 2 sites. At Myrtleford, ‘Royal’ yielded significantly less than ‘Ennis’, whilst at Kettering there was no significant difference. ‘Royal’ is rated as being sensitive to big bud mite (USDA, 2007), which may be a potential disadvantage in Tasmania where big bud mite was found to occur.

The performance of ‘Wanliss Pride’ was highly variable. At Orange, the cultivar failed to grow. At Moss Vale and Myrtleford, nut yields of ‘Wanliss Pride’ were low compared with the highest-yielding cultivar and significantly less than ‘Ennis’ ($P=0.05$). However, at Toolangi and Kettering nut yields of ‘Wanliss Pride’ were not significantly different from ‘Ennis’. It seems possible that ‘Wanliss Pride’ grows and yields better in a more maritime environment. The cultivar has a weak, straggly, growth habit and may perform better as a multi-stemmed tree.

The yields of ‘Hall’s Giant’ were low at all 5 sites. Its main role is probably as a polliniser, as discussed later.

Although, on average, ‘Ennis’ produced the highest yields of these 4 cultivars, it did not produce consistently high yields across all 5 sites. This is in contrast with high yields recorded for ‘Ennis’ by Thompson (1981) and McCluskey et al. (1997) in Oregon, and Santos and Silva (2001) in Portugal. Lagerstedt (1980) reported ‘Ennis’ to be moderately tolerant of big bud mite and moderately resistant to bacterial blight (*Xanthomonas arboricola pv. corylina*). However, its relatively low yields at all sites, other than Orange, suggest there is a need for caution before extensive plantings of this cultivar are made.

It is concluded that although ‘Ennis’, ‘Royal’ and ‘Wanliss Pride’ produce nuts that have high market appeal for the in-shell market, there is a need for more research on these cultivars to further assess factors influencing their productivity and yield potential in Australia.

9.2.2 Cultivars for the confectionery market, small kernels (13-15 mm)

This is a large international market, particularly in Europe. Multi-national companies, such as Cadbury Schweppes, import all of their kernels, mainly from Turkey. Of the cultivars with kernels in this size range that blanch, only ‘Tonda di Giffoni’ and the “Sicilian type” were grown at all sites. ‘Tonda di Giffoni’ grew well at all sites; it was one of the highest-yielding cultivars at Moss Vale but did not yield well at the other sites (Table 9.2), although at Orange it was the highest-yielding cultivar in the small kernel category. The kernels were generally well-filled and blanched well with a kernel/nut ratio of 43%. It is reported to have intermediate tolerance to big bud mite (Solar and Stampar, 1997).

The “Sicilian type” produced nut yields similar to ‘Tonda di Giffoni’, although higher at Myrtleford. As a compact tree, it had the highest yield efficiency at many sites and produced kernels that blanched. The main limitations of the “Sicilian type” are its thick shells and consequent low kernel/nut ratio, 35%. Although not considered very suitable as a commercial cultivar, it could be very useful in a breeding program.

‘Lewis’, ‘Willamette’ and ‘Montebello’ were only grown at Kettering, where they produced nut yields equivalent to ‘Tonda di Giffoni’. ‘Montebello’, had the limitation of a low kernel percentage (Table 8.3).

Table 9.2 Cumulative nut yields 8 years from planting for potential cultivars for the confectionery market (kernel size 13-15 mm)

Cultivar	Orange	Moss Vale	Myrtleford	Toolangi	Kettering
Cultivars with kernels that blanch					
‘Eclipse’	1.17b		8.21c		2.04a
‘Lewis’					1.70a
‘Montebello’					1.57a
‘Negret’			8.13c		
“Sicilian type”	2.94a	5.43b	16.81a	3.30b	2.24a
‘Tonda di Giffoni’	2.60a	7.21a	12.98b	3.63b	2.29a
‘TGDL’			6.33c		0.16b
‘Whiteheart’					0.89b
‘Willamette’					1.40a
Cultivars with kernels that do not blanch but have a thin pellicle					
‘Casina’	0.45b		6.73c		
‘Segorbe’	2.23a	3.37c	12.25b	5.45a	1.49a
LSD (P=0.05)	1.52	1.36	2.74	1.5	1.08

Source - Cumulative nut yields from Tables 7.3-7.7 in Chapter 7.
Note N.D. No data, not grown. Cultivars with the same letter are not significantly different (P = 0.05).

It is concluded that, of the cultivars studied, ‘Tonda di Giffoni’ was the best cultivar for the confectionery market sector, which requires small kernels that blanch. However, the overall relatively low productivity of ‘Tonda di Giffoni’ (relative yield 0.56, Table 7.8) is viewed as a concern for extensive commercial plantings. Despite this, it was early into leaf, indicating relatively low chill requirements for vegetative buds, and may be well-suited to areas with warm summers, mild winters and lower chilling hours.

Of the cultivars that do not blanch, ‘Segorbe’ grew vigorously and yielded moderately well at Myrtleford and Toolangi. It was more productive than ‘Casina’ at the 2 sites where both cultivars were grown. As ‘Tonda di Giffoni’ has a thin smooth pellicle, it could be planted for both the blanched and unblanched market sectors.

9.2.3 Cultivars for the larger kernel market (15-17 mm)

In these studies, there were 7 cultivars (Table 9.3) that were considered suitable for the 15-17 mm kernel market. Kernels of this size are often used for snack and health foods, general catering and baking. Desirable kernel attributes are thin, smooth skins with generally good blanching characteristics.

Both ‘Barcelona’ and ‘TBC’ were generally the most productive cultivars in this group. The trees were vigorous and early into production. The cultivars were ranked equal for scores of relative nut yields across the 5 sites (Chapter 7, Table 7.8).

Table 9.3 Cumulative nut yields 8 years from planting for potential cultivars for the general kernel market

Cultivar	Orange	Moss Vale	Myrtleford	Toolangi	Kettering
‘Atlas’	2.99bc	1.09d	10.71c	N.D.	N.D.
‘Barcelona’	5.44a	5.66b	18.3a	8.1a	2.43c
‘Square Shield’	0.21d		3.46e		1.81c
‘TBC’	4.36ab	8.63a	10.81c	8.0a	4.82b
‘Tonollo’			14.81b		
‘Victoria’	1.61cd	3.99c	7.52d	4.30b	6.57a
‘Wanliss Pride’	Failed	1.79d	6.18d	2.27c	1.85c
LSD (P=0.05)	1.52	1.36	2.74	1.5	1.08

Source - Cumulative nut yields from Tables 7.3-7.7 in Chapter 7.
Note N.D. No data, not grown

‘Victoria’ produced the highest nut yields at Kettering but performed less well at all the other sites. However, as this cultivar has a low kernel percentage and does not blanch well, it is not considered to be a cultivar with good potential for this market. ‘Atlas’ produced nut yields that were not significantly different from ‘TBC’ at Orange and Myrtleford, but were much lower at Moss Vale. ‘Atlas’ is a very early cultivar into anthesis and bud break, it has a lower kernel percentage than ‘TBC’ and does not blanch as well. It may be suited to locations with low chill hours and warm summers.

Comparing the characteristics of ‘TBC’ with those of ‘Barcelona’, ‘TBC’ kernels have slightly less fibre and blanch a little better (Table 9.4), although they are more prone to black tips. ‘TBC’ has a higher mean kernel percentage (kernel/ nut ratio).

Table 9.4 Kernel and other key characteristics of ‘Barcelona’ and ‘TBC’

Characteristics	**‘Barcelona’**	**‘TBC’**
Average kernel size	14-16 mm	14-16 mm
Kernel/nut ratio (Average all sites)	0.42	0.45
Kernel fibre 1 (low) – 5 (high)	3	2.5
Kernel blanching (1 excellent – 7 none)	3.6	3.3
Kernel defects	Some twins	Black tips
Poor fill %	9.3	8.1
Nuts free-falling	Good	Some stick in husks
Tolerance to big bud mite	High (1)	Moderate (2)

Source - Kernel characteristics Table 8.6, Chapter 8.
(1) (Lagerstedt, 1981), (2) Shawn Mehlenbacher (Pers. Comm. Oct 2006)

‘TBC’ appeared to be slightly less susceptible to bacterial blight (*Xanthomonas arboricola pv. corylina)* than ‘Barcelona’ but ‘TBC’ nuts did not fall as freely from the clusters. ‘Barcelona’ has a higher tolerance to big bud mites than ‘TBC’. ‘Barcelona’ kernels were considered to have a slightly stronger nutty flavour. It was concluded that both ‘Barcelona’ and ‘TBC’ could be recommended for planting to produce kernels for the general, larger kernel market sector.

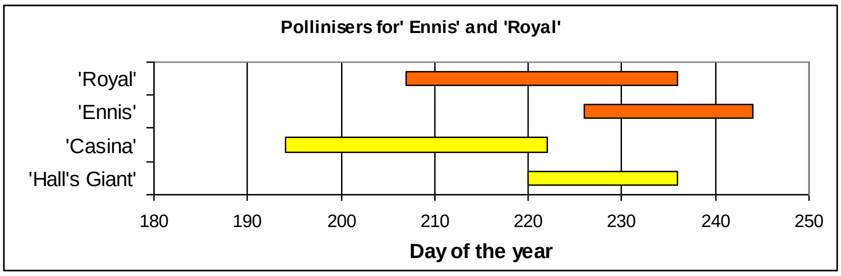
9.2.4 Polliniser cultivars

The cultivars recommended in the previous section would need to be inter-planted with other cultivars for pollination. The polliniser cultivars must be genetically compatible with the main crop cultivar that is to be pollinated. They must shed pollen when the female flowers of the main cultivars are receptive, in order to maximise the opportunities for pollination and subsequent crop yields. The polliniser cultivars should produce large quantities of viable pollen. Although no data was collected on pollen viability, relative catkin numbers were recorded (Section 5.2.1 ‘Catkin abundance’.) Ideally, pollinisers should have nuts or kernels that can be used in a mixture with the main crop cultivars or can be separated from them by size-grading. The pollinisers proposed for the most promising cultivars, in the 3 market sectors discussed above, are shown in Table 9.5 and Figure 9.1. They generally meet the above criteria.

Table 9.5 Potential pollinisers for the most promising cultivars in the 3 main market sectors

		Period of pollen shed relative to the main crop cultivar		
Cultivars and market sectors	**S - alleles**	**Early**	**Mid-season**	**Late**
In-shell				
'Ennis'	1 11	'Hall's Giant' 5 15		
'Royal'	1 3	'Casina' 10 21 (1)	'Hall's Giant' 5 15	
'Wanliss Pride'	2 10	'Lewis' 3 8 (1)		'Hall's Giant' 5 15
Larger kernel sector				
'Barcelona'	1 2	'Lewis' 3 8	'TBC' 5 23	'Hall's Giant' 5 15
'TBC'	5 23	'Lewis' 3 8	'Casina' 10 21 (2)	'Jemtegaard #5' 2 3
Confectionery sector				
'Tonda di Giffoni'	2 23	'Lewis' 3 8,		'Casina' 10 21 (3)

(1) Small nuts requiring size separation
(2) Small nuts that do not blanch requiring size separation
(3) Similar size but do not blanch



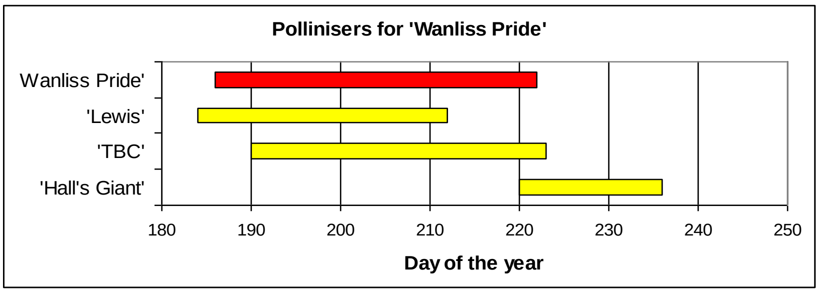


Figure 9.1 Mean periods of female anthesis for potential cultivars for the in-shell market and their suggested polliniser cultivars. Female ant🟥sis pollen🟨hed

'Ennis' is very late into female anthesis, as shown in Figure 9.1. 'Hall's Giant' was one of the latest cultivars to shed pollen yet its main period of pollen shed coincided with the period when the earlier female flowers of 'Ennis' had exerted stigmas. It is possible there may be some yield loss with 'Ennis' due to the lack of a very late polliniser. Suitable pollinisers are available for the other potential main crop cultivars (Figure 9.1). In Oregon, the cultivar 'Butler' is used as a polliniser for 'Ennis' (Lagerstedt, 1980), in these studies, on average, 'Butler' shed pollen before the stigmas of 'Ennis' were exerted.

Although ‘Casina’ and ‘Lewis’ are suggested as pollinisers for ‘Royal’ and ‘Wanliss Pride’, respectively, they produce much small nuts that would be easy to remove by size-grading. The pollinisers suggested for the kernel market cultivars provide a good spread of pollen over their periods of female anthesis (Figure 9.2).

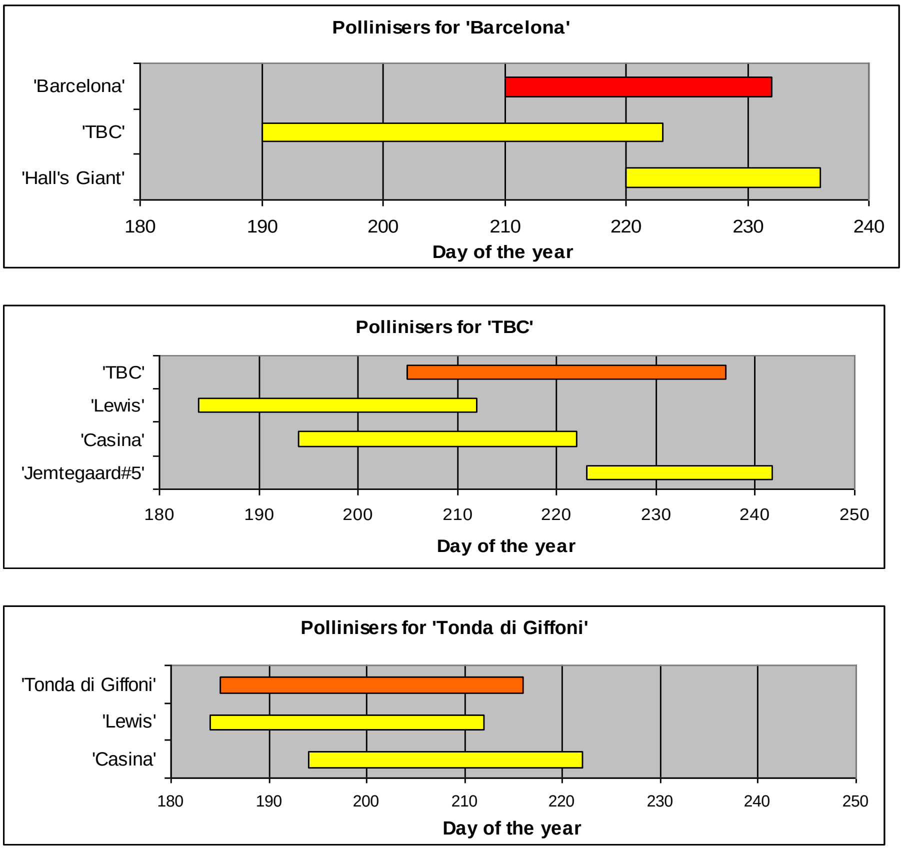


Figure 9.2 Average periods of female anth🟥 for the cultivars ‘Barcelona’, ‘TBC’ and ‘Tonda di Giffoni’ and the average period of pollen 🟨 for the suggested polliniser cultivars.

The cultivar ‘Casina’ is suggested as a polliniser for both ‘TBC’ and ‘Tonda di Giffoni’. As it does not blanch and is not easily separated from the main crop cultivar, this may cause some concern for some kernel buyers in these market segments. However, as it is recommended that a main crop cultivar should not be further than 15 m from a polliniser (Azarenko et al., 1999), the density of pollinisers is about 12% of trees in an orchard, planted at a spacing of 6m between rows and 5 m down the row (333 trees/ha). If only 50% of these polliniser trees were ‘Casina’, the density would be about 6%. As the nut yield of ‘Casina’ was generally low (Table 9.2), the proportion of nuts or kernels from this cultivar may be as low as 3%.

9.3 The effects of climate and soils on hazelnut production

The second key research question was:

- How do environmental conditions affect the growth, phenology and productivity of hazelnut cultivars?

9.3.1 Soils

There were very large differences in tree growth between the sites. High rates of tree growth had a positive influence on nut yields. The differences in growth between sites were considered to be related principally to differences in the texture, depth, structure, aeration and drainage of the soils at the sites (Chapter 4, Section 4.3.5 “Soil effects”). The pH and levels of available nutrients were considered to be at acceptable levels and not limiting factors. The results obtained on the effects of soil type on the growth of hazelnut trees and nut yields were in general agreement with the views of Woodroof (1967), Thompson (1981), Mehlenbacher (1994) and Germain and Sarraquigne (2004), who considered that soils for commercial hazelnut production should be fertile loams that are well-drained, at least 1.5 m deep, with a high water-holding capacity and a pH of 6-7.

