CHAPTER 3

CROP ADAPTATION

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INTRODUCTION

Distribution of commercial crop production throughout the world is governed by many factors, with the main ones being climate, soils, topography, insect pressure, plant disease and economic conditions. In Australia, as in most developed countries, segregation of crop types into particular production areas is largely governed by profit motives, the profitability of specific crops reflecting their adaptation and hence ability to grow and produce moderate to high yields of acceptable quality in those areas. Crop adaptation is determined primarily by genotype-environment interaction, the suitability of a crop to a particular region depending largely on the climatic features of the region in relation to the requirements for normal growth and development of the crop.

Accepting climate as a dominant factor governing crop distribution, this chapter examines the distribution of commercial crop production in relation to environment in Australia, with emphasis on the climatic and physiological factors that confine the major crop species to current production areas.

ADAPTATION

Adaptation of crop plants depends on many factors, and is best considered in relation to a set of conditions (environmental, edaphic (soil) and biotic) rather than to a single factor alone. In many situations, one factor (e.g. water availability) may dominate the prevailing conditions, and the nature of the plant's response then largely reflects its adaptation to the existing level of that factor. More typically, adaptation is expressed as a response to a combination of factors (e.g. temperature and daylength) and the nature of the response then reflects the plant's adaptation to the factors in combination. Success of a plant in a particular environment rarely depends on possession of a single adaptive character. Rather, fitness or adaptation to an environment depends on possession of an optimum combination of characters that minimises the deleterious effects and maximises the advantageous effects. The task of plant breeders is thus difficult and complex, as they generally have to develop genotypes with an optimum combination of adaptive characters, rather than ones with a single adaptive character (Evans, 1996). Whatever the growing conditions, the important consideration is the nature of the adaptive plant response itself and, for commercial purposes, the consequences of that response in terms of the economic output of the crop. For example, a plant that grows well under a given set of conditions, but fails to flower and set seed, is of little value as a grain crop in that situation. It may, however, be an excellent forage crop under those conditions, as the economic product (leaves and stems) is not dependent on flowering and seed set.

Adaptation was described by Wilsie (1962) thus: 'an adaptation may be defined as any feature of an organism which has survival value under the existing conditions of its habitat. Such a feature or features may allow the plant to make fuller use of the nutrients, water, temperature or light, available, or may give protection against adverse factors such as temperature extremes, water stress, disease or insect pressures'. The concept of adaptation can be difficult to define, as it is used in respect to both the evolutionary origins of a character *and* its contribution to the fitness of the plant to survive in its present environment. Adaptation is also heritable, i.e. it is determined by the genotype of the plant. Hence the definition can be refined to 'the *heritable* modifications to a plant which enable it to survive, reproduce, or both, in a given environment' (Kramer, 1980). Reproduction, as well as survival, is a critical consideration in the commercial production of seed (grain) crops, as their economic product results from successful completion of the reproductive phase of their life cycles. In these crops, completion of *all* phases of *development* is fundamental to economic performance. In other crops such as sugar cane or forages, where the economic product is biomass (plant dry matter) that results from vegetative growth, *development* is a less important consideration than *growth*. The concepts of growth and development are important to an understanding of plant adaptation and are discussed below.

Acclimation

In contrast to adaptation, acclimation (or hardening) is the *non-heritable* modification of plant characters caused by exposure to new environmental conditions such as warmer or drier weather. It results from temporary modifications to the plant phenotype caused by the changing environment. Generally, plants subjected to several cycles of mild water or low temperature stress suffer less injury from subsequent drought or very low temperature exposure than plants which have not been previously stressed (Kramer, 1980).

Growth

Growth is the increase in plant biomass (dry matter) over time. About 95% of biomass is the net result of photosynthetic gains and respiratory losses, with the remaining 5% derived from nutrient uptake. Growth is affected by the supply and level of availability of all factors that are essential to normal plant metabolism and function. The major factors are:

- water
- nutrient elements
- light (the visible component of incoming solar radiation – it includes the red and blue wavelengths which provide energy for photosynthesis)
- gases, particularly carbon dioxide (CO_2) for photosynthesis and oxygen (O_2) for respiration.

All of these are usually in finite supply and are frequently the subject of competition between plants or species in a community. Competition will be discussed in more detail in the next section of this chapter.

Temperature is an important factor affecting, and in many cases controlling, plant growth. While the concept of a limited supply does not apply to temperature (i.e. plants do not compete for it), the thermal environment in which a plant is grown has significant effects on growth rate and dry matter yield. Adaptation to temperature is a major factor governing the natural distribution of plants, and is a principal determinant in the selection of crop species for commercial production throughout the world.

Plant adaptation and response to temperature is usually described in terms of so-called Cardinal Temperatures for growth. Cardinal temperatures for any species are:

- a Minimum, below which growth will not occur and above which growth rate will rise with temperature, to

- an Optimum, at which growth rate is maximal, and above which growth rate will decline with increasing temperature, to
- a Maximum, at which growth will cease.

Cardinal temperature ranges for the major plant groups are outlined in Table 3.1.

Table 3.1. Cardinal temperature ranges (^{o}C) for temperate species, tropical legumes, and tropical grasses (adapted from Crofts *et al.,* (1963) and Fitzpatrick and Nix, (1975)).

Adaptation	Minimum	Optimum	Maximum
Temperate species	1 – 3	18 – 22	32 – 35
Tropical legumes	10 – 12	27 – 32	36 – 41
Tropical grasses	12 – 15	37 – 43	50 – 55

DEVELOPMENT

Development is the progression of a plant through the successive stages of its normal life cycle. The life cycle is best considered in two main phases, *Vegetative* and *Reproductive*, each of which includes one or more stages:

Vegetative

- Establishment – seed germination, emergence and, ultimately, independence of seed reserves.
- Vegetative growth – initiation, development and expansion of leaves, stems and roots.

Reproductive

- Floral initiation – the transition of stem apices (growing points) from vegetative (producing leaf and stem primordia [buds]) to reproductive (producing inflorescence structures and floral primordia).
- Flowering and pollination (anthesis), resulting in fertilised ovules which will develop into seeds (grains).
- Seed growth (grain filling) to a maximum wet weight at physiological maturity.
- Seed (grain) maturation – grain dries naturally to a moisture content suitable for harvesting and storage.
- Harvest ripeness – dry (12-14% moisture) grain ready for harvest.

Reproductive development in plants is controlled more by regulatory than by assimilatory processes. The consequences of this are that reproductive development can proceed relatively independently of growth, and can be modified by selection more readily than growth. In many cases, the adaptation of crops to harsher environments has depended more on changes in the length and timing of their life cycles - allowing them to escape the most adverse conditions - than on changes in their ability to tolerate such environments. In contrast to those for growth, the external governing factors for development are principally environmental, with daylength and temperature the most important. As the most regular and predictable component of climate, daylength is the most potent and universal controlling element in the timing of life cycles of both wild and cultivated plants, and the modification of their responses to daylength has been a major factor in the spread and adaptation of many crop plants (Evans, 1996).

Daylength

The physiological response of plants to the relative lengths of the diurnal cycles of light (daylength) and dark periods is called *Photoperiodism*. The most fundamental aspect of this response is the transition from vegetative to reproductive phase in photoperiod sensitive plants, which includes most modern day crop species. Depending on their adaptation, photoperiod sensitive species are induced to progress from vegetative to reproductive phase when subjected to certain critical daylengths. Most species of tropical or subtropical adaptation are classed as Short Day (SD) plants – they grow vegetatively through the long days of late-spring/summer/early-autumn, and undergo floral initiation when autumn daylength *declines* to a certain critical value. In contrast, most species of temperate adaptation are described as Long Day (LD) plants. Their vegetative phase occurs during the short-day late-autumn/winter/early-spring period, floral initiation occurring when spring daylength *increases* to a certain critical value. In a third major group, floral initiation occurs after a certain period of vegetative growth has been completed, regardless of daylength. Plants in this photoperiod-insensitive group are described as Day Neutral (DN).