Australian soils commonly have duplex profiles, with relatively shallow topsoils (A-horizons); the views expressed in the literature that the soils should be at least 1.5 m deep needs to be evaluated in the Australian context. As the selection of suitable soils for hazelnut orchards is considered to be very important, an attempt was made to define key soil attributes that could be used in Australia for site selection, Chapter 4 Table 4.3. These are re-stated below as Table 9.6.

Table 9.6 Key parameters to assess the suitability of soils for hazelnut production.

Soil properties	Comments	Max points
Texture	Loam, range sandy – clay loams	4
Deep>1.0 m	Majority of roots in top 0.6 m going down to at least 1.2 m . A duplex profile with a clay B horizon is probably a major limitation.	4
Good drainage and aeration	Positive indicators are red colour (good aeration), no mottling, stable structured (little dispersion or slaking of soil crumbs)	4
Fertility	Desirable levels for hazelnuts see Table 4.5 (Olsen, 1995)	1
pH 6.0-7.0	Slightly acid to neutral	1

Recommendation for further studies

It is recognised that the use of the parameters in Table 9.6 to assess the suitability of soils for hazelnut production involves some subjectivity. There is a need for scientific studies to ascertain the relationship between soil texture grades, structure, impedance to root growth, drainage and aeration on growth rates and productivity of hazelnuts, with particular reference to duplex soils.

Recommendation for growers

It is recommended that, prior to planting a hazelnut orchard, intending growers should make a thorough assessment of the soil profile with an emphasis on soil texture, soil structure and drainage, in at least the top 800 mm–1 m of soil, to ensure that it is a well-drained, loam soil. The pH should also be tested so that ground limestone can be applied before planting, in order to bring the top soil up to pH 6 as recommended in the literature.

9.3.2 Climate

In Chapter 2, a series of climate parameters were developed from the literature on the effects of climate on the phenology, growth, and productivity of hazelnuts. These were developed as an aid for site selection. These parameters are now reviewed and modified or reinforced in the light of these studies. They are presented in Table 9.7 and discussed in the section below.

Table 9.7 Suggested key climate parameters for hazelnut production

Phenological stage and effects	Climate parameter and period in Australia	Critical level
Flowering, *frost damage to catkins and female inflorescences*	Lowest air temperature in the coldest months	-7°C (Bergoughoux et al., 1978)
Bud break, chill to break dormancy, *insufficient chill may result in poor leafing out*	Total chill hours (0-7°C) May–August (incl.), highest chill cultivars	≥1500 chill hours (Mehlenbacher, 1991)
Bud break and early leafing, *frosts can damage emerging leaves*	October, lowest minimum air temperature	-3°C (Bergoughoux et al., 1978)
Fertilisation, *minimum temperatures for fertilisation*	Mean maximum air temperature, December,	≥21°C (Latorse, 1981)
Nut and kernel development, *sufficient warmth for production*	Minimum heat units 1 November–30 April	Total 800 GDD above a base of 10°C
Nut and kernel development, *heat stress may affect tree growth and kernel development*	January	Mean max. temp ≤30°C
	December–February, consecutive days > 35°C	Max. 2 days >35°C (Thompson, 1981)
Nut and kernel development, *adverse effects of moisture stress*	December–February	≥60% mean RH at 9 am
Overall growth, production and future crop yields, *adequate soil moisture required*	Minimum annual rainfall, with supplementary irrigation	>800 mm (Tous et al., 1994)
Tree growth, *adversely affected by strong winds*	October-March	Not persistent (Bergoughoux et al. 1978).
Nut harvest, *dry conditions required to facilitate harvest*	March mean monthly rainfall	<50 mm (Tous et al., 1994)

Dormant flowers and frost

Air temperatures did not go below -7°C and frost damage to catkins and female flowers was not an issue at any of the sites. However, it is suggested that the minimum of -7°C for the coldest winter months, as recommended by Bergoughoux et al (1978), be retained as 1 of the criteria for site selection. There may be localities, such as the Northern Tablelands of NSW or valleys adjacent to mountain ranges in parts of Tasmania and NSW, where this could be an issue.

Chill to break the dormancy of flowers and buds

The chilling requirements of cultivars for flowering varied considerably (Table 6.3). These requirements appear to be the main factor influencing the timing of pollen shed and female anthesis and the sequence in which cultivars commenced flowering and bud break, as reported in Chapter 5, 'Cultivar Floral Phenology'. This was in general agreement with studies reported by Mehlenbacher (1991).

It was not possible to develop a model that predicted the date of flowering from temperature data, due to the apparent complexities and interactions between chilling, to break dormancy, and warmth to stimulate development. It appeared that there were 2 concurrent processes involved in flowering:- the break-down of growth retardants by chilling and the development of growth stimulants with post-chill warmth (thermal time). The chilling requirements of catkins were found to be less than those of pistillate flowers but the post-chill heat requirements of the catkins were greater than the pistillate flowers, which is in agreement with the reports of Barbeau (1972), Kavardzhikov (1980), Mehlenbacher (1991) and Turcu et al. (2001). Although there was limited data on the post-chill warmth requirements of catkins, it appeared that these were similar across cultivars, which is in agreement with the work of Tiyanon (2008).

It was concluded that difficulties in developing an empirical model to estimate the chilling requirements of hazelnut flowers are related to:

- the method of calculating chilling hours (e.g. chill hours vs. chill units);
- the starting date for the calculation;
- the date when endodormancy is complete; and
- the lack of visual signs of change from endodormancy to ecodormancy.

Similarly, difficulties in estimating the heat unit requirements of flowers are related to:

- determining the base temperature for calculations; and
- knowing when to commence the calculation of the thermal sums.

It is considered that further studies using growth cabinets, in combination with field studies on floral phenology, would provide a better understanding of the effects of temperature on floral development in hazelnuts. This should be complemented by studies on the levels of growth-retarding and stimulating substances through dormancy to flowering and bud break.

Bud break

In a similar manner to flowering, the variation in dates of bud break between cultivars appeared to be associated with the chill requirements of cultivars to break dormancy and the post-chill warmth required to stimulate leaf development. It is possible that daylength was an additional factor, as reported by Heide, 1993.

The accumulated chill hours to bud break at Orange ranged from 1100 for ‘Tonda di Giffoni’ to 1600 chill hours for the latest-leafing cultivar ‘Hall’s Giant’ in 2002. Although only limited data was obtained on chill requirements to overcome the dormancy of buds in this research, it is considered that the climate parameter of 1500 accumulated chill hours in April–August, as suggested by Mehlenbacher (1991), is a valid, but conservatively high, figure when evaluating sites for their suitability to grow hazelnuts. The formula, developed by da Mota (1957) for the estimation of monthly chill hours (0-7°C) from mean monthly temperature data, was found to over-estimate chill requirements across the 5 sites, but was considered a useful tool when assessing the suitability of sites, if chill hour data is not available.

Freezing temperatures at bud break and early leafing

The data on the effects of freezing temperatures after bud break, at Orange and other sites, supports the view that a climate parameter of a minimum temperature of -3°C in October is an appropriate critical value for hazelnuts, as proposed by Bergoughoux et al. (1978).

Fertilisation – mean maximum temperatures

Latorse (1981) considered the mean maximum air temperature at the time of fertilisation, late May–early June in France, should be ≥ 21°C. Rapid growth of the nut shell is considered to occur 10 days before fertilisation (Germain, 1994). It is likely that, in these studies, fertilisation occurred in early–mid December, as nuts were first observed on trees early in that month. Although no studies were undertaken on fertilisation, this did not appear to be a major problem, as nut development proceeded, with minimal loss, throughout December. This was despite mean maximum temperatures at Toolangi and Kettering being only 20°C in December. As no studies were undertaken on fertilisation, it is suggested that the figure of ≥ 21°C, as recommended by Latorse (1981), be applied for the month of December.

Nut and kernel development - GDD for production

The main period of nut fall for most cultivars was over a period of about 5 weeks, with most blank nuts falling at the beginning of this period. The peak date of nut fall varied slightly between cultivars and seasons. Nut fall was influenced by the accumulated GDD above a base temperature of 10°C from 1 November. It was considered that 800 GDD, in the period 1 November to 30 April, is the minimum for commercial hazelnut production. However, there is a need for further studies or analysis on this matter.

Nut and kernel development, heat and moisture stress

Thompson (1981) and Germain and Sarraquigne (1997) reported that, in Oregon and France respectively, hazelnuts can be adversely affected by extremes of heat and low humidity. The highest maximum temperatures were recorded at the Myrtleford site, where mean maximum temperatures in January and February were just over 30°C, but there were several periods when maximum temperatures, in the range 32°C–38°C, were recorded, in association with relative humidity below 20%. The highest temperatures recorded during the period of study were at Myrtleford in January 2003, with maximum temperatures of 40°C for 2 days with northerly winds and minimum relative humidity down to 17%, Table 9.8.

Table 9.8 Temperature and relative humidity extremes recorded at Myrtleford in January 2003.

	Temperature °C		**Relative humidity %**		**Evaporation (mm)**	**Solar radiation (MJ/m^2)**	**Wind run (km)**
Date	**Max**	**Min**	**Max**	**Min**			
26/01/2003	40.6	18.7	85	20	5.4	21.6	89
27/01/2003	39.7	19.3	79	17	6.2	18.5	117
28/01/2003	33.7	17.8	97	18	5.3	21.5	93

During this period of hot dry weather, the trees were in their sixth year from planting and were well-grown. Trees were being irrigated weekly with micro-sprinklers to minimise moisture stress and restore soils to approximately field capacity. There were signs of some moisture stress associated with these conditions of high temperature and low humidity with some wilting and scorching of leaf margins. The suggestion of no more than 2 concurrent days with maximum temperatures above 35°C is a simplified index of when hazelnut plants may be stressed. It needs to be coupled with an index for relative humidity.

It was concluded that hazelnut trees can tolerate temperatures up to 40°C, provided they have adequate soil moisture. However, it is suggested, until further information is gathered on the effects of high temperatures on hazelnut production, that the mean maximum temperatures in the hottest months, January and February, should not be greater than 30°C and that irrigation should be available, to minimise moisture stress. Higher temperatures are likely to be above the optimum for net photosynthesis, which, for apples and peaches, is in the range 28-30°C (Tromp et al., 2005b).

Relative humidity

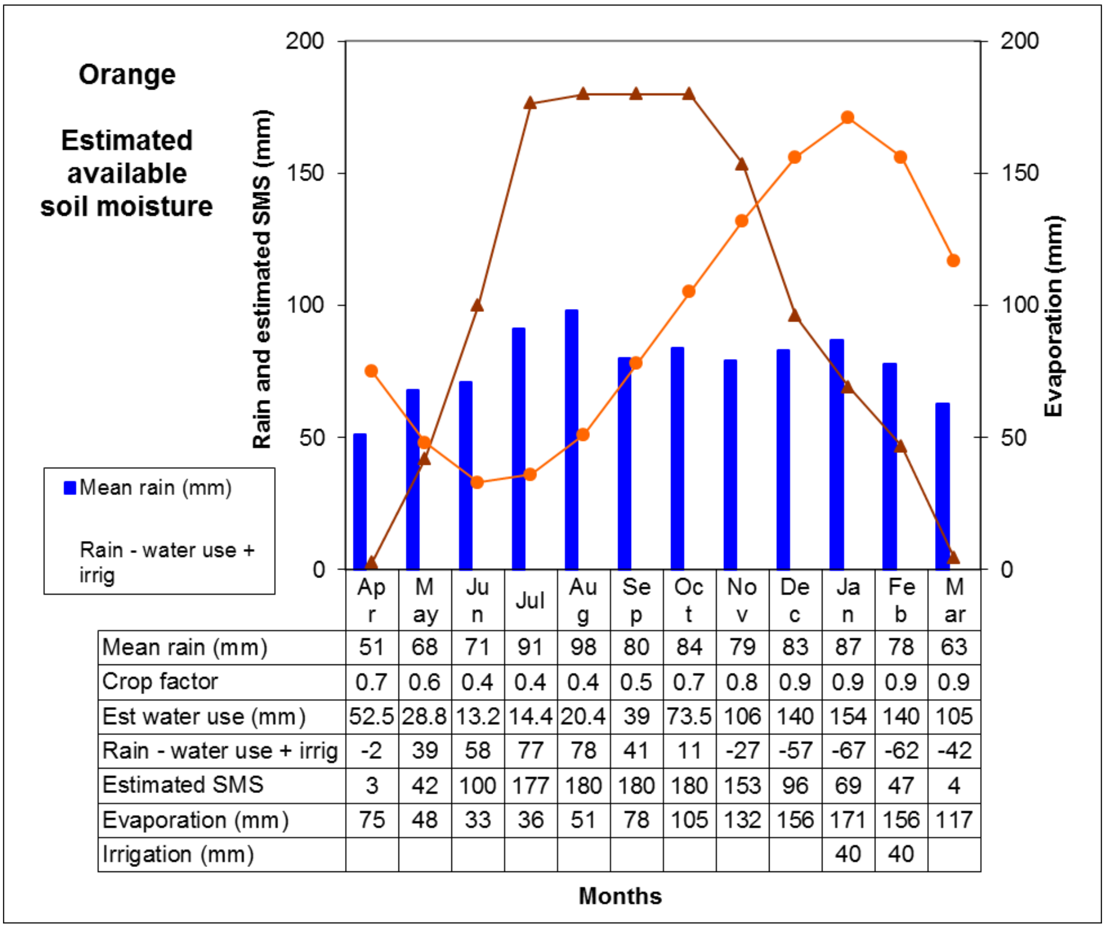
Low levels of relative humidity are commonly associated with high levels of moisture loss through plant leaves. Under conditions of very high water loss, leaves may lose their turgidity and become wilted, with closure of stomata to prevent water loss and dehydration. This can led to desiccation under extreme conditions. Grau and Sandoval (2009) considered that hazelnuts lack an adaptive mechanism to endure high water deficits. Studies on pre-dawn xylemic water potential (Ψx) in Chile, by these researchers, showed an increase in Ψx values following a period when the relative humidity had fallen to 50%. These levels were commonly reached in January at the Myrtleford site, where the minimum mean relative humidity in January was 34% over 9 years, which is similar to that recorded by the Australian Bureau of Meteorology of 32% (www.bom.gov.au/climate/averages).

It is difficult to define a minimum relative humidity value for hazelnuts. A long-term mean value of 56% at 9 a.m. was recorded for Myrtleford by the Australian Bureau of Meteorology (www.bom.gov.au/climate/averages). Data on relative humidity is commonly only available for 9 a.m. readings. Therefore, a parameter value for 9 a.m. readings has been developed. It is considered that a minimum relative humidity value of 60% at 9 a.m. could be an appropriate index. This is lower than the level of 70% recommended by Bergoughoux et al. (1978) and Grau and Sandoval (2009), as presented in Chapter 2, ‘Literature Review’, Table 2.1.

Rainfall and soil moisture

Rainfall and its influence on soil moisture availability was a key factor influencing tree growth, nut yields and kernel quality. The dry conditions, in the spring of 2002 at Moss Vale, had an adverse effect on tree growth and production. Tombesi (1994), Mingeau et al. (1994) and Bignami and Natali (1997) found that late spring was a time when water stress reduced both trunk and shoot growth, and consequently yield potential for the following season. Although the study sites were irrigated, moisture stress during kernel-fill had an adverse effect on kernel quality. Mingeau et al (1994) found that hazelnuts were very sensitive to moisture stress from fertilisation to kernel-fill, the most sensitive phase being fertilisation, which, in Australia, generally occurs in late November to mid-December. Moisture stress during nut development in December reduces both the number and size of the nuts (Mingeau et al. 1994). In January, moisture stress can lead to poorly-filled nuts with shrivelled kernels (ibid, 1994).

The irrigation requirements of hazelnuts depends on annual rainfall, its distribution and evaporation rates. Rainfall and evaporation data for Orange are used as an example to estimate the irrigation requirements of a mature orchard in a year of average rainfall, using crop coefficients developed by Mingeau and Rouseau (1994). This estimate assumes a loam soil with a water-holding capacity of 180 mm per metre depth, with a rooting depth of 1 m for the trees.



	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Mean rain (mm)	51	68	71	91	98	80	84	79	83	87	78	63
Crop factor	0.7	0.6	0.4	0.4	0.4	0.5	0.7	0.8	0.9	0.9	0.9	0.9
Est water use (mm)	52.5	28.8	13.2	14.4	20.4	39	73.5	106	140	154	140	105
Rain - water use + irrig	-2	39	58	77	78	41	11	-27	-57	-67	-62	-42
Estimated SMS	3	42	100	177	180	180	180	153	96	69	47	4
Evaporation (mm)	75	48	33	36	51	78	105	132	156	171	156	117
Irrigation (mm)										40	40	

Figure 9.3 Estimated soil moisture store and irrigation requirements for a mature hazelnut orchard in the Orange district, mean annual rainfall 930mm

The theoretical calculations in Figure 9.3 indicate a total irrigation requirement of approximately 0.8 ML/ha, based on the average annual rainfall in the Orange district, which is about 900mm (www.bom.gov.au/climate/averages). However, as rainfall is erratic, it would seem prudent to budget for around 2ML/ha for a drought year as, in such a year, more irrigation would be required in order to maintain good tree growth and high yields of good quality nuts.

This data indicates that, for every reduction in rainfall of 100 mm below the 900 mm recorded at Orange, there is a need for an additional 1 ML/ha of irrigation. However, if the decrease in rainfall is also associated with an increase in evaporation, the estimated irrigation requirements would be greater than this.

Recommendation

As this is only an estimate it would be very valuable to establish a research project in which there is monitoring of soil moisture and the application of irrigation to validate this model.

Wind

Strong winds were observed to adversely affect tree growth but were not considered to be a major factor influencing differences in tree growth between the sites; growers should avoid sites with persistent winds, as recommended by Bergoughoux et al (1978). However, wind speed influences evapotranspiration rates and moisture stress in plants, particularly when humidity is low.

Hail

Although there were no serious incidents of hail recorded at the research sites, observations on commercial crops show that hail can be damaging, depending on its severity and timing. In the Orange district, hail was observed to damage the bark of young trees which subsequently became infected with bacterial blight. The leaves of trees in full leaf in late spring have also been damaged by severe hail storms.

9.4 The productive potential of hazelnuts (Corylus avellana L.) in Australia

The third key research question was:

- What is the productive potential of hazelnuts (*Corylus avellana* L.) in Australia?

9.4.1 Productive potential and opportunities

The site at Myrtleford provided a good indication of the potential of hazelnuts as a crop. A comparison of nut yields from Myrtleford with those from experimental sites in Corvallis, Oregon was made for the cultivar ‘Barcelona’ (Figure 9.4), using data from cultivar evaluation experiments conducted by the Oregon State University research team (McCluskey et al., 2001 and 2005). One year-old trees were planted at Corvallis, whereas rooted suckers (whips) were planted at Myrtleford.

The trees at Corvallis were grown at a wider spacing (4.5 x 5.5 m) than those at Myrtleford (3 x 5 m). However, it is considered that the difference in density would have had little effect on tree growth and yields before the sixth year from planting. The yield from the ‘Barcelona’ trees grown at Myrtleford compared very favourably with those in Oregon, Figure 9.4.

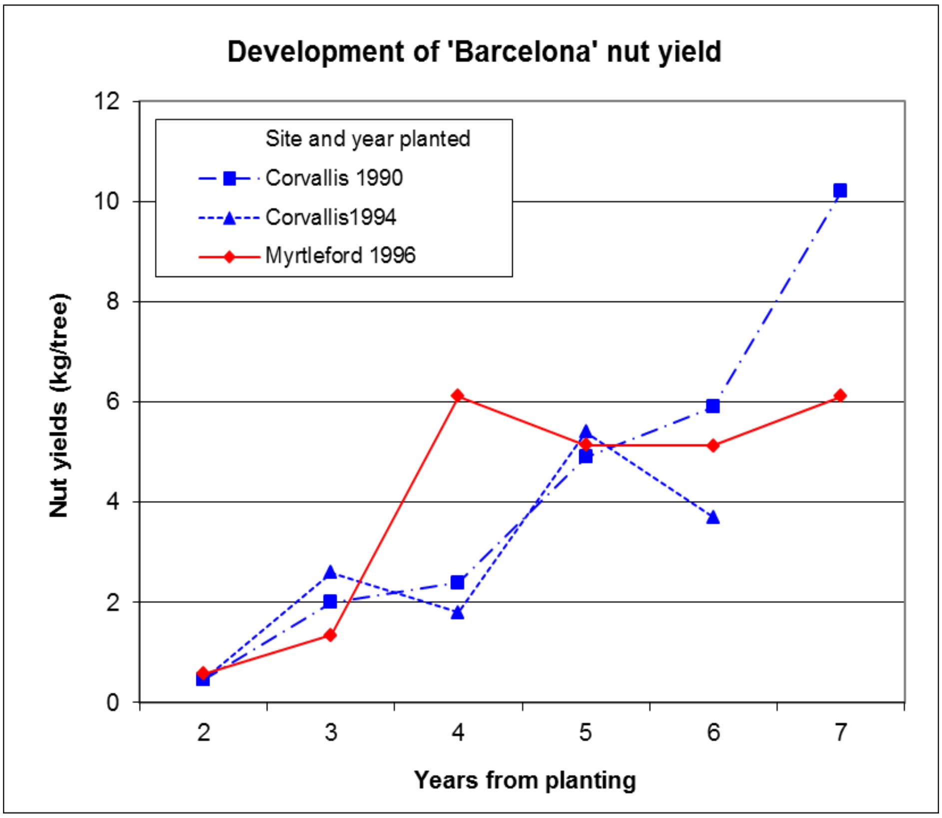


Figure 9.4 Comparisons of the development in nut yield for the cultivar 'Barcelona' grown at Myrtleford, Australia and Oregon, USA.

This data generally suggests great promise for hazelnuts grown in favourable situations in Australia, as the average yields of commercial hazelnut orchards in Oregon were 2.5 t/ha in the decade 1993-2002 (Mehlenbacher, 2005) and amongst the highest in the world (Tous et al., 1994).

World production of hazelnuts is static or slightly declining, in the northern hemisphere, whereas world demand appears to be increasing (Fideghelli and De Salvador, 2009). The dominant producing country is Turkey, where the orchards are very small and the crop is hand-picked. The labour requirements per hectare for established orchards in Turkey are around 400-700 hours/year compared with
35-40 hours/year for the large mechanised orchards in Oregon, USA (Tous et al., 1994).
A potential shortage of hazelnuts has been recognised in Chile, where over 7400 hectares have been planted in recent years by the Ferrero Group (Simcoe, 2011).
It is argued that there is scope for some import substitution in Australia, as well as developing new markets in this country, as hazelnuts have both nutritional and health benefits. The high oleic acid content has been shown to increase the level of high density lipoprotein (HDL) in blood. HDL, in turn, lowers blood cholesterol and thus protects against arteriosclerosis. The risk of death from coronary heart disease is reduced by 50%

in people consuming hazelnuts at least once per day (Alphan E, et al. 1997). The health benefits from including nuts in the diet have been strongly promoted to health professionals through the “Nuts for Life” program, www.nutsforlife.com.au and, in recent years, nut consumption in Australia has been increasing. This program is based on a thorough research of the scientific literature.

Australian production of hazelnuts in 2012 was estimated to be about 70 tonnes of nut in-shell (Australian Nut Industry Council, www.nutindustry.org.au), equivalent to about 30 tonnes of kernels or about 1% of our imports. The experiments conducted in this study indicate that a yield of 4 kg/tree is achievable at a spacing of 3 x 5 m or about 650 trees/ha. This is equivalent to 2.5 tonnes/ha. Such yields are comparable to those achieved with good management in Italy, Spain, Oregon and France (Tous et al. 1994), indicating that with well-selected sites and good orchard management, Australia has a good potential for hazelnut production. Current imports of hazelnut kernels are approximately 2000 tonnes per annum; if the industry aimed to meet this demand it would need to plant approximately 2500 ha of orchard, achieving average nut yields of 2 t/ha and a crack-out of 40%. The orchard sites would need to be carefully selected, well-managed and mechanised to compete with cheap imports from countries such as Turkey, where labour costs are low.

9.4.2 Potential areas for production

Potential areas for hazelnut production in South-eastern Australia are considered on the basis of the key climate parameters, from Table 9.7. As hazelnuts are particularly sensitive to moisture stress in summer, 2 key parameters have been used to show potential locations for hazelnut production, based on a mean maximum temperature of ≤30°C in January and a mean relative humidity at 9 am in January ≥60%. Images from the Bureau of Meteorology web site, www.bom.gov.au, showing zones with mild to warm summers (mean maximum January temperatures ≤30°C), with cold winters, and isohumes of mean relative humidity in Australia, were used to produce the maps in Figure 9.5.

On the mainland of Australia, the zones where summers are mild to warm with cold winters are principally located at higher elevations on or near the Great Dividing Range, whereas the whole of Tasmania is in this climatic zone, Figure 9.5, Map A. The zones where the mean 9 a.m. relative humidity is ≥60% occur on the eastern side of NSW and the southern part of Victoria as well as the whole of Tasmania, Figure 9.5, Map B.

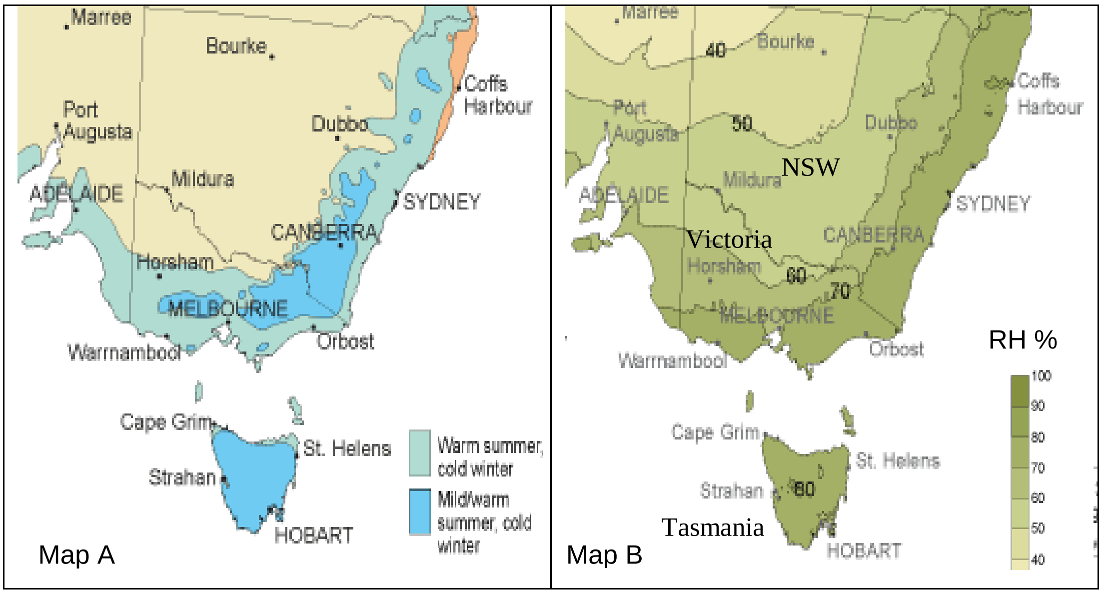
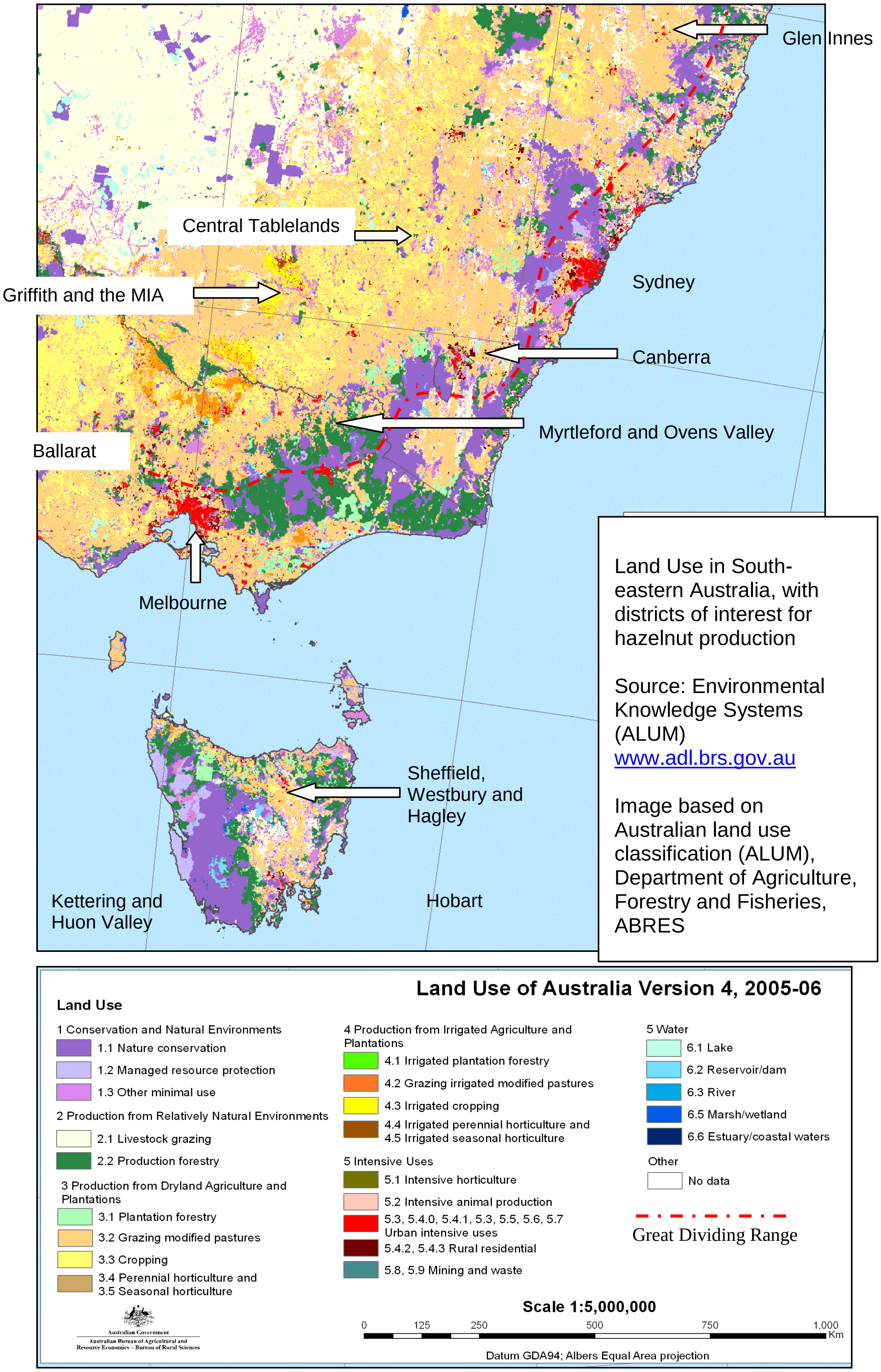


Figure 9.5 Climatic zones based on mean average daily maximum temperatures (°C) in January and thermal heat units in winter (Map A) and average relative humidity (%) at 9 a.m. in January (Map B), in South-eastern Australia, 30-year means.

Source: Commonwealth of Australia, Bureau of Meteorology www.bom.gov.au



Land Use in South-eastern Australia, with districts of interest for hazelnut production

Source: Environmental Knowledge Systems (ALUM) www.adl.brs.gov.au

Image based on Australian land use classification (ALUM), Department of Agriculture, Forestry and Fisheries, ABRES

Figure 9.6 Land use in South-eastern Australia

Soil type is another factor influencing selection of potential areas. The Land Use map,

Figure 9.6, gives some indication of land suitability. On the mainland of Australia, the land in the zone with a mild to warm summer lies at a relatively high altitude, just inland from the eastern seaboard, either abreast or close to the Great Dividing Range, Figure 9.6. The terrain in this zone varies from undulating to steep hills and rugged mountains. Land use varies from livestock grazing, on the undulating hills, through to forestry and natural vegetation on the mountainous areas, with limited scope for cool climate intensive horticulture.

Similarly, in Tasmania, the land use on the mountainous areas in the western part of the state is either conserved natural vegetation or forestry. The Midlands are relatively dry and used principally for livestock grazing. The areas used for intensive agriculture, dairying and horticulture are limited to the coastal areas in the north of the State and the river valleys in the south. The integration of climate parameters with current land use forms the basis of the discussion of potential areas for hazelnut production.

New South Wales

Potential areas for hazelnut production in New South Wales are the high altitude areas of the Northern and Central Tablelands and the South-west Slopes. These include Glen Innes on the Northern Tablelands, inland from Coffs Harbour, Orange on the Central Tablelands, inland from Sydney and Tumbarumba, south-west from Canberra. All 3 areas are apple-growing districts and have appropriate climates and some areas of suitable soils. At Glen Innes, the main limitations are the area of appropriate land, the dominance of summer–autumn rainfall, which may hamper harvest operations, and the relatively low rainfall of winter–spring, which may limit plant growth in spring and subsequent production. This district records minimum temperatures and late frosts that may damage catkins, female flowers and young leaves after bud break.