Daylength variation at any location depends on its latitude. Daylength increases with increasing latitude in summer, from 12 hours at the Equator to 24 at the Pole. In winter, it decreases with increasing latitude, from 12 hours at the Equator to zero at the Pole. Hence higher latitude locations experience greater daylength variation through the year than those in the Equatorial zone - daylength at the Equator itself remains constant at 12 hours throughout the year. The effects of latitude on daylength are shown in Table 3.2.

Over the last 50 years, plant breeders have consistently strived to develop improved cultivars of the major crop species by reducing their dependence on daylength to initiate the reproductive phase. Their aim has been to increase flexibility in the length of the crop life cycle and thus extend the optional range for sowing time. This has been an important strategy in the development of better adapted cultivars for rainfed crop production in Australia, where unreliable rainfall, (either too low or too high), often delays sowing. Development of modern crop plants has seen the manipulation of the processes regulating reproductive development by selection and breeding, with sensitivity to daylength being considerably reduced or muted in some, and even enhanced in others. Although floral initiation is often the most sensitive stage, all stages may respond to daylength, and in some cases such as grain legumes, the later stages of grain filling may be the most sensitive (Evans, 1996). Although emphasis in crop breeding programs has been on the advantages of daylength neutrality, Evans considered that sensitivity still has an important role to play in predictably adverse environments.

Table 3.2 Duration of daylength (length of astronomical day in hours [h] and minutes[m]) at selected latitudes in Australia. (Adapted from Gentilli, 1971, based on data from *Astronomical Ephemeris*, HMSO, London).

	Season (Southern Hemisphere)							
	Autumn March		Winter June		Spring September		Summer December	
Latitude (^{o}S)	h	m	h	m	h	m	h	m
10	12	08	11	33	12	07	12	42
20	12	08	10	55	12	07	13	20

30	12	10	10	13	12	08	14	04
40	12	12	9	20	12	09	15	01

Temperature

Thermoperiodism Some temperate crop species, particularly the cereals (wheat, oats, barley, rye and triticale) and brassicas (canola, rape) have both ‘winter’ and ‘spring’ types. Winter types require a period of exposure to very low temperatures (0-2^{o}C) before they can respond to increasing spring daylength. In Europe, Canada and the USA they are planted in autumn, remain dormant through an intensely cold winter, often under snow, then undergo floral initiation as days lengthen in spring. True winter types will not respond to daylength until the cold requirement has been met. It can also be met by subjecting pre-soaked, germinating seeds to an intense cold period (e.g. 21 days at 1^{o}C), a process known as *vernalisation*. Spring types, in contrast, exhibit no cold requirement and varying degrees of LD requirement for floral initiation. Modified winter wheats have found a place as grazing and grain crops in southern Australia, but apart from those, practically all Australian temperate crops are spring types that are shorter season and lower yielding than their winter counterparts. Winter types are generally too late maturing for successful grain production in the water limited conditions of late-spring/early-summer in Australian production areas.

Heat units. The lengths of the vegetative and reproductive phases in DN species are temperature dependent, being shorter when conditions are warm to hot and longer when it is cold. For example, in Gabo, a photoperiod insensitive wheat cultivar, development from planting to anthesis took 8 and 20 weeks respectively when planted in relatively warm (Queensland) and cold (Victoria) environments (Nix, 1975). Base (Minimum) temperatures for temperate (e.g. wheat) and tropical (e.g. maize) species are around 2 and 10^{o}C respectively. To complete each phase or stage of development requires the accumulation of a certain total number of ‘heat units’ – the warmer the environment, the more rapidly the units are accumulated and the plant progresses to the next developmental phase or stage. The standard heat unit expression is degree days (^{o}D), which are calculated for each day as the average temperature minus the base temperature for the species or cultivar. For example, a day with an average temperature of 16^{o}C would count as 14^{o}D for wheat and 6^{o}D for maize. Total ^{o}D for any period is calculated as the sum of daily ^{o}D for all days in the period. A variation on this approach has been used successfully for winter crop management in southern Australia by French (1996) using ^{o}D summations based on daily maximum, rather than average, temperature.

Once floral initiation has occurred, plants in all groups will then progress through the successive stages of the reproductive phase to maturity, provided they are not disrupted by adverse weather, pest and disease conditions. The rate of progress from floral initiation to maturity depends on subsequent temperature and daylength conditions. At high temperatures, individual stages will progress rapidly and be of short duration, leading to early maturity and usually lower grain yield, because the grain filling period has been shortened. In some crop plants, such as soybeans and many of the grain legumes, development after floral initiation is particularly sensitive to daylength as well as to temperature.

Competition

The concept of competition is fundamental to an understanding of adaptation, particularly with crop plants that are grown in moderate to high density monocultures. Here, competition for one or more factors almost always limits growth and yield in Australian rainfed (dryland) production systems. The outcomes of competition illustrate the relative adaptation of competing plants in optimising their capture or use of essential factors for growth that are in limited supply. Plants compete only for factors that are necessary for growth – *not development* - and that are available to the plant community from a finite pool or supply. The occurrence and intensity of competition for any factor is determined by the amount of the factor available *and* the number of plants competing for it.

Competition arises in plant communities '*when the supply of a single necessary factor for plant growth falls below the combined needs of the plant and its neighbours (competitors)'* (Donald, 1963). It does not occur when the available pool of each factor exceeds the total needs of the plant community. Much of the following brief overview of competition is drawn from the landmark review of the subject by Donald in 1963, to which the reader is referred for further information.

At community level, competition may be *interspecific* (between plants of different species, for example weeds in a crop) or *intraspecific* (between plants of the same species, for example neighbouring crop plants). The outcomes of *interspecific* competition reflect the differences in relative competitive ability between the species present for the factor in limited supply, and one species will eventually dominate the other(s). In contrast, where *intraspecific* competition occurs, all plants are of similar competitive ability and are affected equally, and at about the same time. At individual plant level, competition may be *interplant* (between different, neighbouring plants) or *intraplant* (between different parts of the same plant).

Factors for which plants compete

The main factors are:

- water
- nutrients
- light (solar radiation)
- gases (carbon dioxide [CO_2] and oxygen [O_2])

Competition for water Adaptation to water limited conditions reflects the ability of the plant to either access and use limited available water at the expense of its competitors, or to limit transpiration water loss better than its competitors, or both. Superior access to and use of water usually results from more rapid and extensive root growth, enabling the limited pool of available soil water to be exploited before the roots of less well adapted competitors can reach it. Limiting water loss under stress conditions may result from adaptive characteristics such as rough leaf surfaces that shield stomates, and from leaf rolling. Both limit direct stomatal exposure to solar radiation and wind, thereby reducing transpiration. While sunken stomates and rough leaf surfaces are typical of arid zone plants (xerophytes), some commercial crop species (e.g. sorghum, millets and maize) exhibit leaf rolling under water stress. Millets and sorghum also exhibit rapid stomatal closure when stress develops, which reflects their adaptation to the hot and often arid environments of their African centres of origin. When the stress is relieved, these species are able to rapidly resume active growth. In contrast, crop species such as sunflower and soybeans exhibit rather lax stomatal control, resulting in slow stomatal closure, such that transpiration water loss may continue for some time after stress is imposed and root water uptake has ceased. As a result, water loss temporarily exceeds uptake and the plant loses turgor (wilts), closing its stomates to prevent further water loss. Recovery from water stress with these species is slower, and the yield penalty usually greater, than in sorghum or millet. As will be outlined later, these adaptive characteristics are reflected in the geographic distribution of rainfed commercial production of these species in Australia.

In the rainfed environment of the vast majority of Australian croplands, competition for water is the principal constraint on crop performance and yield. One of the first and most critical principles of crop production in these environments is to minimise the number of unwanted competitors by eliminating weeds.