The Orange district probably has the greatest potential with reasonably large areas of well-drained, fertile basaltic loam soils as well as a suitable climate. The area of suitable soils at Tumbarumba is probably limited.

There is a relatively narrow coastal strip of land south of Sydney that is suitable for agricultural use, as well as the Southern Highlands between Sydney and Canberra in the Moss Vale area. The climate in these areas would be very suitable for hazelnut production but care would be needed to select sites with appropriate soils.

Using the climate parameters in Table 9.7, the inland irrigation districts, such as Mildura and the Murrumbidgee Irrigation Area (MIA) to the east, at Griffith, are likely to be too arid for hazelnuts, unless special measures are taken, such as misting or overhead watering under extreme conditions of moisture loss. The mean maximum temperatures in January can be greater than 32°C, with several days in the month above 35°C, and mean relative humidity at 9 a.m. of less than 60% (Maps A and B). Crops grown under irrigation in these areas include citrus and almonds. However, a citrus grower has planted 'Ennis' trees on a property near Narrandera on the Murrumbidgee, with reports of the 'Ennis' trees coming into production, 6 years after planting (Narrandera Argus, 14 July, 2013). At the time of writing, a company, Agri Australis, was seeking approval to plant over 1 million trees in the Narrandera district (Narrandera Argus, 14 July, 2013).

Victoria

Areas of potential in Victoria include the Upper Ovens Valley, the hills to the east of Melbourne and the Ballarat area, to the west of Melbourne. Coastal areas to both the east and west of Melbourne would also be suitable. In all these locations, areas of suitable soils are limited and careful site selection would be essential. There are irrigation areas in the Goulburn Valley in northern Victoria, where a range of horticultural crops have been grown. Soil types are very variable, but detailed soil surveys have been conducted in the area (Cockroft, 1965). Mean annual rainfall in this district is in the range 450-600 mm, which would necessitate the use of irrigation for hazelnut production. However, maximum temperatures and relative humidity in January indicate the area could be too warm and arid. Returns from hazelnuts would need to be comparable with those from existing land uses.

Tasmania

This State is considered to have the greatest scope for growing hazelnuts, due to its cool climate (Figure 9.5, Map A) and areas of relatively high rainfall. Potential areas in the north of the state include the Sheffield district, the Meander Valley, Hagley and Westbury areas, as highlighted by Baldwin (1999). An irrigation pipeline provides water to the Hagley district from the Meander Dam www.tasmanianirrigation.com.au.

There is also some potential in the old orcharding areas of the Tamar Valley, north of Launceston and to the south of Hobart in the Channel and Huon districts, although many soils in these areas are poorly-drained and similar to the soils of the Kettering site. Rainfall and soils vary quite markedly over relatively short distances, so sites would need to be carefully evaluated. Big bud mites have been found in Tasmania, having been there probably for many years. These can have a very damaging effect on susceptible cultivars; the best strategy for control being to plant resistant cultivars.

South Australia

The potential areas of production in this State are relatively small and limited to the higher rainfall areas of the Adelaide Hills, such as at Lenswood, and the Mount Gambier–Penola district in the South-east of the State. Key limitations to production are limited areas of suitable soils, high land prices and limited water supplies for irrigation.

Western Australia

The higher rainfall districts in the south-west of the state, where apples are grown, such as at Manjimup, are suitable for hazelnut growing. Rainfall has a very high winter incidence with very little summer rainfall, so irrigation would be essential. A small hazelnut plantation did exist at the Manjimup Research Station, in the south-west of Western Australia. Hazelnuts have been planted in this area by the Wine and Truffle Company for truffle production, http://wineandtruffle.com.au/ . The orchards are well-irrigated throughout the summer. Seedling trees were planted, which were inoculated with the black truffle fungus. The author visited the orchard in January 2007 and inspected the trees, which had grown well. Summer temperatures are high and the areas of appropriate soils are limited, as are water resources, so the area suitable for hazelnut production is probably limited.

Climate change

It is predicted that, by 2030, mean temperatures will rise by 0.3-0.6°C, with a further rise of up to 2.5-3°C by 2070 (Stokes and Howden, 2008). Maximum temperatures will rise faster than minimums; chilling hours will decrease, as will relative humidity, in southern Australia. All these factors will impact on cool climate horticulture and the suitability of locations for hazelnut production. Locations that are currently just sufficiently mild, might in the future be too warm and unsuitable for production.

Climate change models predict the likelihood of less rainfall in southern Australia, particularly winter–spring rainfall, with decreased inflows into catchments and reductions in water availability for irrigation. It is therefore suggested that those investing in hazelnut production should err on the conservative side when assessing potential locations for production, using the climate parameters in Table 9.7.

9.5 Economics

9.5.1 Potential profitability

It is difficult to be precise about the profitability of hazelnut growing as this depends on the situation in which the crop is grown, the yields obtained, the market opportunities, and the growers' management skills. An estimate of the cost of establishing a hazelnut orchard (Table 9.9) was undertaken by the Tasmanian Department of Primary Industries, Parks, Water and the Environment. The spreadsheet "Hazelnut Profitability and Gross Margin Analysis" is based on information provided by growers and is available at http://www.dpiw.tas.gov.au/inter/nsf/WebPages/LBUN-8M589T?open#GrossMarginAnalysisT

The estimated establishment costs are $9000/ha, based on the need to apply ground limestone before planting to raise soil pH levels, the availability of contractors to prepare the land and to plant the trees. It assumes whips or young trees will be purchased at a cost of $10 per tree and that the grower has a water supply and irrigation licence for the property. Irrigation costs are for materials only in the orchard and assume the irrigation system will be installed by the grower. It is based on a density of 330 trees/ha, rows 6 m apart with trees at a 5 m inter-row spacing. The two major cost items are the purchase of the planting material and setting up the irrigation system (Table 9.9).

Table 9.9 Estimate of approximate material costs of establishment per hectare, excluding labour

Item	**Approximate cost $/ha**
Interest foregone on land purchase 5% at $10,000/ha	500
Lime 5t/ha @ $70/t, applied by contractor	350
Land preparation, spraying, ripping, cultivation and levelling	350
330 trees @ $10/tree (Spacing 6m x 5m)	3300
Planting cost (labour)	500
Irrigation system (Irrigation mains, sub-mains, drip lines and 4 emitters/tree). Assumes water to site.	4000
Total materials costs	**$9000**

Source: Based on Hazelnut Profitability and Gross Margin Analysis

http://www.dpiw.tas.gov.au/inter/nsf/WebPages/LBUN-8M589T?open#GrossMarginAnalysisT

The estimated costs of orchard establishment in Australia are higher than those for Oregon, where establishment costs were estimated by Julian and Seavert (2009) to be the equivalent of A$3000/ha. The main factors contributing to the lower costs in Oregon were trees at A$5 each compared with A$10 in Australia and no costs for irrigation in Oregon as the orchards are not irrigated.

The data from the research sites indicates it could take from 8-15 years to achieve peak yields from an orchard. This will depend on the quality of the planting material, the site and the growers' management skills. The gross margin for an orchard that is yielding 2 t/ha was estimated using the Tasmanian Hazelnut Profitability and Gross Margin Analysis (Table 9.10). Assumptions in this gross margin are that the grower will apply sprays for the control of hazelnut blight, suckers and weeds in the tree rows. As it is difficult to control all the suckers by spraying, a cost item has been included for contractors to cut uncontrolled suckers and to do some pruning. Although there is a cost for mowing by contractors, it is very likely the grower would do the mowing. It is assumed that raking the nuts and harvesting would be done by a contractor with the grower carting the harvested crop and drying it.

Based on these assumptions, the approximate direct expenses are estimated to be $2000/ha, with a gross margin of $5000, based on a nut yield of 2000 kg/ha and a selling price of $3.50/kg.

Table 9.10 Estimated gross margin ($/ha) for a well-managed orchard assuming harvesting by contractor with assistance from the grower

			Expenses ($/ha)	Income ($/ha)
Income				
Hazelnuts in-shell, 2 tonnes/ha @ $3.50/kg				**7000**
Expenses	No. or amount	Unit cost		
Lime (5t/ha every third year)	1.68 t	$65/t	110	
Fertilisers (N.P.K mix)	250 kg	$350/t	90	
Chemicals				
Bordeaux mix for bacterial blight control	3	$10	30	
Sucker spraying (e.g. Basta)	6	$10	60	
Weed control in the tree rows (eg Roundup)	4	$10	40	
Fuel and oil			100	
Irrigation (pumping costs 1 ML/ha)			300	
Contractors				
Mowing	8	$40	320	
Labour - pruning/sucker cutting	12 hrs.	$25	300	
Mechanical raking nuts at harvest ($/hectare)			50	
Mechanical harvesting	2 t	$100/t	200	
Drying	2 t	20c/kg	400	
Total direct costs			**2000**	
Gross margin ($ per hectare)				**5000**

Peak nut yields of 2000 kg/ha or more were achieved by the highest yielding cultivars at 4 of the sites, Table 9.11. At Kettering, yields were still increasing 8 years from planting.

Table 9.11 Estimates of nut yields per hectare for the higher yielding cultivars at the study sites

Site	Cultivars	Years from planting	Approx peak tree yield (kg/tree)	Approx yield per hectare (kg/ha)
Orange	Barcelona	10	4	2600
Moss Vale	TBC	8	4	2600
Myrtleford	Barcelona	7	6.2	4030
Toolangi	Barcelona and TBC	6	3	2000
Kettering	TBC	8	2	1300(1)

Notes: Yields per hectare based on peak nut yields per tree multiplied by trees per hectare at the spacing of 3 m x 5 m, 650 trees per hectare.

(1) *The trees had not achieved peak yields.*

Two key factors influencing the profitability of hazelnut growing are the price received for the crop and the yield obtained. At a price of $2/kg and a nut yield of 1 t/ha, the crop returns equal the direct expenses of production. If the price received is raised to $4/kg, the gross margin is $2000/ha. Increasing the productivity to 3 t/ha improves the gross margin considerably, particularly if the grower receives $4/kg (Figure 9.7).

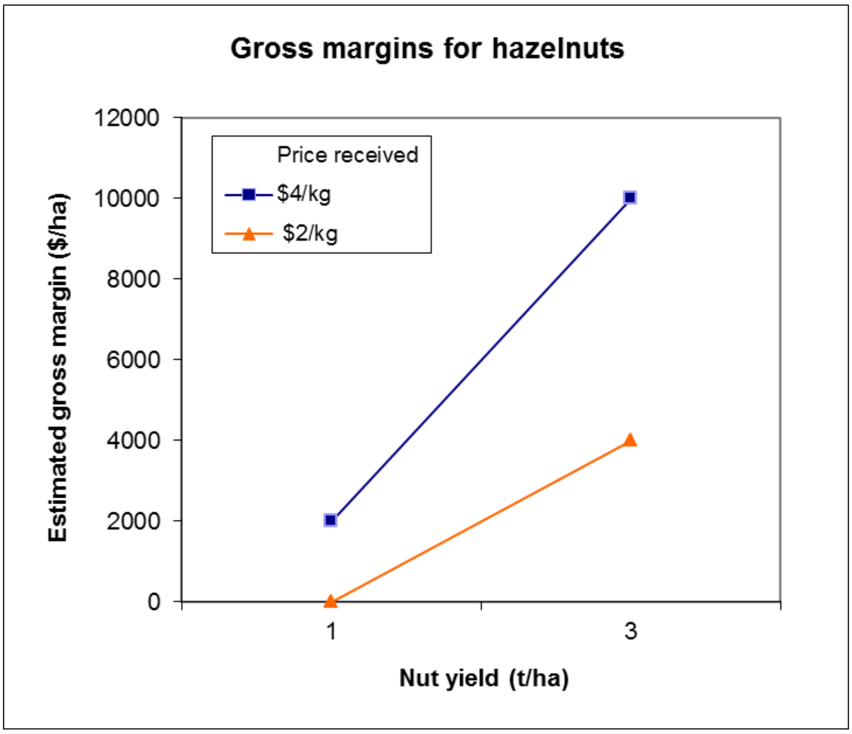


Figure 9.7 Effect of changes in nut yields and the price received on estimated hazelnut gross margins

The total direct costs in the estimated gross margin (Table 9.10) equate to about $1/kg of nuts in-shell. In Oregon, growers' returns are generally less than A$2/kg of nuts in-shell (Julian and Seavert, 2009). For Australian growers to compete with overseas imports, it is likely they would be required to accept payments of no more than $2.50/kg for nuts in-shell. In order to be cost-competitive, orchards would need to be highly productive, requiring good site selection, productive cultivars and a high level of management.

Hazelnut production compared with other land uses

Alternative land uses to hazelnut production vary considerably between districts. It is possible that the land use prior to planting a hazelnut crop would be a grazing enterprise, such as sheep for lamb production. A potential gross margin for hazelnuts can be compared with a grazing enterprise to gain some idea of the alternative to the current land use (Table 9.12). A further comparison might be with an alternative tree crop, such as cherries. Even at the low figure of $2.50/kg for nuts, a hazelnut orchard, when in full production, would give a far higher gross margin than prime lamb production, although far less than a cherry orchard (Table 9.12).

Table 9.12 Gross margins for a grazing enterprise and a high-value horticultural crop compared with hazelnuts

Land use	Assumptions	Gross margin	Comments
First cross ewes for prime lambs	3.7 ewes/ha	$337/ha	Low investment costs, lower direct inputs costs and less labour
Cherries (640 trees/ha)	10 000 kg/ha @ $4.00/kg	$9800/ha	High investment costs, labour in pruning and harvesting, high risk
Hazelnuts (330 trees/ha)	2000 kg @ $2.50/kg	$3000/ha	Relatively high investment costs, mechanised harvesting, low risk

Source: NSW DII. www.dpi.nsw.gov/agriculture/farm-business/budgets

Although gross margins provide an indication of the relative profitability of alternative land uses, there are many other factors to consider in these enterprise options, such as the investment and operating costs, the time or labour requirements, the risks associated with the weather and fluctuating market prices. The keeping qualities of the product and issues associated with harvest and transport to the market need to be considered. The skills and interest of the land owner are an important consideration. Positive attributes of hazelnuts are that most operations can be mechanised, they require minimal pruning and keep well once dry, with market opportunities for the locally-grown product.

9.5.2 Market potential

As stated in Chapter 1, total world production of hazelnuts is increasing; production for the triennium 2005-2007 was 19% greater than the previous triennium (Fideghilli and De Salvador, 2009). World production in 2007 was estimated to be 812 236 tonnes in-shell (FAOSTAT, 2010).

Turkey is the leading hazelnut producer, with approximately 550 000 tonnes of nut in-shell per annum, approximately two-thirds of world production. The orchards in Turkey are very small and the crop is hand-picked (Bozolglu, 2005). The labour requirements per hectare are around 400-700 hours/year compared with 35-40 hours/year for the large mechanised orchards in Oregon, USA (Tous, 2004). It is argued that there is scope for import substitution in Australia, as well as developing new markets in this country, as hazelnuts have nutritional and health benefits.

Australian production of hazelnuts is estimated to be about 60 tonnes of nut in-shell per annum (Hazelnut Growers of Australia www.hazelnuts/org/au). This is equivalent to about 25 tonnes of kernels, or about 1% of Australian imports. This research indicates that yields of 2 t/ha are achievable (Table 9.11). Such yields are comparable to those achieved with good management in Italy, Spain, Oregon and France (Tous 2004), indicating that with carefully-selected and well-managed orchards, Australia has a good potential for hazelnut production. At a crack-out of 40% (kernel/nut weight), 2 t/ha equates to 0.8 t/ha of kernels. As Australia imports approximately 2000 tonnes of kernels annually, a total production area of about 1500 ha could meet current market needs. However, it would be essential that the cultivars planted were those sought by the key buyers, to ensure the nuts were suitable to their needs.

An industry grower's body exists, the Hazelnut Growers of Australia, which could liaise between prospective growers and hazelnut buyers to guide this process of development. As machinery for harvesting can be imported, it should be feasible to develop a highly-mechanised industry to harvest and handle the crop mechanically, in order to achieve high levels of efficiency and productivity that would enable the industry to be economically competitive. Facilities for hazelnut drying and processing exist on a small scale (www.hazelnuts/org/au), with sophisticated facilities for other major nut crops, such as almonds. It would be relatively easy to develop large-scale facilities for cracking nuts and sorting kernels. It would be desirable to establish some key centres of production, such as in northern Tasmania or the Central Tablelands of NSW, to enable an integrated industry with growers providing crop to centralised processing facilities. This would be supported by advisors on technical, financial and marketing matters to produce product that can be produced at competitive prices and marketed in Australia and overseas. It is likely that, in time, a breeding program could be established to produce higher-yielding cultivars, better suited to the Australian environment.

9.6 Overall conclusion

This study has shown that high yields of hazelnuts can be achieved in Australia, when appropriate cultivars are grown on suitable soils in a favourable climate. The research provides details of cultivar performance along with nut and kernel characteristics that enable those planning future investments in hazelnut orchards to select suitable cultivars for production and to meet targeted market outlets.

Data generated on floral phenology, coupled with published information on genetic incompatibility, enables suitable pollinisers to be selected for main crop cultivars. Decisions on appropriate sites for future plantings should be based on the desirable soil characteristics and climate parameters that have been identified for hazelnut production. The research demonstrated the need for supplementary irrigation to minimise any adverse effects of variable rainfall and to ensure adequate soil moisture from the time of fertilisation through to kernel fill. The implementation of these decisions needs to be coupled with orchard management practices that facilitate healthy tree growth.

The results of these studies indicate the potential to establish an industry that could be internationally competitive and provide high quality hazelnuts into world markets.

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APPENDIX A - THE IDENTIFICATION OF HAZELNUT CULTIVARS

Introduction

When conducting research that involves the assessment of cultivar performance, it is essential to ensure that the cultivars being evaluated are true to name, otherwise any conclusions drawn from the research would be incorrect and misleading. Most cultivars used in this study were vegetatively propagated from the suckers of mother trees in stool beds. As propagating material was scarce for some cultivars, there was a need to propagate these by grafting the cultivar scion wood onto rootstocks of *Corylus avellana* L. cultivars. This grafted material was planted with the graft below soil level and a metal tie above the graft so that, in time, the scion developed its own roots. However, in a few cases the grafts failed, resulting in plants arising from the rootstock rather than the scion wood. As it is easy for misidentification of genetic material to occur and for errors to arise in the propagation, handling and planting of trees, it was considered essential to identify all the plants at all sites. When the field experiments were initiated, the author was unfamiliar with the morphological and phenological characteristics of the cultivars made available for the research. It was, therefore, considered essential to develop a methodology to assess whether the cultivars were true to type as there was limited expertise in Australia on hazelnut identification.

The issue of correct identification of hazelnut cultivars is of international importance. A system to describe hazelnut clonal material, based on a range of observable genetically-linked plant characteristics, was suggested by Thompson et al (1978). Subsequently, this was refined and expanded into “Descriptors for hazelnuts (*Corylus avellana*, L.)” (Bioversity, FAO and CIHEAM, 2008). Some traits, such as nut yield, 10-nut weight and percentage kernel can be objectively measured. Many phenological events, such as calendar dates for staminate and pistillate anthesis, leafing out and nut fall are influenced by environmental factors as well as being genetic traits. However, as there is commonly a sequential order for the relative timing of these events, sets of standard cultivars are used against which cultivars or selection lines can be compared (Thompson et al, 1978).

Over a period of several years, a collection of hazelnut cultivars has been established by the United States Department of Agriculture (USDA) at Corvallis in Oregon. There are 431 accessions of *Corylus avellana* L. in the collection, from 28 countries. The material has been obtained from authoritative sources in the countries where the cultivars or selections originated. The main characteristics of a large number of these cultivars have been recorded using a descriptive system very similar to that suggested by Thompson et al (1978). The *Crop Descriptors* for the assessed material is available on the internet and can be accessed through the USDA, Agricultural Research Service at www.ars.usda.gov/Main/docshtm?docid=11305 . Descriptions of the individual cultivars can be accessed through the link, *Hazelnut Cultivars and Selections.*

The database prepared from the USDA germplasm collection has been used in this study as a standard, in order to make comparisons with the cultivars planted in the 5 field experiments described in this thesis, to ascertain if the cultivars evaluated were considered to be true to name. However, some cultivar types were of Australian origin and needed to have descriptors developed for them.

Background and key characteristics of the available cultivars

A literature review was conducted to obtain information on the origin of all the cultivars included in this study along with their key traits.

‘Atlas’

‘Atlas’ was evaluated in a study commenced in 1937 by NSW Agriculture at Glen Innes (Trimmer, 1965), where it yielded well. It was subsequently transferred to the NSW DPI collection at Orange in the 1970s, where it was reported as the highest-yielding cultivar in that collection (Department of Agriculture, NSW, 1982). Whilst the origin of the Australian ‘Atlas’ genotype is unclear, Bean and Kenez (1991) found that in 1887, Goeschke had considered ‘Atlas’ to be a synonym for the cultivar ‘Englische Zellernuss’. Allen (1986) recorded that ‘Atlas’ was also known as ‘Downton’ or ‘Pearson's Prolific’, which is in the USDA germplasm collection as an English cultivar. It is described as “vigorous, early, a fair cropper, nuts large and plump, downy with a thick shell having a kernel with good flavour". Allen (1986) considered that 'Imperial de Trebizonde' and 'Hall's Giant' were pollinisers for Atlas. Observations made on the 'Atlas' genotypes in the Orange collection, by Baldwin and Baldwin (1991), appeared to match the general description of 'Pearson's Prolific' given above by Allen (1986). However, in 1981, Dr Maxine Thompson of Oregon State University (OSU) inspected the hazelnut collection at Orange. She was of the opinion that all the genotypes were of seedling origin, as none had characteristics with which she was familiar; they all had relatively thick shells and many had names that were corruptions of European cultivar names (Bean and Kenez, 1991).

'Barcelona'

Synonyms: 'Fertile de Coutard', 'Grosse Blanche d'Angleterre', 'Castanyera'. 'Barcelona' is a versatile cultivar that appears to adapt to a wide range of conditions. It is an old cultivar which is widely distributed in Western Europe. It was introduced into the US by Felix Gillet in the 1880s (USDA, 2007), as 'Grosse Blanche d'Angleterre'. It originated in Spain and is synonymous with 'Fertile de Coutard', which is grown in France. 'Barcelona' was found in the early 1900s to be more productive than other cultivars of European origin and became the basis of the Oregon industry (Thompson, 1981).

'Barcelona' is a vigorous-growing cultivar (McCluskey et al., 1997). The nut is medium to large, nearly round with an average weight of 3.2-3.4 g/nut (Mehlenbacher and Miller, 1989). Nuts are oval to triangular in cross-section outline, with a fairly flat base and are borne in clusters of 1 to 3. The shell is of medium thickness and is described as having a rich brown colour with darker striping, lost in pubescence on the upper third of the shell. The kernel is fibrous. The husk, one-third longer than the nut, opens and sheds the nut freely (USDA, 2007). 'Barcelona' kernels have a good nutty flavour and blanch quite well. The cultivar often has shrivelled and poorly-filled kernels (McCluskey et al., 1997), which generally have an off-flavour, do not blanch and need to be removed to produce a good quality product. 'Barcelona' has a tendency to produce some twin kernels. The crack-out or proportion of good kernels is relatively low at 40–42% (Thompson, 1981). 'Barcelona' sheds its pollen early and female flowers are receptive early (Mehlenbacher and Miller, 1989).

‘Barcelona’ is susceptible to bacterial blight (*Xanthomonas arboricola pv corylin)* which is most severe in young trees. ‘Barcelona’ is moderately resistant to the fungal disease, eastern filbert blight (*Anisogramma anomala),* but eventually succumbs to this disease. ‘Barcelona’ is resistant to big bud mites (*Phytoptus avellanae* Nal. and *Cecidophyopsis vermiformi* Nal.*),* (Mehlenbacher and Miller, 1989).

‘Butler’

‘Butler’ was named after Joseph Butler who found it as a seedling in his orchard in the Pacific Northwest of the USA (Lagerstedt, 1980). In 1957, ‘Butler’ was introduced into orchards in Oregon as a polliniser to replace’ Daviana’, due to its higher productivity. In Oregon, ‘Butler’ sheds pollen over a similar period of time to ‘Daviana’; it normally covers the latter half of ‘Barcelona’ bloom and the early part of ‘Ennis’ bloom. In Oregon, ‘Butler’ is very vigorous and highly productive (Lagerstedt, 1980). Santos and Silva (2001) reported the cultivar to be high-yielding and precocious in Portugal. ‘Butler’ nuts are generally borne in clusters of 2 or 3. The nuts have a ‘blocky’ or rectangular shape; they are slightly bigger than ‘Barcelona’ but have a thinner shell with a much higher percentage kernel (45–47%). The nuts ripen approximately 1 week earlier than ‘Barcelona’ and drop freely from the husk (USDA, 2007). The medium-sized nut is considered to be attractive but the kernels do not blanch and have quite a bland flavour. ‘Butler’ is considered to be sensitive to bacterial blight and also to big bud mite (Lagerstedt, 1980).

‘Casina’

This cultivar originated in the Asturias region of Spain, where it is a minor cultivar of no commercial importance. It was introduced into the US by Q. Zielinski, in approximately 1960, and propagated by nurseries in the late 1980s (Thompson et al., 1996). ‘Casina’ was found to grow well in Oregon and produce high yields of nuts and kernels with good yield efficiency, (McCluskey et al., 1997). Fruit clusters contain 3-5 nuts; the husks are 50% longer than the nuts. Most husks have a slit on one side, allowing two thirds of the nuts to fall freely to the ground (Mehlenbacher, 1993). Nuts are small (1.8 g), round to oval in shape and dull brown in colour with a crack-out of 56% (Olsen, 1993). Kernels do not blanch well but the flavour and texture are very good, making ‘Casina’ suitable for the unblanched kernel market.

‘Daviana’

Synonyms: ‘Duchess of Edinburgh’, ‘Des Anglais’.

This cultivar originated in England where it was raised by Richard Webb and was named as a compliment to the eminent scientist, Sir Humphrey Davy. It has been used as a polliniser for ‘Barcelona’ in the Pacific Northwest, USA as has ‘Du Chilly’ (syn. ‘Kentish Cob’). However, ‘Daviana’ was found by Schuster (1924) to be a better polliniser for ‘Barcelona’ than ‘Du Chilly’. ‘Daviana’ and the late-flowering ‘Hall’s Giant’ became the 2 principal pollinisers used in ‘Barcelona’ orchards (Mehlenbacher and Miller, 1989). ‘Daviana’ is described as being a vigorous, upright tree, close-growing, but giving low yields and it is susceptible to big bud mite. The nuts are medium to large (2.9 g), long, light brown in colour with stripes. The shell is thin and the crack-out is 56% kernel by weight. The pellicle is not removed by blanching. Husks are longer than the nuts, which mainly fall free and mature 1 week earlier than ‘Barcelona’. The kernel is loose, laterally dented or round, and is very white inside. It has a fairly good flavour (USDA, 2007). ‘Daviana’ is highly susceptible to big bud mite (Mehlenbacher and Miller, 1989).

‘Eclipse’

‘Eclipse’ is an Australian seedling selection, collected by Milan Paskas of Nar Nar Goon in Victoria, who was a collector and propagator of hazelnut genotypes. It was found in old plantings in the Upper Ovens Valley of Victoria. The tree has a spreading growth habit and is of relatively low vigour. The nut is relatively round and of medium size, similar in shape to ‘Wanliss Pride’. It was considered to have some potential for the kernel market.

‘Ennis’

‘Ennis’ is a US cultivar which was thought to have occurred as a seedling in Washington State. It probably arose from a cross between ‘Barcelona’ and ‘Daviana’ and was selected primarily for its large nut size and high-yielding capacity (Lagerstedt, 1980). It was described by Lagerstedt (1980) as a compact tree. McCluskey et al. (1997) reported high yields and a high yield efficiency. In Northern Portugal, Santos and Silva (2001) found the cultivar to be high-yielding and precocious, coming into bearing early.

When size-graded, more than 50% of the nuts of 'Ennis' fall in the 2 largest grades, giant (>23.8 mm diameter) and jumbo (>22.2 mm in diameter). Average nut weight is about 4.0 g. Nuts are almost round, but have a distinct point. The shell of the nut is medium to light brown with attractive stripes and a flat basal scar (Lagerstedt, 1980). The crack-out ranges from 45-49%. In the Oregon environment, the kernels are generally plump and have a less wrinkled appearance than kernels of most other large-sized nuts. They also have a cleaner, smoother appearance than those of 'Barcelona' (USDA, 2007). Most of the nuts develop from small flower clusters occurring on catkin peduncles. They also develop from larger flower clusters, occurring on 1 year-old shoots.

'Ennis' is not an effective polliniser as its catkins are small, open late and release a high proportion of non-viable pollen (Lagerstedt, 1980).

'Hall's Giant'

Synonym: 'Merveille de Bollwiller', 'Geante de Halle', 'Halle'sche Reisennuss'. 'Hall's Giant' originated in 1788 as a seedling selection by C.G. Bultner at Halle, Germany. It was subsequently introduced into France where it is known as 'Merveille de Bollwiller' and later introduced into the US by Felix Gillet about 1890. The large nut is round with a conical top, brown in colour with a thick shell and a crack-out of about 40% (McCluskey et al., 1997). The kernels have a thin pellicle and were reported to blanch well by Solar and Stampar (1997). It matures after 'Barcelona'. The tree is vigorous and erect but not productive in Oregon (McCluskey et al., 1997). However, good yields were reported in the Netherlands by Wertheim (1994) and in Croatia by Solar and Stamper (1997). It is highly resistant to big bud mite (USDA, 2007) and (Solar and Stamper, 1997) and it is tolerant of bacterial blight (Bergoughoux et al., 1978).

‘Hammond#17’

This high-yielding genotype was found in a garden collection near Orange, NSW, where it had produced very high nut yields. Its origin is unknown, but it may be related to ‘Butler’, as its nuts look similar.

‘Kentish Cob’

Synonyms: ‘Du Chilly’ and ‘Longue d’Espagne’

This cultivar originated in Kent, England as a seedling selection. In Kent, nuts are hand-harvested in their green husks for the fresh market. The tree of ‘Kentish Cob’ is of relatively low vigour, semi-erect and moderately productive. Pollen shed is late, making it a potential late polliniser. However, it is noteworthy that in Oregon, Schuster (1924) considered ‘Daviana’ to be a better polliniser for ‘Barcelona’ than ‘Kentish Cob’ (‘Du Chilly’). The nuts of ‘Kentish Cob’ are large, long and flattened. The shell is of medium thickness and slightly rough. The husk is about 50% longer than the nut. The kernels do not blanch. ‘Kentish Cob’ was introduced into the US in the 1870s; it is moderately resistant to big bud mite (USDA, 2007).

‘Jemtegaard 5’ (‘J#5’)

‘Jemtegaard 5’ is a US selection, by Olgar Jemtegaard at Boring in Oregon. It is late in pollen shed and has occasionally been used as a polliniser for ‘Barcelona’. In France, it is used as a polliniser for ‘Segorbe’, ‘Ennis’ and ‘Merveille de Bollwiller’ (Germain and Sarraquigne, 2004). The tree is of medium to high vigour but is of low productivity (Lagerstedt, 1981). It bears clusters of 2-3 nuts which are medium to large (19-21 mm), sub-spherical with a kernel yield of 47-51% (Germain and Sarraquigne, 2004).

‘Lewis’ (‘OSU 243.002’)

‘Lewis’ is a cultivar developed from a cross made by Dr Maxine Thompson, of OSU, in 1981, between OSU 17.028 (‘Barcelona’ x ‘Tombul Ghiaghli’) and ‘Willamette’. It was assessed as OSU 243.002 and released as ‘Lewis’ in 1997.

‘Lewis’ is earlier into bearing than ‘Barcelona’ and is a smaller tree; nut-fall is earlier and it has fewer kernel defects. Nut yields were 35% higher than those of ‘Barcelona’ in a trial planted in 1998 in Oregon (McCluskey et al. 2005). Nut clusters contain 3-6 nuts which fall freely and are ready to harvest 5-7 days earlier than ‘Barcelona’ (McCluskey et al., 2001), although in a later trial, McCluskey et al. (2005) reported an extended period of nut fall for ‘Lewis’. ‘Lewis’ nuts are small (2.6-2.9 g/nut) compared with ‘Barcelona’ (3.4-3.6 g/nut), and have a higher crack-out 44-47%. Kernels have very little fibre; they blanch slightly better than ‘Barcelona’ and have good flavour and texture. ‘Lewis’ has moderate tolerance to big bud mites (USDA, 2007).

‘Montebello’

Synonym: ‘Siciliana’

A cultivar of Italian origin, ‘Montebello’ is early-flowering, moderately vigorous and productive. It has medium-sized greyish-brown nuts with distinct stripes (USDA, 2007). It is partially self–incompatible, being able to bear some nuts without cross-pollination, and is resistant to big bud mite (Mehlenbacher, 1994). In Oregon, it is prone to extreme biennial-bearing (Azarenko et al., 2005).

‘Negret’

Synonyms: ‘La Maso’, ‘Negreta’, ‘La Selva’, ‘Pobla de Mafume’

A cultivar of Spanish origin, ‘Negret’ has a small nut and kernel that blanches well. The tree is relatively small and compact. It is the main cultivar grown in the Tarragona area of Spain, where it grows well and produces good nut yields. The kernels are used in the confectionery trade. A higher-yielding clone (‘IRTA-N-9’) has been selected that is free of apple mosaic virus (Tous, 2005).