Competition for nutrients Adaptations which enable successful competition for nutrients include:

- more rapid and extensive root growth, which enables one competitor to access and exploit available nutrients at the expense of its neighbours;
- the capability to take up and use a nutrient which may be present in the soil in a chemical form which their competitors are not able to utilise;
- the ability to meet its own requirements for an essential nutrient independently of soil supply (e.g. a legume growing in a nitrogen deficient soil);
- tolerance of low levels of essential nutrients in the soil which enables normal growth at levels too low for other species to grow, or even survive. This is typical of many Australian native species that are adapted to low soil levels of nitrogen and phosphorous;
- tolerance of soil conditions such as low pH or high salinity which enables adequate uptake of essential nutrient elements under conditions where other species are unable to grow, or even survive.

Competition for light Competition for light arises where one leaf shades another, regardless of whether the competing leaves are on the same or on different plants. In contrast to water and nutrients, light energy can not be redistributed internally in the plant unless it has been captured by chlorophyll in the photosynthetic tissue of the leaves or stems. It is instantaneously available, and must be instantaneously intercepted and absorbed by chlorophyll, or it is lost. Competition for light usually arises as the result of superior growth of one plant or species relative to another, which frequently reflects the outcomes of earlier competition for water and/or nutrients. The greater growth of the successful competitor results in shading of its neighbours, exacerbating the effects of existing competition for water and/or nutrients.

Successful competition for light may also result directly from adaptive characteristics that enable a more rapid and/or extensive development of the leaf canopy, resulting in an early onset of shading of less well adapted competitors. This situation is usually exacerbated with time, resulting in increasing shading and suppression of the inferior plant or species. Where competition for nutrients or water also exists, the inferior plant or species may be completely suppressed. Leaf display and canopy structure are also significant factors, particularly in the high density monocultures typical of commercial crops. The vertical leaf display of grass species enables more efficient capture of incoming light than the more horizontally disposed canopies of broadleaf species, particularly at high light intensities, which are typical of the Australian croplands during the summer months.

Competition for gases Competition for carbon dioxide may arise where a crop, well supplied with water and nutrients, and under high light intensity conditions around midday, is photosynthesising at a high rate. Under these conditions, rapid uptake of CO_2 depletes its concentration in the air within the canopy, causing a decline in photosynthetic rate. This happens only under still conditions, where the absence of air mixing by wind prevents CO_2 being replenished from outside the canopy. It occurs mainly in intensive production systems, where irrigated and well fertilised crops are grown in typically high density monocultures.

Most modern crop species show a positive growth response to higher air CO_2 levels than those in normal air, which reflects their ancient origins when air levels of CO_2 were much higher (~0.10%) than those of today (0.034 – 0.036%) (Conroy *et al.,* 1998). The C_4 photosynthetic pathway, described later in this chapter, is a successful adaptation which enables C_4 species such as maize, sugar cane and sorghum to maintain high photosynthetic rates even at the comparatively low air CO_2 levels of modern times.

Competition may also occur for oxygen (O_2), typically in waterlogged soils. With the exception of rice, no commercial crop species are able to survive continuous root inundation, although many can tolerate periodic inundation in waterlogged soils. Waterlogging severely reduces O_2 supply to root cells, inhibiting their respiration and hence normal nutrient uptake. Crop yellowing in waterlogged, low lying areas of paddocks during wet periods is a common occurrence and usually reflects an induced nitrogen deficiency, as uptake is severely limited or even prevented.

Types of Adaptive Responses

Adaptive strategies in plants can be considered as their responses to stress, disturbance, or both. Stress is defined as *any sub-optimal or deleterious factor(s) in the plant environment.* Disturbance means *any disruption of the plant's natural growth or biomass brought about by artificial (e.g. grazing, ploughing, spraying) or natural (e.g. erosion, frost, drought) means.* The possible combinations of stress and disturbance create four kinds of habitats, three of which are viable for plant survival, growth and development (Table 3.3).

Table 3.3. Adaptive response types under different combinations of stress and disturbance (adapted from Daubenmire, 1968).

		Stress Intensity	
		Low	High
Disturbance	Low	Competitors	Stress Tolerators
Intensity	High	Ruderals	Not Viable

Commercial crop species are typically adapted to productive, low disturbance situations and are classed as Competitors. In fertile situations, competition for light is the principal constraint and arises from extensive leaf canopy development. In infertile situations, however, canopy development is restricted and most competition occurs below ground for water and nutrients. Competitive ability in these species is a function of area, activity and distribution, in space and time, of plant surfaces that enable high rates of resource capture through absorption surfaces – roots (water and nutrients) and leaves (light and CO_2) – in productive, crowded communities. These factors include canopy development (rate, height and lateral spread), photosynthetic pathway and capacity, phenology (timing and pattern of development), growth rate, stress response and disturbance response. Competitors are characterised by their high rate of absorptive surface development and the ability to constantly adjust to resource availability. Successful weed species in crop situations are also classed as Competitors.

Competitors are replaced by Stress Tolerators in chronically unproductive situations with frequent stress but only occasional disturbance, and by Ruderals in productive low stress situations with a high degree of disturbance. Ruderals are typically ephemeral species with rapid growth rates, short life spans and high seed production – their adaptive strategy ensures seed production and survival in highly disturbed situations. Jojoba is the only Stress Tolerator commercially produced in Australia, but other arid zone plants such as Lesquerella (Senft, 1993) may show potential for the drier inland margins of existing croplands (Figure 3.3). No species with the Ruderal adaptive response are commercially produced as field crops in Australia.

Photosynthetic Pathway as an Adaptive Mechanism

A plant species that is capable of maximising photosynthesis, within the constraints of the available resources in its physical environment, will have a significant competitive advantage over other species present in the community. The process of photosynthesis depends on the intake of CO_2 through open stomates in the leaves. This intake is, however, inextricably linked with the parallel process of water loss when the stomates are open, and photosynthetic rates may be severely limited by partial or complete stomatal closure under water stress conditions. Once taken in, CO_2 must diffuse to the leaf chloroplasts for photosynthesis to proceed. The rate of diffusion is controlled by the concentration of CO_2 at the chloroplast, and by the resistances to diffusion encountered in the path to the chloroplast. The most important resistance is imposed by the stomatal opening. Most plants initially incorporate CO_2 into 3-carbon (3C) molecules, and these species are known as C_3 plants. In the second major group, C_4 plants, CO_2 is initially incorporated into 4-carbon (4C) molecules. Regardless of the initial incorporation pathway, the final outcomes of photosynthesis in each case are 6-carbon (6C) sugars, from which various other carbohydrates are subsequently synthesised. At high levels of illumination, the rate of photosynthesis is dependant upon the CO_2 concentration at the chloroplast, which in turn depends on the affinity for CO_2 of the enzyme that catalyses the initial incorporation into either 3C or 4C molecules. In C_3 species, this enzyme (rubisco [RuDP carboxylase]) has a weak affinity and hence attraction for CO_2, while in C_4 species the affinity and resultant attraction of the enzyme (PEP carboxylase) is much stronger. As a result, C_4 plants can maintain higher rates of CO_2 diffusion and photosynthesis than those with the C_3 pathway, particularly when their stomates are partially closed by water stress. The C_4 pathway is thus an effective adaptation to hot, dry environments and to low atmospheric CO_2 levels (Solbrig and Orians, 1977).

The two groups show a differential photosynthetic response to light intensity. C_3 species have low net photosynthetic rates, high CO_2 compensation levels (50-150 ppm) and high photorespiration rates. This group includes the important winter-growing temperate crops wheat, barley, oats, rye and triticale, canola, lupins, chickpeas, field peas and faba beans, together with the summer-growing crops rice, sunflower, peanuts, soybeans, cotton, sugar beet and tobacco. The C_4 group, in contrast, exhibits high net photosynthetic rates, low CO_2 compensation points (0-10 ppm) and low photorespiration rates. It includes the summer-growing crops sugar cane, maize, sorghum and millet. C_4 species make more efficient use of CO_2 and water than do those of the C_3 group (Hartmann *et al.*, 1981). While better adapted to low water availability, C_4 species are also highly productive in the absence of water stress and produce high yields under irrigation. Even so, some of the highest short-term growth rates have been recorded by C_3 species, although total biomass and grain yields are generally much higher in the C_4 group (Evans, 1996).