In Oregon, ‘Negret’ trees were of low vigour and produced nut yields lower than ‘Willamette’, ‘Barcelona’ and ‘Casina’. It produced a relatively high number of blank nuts, but gave a high crack-out of 55%. The kernels blanched perfectly (McCluskey et al., 1997). By contrast, in Croatia, ‘Negret’ was found to grow vigorously and was productive, giving nut yields similar to ‘Barcelona’ (Miljkovic and Prgomet, 1994). It was also reported to grow well and produce high yields in Chile (Grau, 2001). The number of blanks produced in Croatia was relatively high, similar to that reported in Oregon by McCluskey et al. (1997) but was lower in Chile (Grau, 2001).

‘Riccia di Talanico’

This cultivar was introduced into Australia in the 1990s by the Ferrero confectionery company. It originates from Italy, where it is grown in the Campania region. It has round, thin-shelled nuts with good sensory characteristics (Tombesi, 2005). ‘Riccia di Talanico’ did not become available for evaluation until the latter part of the field studies.

‘Royal’

Originating in Stayton, Oregon, E. Roy crossed ‘Barcelona’ and ‘Daviana’ to produce ‘Royal’. It was introduced into orchards in Oregon in 1934 by H.L. Pearcy of Salem. The nuts are large with thin shells and have colour and markings similar to ‘Daviana’. Nuts ripen about the same time as ‘Barcelona’. The tree is early into production and sheds pollen early to mid in the season. ‘Royal’ is susceptible to big bud mite (USDA, 2007).

‘Square Shield’

This Australian seedling selection was collected by Milan Paskas from old plantings in the Upper Ovens Valley of Victoria. ‘Square Shield’ is a small to medium-sized tree with a fairly erect growth habit and a medium-sized nut (Paskas, *pers. comm.*).

‘Segorbe’

This cultivar is of French origin. It is vigorous and hardy with a semi-erect growth habit. It is early into bearing and productive (Bergoughoux et al., 1978). Fruit clusters contain 3-4 nuts. The husk is about 30% longer than the nut. Nuts are sub-spherical and medium in size (18-20mm); they are relatively thick-shelled, light brown in colour with some banding. The kernel yield is 40-45%. Kernels have a thin pellicle but do not blanch readily. ‘Segorbe’ is grown in France as a polliniser for ‘Fertile de Coutard’ and for its kernels (Germain and Sarraquigne, 2004). It is relatively early into pollen shed and relatively late into female bloom. It is moderately susceptible to big bud mite.

‘TBC’ (‘Tokolyi Brownfield Cosford’)

While the origin of this genotype is unclear, it is probably an Australian seedling which was initially selected by Imre Tokolyi in Victoria (Tokolyi, N.D.). It was planted extensively in the Brownfield orchard at Acheron, Victoria. It is purported that subsequent selection was made in that orchard. The nuts are light brown, globular, with a small point. They have a corrugated shell and are slightly smaller than ‘Barcelona’. The kernels blanch quite well.

Scion wood from a ‘TBC’ tree at Orange was taken to Oregon by Professor Shawn Mehlenbacher, who subsequently determined its S-alleles. Observations by growers and studies by Cox (2010) suggest that ‘TBC’ is pollinated by the Australian seedling selections known as ‘Turkish Cosford’ and ‘Woodnut’. Professor Mehlenbacher (Pers. Comm., October 2006) reported that ‘TBC’ had moderate tolerance to big bud mite.

Although the name ‘Cosford’ was used by Tokolyi to name ‘TBC’, it is very different from the old English cultivar of that name. In the UK, ‘Cosford’ is also known as ‘Coxford’ and ‘Miss Young’s’, which was probably named after the ‘hundred’ of Cosford in Suffolk. True ‘Cosford’ nuts are elongated with a thin shell and are shed readily from the husks (USDA, 2007). Why Imre Tokolyi used the word ‘Cosford’ to describe this selection is not known.

‘Tonda di Giffoni’

This is an Italian cultivar that originated in the Campania region of Italy, north of Naples (Mehlenbacher, 1993). In Campania, it is the main cultivar in new plantations and shows a good adaptation to flat lands as well as to moderately hilly sites. Soils in this region were described by Tous et al. (1994) as being of volcanic origin, fertile and of neutral pH. The valuable characteristics if its fruit assure ‘Tonda di Giffoni’ the first place among the cultivars of Campania for utilization by the confectionery industry. The nuts are round and are described as being easy to shell. The kernel is almost spherical, often showing a pronounced groove (Bergoughoux et al., 1978). The kernel yield is approximately 46-48% (USDA, 2007). It was found to blanch well by Solar and Stampar (1997) and McCluskey et al. (1997).

‘Tonda di Giffoni’ is a strong-growing tree, described in the Italian literature as being “rustic”. It has relatively low chill requirements for catkins and vegetative buds and may be well-suited to areas with mild winters and lower chilling hours. It has moderately good tolerance to big bud mite (Solar and Stampar, 1997). Very good nut yields were obtained from this cultivar in Croatia (Solar and Stampar, 1997) and in Oregon, where nut yields were comparable with ‘Barcelona’, but the yield efficiency of the ‘Tonda di Giffoni’ trees was much higher than ‘Barcelona’ (McCluskey et al., 2001).

‘Tonda Romana’

Synonyms: ‘Tonda Gentile Romana’, ‘Tonda Gentile di Viterbo’

This cultivar originates from the Latium region of Italy, where it represents 85% of production (Tombesi, 2005). It is of weak-medium vigour, has an erect habit of growth and is of high productivity on the volcanic soils of the Monti Cimini area. The nuts are round with a thin shell and high crack-out, 44-48% (Bergoughoux et al., 1978). The kernels are small, roundish, do not readily blanch but are of excellent flavour (Tombesi, 2005).

In Oregon, ‘Tonda Romana’ trees were of medium vigour with nut yields about 50% less than ‘Barcelona’ but kernel quality was good, although they did not blanch (McCluskey et al., 1997). ‘Tonda Romana’ produced good yields in Chile with a high yield efficiency (Grau and Bastias, 2005).

‘Tonda Gentile delle Langhe’ (‘TGDL)’

Synonyms: ‘Ronde du Piemont’, ‘Tonda Gentile del Piemonte’

This is the predominant cultivar grown in the Piedmont region of north-western Italy (Tombesi, 2005). The term 'Tonda' means 'round', which is related to the shape of its small nut. Nuts fall freely from the husks and crack-out is high (45-52%). The kernels are relatively small and round; they blanch well and are highly prized in the European confectionery trade. ‘TGDL’ is very early in pollen shed and leafing out (Bergoughhoux et al., 1978).

Although this cultivar grew well in Chile in cultivar evaluation trials, its yield was very low (Grau and Bastias, 2005). In Oregon, it lacked vigour and produced low nut yields (McCluskey et al., 1997).

‘Tonollo’

This was reported as the highest-yielding genotype in the field assessment conducted at Glen Innes in northern NSW (Trimmer, 1965). Its origin is unknown but it is likely to be a seedling type and appears to be closely related to ‘Barcelona’. When Dr Maxine Thompson of OSU inspected the collection at Orange in 1981, she was of the opinion that it was of seedling origin.

There is an Italian variety known as ‘Tonnolella’ in the USDA germplasm collection but the limited data on that variety indicates that ‘Tonollo’ is very different and it is not simply a misspelling of ‘Tonnolella’. Professor Shawn Mehlenbacher of OSU also took scion wood of ‘Tonollo’ back to Oregon from Australia and subsequently determined its S alleles, which are the same as those of ‘Barcelona’.

‘Turkish Cosford’

As far as can be ascertained, this Australian seedling was selected by Imre Tokolyi as a polliniser for his ‘Tokolyi Cosford’ (Tokolyi, N.D.). The nuts are small but do not resemble those of ‘Cosford’. ‘Turkish Cosford’ produces numerous catkins and appears to be compatible with ‘TBC’ (Cox, 2010), although the S-alleles are unknown.

‘Victoria’

‘Victoria’ is probably an Australian seedling selection. It was found as a single tree at the Knoxfield Research Centre in Victoria and was named by officers of the Department of Agriculture (Bean and Kenez, 1991). It is a vigorous genotype that produces medium to large nuts. The kernels do not blanch.

‘Wanliss Pride’

Synonyms: ‘Wandils Pride’, ‘Simpson’s Pride’, ‘White American’

Although the origin of ‘Wanliss Pride’ is unclear, it appears to be very similar to the Turkish cultivar, ‘Kargalak’, (syn. ‘Imperial de Trebizonde’). Allen (1986) considered ‘Wanliss Pride’ to be a selection of ‘Imperial de Trebizonde’. It appears that the name ‘Wanliss Pride’ arose from the trees grown on the property of the Wanliss family at Wandiligong in north-east Victoria (Bean and Kenez, 1991).

‘Wanliss Pride’ grows as a straggly tree that is difficult to train into a single trunk, open-vase shape. It seems to grow better as a tree with 3 or 4 stems. It was the main cultivar grown in the Ovens Valley in the 1920s (Paskas, 1988). It produces an attractive large nut and a pleasant, sweet-flavoured kernel. Allen (1986) recorded it as a high-yielding cultivar that is pollinated by ‘White Avelline’ and ‘Cosford’. ‘Imperial de Trebizonde’, also has an irregular or straggly growth habit. The nuts are large and oval at the base, tapering sharply to a point (USDA, 2007).

Tokolyi (N.D.) had a selection that he named ‘White American’. It was “*early into leaf, with a light green husk and a pure white shell*” (presumably this was the immature nut). The nuts fell free from the husks. No data was provided by Tokolyi of the nut size or shape. However, Bean and Kenez (1991) described the nuts as being very similar to ‘Wanliss Pride’, and ‘Imperial de Trebizonde’.

‘White Avelline’

Synonyms: ‘White Filbert’, ‘Weisse Lamberts Nuss’, ‘Avelline Blanche’

‘White Avelline’ is a very old hazelnut cultivar, having been grown in Europe since the 1600s. It is an excellent polliniser and the catkins are abundant and hardy. Because the nuts are small and the tree is only moderately vigorous, the commercial value of the cultivar is doubtful. However, the cultivar is good for home gardens, due to the thin shell and high quality of the nut. The husk is pubescent and granular, twice as long as the nut and often split down 1 side. The nuts are found in clusters of 1 to 7 but more usually 3 to 4, are bluntly pointed, slightly grooved, dull brown, with an occasional faint stripe of darker brown. The base of the nut is bluntly pointed to round. The nuts are medium in size with a relatively thick shell. The kernel is long and regular, with a curved suture running from the base to the apex. ‘White Avelline’ is rated as having excellent flavour (USDA, 2007).

There is also a red-leaved type, known as ‘Red Avelline’, which, other than its red tints, has very similar characteristics to ‘White Avelline’. These cultivars are distinctly different from the old English cultivars of ‘Red Filbert’ (Syn. ‘Red Lambert’) and ‘Avelline d’Angleterre’.

‘Whiteheart’

‘Whiteheart’ is considered to have originated in New Zealand and to be related to the cultivar ‘Waterloo’, which was possibly introduced into that country from Europe. ‘Waterloo’ has round, thin-shelled nuts, with a high percentage crack-out and kernels that blanch well (USDA, 2007).

‘Whiteheart’ is widely planted in New Zealand for the production of high-quality kernels (McNeil, 1999). The average nut weight is 2.5-2.6 g/nut, the kernel yield is 47-48% and it blanches well. It is a small compact tree with relatively high nut yield efficiency under New Zealand conditions. It is very late in female bloom. ‘Lansing’ and the New Zealand cultivar ‘Alexandra’ are the most suitable pollinisers in New Zealand (ibid). ‘Whiteheart’ has round thin-shelled nuts and tends to bear its nut clusters on the ends of the branches. It is very sensitive to big bud mite. It was introduced into Australia from New Zealand in the late 1990s (McNeil, 1999).

‘Willamette’ (‘OSU 43-58’)

The cultivar was derived from a cross that was made in 1973, in the OSU breeding program, between ‘Montebello’ and ‘Compton’. ‘Montebello’ is a cultivar from Sicily and ‘Compton’ was a selection of O.C. Compton in Oregon. ‘Compton’ is considered to be a ‘Barcelona’ x ‘Daviana’ hybrid. ‘Willamette’ was selected in 1979 and tested as OSU 43-58. It was released as a named cultivar in 1990 (Mehlenbacher et al., 1991).

‘Willamette’ trees are vigorous, upright to spreading and similar in size and growth to ‘Barcelona’. Nut yields are slightly higher than ‘Barcelona’ (Mehlenbacher et al., 1991). The nuts of ‘Willamette’ are medium in size and dark brown, smaller than ‘Barcelona’. In cultivar trials, ‘Willamette’ has produced higher nut and kernel yields than ‘Barcelona’ (McCluskey et al., 1997). The nuts are attractive but not acceptable for in-shell sales because the fibre on the pellicle imparts a bitter taste to the kernel. The nuts have thin shells with a crack-out of about 50%. ‘Willamette’ matures 1 week later than ‘Barcelona’. The kernels of ‘Willamette’ blanch easily and are of excellent quality for use in pastries and confectionery. The husk is 50% longer than the nut. Nuts are not entirely free-falling. The trees are vigorous, productive, but have intermediate susceptible to big bud mite (USDA, 2007). ‘Willamette’ was introduced into Australia in 1990.

‘Willamette’ is now of lesser significance in Oregon since the release of ‘Lewis’ and ‘Clark’ (Mehlenbacher, 2005) and cultivars such as ‘Santiam’ and ‘Yamhill’ that have complete resistance to eastern filbert blight (McCluskey et al., 2009).

‘Woodnut’

It seems highly likely that this is an Australian seedling that originated in the Wandiligong area of Victoria (Bean and Kenez, 1991). ‘Woodnut’ is a relatively small tree that produces many catkins which shed pollen late in the season. It is considered to be a good polliniser for ‘TBC’, but its S-alleles are not known. It produces medium to large nuts that are light brown in colour. It has a characteristic husk that spreads out rather like a skirt. The kernels have little fibre but do not blanch.

Methods used for cultivar identification

As described in Chapter 3, Methods, Section 3.5 ‘Experimental design and cultivars’, a total of 26 hazelnut cultivars were evaluated for floral phenology, growth, nut yields and some aspects of kernel quality, with data on fruit characteristics also being obtained. Some additional cultivars were included in surrounding buffer rows as pollinisers; some phenological data was obtained on these as well as fruit, nut and kernel characteristics.

The cultivars included in the experiments were mainly named cultivars, of European and North American origin, but also included some Australian selections such as ‘Atlas’, ‘Tonollo’ and ‘Tokolyi Brownfield Cosford’ (‘TBC’). The planting material used for the experiments was obtained from a range of sources, including nursery propagators and individual growers, as explained in Chapter 3, Methods.

The USDA database uses a total of 40 descriptors, based on the evaluation system recommended by Thompson et al. (1987). It includes descriptors of growth and morphological, phenological and production characteristics. In this research, 16 of these key descriptors have been used, Table A1.1, to describe all the cultivars evaluated in the field experiments, including some additional cultivars that were planted in the rows surrounding the experimental plots. These descriptors have been placed in 2 broad groups. The first is based on morphological characteristics that are observed in the winter–spring period, along with phenological developments of anthesis and bud break. The second group are based on morphological traits of fruits, nuts and kernels that are observed in the summer. Observations of these key characteristics were recorded for the cultivars at all sites. The recorded indicators for the imported cultivars have been compared with the observations for the same cultivars in the USDA database to ascertain if they were true to cultivar name. Comparisons are shown in Tables A1.2 and A1.3. As descriptors were not available for all the imported cultivars, the “Narrative” on the cultivars has been used to try and develop the descriptors as well as to use the key characteristics given to ascertain trueness to cultivar name.

In addition, samples of fruits and nuts of all cultivars were sent to Professor Shawn Mehlenbacher, a hazelnut breeder at the Oregon State University, to obtain his opinion of whether they were true to name.

Descriptors for the Australian selections were also developed. These are shown in Tables A1.4 and A1.5 and are available so that Australian growers can compare data obtained from their own trees to assess the cultivars in their orchards. This information has been made available to growers through a report prepared for the Hazelnut Growers of Australia (HGA) using funds from Horticulture Australia Ltd. (Project NT04010, Baldwin, 2007).

Comments on the value of the descriptors and any difficulties encountered in their use are included in Table A1.1.

Table A.1.1 Characteristics used to describe cultivars and Australian seedling selections, based on those used for the USDA hazelnut germplasm collection.