Crop Selection

For any situation, the selection of appropriate crop species for commercial production depends on economic factors as well as on the likely performance of the selected crops in the production environment. The importance of thorough analysis of the possible yield, price and marketing opportunities of the crop cannot be too strongly emphasised, and this has been a major focus of the Australian New Crops Movement (Ferguson, 1997). Crop performance will reflect a combination of the quality of the agronomic management regime imposed, the seasonal conditions experienced, and the adaptation of the crop species and cultivar to both. Of particular importance is the degree of adaptation to the severity and timing of adverse conditions or events, such as water stress or frost, relative to the timing of critical stages of crop development.

Australian Field Crops

Major structural changes in Australian agriculture have occurred through the 1990s, with a steadily increasing grains area and a large increase in capital equipment investment. Growth of the grains industries is reflected by increases in sown area, capital investment and yields, and this growth is forecast to continue in the medium term (ABARE, 1999). Details of the major crops are outlined in Table 3.4. While seven families are listed, the dominance of the *Poaceae* or grass family is evident.

The introduction of wheat production quotas in 1969 caused the first major shift in the Australian grains industries away from their traditional winter cereal base, to previously minor or untried alternative crops. Few species emerged from the extensive field research programs of the early 1970s as viable commercial alternatives to wheat, but those that did are now well established or emerging oilseed (canola, sunflower, soybean) and grain legume (lupins, field peas, chickpeas, faba beans, lentils, vetch) industries. The rapid expansion of these crops over the last decade is evident in Table 3.4.

Table 3.4 Major Australian field crops–classification, principal uses and average area sown for the 5 year periods 1987 to 1991 and 1996 to 2000. Crop species within each family are listed in two groups (temperate and tropical/sub-tropical) on the basis of climatic adaptation and production period (autumn-winter-spring and spring-summer-autumn respectively) under Australian conditions. *Source*: ABS, (1994, 1996, 2001); ABARE, (1999)

Crop	Species	Principal uses	Average area sown ('000 ha)	
			1987-91	1996-00
Family *Poaceae (Gramineae)*				
Temperate species Wheat	*Triticum aestivum,*	Human consumption – grain and grain products	9,438	10,862

	Triticum durum	Hay and green forage	58	[b]
Barley	*Hordeum vulgare*	Grain for malting and stock feed	2,335	3,152
		Green forage and hay	54	[b]
Oats	*Avena sativa* *Avena byzantina*	Grain – stock feed and human consumption	1,171	924
		Hay and green forage	416	[b]
Rye	*Secale cereale*	Grain – stock feed and human consumption	46	18
		Land stabilisation, hay and green forage	19	na[c]
Canary seed	*Phalaris canariensis*	Bird seed	12	na[c]
Triticale	*Triticosecale*[a]	Stock feed grain and green forage	117	336
Tropical species				
Maize	*Zea mays*	Grain – stock feed and human consumption	53	65
		Green feed and silage	6	[b]
Grain sorghum	*Sorghum bicolor*	Stock feed grain	589	606
Forage sorghum	*Sorghum* spp. Hybrids	Green feed and silage	119	[b]
Rice	*Oryza sativa*	Grain – human consumption	99	145
Millets				
White Panic	*Echinochloa frumentacea*			
White French	*Panicum miliaceum*			
Panicum				
Panorama		Birdseed grain	35	34[d]
Hungarian				
Siberian				
Setaria	*Setaria italica*	Hay	18[e]	[b]
Foxtail				
Italian		Green forage	108[f]	[c]
Japanese Shirohie	*Echinochloa utilis*			
Pearl	*Pennisetum Americanum* (syn. *Pennisetum glaucum*)	Green forage		
Cereals for hay	All species	Hay and green forage		377[g]

Sugar cane	*Saccharum officinarum*	Sugar production	393	409
Total, *Poaceae*			15 080	16 551
Family *Fabaceae*				
Temperate species				
Lupins	*Lupinus angustifolius* *Lupinus cosentinii* *Lupinus albus* *Lupinus luteus*	Stock feed – high protein grain	841	1,352
Field peas	*Pisum arvense* (syn. *Pisum sativum* var. *arvense*)	Grain – human consumption and stock feed. Green manure	371	332
Chickpeas	*Cicer arietinum*	Grain – human consumption and stock feed	[h]	227
Faba beans	*Vicia faba*	Grain –human consumption, stock feed	[h]	108
Lentils	*Lens culinaris*	Grain – human consumption	[h]	37
Vetch	*Lathyrus sativus* *Lathyrus cicera*	Grain – human consumption and stock feed; hay and green forage	[h]	43
Tropical species				
Cowpeas (Poona peas)	*Vigna sinensis* (syn. *Vigna unguiculata*)	Forage, green manure Grain – stock feed	190	5[f]
Navy beans	*Phaseolus vulgaris*	Grain – human consumption		6
Pigeonpea	*Cajanus cajan*	Grain – stock feed		na[c]
Peanuts	*Arachis hypogea*	Grain – confectionery, oil and protein meal	25	21
Soybeans	*Glycine max*	Grain – protein and oil	51	52
Total, *Fabaceae*			1,478	2,196
Family *Asteraceae*				
Temperate species				
Safflower	*Carthamus tinctorius*	Grain – oil and protein meal	33	35[l]

Tropical species Sunflower	*Helianthus annuus*	Grain – oil and protein meal	162	128
Total, *Asteraceae*			195	163
Family *Malvaceae*				
Tropical species Cotton	*Gossypium hirsutum*	Cotton fibre, oil and protein meal from seed	223	432
Total, *Malvaceae*			223	432
Family *Brassicaceae (Cruciferae)*				
Temperate species Canola	*Brassica napus* *B.campestris*	Oil and protein meal	58	928
Indian Mustard	*Brassica juncea*	Oil and protein meal	na	na[c]
Forage Rape Turnips Swedes Kale chou mollier	*Brassica oleracea* *Brassica napus* *Brassica oleracea* *Brassica oleracea*	Forage crops	22	na[c]
Total, *Brassicaceae*			80	928
Family *Linaceae*				
Temperate species Linseed (flax)	*Linum usitatissimum*	Oil – industrial uses, stock feed, protein meal	5	2
Total, *Linaceae*			5	2
Family *Solanaceae*				
Tropical species Tobacco	*Nicotiana tabacum*	Tobacco products	5	3
Total, *Solanaceae*			5	3
TOTAL, ALL CROPS			17,066	20,621

[a]Taxonomy not resolved. [b]Included in cereals for hay after 1995. [c]Not collected separately after 1995. [d]Average 1995-96 only. [e]Includes millets, sorghum, sorghum-sudan hybrids and cereal rye for hay. [f]Includes millets, triticale, cowpeas and poona peas for green forage. [g]Includes wheat, oats, barley, triticale for hay after 1995. [h] Included in legumes for grain. [i]Average 1995-97 only.

Table 3.5 Area (million ha) of crops sown in Australia, 1991 to 2000 (year ending 31 March) excluding pastures, nurseries, fruit and vegetables. *Source*: ABS (2000a, 2000b)

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Total area	17.4	16.4	17.3	18.0	17.0	19.4	21.1	21.6	23.3	23.7

Australian Croplands

The geographic distribution of crop production (excluding sown pastures, fruit, vegetables and nurseries) in Australia is shown in Figure 3.1. Five major regions dominate, namely the:

1. Atherton Tableland, coastal plains, southeastern downs and central highlands of Queensland;
2. coastal plain, tablelands, slopes, and eastern margin of the Western Plains of New South Wales;
3. coastal and sub-coastal plains and the Mallee country of western Victoria and southeastern South Australia;
4. coastal and sub-coastal plains of southwestern Western Australia; and
5. midlands region of Tasmania.

In any year, total area of all field crops amounts to only 2 to 3% of the Australian continental area of 787 million ha. Annual sown area varies with market outlook, seasonal conditions and other factors, and peaked at 23.7 million ha in 2000 (Table 3.5).

The great majority of production areas is located in the temperate region, reflecting the predominance of the temperate crops wheat, oats, barley, triticale, lupins, field peas, chickpeas and canola. The inland margins of the Australian croplands reflect the overriding influence of low and unreliable rainfall. The general production period for temperate crops coincides with the most favourable rainfall regime, but a less favourable temperature environment (Nix, 1975).

Water supply and temperature, sometimes aided by buildup of pests and diseases, determine the maximum length of the growing season, the range of crops that can be grown, their relative importance, their optimum duration and their likely yield. The longer a crop is able to grow, the larger is its biomass, reflecting a greater opportunity to intercept solar radiation and to take up nutrients over a longer time period. Grain yield, however, does not usually show the same relationship, often plateauing out with a longer-duration growth cycle. Grain yield increases with growth cycle duration up to a certain point, but what happens from then on depends on subsequent environmental, biotic (e.g. pest and disease buildup) and agronomic conditions. Under water limited conditions, earlier flowering and maturity can be critical to yield performance, as they enable flowering and grain fill before available water supply is exhausted (Evans, 1996).

Temperate (Winter) Crops

Production principles for temperate crops largely reflect strategies to capitalise on available moisture throughout the growing period, and to minimise both frost risk and exposure to high temperatures during flowering and grain filling. All are sensitive to water stress throughout growth, particularly through the flowering and grain filling stages which are critical to grain yield and quality. Frost sensitivity is limited during establishment and vegetative growth and probably has little yield effect, but all are frost-sensitive during the flowering and early grain filling stages. The cereals are all determinate (flower over a short [5-7 day] period) and even one severe frost event right at anthesis (pollination) can be catastrophic (Woodruff *et al.,* 1997). Most commercial cultivars of broadleaf grain legume and oilseed crops are indeterminate (flower over a 20-40 day period, depending on species), allowing some frost avoidance and partial compensation by later flowers for earlier ones killed by frost. Losses, however, can still be severe with these crops and frost at flowering and pod fill can be a significant constraint on yield and quality in canola and grain legumes. Apart from direct frost damage to pollinating flowers and young pods, grain from later flowers may fail to adequately fill if soil moisture reserves are exhausted before grain filling is completed. All temperate crop species can be affected by high temperature during flowering and grain filling, the effects including inhibited grain filling through induced water stress and accelerated development, and deleterious effects on grain composition, particularly in oilseeds and grain legumes.

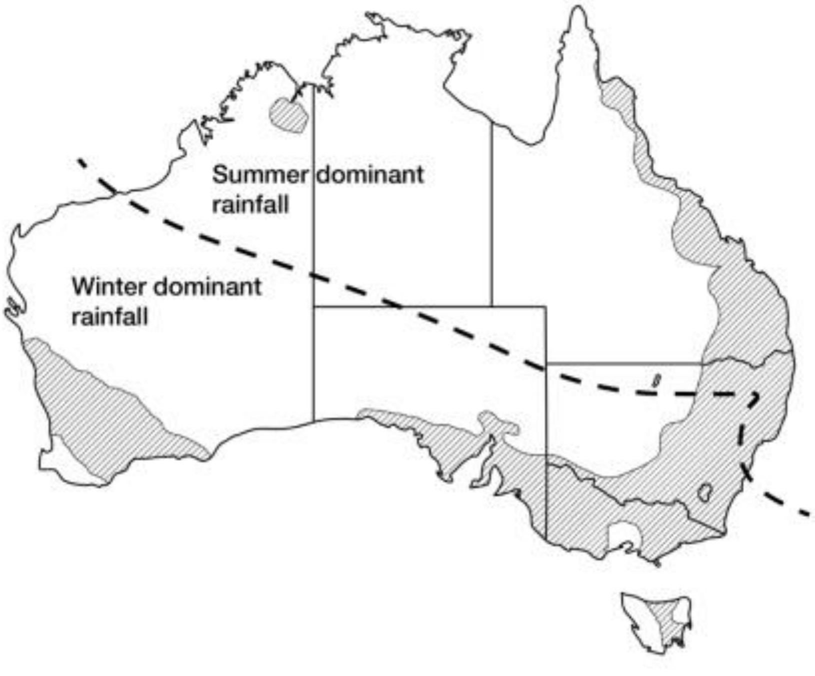


Figure 3.1 Australian croplands – distribution of field crop production for all purposes: grain, forage, fibre, sugar, hay and silage, in Australia. (Adapted from Kelleher, 1994; Coombs, 1994; ABS local government statistics, Pulse Australia, 2001; and Australian Natural Resources Atlas, 2002)

Seasonal Conditions and Production Strategies

Temperate crops grown in Australia are generally well adapted to the seasonal production environment (Table 3.6). They are planted from autumn to mid-winter and undergo vegetative growth in short days and cool to cold temperatures during winter. Floral initiation and inflorescence development occur under conditions of increasing daylength, temperature and solar radiation through late winter and early spring. Pollination (anthesis) and grain development subsequently occur under a combination of rising temperatures and rapidly increasing water stress in late spring and early summer. Within this environment, production strategies are governed by water availability for planting, adaptation of the species and cultivar being grown, frost risk at pollination/anthesis and expected rainfall and temperature conditions for grain development and maturation (Evans, 1975).

Table 3.6 Typical calendar of operations and development stages for temperate crops in Australia

		AUTUMN		WINTER			SPRING		SUMMER		
Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
		PLANTING						HARVESTING			
				Establishment			Flowering				
						Floral Initiation	Grain Filling				
								Maturity			

Crop and cultivar selection The range of commercial cultivars available varies from a few, in the more recent grain legume and oilseed crops, to many in the cereals. As a result, the cereals have a range of adapted cultivars covering most of the temperate and sub-tropical production environments encountered in the broad geographic spread shown in Figure 3.3. In contrast, the grain legume and oilseed cultivars available cover a more limited adapted range and geographical spread. Commercially, selection is based on a combination of local knowledge and advice from government and private advisers. Local knowledge includes grower experience, current season crop performance, seed availability, and seasonal conditions in late summer and autumn of the new crop year. Delays in sowing caused by an unseasonably dry or wet autumn in most cases do not result in a change of cultivars, as seed purchases have already been finalised. The outcome is usually a yield penalty because of accelerated crop development, the shortened vegetative phase resulting in restricted branching/tillering, a low biomass at flowering and reduced yield potential. In northern summer rainfall areas, sowing of the temperate crop may be abandoned and plans changed to sowing a summer crop in the following spring.

Planting time: Optimum planting time is determined by a combination of factors, the most critical being:

(i) *Cultivar adaptation.* For a given location and a cultivar with limited photoperiod requirement, the expected timing of crop development can be approximated using a combination of heat unit summations based on average temperature data for the location, and phenological data for the cultivar. A ‘safe’ anthesis date can thus be determined, from which it is possible to extrapolate back to a ‘safe’ sowing date to achieve anthesis at or soon after the average date of last spring frost. A good example of the application of this method can be found in French (1996). The approach is limited by the availability of phenological data for the cultivars of most species, other than the cereals. For photoperiod sensitive species, the timing of pollination/anthesis of any cultivar is best estimated from previous local research or commercial experience with the crop, as it will be fairly consistent from year to year, almost regardless of planting time, for that location.