Trait	**Ratings/descriptor**	**Comments**
Winter-spring observations of vegetative buds, flowering and leafing out		
Tree habit	1 (very upright) – 5 (very spreading)	Not very useful as the range for standard cultivars included in these studies were restricted to the 2-3 category
Tree vigour	1 (very weak) – 5 (very vigorous)	Observed bare trees in winter 'Negret' (3), 'Barcelona' (4)
Catkins – average number	Average number of catkins per cluster	Generally a range of 1-5, average taken over 10 bunches
Catkins – relative number	The relative number of catkins 1 (few) – 6 (many)	Assessed on dormant trees prior to pollen shed.
Dormant buds – size and shape	L (large), M (medium), S (small). P (pointed), R (round).	Difficult to be definitive about size as there was a gradation of sizes
Dormant buds – colour	BR (brown), GR (green), R (red), T (tan)	Tan is a golden or yellow brown
Staminate anthesis (Relative date of pollen shed)	1 (very early) – 9 (very late)	A relative measure, compared over a range of cultivars. It appeared to be a useful descriptor.
Pistillate anthesis (Relative date of female anthesis)	1 (very early) – 9 (very late)	A relative measure of the date of female flowering of cultivars. Also a useful descriptor.
Leafing out	Julian day of leafing out	Averaged over all seasons and sites
Summer - autumn observations of fruits, nuts and kernels		
Nuts per cluster	Average number of nuts per cluster	Generally a range such as 1-6, average taken over 10 clusters
Relative husk length	1 (short) – 9 (long)	Examples: Negret (3) and Du Chilly (8)
Average nut weight (g)	Average weight of nuts in grams	Average of 100 nuts, varies with seasons
Nut shape index	Length/width	Long nuts have a high ratio
Shell colour	DB (dark brown), LB (light brown), T (tan).	Colour of freshly-harvested nuts
Shell stripe	1 (inconspicuous) – 3 (pronounced)	Degree of striping on the nut shell
Percent kernel	Using 10 good kernels (Kernel wt/nut wt)	Range: 0.4 'Halls Giant' – 0.52 'Daviana'
Kernel fibre	1 (none) – 4 (high fibre)	Observed after cracking
Blanching	Removal of pellicle 1 (complete) – 7 (no pellicle removal)	Pellicle remaining after rubbing the kernels, following heating at 150°C for 20 minutes

Observations and measurements on tree habit, tree vigour, the relative number of catkins, the relative dates of pollen shed, female anthesis and leafing out, average nut weight (g), percent kernel, kernel fibre and blanching were made for all cultivars at all sites throughout the course of the study. Any plants that did not appear to have the general characteristics of the cultivar that was planted were noted as they were potentially not true to the cultivar being evaluated and could contribute to erroneous data.

In 2005, data was collected on the average number of catkins, the size, shape and colour of dormant buds, the number of nuts per cluster, the relative husk length, the nut shape index and the colour and striping on the nut shell, from the cultivars at the Orange, Myrtleford and Kettering sites.

All the data collected was collated and summarised to provide scores for the cultivars in the study, as described in *Crop descriptors for hazelnuts* under Hazelnut Genetic Resources at www.ars.usda.gov/Main/docshtm?docid=11305 . The data is presented in the next section.

Results and discussion

The observations on some floral characteristics and buds are shown in Table A1.2 for the imported cultivars included in the field experiments, compared with those in the USDA database. Some cultivars, such as 'Royal', are included in the *Corylus* germplasm repository at Corvallis but there is only general narrative available with no descriptors. In such cases, the general narrative has been used to produce the clonal descriptors in the tables. There were a few cultivars, such as 'Whiteheart', that are not in the repository at Corvallis; in those cases, ratings for characteristics have been constructed from other reference sources with notations below the table.

The day of the year (DOY) for leafing out is based on the average day at the study sites; a value of 180 days was added to the USDA (CGR-C) data for comparative purposes.

Table A.1.2 Observations of catkins, relative dates of pollen shed and bloom, dormant bud morphology and the date of leafing out for a range of imported cultivars grown at the study sites compared with observations for the same cultivars in the Corylus germplasm repository in Corvallis (CGR).

Cultivar	**Data source**	**Catkins**		**Relative date**		**Dormant buds**		**Leafing out (DOY)**
		Average number.	**Relative number**	**Pollen shed (1-9)**	**Female anthesis**	**Size and shape**	**Colour**	
‘Barcelona’	Obs.	3	3	3	4	MP	T	246
	CGR	3	3	3	4	-	-	250
‘Butler’	Obs.	3	2	4	7	MP	BR	266
	CGR	3	3-4	5	5	MR	BR	260
‘Casina’	Obs.	3	3	6	7	MR	GR	264
	CGR	3	5	6	6	MR	T	260
‘Daviana’	Obs.	2	3	6	7	M,P	GR	267
	CGR	3	2-3	6	7	-	-	275
‘Ennis’	Obs.	3	3	4	7	SP	GR	265
	CGR	4	5	5	7	MP	GR	268
‘Halls Giant’	Obs.	2	4	7	8	MP	R	270
	CGR	3	5	7	7	-	-	275
Jemtegaard 5	Aus	3	4	8	8	MR	GR	266
	Nar3			6-7	6-7			
‘Kentish Cob’ (‘Du Chilly’)	Obs.	2	2	6-7	7			270
	CGR	3	2	7	7	-	-	275
‘Lewis’	Obs.	3	3	5	5	SP	BR	242
	Nar4				4			
‘Montebello’ (‘Nocchione’)	Obs.		3	3	3	SR	GR	243
	Nar1 &2	3	4-5	3	3	SR	GR	250
‘Negret’	Obs.	2	2	5	4	MR	BR	256
	CGR	3	3-5	5	4	MR	BR	255
‘Royal’	Obs.	2	3	3	6	SP	BR	238
	Nar1			3	4-5	MR	GR	
‘Segorbe’	Obs.	3	3	3	6	SP	GR	260
	CGR	4	5	4	6	SP	GR	259
‘Tonda Gentile delle Langhe’	Obs.	2	2	1	3	SR	GR	233
	CGR	2	2	2	3	SR	GR	240
‘Tonda di Giffoni’	Obs.	2	3	3	3	MR	GR	232
	CGR	2	3-4	2	3	MR	GR	250
‘Tonda Romana’	Obs.	2	4	**2**	**3**	SR	BR	**242**
	CGR	2	3-5	**6**	**5**	-	BR	**252**
‘Wanliss Pride’ (‘Imperial de Trebizonde’)	Obs.	2	2	5	4	MP	BR	242
	CGR	-	3	4	4	-	-	-
‘White Avelline’	Obs.	2	2	6	7	LR	R	240
	Nar1							
‘Whiteheart’	Obs	2	2	7	9	LR	BR	260
	Nar2			6	9	R	GR	
‘Willamette’	Obs.	3	2	5	6	LR	BR	260
	Nar5	2	3	4	5	LR	BR	247

Source: CGR USDA, Agricultural Research Service, Hazelnut Clonal Germplasm Repository, Corvallis, GRIN database www.ars.usda.gov/Main/docshtm?docid=11305 .
Nar 1 Agricultural Research Service, Hazelnut Clonal Germplasm Repository – Corvallis
Nar 2 New Zealand Nutgrowers Association 2010 hazelnut.org.nz/variety/whiteheart.html
Nar3 Germain and Sarraquigne, 2004a
Nar4 Mehlenbacher et al, 2000
Nar5 Mehlenbacher et al, 1991

Table A.1.3 Observations of fruits, nuts and kernels for a range of imported cultivars compared with observations for the same cultivars in the USDA collection at Corvallis.

.	**Data source**	**Nuts per cluster**	**Rel. husk length**	**Av nut wt (g)**	**Nut shape index**	**Shell colour**	**Shell stripe**	**Kernel %**	**Kernel fibre (1-4)**	**Blanch (1-7)**
'Barcelona'	Aus	3	5	3.1	0.95	DB	2		3	3.6
	CGR	2-3	4-5	3.6	0.91	DB	pron		3	4
'Butler'	Aus	2	4	3.3	0.95	T	3		2	6.3
	CGR	3	3	NA	0.84	NA	NA		2	6
'Casina'	Aus	4	6	1.8	0.94	LB	1		1.5	5.7
	CGR	2-4	6	2.0	0.97	LB	2		NA	5
'Daviana'	Aus	2	5	2.8	1.1	LB	2		2	5.4
	CGR	1	6	3.2	0.7	LB	2		NA	7
'Ennis'	Aus	2	5	4	1.1	LB	pron		1.5	6.6
	CGR	2	4 - 5	4.3	0.87	LB	pron		NA	7
'Halls Giant' ('Merveille de Bollwiller')	Aus	3	6	3.4	1.0	LB	1		1.3	3.4
	CGR	2	4	3.6	0.85	LB	2		NA	4
'Jemtegaard 5'	Aus									
	Nar3	2-3	4	3.1				49	3	
'Kentish Cob' ('Du Chilly')	Aus									
	CGR	2	8	2.3				48	2	7
'Lewis'	Aus									
	Nar4			3.0				45		3
'Montebello' ('Nocchione')	Aus	NA	NA	2.9	0.92	DB	1		2.5	2.7
	Nar1& 2	3-4	4-5	3	1	GB	1	35-38	3	1-2
'Negret'	Aus	3	4	1.7	0.87	LB	1		2	1.7
	CGR	3	3	2.4	0.74	LB	2		NA	1
'Royal'	Obs.	2-4	5	3.9	1.2	T	3		4	4.5
	Nar1				1.1			M-H		
'Segorbe'	Aus	4	5	2.3	0.95	LB	2		1.7	4.5
	CGR	2-4	4	2.8	0.9	LB	2		NA	4
'Tonda Gentile delle Langhe'	Aus	3	4	2.1	0.99	T	2		2	3.2
	CGR	3	3	2.6	0.94	T	2		3	2
'Tonda di Giffoni'	Aus	4	5	2.6	0.9	LB	2		2	3.1
	CGR	4	4	3.1	1	LB	pron		2	1
'Tonda Romana'	Aus	4	4	3	0.99	LB	2		2	3
	CGR	2-4	6	3	0.95	LBr	pron	44-48	2	6
'Wanliss Pride'	Obs.	3-4	6	3.1	0.81	T	1		2	2
'Imperial de Trebizonde'	CGR	5	7	2.9				50	1	1
'White Avelline'	Obs.	5-6	7	2.3		Dull Br			1	
	Nar1	3-5	7			DullBr				
'Whiteheart'	Obs	3-5	6	1.9	0.99	DB	1		2	2.8
	Nar2	3-8	7		RD	B		47-50	1	1
'Willamette'	Obs.	3.5	6	2.5	1.0	LB	1		1	1
	Nar 5			2.8		B		50	1	1

Source: CGR USDA, Agricultural Research Service, Hazelnut Clonal Germplasm Repository, Corvallis, GRIN database www.ars.usda.gov/Main/docshtm?docid=11305 .

Nar 1 Agricultural Research Service, Hazelnut Clonal Germplasm Repository – Corvallis

Nar 2 New Zealand Nutgrowers Association 2010 hazelnut.org.nz/variety/whiteheart.html

Nar3 Germain and Sarraquigne, 2004a

Nar4 Mehlenbacher et al, 2000

Nar5 Mehlenbacher et al, 1991

It can be seen that all the imported cultivars had descriptors that generally matched either those from the Hazelnut Germplasm Repository in Corvallis or those obtained from other sources. However, the cultivar provided by Milan Paskas known as ‘Tonda Romana’, which had been imported by Baxter of the Victorian Department of Agriculture, did not match the descriptors of the ‘Tonda Romana’ in the Corvallis collection. The material provided by Paskas was earlier into pollen shed and female anthesis. It was also earlier into leaf. It had short husks with no pronounced stripe on the nuts. The shell was relatively thick with a relatively low kernel percentage and the kernels blanched more readily than the ‘Tonda Romana’ in the USDA collection. These variations gave a strong indication that the plants provided as ‘Tonda Romana’ were not that cultivar.

Samples of nuts of all the cultivars were sent to Professor Shawn Mehlenbacher, a hazelnut breeder at the Corvallis State University, his comments on the imported cultivars are given in Table A1.4 (Mehlenbacher, pers. comm., 18 July 2003).

Table A.1.4 Feedback on nut samples of imported cultivars from Myrtleford, inspected by Professor Shawn Mehlenbacher on 18 July 2003.

Cultivars	Comments
‘Barcelona’	OK
‘Butler’	OK
‘Casina’	OK
‘Daviana’	OK
‘Ennis’	OK
‘Hall's Giant’ and ‘Merveille de Bollwiller’	Both OK
‘Montebello’	OK
‘Negret’	OK
‘Royal’	OK
‘Segorbe’	Not sure. Shell colour, size and shape are similar but not quite identical to our ‘Segorbe’ but the difference may be due to climate or location. A comparison of husks would help.
‘Tonda di Giffoni’	OK
‘Tonda Gentile delle Langhe’	Initial sample - NO. This is ‘Montebello’ with a large apical scar. A subsequent sample was considered OK.
‘Tonda Romana’ Provided by Milan Paskas, imported by Baxter.	NO. This looks like ‘Montebello’. It is NOT ‘Tonda Romana’. This appears to be a Sicilian type, and thus closely related to ‘Montebello’. But the apical scar is very small, while that of ‘Montebello’ is large.
‘Willamette’	OK although nuts are small for this cultivar

The ‘Tonda Romana’ from Paskas was not considered to be true to type and could not be identified as a specific cultivar. As it could possibly have been of Sicilian origin, it was named “Sicilian type” in this thesis.

Professor Mehlenbacher also had some reservations about ‘Segorbe’ but a subsequent examination of husks and other plant characteristics indicated that this cultivar was true to name.

A subsequent importation of ‘Tonda Romana’ by Ferrero appeared to be true to cultivar name.

Australian selections

Observations on morphological, phenological and fruiting characteristics were recorded for the Australian cultivar selections. These are presented in Tables A1.5 and A1.6. Comparisons were made with the descriptors of cultivars in the Corvallis hazelnut germplasm repository that had similar names. However, apart from the ‘TBC’ and ‘Wanliss Pride’ which are in the repository, none of the selections matched the descriptors of any material in the collection.

Table A.1.5 Observations of catkins, relative dates of pollen shed and bloom, dormant buds and the average date of leafing-out for a range of Australian seedling selections.

Variety	Catkins		Relative date		Dormant buds		Leafing-out (JD)
	Average number	Relative number	Pollen shed	Bloom	Size and shape	Colour	
‘Atlas’	2	3	2	2	LR	BR	238
‘Eclipse’	3	3.	6	7	MP	GR	266
‘Hammond#17’	3	3	5	7	MP	GR	268
‘Square Shield’	3	4	6	7	MP	R	266
‘TBC’	3	5	5	6	MP	BR	261
‘Tonollo’	3	2	2	4	LR	BR	253
‘Victoria’	2.5	4	4	6	SP	GR	260
‘Wanliss Pride’	2	2	5	4	MP	BR	242
‘Woodnut’	2.5	4	8	8	MP	GR	266

Table A.1.6 Observations of fruits, nuts and kernels for a range of Australian seedling selections

	Nuts per cluster	Relative husk length	Av nut wt (g)	Nut shape index	Shell colour	Shell stripe	Kernel fibre	Blanching (1-7)
‘Atlas’	2.1	4	3.1	0.93	LB	1	3	4.1
‘Eclipse’	3.8	4	2.6	0.96	LB	1	2	3.5
‘Hammond#17’	2.4	4	3.3	1.1	T	3	2	5.5
‘Square Shield’	2.8	3	3.0	0.99	LB	1	2	5.1
‘TBC’	3.0	5	3.0	1.05	LB	2	3	3.3
‘Tonollo’	2.6	4	3.3	0.98	LB	1	3	3.8
‘Victoria’	5.6	4	3.0	1.06	T	2	2	5.3
‘Wanliss Pride’	3.2	6	3.1	0.81	T	1	2	2.7
‘Woodnut’	2.1	5	2.9	1.3	LB	2	1	7 (none)

Nuts of these selections were also sent to Professor Mehlenbacher, who commented that apart from the ‘TBC’ and ‘Wanliss Pride’, none of the nuts matched samples in the Corvallis collection (Table A1.7). Mehlenbacher’s comments (Mehlenbacher, pers comm. 18 July, 2003) on the Australian cultivars gives weight to the view that they are seedling selections and not true to cultivar name, as stated by Dr Maxine Thompson and reported by Bean and Kenez, (1991). The data collected on the descriptors of the imported cultivars and the Australian selections was used to prepare a booklet for hazelnut growers to aid in cultivar identification (Baldwin, 2007).

Table A.1.7 Feedback on nut samples of Australian selections from Myrtleford inspected by Professor Shawn Mehlenbacher on 18 July 2003

Australian selections	
‘Hammond #17’	I am not familiar with this one. It is similar to ‘Butler’, but is probably a seedling of some sort.
‘Victoria’	Appears to have a big problem with poorly-filled nuts
‘Wanliss Pride’ and ‘TBC’	Same as our trees in Corvallis
‘Atlas’, ‘Eclipse’, ‘Square Shield’, ‘Tonollo’	Local Australian cultivars and others for which I have no nut samples, and so cannot determine trueness-to-name.