(ii) *Soil water status.* For all crops, adequate starting soil water for germination and emergence is essential for successful establishment and ultimately growth and yield. Methods of estimating starting soil water and planting opportunities range from rainfall-based budgets to direct measurement using simple push probes, or neutron probes in the more intensive irrigated crop industries. Deep planting into moist soil below a dry surface layer is a common practice, but most crops have definite limits to planting depth, beyond which seedling emergence may be significantly reduced. In these circumstances, moisture seeking tines can enable successful establishment, as they enable planting at a safe depth into moist soil by removing the dry soil overlying the planted row.

Planting rate: Planting rates are generally well established for most crop-location combinations and planting guides are readily available from advisory and retail services in each state. Research over many years has shown that where planting is delayed, the planting rate for all crops should be increased to compensate for reduced tillering or branching, smaller mature plant biomass and lower individual plant grain yield.

Crop Distribution Maps

Maps in the following sections that show the distribution of individual commercial crop species in Australia are based on published information as acknowledged, and illustrate the estimated current distribution. Actual distribution will vary from year to year, depending on market and climatic conditions, as well as on the development of new cultivars that could extend the range of a particular species into previously untried regions. These maps show the general distribution of the main production areas within the period 1991-2001. Each map includes a line delineating summer- and winter-dominant rainfall zones, based on the Bureau of Meteorology seasonal rainfall zones map (BOM, 1975), as cited in Linacre and Hobbs (1977). The line intersects the northwest coast at approximately 25°S and the southeast coast at approximately 35°S.

Temperate Cereals

The temperate cereals grown in Australia are wheat, oats, barley, triticale and cereal rye (ryecorn). Commercial cultivars generally have no cold requirement and limited LD response for floral initiation. With the exception of a small number of winter-type cultivars in wheat, triticale and cereal rye, all commercial cultivars are spring types with reduced daylength sensitivity. They are grown in a broad, crescent-shaped area extending from south-eastern Queensland, through central New South Wales to northern Victoria and southern South Australia, with further separate concentrations in southwestern Western Australia and in Tasmania. The southern production areas of Western Australia, South Australia, Victoria, Tasmania and southern New South Wales lie within the temperate moist and semi-arid zones typified by uniformly distributed to winter dominant rainfall and a pronounced late spring and summer drought. The central New South Wales sector experiences more uniformly distributed rainfall, although both annual receipts and reliability diminish rapidly with distance inland. The northern New South Wales and southeastern Queensland areas receive uniform to summer-dominant rainfall – a feature of these areas is the low and erratic nature of winter and early spring rainfall, making successful winter crop production heavily reliant on fallow storage of summer and autumn rainfall. In the southern, winter-dominant rainfall areas, little grain yield advantage is achieved by summer fallowing in years of adequate crop season rainfall. As a result, summer fallowing has been largely discontinued in all southern areas, except northern Victoria, since the 1950s. With the exception of small areas of irrigated wheat and triticale for grain, and irrigated oats and barley for green forage, winter cereals are grown under dryland (rainfed) conditions.

Winter temperatures impose the second major constraint on growth and development within the winter cereal zone. In the northern sector, warm days, which promote rapid vegetative growth, are combined with clear nights and relatively high frost incidence. In the southern, winter rainfall sector, days are cool to cold, while the relatively high incidence of cloud and greater air movement associated with the westerlies results in fewer frosts. In addition to greater frequency, frosts in the north are generally more severe than those in the south.

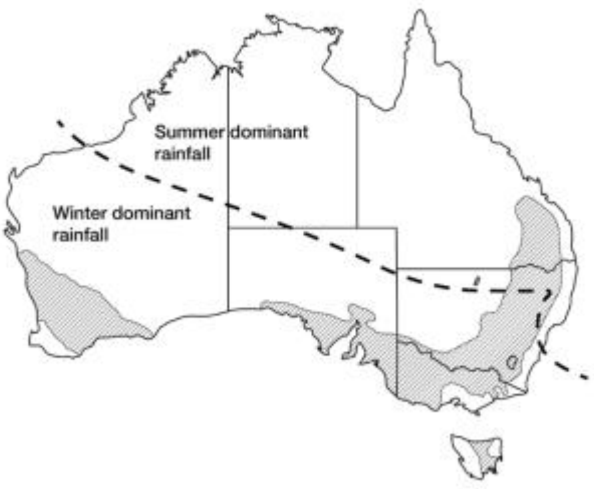
In summary, temperate cereal production in Australia is carried out successfully over a wide range of moisture, temperature and light regimes, much of the success being attributable to matching cultivar adaptation and management strategies to environmental conditions. Apart from absolute limits to the timing and duration of the crop cycle set by seasonal water availability, the major constraints on Australian wheat production systems were summarised by Nix (1975) as:

- the timing of sowing rains;
- the duration of the mid-winter depression in temperature and solar radiation;
- the timing of earliest safe ear emergence date as set by frost occurrence; and
- the rapid increase in temperature and evaporation rate during spring and early summer

Allowing for some differences between species and cultivars in their particular adaptation, these constraints also apply to the other temperate cereals.

WHEAT

The geographic distribution of wheat production areas in Australia is shown in Figure 3.2. Australia today produces three types of wheat, with bread wheat by far the dominant type and grown throughout the wheat belt. Durum wheats for pasta production are concentrated in northern New South Wales and Queensland, with an annual production of about 90,000 tonnes. A steadily growing durum industry is now well established in South Australia and a new cultivar for this region will be



commercially released in 2003. Most durum production is concentrated on the fertile cracking clays of the northern wheat region, but serious outbreaks of Fusarium Head Blight, to which it is particularly susceptible, pose a threat to existing production areas where stubble retention, now an integral part of farming systems in the region, is practised. The release of modified winter wheat cultivars for forage and feed grain production in the high rainfall areas of the Tablelands, where disease has previously prevented bread wheat production, is a recent development. The first, stem rust susceptible, cultivar was released in 1994. More cultivars with better rust resistance are now available and the industry is steadily growing. Australian cultivars of bread and durum wheats (*Triticum aestivum*, *T. durum*), particularly those grown in the northern sector, are predominantly short season spring types with limited photoperiod sensitivity. Early Australian wheats had a pronounced long-day requirement for floral initiation, but this has been greatly reduced through the use of Gabo and Mexican wheats of Gabo parentage in breeding programs. This has endowed both earlier maturity and a higher degree of adaptability on current cultivars, allowing them to be grown successfully over a wider latitudinal range than those with a strong photoperiod requirement. Their earlier maturity in particular makes them less prone to early summer drought damage during the critical phases of anthesis and grain filling. Although the LD requirement has been significantly reduced through breeding, daylength is still an important influence on their development and Evans, (1996) regarded it as a significant factor governing pre-anthesis development.

Development during the pre-anthesis phase is largely governed by temperature and daylength (depending on LD sensitivity) while, post anthesis, water availability is usually the principal control. Frost, wet conditions and disease outbreaks may also impose major constraints in some years. In the northern, summer rainfall growing areas, mild winter temperatures often stimulate rapid pre-anthesis development, but subsequent low spring rainfall and water stress can seriously limit grain yield and quality. In these regions, a successful crop finish is reliant on carryover water stored in the soil during the previous summer fallow. Rapid vegetative development may predispose the crop to severe frost damage. Here sowing times are determined by the need to delay anthesis until after severe frost risk has passed, yet early enough for good grain filling to occur before high temperature and water stresses become severe. In contrast, development in the colder, southern, winter rainfall areas of Victoria, South Australia and Western Australia is comparatively slow, resulting in delayed anthesis, with subsequent grain filling under conditions of increasing stress, imposed by high temperature and rapidly declining water availability, in the typical late spring-early summer drought. Available water is almost entirely derived from crop season rainfall, as summer fallowing is largely ineffective in these regions.

Commercial release of modified winter cultivars with a strong cold requirement but a weak LD response has enabled early sowing with the opening autumn rainfall break, often four to six weeks earlier than the safe sowing time for spring cultivars. Their cold requirement delays floral initiation and anthesis to much the same time as the later sown spring types. They are well suited to heavy clay soils, particularly in winter rainfall areas where late autumn-early winter sowing of spring cultivars is often delayed, if not prevented, by wet soil conditions. The high yield potential, early sowing time and grazing value of winter wheat, particularly for high rainfall areas, has been described by Davidson (1998).

The effects of the major climatic constraints can be summarised as follows:

Frost: severe spring frosts are typically associated with cool, still and dry conditions followed by a light southerly air stream, particularly in low-lying areas of the northern wheat belt. Frost damage is most severe during the anthesis-grain filling period, after the developing ear has been extruded from the protective flag leaf base (boot). If heading occurs during a period of high frost risk, extensive ear and floret damage can result.

All Australian wheat cultivars are susceptible, but they can develop ‘cold hardiness’ if subjected to low but not lethal temperatures from germination onwards, although this offers little protection once heading has occurred. Frost damage is most severe in northern New South Wales and Queensland, where mild winter day temperatures may prevent development of cold hardiness, resulting in ‘soft’ growth and rapid development. Crops head during the spring frost danger period, unless sown late to delay heading. In contrast, winters in the southern zone of the wheat belt are uniformly cold and cause slow crop development, development of cold hardiness, and later ear emergence with lower frost risk. In these areas, early to mid-winter sowing into cold wet seedbeds can significantly delay germination and cause patchy establishment, while waterlogging may also cause serious problems. Early sowing of winter wheats in these areas is increasing steadily (Freebairn *et al.,* 2002).

Water availability: low water availability during grain filling reduces grain yield and quality. The extent of yield reduction depends on the degree of water stress and can, if severe, result in the crop being cut for hay or grazed by livestock. Grain quality is reduced when poor grain filling results in small ‘pinched’ grain, typically with a high test weight (weight per unit volume), and protein percentage, both resulting from failure of the grain carbohydrate supply.

: high water availability during grain filling and ripening can cause serious disease outbreaks, particularly of stem rust (*Puccinia graminis*), Septoria spot (*Septoria tritici*) and root rots, while serious yield and quality reductions can also be incurred through lodging, harvesting difficulties, delayed maturity, loss of grain weight through endosperm leaching, and pre-harvest sprouting. Wet, humid conditions during grain ripening can cause serious grain quality decline, by initiating α-amylase activity when sprouting occurs. Such conditions frequently occur in the northern wheat belt. Sprouting can account for annual losses as high as 35%, the average annual loss being about 20% for northern New South Wales and Queensland, with a much lower proportion in southern areas that have a lower frequency of wet springs. Losses result from reduced crop value, while large volumes of downgraded wheat can create substantial storage and marketing problems. Sprouting resistance in white hard wheat for northern areas is a major breeding objective. A number of sprouting resistant or tolerant white wheat lines are under development. Hard red wheats from Northern America are sprouting resistant, but the Australian wheat industry has an international market niche with hard white wheats and the emphasis in breeding programs is on developing resistant white cultivars. Two tolerant white cultivars (Suneca and Sunelg) have been released and further development of resistant lines is continuing.

OATS

Oats are produced on a wider geographical scale than wheat, being grown as a multi-purpose grazing, grain and hay crop throughout the wheat belt (Figure 3.3). Oats is subject to the same climatic constraints outlined earlier for wheat, but is considered less prone to frost injury. The main areas for grain production are concentrated in the winter-dominant and uniformly distributed rainfall areas of the wheat belt in Western Australia, South

Australia, Victoria and southwestern and central New South Wales. Its use as a forage crop extends beyond both the drier inland and wetter coastward margins of the wheat belt. High (up to 1200 mm p.a.) rainfall and disease precludes its use as a grain crop in the coastal margins, where it is grown primarily for forage and hay (Macrae, 2002). In the dry inland areas, where pasture establishment carries high risk, oats are grown essentially as a forage crop and, in good seasons, an opportunity grain crop. Oats is the most widely grown crop for hay and green forage, and is the most important crop grown in New South Wales for the dual purposes of grazing and grain. Australian cultivars are primarily spring types with little or no cold requirement, but with varying degrees of LD requirement and a range of maturity types from very early to very late. Sowing times for grain crops are governed by cultivar maturity rating and spring frost risk, tempered by the timing of sowing rains, with most crops sown in early to late winter. Oats has a similar to, but more rapid, development pattern than wheat, and undergoes grain filling earlier in spring, when water stress is typically less severe. This predisposes it to a greater risk of post-heading frost injury, although frost impact tends to be less severe than in wheat. Oats are frost sensitive during both the early vegetative and post-heading phases, damage during the early vegetative stages being accentuated by grazing injury. Extension of oat grain production into the warmer regions of the northern wheat belt is precluded largely by its lower tolerance to high spring temperatures than wheat and the risk of crown rust outbreaks. However, its greater cold tolerance allows it to be successfully grown for grain in the higher tableland margins of the northern New South Wales wheat belt, where wheat production is limited.

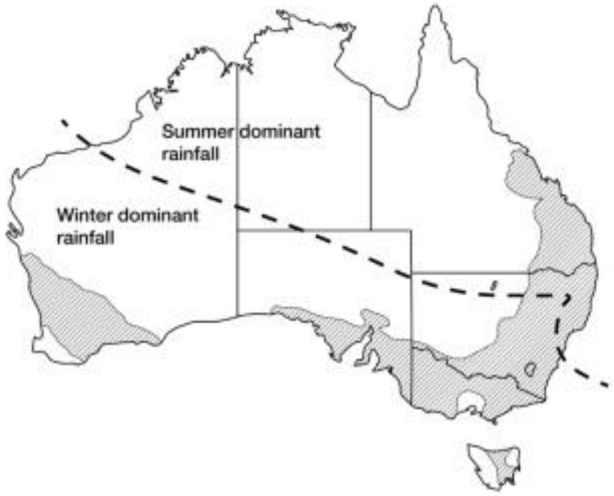


Figure 3.3 Australian oat production areas, for all purposes (after Kelleher, 1994; ABS 2002; and Australian Natural Resources Atlas, 2002)

BARLEY

Like oats, barley is grown throughout the wheat belt for grain, green forage and, to a small extent, hay. Distribution of the main grain production areas is similar to that of wheat. Since the early 1970s, production has expanded steadily and barley is now second only to wheat as Australia's most widely grown grain crop (Figure 3.2). It is grown extensively for green forage over a similar geographic range to oats, although forage and hay sown areas are considerably less than those of oats. Compared to the other temperate cereals, its early maturity enables it to be grown successfully for grain in areas where the season is cut short by low-water/high-temperature stress in spring. Its earlier maturity has led to it being regarded in many countries as drought resistant, but this is really a reflection of drought escape rather than resistance *per se* (Araus, 2002).

Growth and development are very similar to that of wheat, and are subject to the same general climatic controls. Water availability is the major consideration and crop yield potential is generally correlated with water supply during the growing period. Even short periods of moisture stress, particularly during the post-heading phase in spring, can have serious effects on yield and grain quality. Premium-quality malting barley must have large, well filled grains with high carbohydrate and relatively low (<9%) protein contents. This requires moderate to high humidity, mild temperatures and adequate soil moisture post-heading, resulting in a long period of grain fill (Savin and Molina-Cano, 2002). These conditions are typical of early spring in the southern grain-producing areas. It also requires moderate soil nitrogen levels and hence should not follow a legume phase in rotations. Starch deposition in the grain largely occurs after that of protein, and water stress during grain filling results in small, high protein grain that does not meet malting standards. Genes influencing low grain protein content have been identified in Victoria, and may enable inherently lower protein malting cultivars to be developed for low rainfall areas in the south (GRDC, 2002). Sowing time is critical, late sowing reducing grain quality and suitability for malting. Malting barley in Australia is derived from two-row cultivars, while 'feed' barley is largely from six-row types. Even where grain meets malting quality standards at harvest, subsequent post-harvest handling and storage can impact on its acceptance, as malting grade criteria include a minimum of 96% germination. Six-row barley is grown successfully throughout the wheat belt, and is adaptable to a wider range of soil and climatic conditions than two-row cultivars. It produces more dependable yields than either oats or wheat on low fertility soils, and profitable crops are grown in areas either too dry or hot in spring for malting barley. It is not tolerant of wet soil conditions and is much inferior to wheat, oats and triticale in wet situations. Feed grain quality standards emphasise high protein and starch contents to meet stringent export requirements, particularly for the Middle East market. Barley has proved a very useful alternative to wheat in much of the southern wheat belt, particularly in seasons with a delayed autumn rainfall break, necessitating late sowing. Here, its early maturity makes it a safer proposition than wheat, particularly in these spring-drought prone southern areas.