Discussion and Conclusions

Apart from the ‘Tonda Romana’ provided by Paskas from a collection by Baxter, all the imported cultivars assessed in this study were considered to be true to cultivar name. However, some individual trees in the field were not true to type, due to some planting errors and failure of some grafted material. When errors were noted, the data from those incorrect trees was not used. As the research progressed, the author became more proficient in recognising the traits of the cultivars and more able to identify any errors in the cultivar treatments.

Although morphological and phenological data was used in this study to assess whether the cultivars were true to name, it is recognised that biochemical tests can be used for the genetic identification of hazelnuts. The visual tests were chosen in this instance for reasons of lower cost and to provide a tool that growers could also use to identify their own cultivars.

APPENDIX B - SITE PLANS

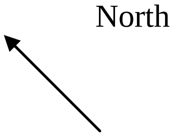
Orange site

Initial plantings, July 1995

Layout: 4 replicates, each with 4 rows of trees and 4 treatment plots (cultivars) within each row consisting of 4 trees per plot.

The borders of replicates are shown in red.

The rows were at 5 m spacing with trees 3 m apart in the rows.



Original planting plan

	8	7	6	5	4	3	2	1	
		REP 1				**REP 2**			
M.de Bollwiller	Daviana	TBC	TBC	Daviana	TBC	Daviana	TBC	Royal	Wanliss Pride
Mon W. P Victoria Daviana TBC	Hall's Giant	Ennis	Casina**	Wanliss Pride	Atlas	Square Shield**	Casina**	Negret** /Willamette	Tonollo Royal Red Avelline F. de Coutarde
M.de Bollwiller Royal Daviana Werai 2	Tonda di Giffoni	Barcelona	Atlas	Segorbe	Tonda Romana	Wanliss Pride	T.G.D.L. (Lewis)	Segorbe	Victoria M de Bollwiller Daviana Jemtegaard. 5
Mon. W. P. F. de Coutarde Victoria N. E Barc	TBC	Victoria	Negret** /Willamette	Tonda Romana	Hall's Giant	TBC	Tonda di Giffoni	Eclipse	Mon. WP F. de Coutarde Jemteg. 5 White Aveline
Daviana F. de Coutarde White Aveline Daviana	Eclipse	Butler	Square Shield**	T.G.D.L. (Lewis)	Butler	Barcelona	Victoria	Ennis	Daviana F. de Coutarde Victoria M de Bollwiller
Mon. W.P. M.de Bollwiller F. de Coutarde Victoria	Barcelona	Casina**	Eclipse	Tonda Romana	Victoria	Atlas	Wanliss Pride	Eclipse	Mon. W. P. Werai 2 F. de Coutarde Victoria
Werai 1 Daviana F. de Coutarde TBC	Atlas	Ennis	T.G.D.L. (Lewis)	TBC	Square Shield**	Ennis	Tonda di Giffoni	Tonda Romana	White Aveline Daviana F. de Coutarde Werai 1
Mon. W. P Royal White Aveline Daviana	Segorbe	Hall's Giant	Square Shield**	Victoria	Segorbe	TBC	Butler	Casina**	Mon W P N.E. Barc. White Aveline Daviana
F. de Coutarde Daviana M.de Bollwiller Victoria	Tonda di Giffoni	Wanliss Pride	Butler	Negret** /Willamette	Hall's Giant	T.G.D.L. (Lewis)	Negret** /Willamette	Barcelona	F. de Coutarde Victoria Casina Woodnut
Red Avelline	Butler	Woodnut	Kentish Cob	Hammond 17	Butler	Red Avelline	Woodnut	Butler**	Royal
		REP 3				**REP 4**			

Notes: A cultivar known as 'Tonda Romana' was planted at all sites. It was not true to type and was later considered to be a "Sicilian type" and named thus throughout the thesis. The plants of 'Negret' and 'TGDL', that were planted initially, failed to develop. The middle 2 plants in each treatment of these 2 cultivars were removed and replaced with 'Willamette' and 'Lewis', respectively.

Moss Vale

Initial plantings July 1996

Layout: 4 replicates, each with 4 rows of trees and 3 treatment plots (cultivars) within each row consisting of 2 trees per plot.

The borders of replicates are shown in red.

→ North

The rows were at 5 m spacing with trees 3 m apart in the rows.

Original planting plan

		REP 1				**REP 2**			
Rows	1	2	3	4	5	6	7	8	
Atlas	TBC	Negret	TBC	W.Avelline	TBC	Daviana	TBC	Butler	Waterloo
Daviana Turk Cos	Barcelona	T. di Giffoni	W. Pride	T. Romana (Sicilian type)	Royal	Atlas	Barcelona	Casina**	Werai 1 TBC
Woodnut TBC	Segorbe	Halls Giant	Atlas	Ennis	Ennis	T. di Giffoni	W. Pride	Segorbe	W. Avelline TBC
MonbulkWP Barcelona	Casina**	Royal	Victoria	TBC	Halls Giant	TBC	T. Romana (Sicilian type)	Victoria	MonbulkWP Barcelona
W. Avelline Barcelona	Royal	Casina**	Halls Giant	W. Pride	Segorbe	T. Romana (Sicilian type)	Ennis	Royal	Werai 2 Barcelona
Daviana Barcelona	Barcelona	Ennis	TBC	T. di Giffoni	Casina**	Victoria	T. di Giffoni	Atlas	Paskas Late Barcelona
Negret* Atlas	Victoria	Atlas	Segorbe	T. Romana (Sicilian type)	Barcelona	Halls Giant	W. Pride	TBC	Woodnut Butler
Waterloo	Butler	Woodnut	W. Avelline	TBC	Turkish Cos	TBC	Werai 1	TBC	Tonollo
		REP 3				**REP 4**			

Notes:

- *'Monbulk WP' ('Wanliss Pride'). Source: Monbulk Nurseries, Victoria. It was not discernible from any other source of 'Wanliss Pride'*
- *** grafted trees*
- *The cultivar shown as 'Tonda Romana' was not true to type and was considered to be a "Sicilian type".*

Myrtleford

Initial plantings July 1996

Layout: 4 replicates, each with 6 rows of trees and 4 treatment plots (cultivars) within each row consisting of 2 trees per plot.

The borders of replicates are shown in red.

The rows were at 5 m spacing with trees 3 m apart in the rows.

Original planting plan

				REP 1						REP 2			
Rows	1	2	3	4	5	6	7	8	9	10	11	12	
TBC	Atlas	TBC	Atlas	TBC	Atlas	TBC	Atlas	TBC	Atlas	TBC	Atlas	TBC	TBC
W. Avelline	Woodnut	Werai II	TBC	W. Avelline	TBC	W. Avelline	Woodnut	W. Avelline	L d'Espagne	W. Avelline	TBC	W. Avelline	Woodnut
Wanliss Pride Werai II	Tonollo	Tond di Giffoni	Merveille de Bollwiller	Hamm. 17**	Butler**	Montebello	TBC	TGDL	Sq Shield**	Casina**	Hall's Giant*	Montebello	Werai II Wanliss Pride
Wanliss Pride Werai I	Ennis** (Willamette)	Victoria	Eclipse**	Negret*	Ennis	Atlas	Hamm. 17*	Ennis	Segorbe	Butler**	Victoria	Negret*	W. Avelline Wanliss Pride
Woodnut W. Avelline	Segorbe	Casina**	American White (Lewis)	TBC	Barcelona	Hall's Giant*	Atlas	Daviana*	Tonollo	Wanliss Pride	Tonda Romana	Tond di Giffoni	Werai I Woodnut
Wanliss Pride Werai II	Tonda Romana	T.G.D.L.	Royal	Daviana	Wanliss Pride	Sq. Shield**	Merveille de Bollwiller	Barcelona	American White (Lewis)	Ennis** (Willamette)	Royal	Eclipse**	W. Avelline Wanliss Pride
Wanliss Pride Werai I	Daviana	Segorbe	Barcelona	Eclipse**	Hall's Giant*	Butler**	Montebello	Tonollo	Hamm. 17**	Daviana	Merveille de Bollwiller	Segorbe	Werai II N.E. Barc
Woodnut W. Avelline	Montebello	Hamm. 17**	Casina**	Ennis** (Willamette)	Merveille de Bollwiller	T.GD.L.	Casina**	TBC	Wanliss Pride	Victoria	Sq Shield**	Negret*	Werai I Woodnut
Wanliss Pride Werai II	Royal	Sq. Shield**	Tonda Romana	Negret*	American White (Lewis)	Victoria	Royal	Hall's Giant*	American White (Lewis)	Atlas	Barcelona	TGDL	W. Avelline Wanliss Pride
Wanliss Pride W. Avelline	Atlas	Tonollo	Ennis	Wanliss Pride	Tond di Giffoni	TBC	Ennis	Ennis** (Willamette)	Tonda Romana	Eclipse**	Butler**	Tond di Giffoni	W. Avelline Werai I
Woodnut	L d'Espagne	W. Pride	R. Avelline	W. Pride	L d'Espagne	W. Pride	R. Avelline	W. Pride	L d'Espagne	W. Pride	R. Avelline	W. Pride	L d'Espagne
TBC	Hamm. 4**	Hamm. 4**	W. Pride (M)	R. Avelline	W Pride (M)	R Avelline	W Pride (M)	R. Avelline	W. Pride (M)	R Avelline	W Pride (M)	W Pride (M)	unknown
				REP 3						REP 4			

Notes:

- *** grafted and girdled trees*
- *The graft on some 'TGDL' failed; the rootstock produced a small tree that produced a heavy crop of nuts with relatively thick shells. It became known as a Damn Fine Tree (DFT)!*
- *A cultivar known as 'Tonda Romana' was planted at all sites. It was not true to type and was considered to be a "Sicilian type". It is shown on the plan as 'Sicilian'.*
- *'Willamette' was planted in 1999 it replaced grafted Ennis' trees*
- *'Lewis' was planted in 2001; it replaced 'American White' which appeared to be identical to 'Wanliss Pride'.*

Toolangi

Initial plantings July 1995

Layout: 4 replicates, each with 4 rows of trees and 4 treatment plots (cultivars) within each row consisting of 4 trees per plot.

The borders of replicates are shown in red.

The rows were at 5 m spacing with trees 3 m apart within the rows.

Original planting plan

	REP 1				**REP 2**				→N
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Atlas	Woodnut	Butler	Werai 1	2 - 1	W. Avelline	N.E. Barcelona	Red Avelline	F. de Coutarde	Atlas
W. Avellline	Barcelona	Negret	T.G.D.L.	Hall's Giant	Negret	Butler	W. Pride	Victoria	Butler
F. de Coutarde									Woodnut
W. Aveline									W. Avelline
W. Pride									W. Pride
TBC	Casina	Butler	TBC	Segorbe	T. di Giffoni	Sq. Shield	Hall's Giant	Segorbe	TBC
F. de Coutarde									F de C
W. Avellline									Red Avelline
Daviana									Daviana
W. Pride	T. Romana	Victoria	Ennis	Sq. Shield	TBC	T.G.D.L.	Ennis	Atlas	W. Pride
F. de Coutarde									F de C
W. Pride									W. Pride
Red.Avelline									Red Avelline
W. Avellline	Eclipse	W. Pride	Atlas	T. di Giffoni	T. Romana	Eclipse	Casina	Barcelona	W. Avelline
W. Pride									W.Pride
TBC									TBC
F. de Coutarde									F de C
R .Aveline	Ennis	T. di Giffoni	Barcelona	Butler	T.G.D.L.	Sq. Shield	Butler	Eclipse	Red Avelline
Daviana									Dav
F. de Coutarde									F de C
Werai 1									Werai1
TBC	Eclipse	Victoria	TBC	Hall's Giant	T. Romana	Negret	T. di Giffoni	TBC	TBC
F. de Coutarde									F de C
Red.Avelline									Red Avelline
W. Pride									W. Pride
F. de Coutarde	Segorbe	T.G.D.L.	W. Pride	T. Romana	Segorbe	Atlas	Barcelona	Victoria	F de C
W. Pride									W. Avelline
Daviana									Royal
F. de Coutarde									F de Coutarde
TBC	Negret	Casina	Sq. Shield	Atlas	W. Pride	Casina	Ennis	Hall's Giant	TBC
Red Avelline									Red Avelline
W. Pride									W. Pride
W. Avellline									W. Avelline
F. de Coutarde	Werai 1	F. de Coutarde	Daviana	Red Avelline	?	W. Pride	F. de Coutarde	N.E. Barcelona	F de C
GATE			**REP 3**			**REP 4**			

Notes:

‘Butler’, ‘Casina’, ‘Negret’, ‘Tonda di Giffoni’ and ‘Victoria’ were planted in 1996

Kettering

Initial plantings July 1999

Layout: 3 replicates, each with 4 rows of trees and 5 treatment plots (cultivars) within each row consisting of 2 trees per plot.

The borders of replicates are shown in red.

North
→

The rows were at 5 m spacing with trees 3 m apart within the rows.

Original planting plan

REP 1				REP 2				REP 3			
Rows 1	2	3	4	5	6	7	8	9	10	11	12
Ennis	Tonda Romana (Sicillian)	Merveille de Bollwiller	Hammond. 17	Segorbe	Barcelona	TBC	Lewis	T.G.D.L.	Butler	Whiteheart	Victoria
T.G.D.L.	Tonda di Giffoni	Segorbe	Montebello	Willamette	Casina	Merveille de Bollwiller	Butler	Square Shield	Eclipse	Hammond. 17	Wanliss Pride
Eclipse	Willamette	Square Shield	TBC	Hammond. 17	Victoria	T.G.D.L.	Tonda Romana (Sicillian)	Royal	Tonda di Giffoni	Casina	Segorbe
Royal	Wanliss Pride	Barcelona	Butler	Ennis	Eclipse	Whiteheart	Square Shield	Lewis	Montebello	Tonda Romana (Sicillian)	TBC
Whiteheart	Casina	Lewis	Victoria	Royal	Montebello	Wanliss Pride	Tonda di Giffoni	Ennis	Merveille de Bollwiller	Barcelona	Willamette

Notes:
'Segorbe' and 'Whiteheart' were planted in 2000

APPENDIX C

Manganese Sand Culture Experiment

Objective

The sand culture nutrition experiment was designed to test the hypothesis that hazelnuts could be sensitive to manganese and that there could be a difference in cultivar tolerance.

Methods

Six (6) levels of Mn solution: 0, 0.5, 2, 5, 20 and 50 ppm
Two (2) cultivars of *Corylus avellana*: ‘Wanliss Pride’ and ‘Barcelona’
A factorial design was used, ie 12 treatments, with 2 replicates, giving a total of 24 treatments.

Twenty four (24) plastic tubs measuring 430 mm diameter and 310 mm height with a capacity of 40L had four (4) holes of 5 mm diameter drilled in their base for drainage. Dormant hazelnut plants of the cultivars ‘Barcelona’ and ‘Wanliss Pride’ were planted in these on 13 September 2004. The tubs were filled with washed river sand to within 5 cm of their tops. The tubs were watered and kept moist. Bud burst occurred about 19 September. On 5 October, when the trees were at the early leafing stage 2L/pot of a nutrient solution prepared from Manutec ® Hydroponic Nutrient for Flowers and Vegetables, was applied at half strength. Subsequent applications were at the full strength and given at weekly intervals. The levels of nutrients in the recommended rate for full strength are given in Table 1.

Table C1. Levels of nutrients (ppm) in the Manutec® Hydroponic Nutrient mix for flowers and vegetables at the recommended full strength of 200g/100 L water compared with Long Ashton Standard Nutrient Solution for fruit trees.

	Manutec® solution (Full strength) ppm	Long Ashton Standard Nutrient Solution(1) (ppm).
Nitrogen	215	168
Phosphorus	37	41
Potassium	218	156
Calcium	152	160
Sulphur	54	48
Magnesium	42	36
Sodium	N/A	31
Iron	4	5.6
Manganese	0.96	0.6
Copper	0.36	0.06
Zinc	0.48	0.07
Boron	0.04	0.5
Molybdenum	0.01	0.05

Notes (1) Hewitt, E.J. 1966, Chapter 22, Tables 40 and 41.

Manganese treatments

Manganese sulphate ($MnSO_4.H_2O$), purity 99%

$MnSO_4$ MW=169, MW Mn=55

Therefore 154 g of contains 50g Mn

154 g $MnSO_4$ in 1000 L water = 50 ppm Mn

Equivalent to 0.77g in 5 L water

Preparation of Mn solutions:

A solution 50 ppm was prepared with lower levels of Mn derived by dilution
50 ppm = 0.77g $MnSO_4$ in 5 L water
5 ppm Mn = 1 L of 50 ppm mixed with 9 L water
0.5 ppm Mn = 1 L of 5 ppm mixed with 9 L water

20 ppm = 0.31g $MnSO_4$ in 5 L water
2 ppm = 1 L of 20 ppm mixed with 9 L water

Applied 1 L of each solution per tub weekly from early November

Sulphur

Additional sulphur (S) = 14% $MnSO_4$

50 ppm Mn concentration supplied an additional 2 ppm of S, cv 54 ppm in Manutec solution.