Breeding programs for the northern region emphasise increased yield, improved resistance to lodging, stem rust and leaf rust and adequate seed dormancy to prevent sprouting before harvest. Improvement programs for the southern region emphasise better malting quality cultivars and appropriate agronomic management to maximise their production of high quality malting grain (GRDC, 2002).

CEREAL RYE (RYECORN)

The most winter-hardy and low-fertility tolerant of all the winter cereals, cereal rye is a multi-purpose crop grown on a small scale throughout the drier and colder margins of the wheat belt. Its uses vary by time, state and region, but have historically been as follows:

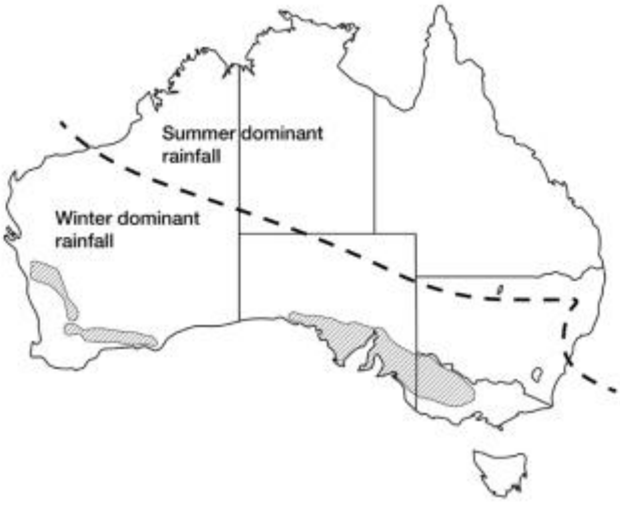


Figure 3.4 Australian cereal rye production areas (after Darvey, 1994)

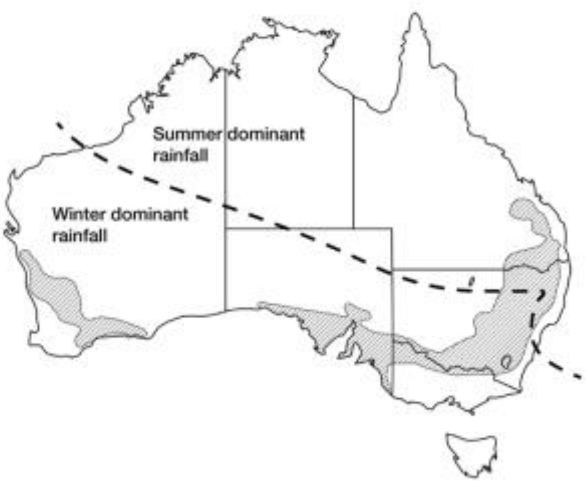
New South Wales	-	tablelands for forage and grain
	-	coast for green forage
South Australia and Victoria	-	primarily for sand dune stabilisation and land reclamation, forage and grain
Tasmania	-	green forage
Western Australia	-	erosion control and green forage
Queensland	-	grain (very small area)

Compared with the other temperate cereals it is a minor grain crop in Australia. Grain production is concentrated in southeastern South Australia, where some 70% of the Australian crop is produced (Figure 3.4). The most cold tolerant temperate cereal, it is grown in Europe in areas extending beyond the Artic Circle, replacing wheat in areas of intense winter cold. In Australia, its cold tolerance has enabled its use for green forage in place of oats in elevated tableland districts, which are too cold for active growth in oats (Macrae, 2002). Despite its extreme cold tolerance during vegetative growth, rye is quite sensitive to post-heading frost damage, and has usually been grazed out in these elevated regions. It can also withstand hot dry conditions, its extensive root system imparting considerably greater drought tolerance than that of wheat or oats. Its drought tolerance, combined with the excellent soil-binding properties of its root system and its resistance to sand blast, enable vigorous vegetative growth on dry sand dunes, where wheat, oats and barley would barely survive (Darvey, 1994). As a result, it has had widespread historic appeal as a primary coloniser of sand drifts and dunes in the dry inland margins of the Victorian, South Australian and Western Australian wheat lands. Despite this, it is extremely sensitive to hot dry conditions at anthesis. Unlike other temperate cereals it is largely wind pollinated, and high temperatures with low-humidity at anthesis desiccate wind borne pollen and severely limit potential grain set. In the main grain-growing areas of South Australia, reliable winter rainfall combined with the early maturity of cereal rye enables it to escape the hot dry conditions typical of late spring (Darvey, 1994).

There has been renewed interest in cereal rye as a green fodder and grain crop in acid soil areas of New South Wales, with the release of two cultivars with resistance to stem rust. However, the total area of cereal rye sown is unlikely to increase significantly in future, with production limited to existing areas. The advent of triticale may further reduce the importance of rye as a commercial crop.

TRITICALE

Triticale is a hybrid between wheat and cereal rye, with most of the genetic material contributed by the wheat parent. It combines the productivity of wheat with the hardiness of rye and makes good use of land that is marginal for other cereals. It outyields wheat on acid soils, in cool high rainfall areas and on soils with trace element deficiencies (GRDC, 1994). It was first grown commercially in 1976, but initial grain yields were much lower than those of wheat. New cultivars developed in New South Wales, Victoria and South Australia led to substantial interest in the crop for acid soils with high levels of available aluminium, where it significantly out-yielded wheat and barley. On these soils, severely reduced root growth in aluminium sensitive wheat and barley also induce water stress by limiting access to available soil water (Zhang *et al.,* 2001). Triticale was initially promoted for grazing and grain, but forage yields were inferior to those of oats and barley, except under harsh conditions of low winter temperatures and acid soils. Under those conditions, however, it was inferior to cereal rye, and its use for forage has been limited until the subsequent release of later maturing cultivars with better forage performance and reasonable grain yields. Most commercial cultivars are grain types and its good resistance to rust and root lesion nematodes make it a valuable disease break option in crop rotations (Parker, 1994). It produces a good stubble and root mass, making it suitable for stabilising sandy soils. It is quite tolerant of waterlogging, is adapted to a wide pH range, and is effective in accessing trace elements in alkaline soils. Triticale is a good hay crop and out-yields oats for this purpose in low rainfall environments (Cooper, 2001). It is grown throughout the wheat belt (Figure 3.2) and the annual sown area is increasing steadily. Future competition with wheat on average and better soils will depend largely on relative yields and prices.



Under irrigation, triticale out-yields wheat by 10 to 15%, and its substitution for wheat as an irrigated disease-break crop in cotton rotations is increasing. Where available irrigation water is limited, maximum grain yield response is obtained from post- rather than pre-anthesis application. Under water limited rainfed conditions, however, grain yields are significantly lower than those of wheat, which limits expansion of the crop into the drier inland margins of the wheat belt.

Temperate Oilseeds

The winter-growing temperate oilseeds grown in Australia are canola, linseed, linola and safflower. Each is valued as a rotation crop in cereal production systems, as a disease-break (buffer) crop and as a means of improving soil physical conditions. All except linseed/linola have deep and vigorous tap-roots, which break up hard soil layers and improve both subsequent cereal crop performance and soil structure. Their distribution in Australia is confined to the temperate moist and semi-arid zones of uniform to winter-dominant rainfall, extending into the summer rainfall sub-tropical region of southern Queensland.

CANOLA

Canola (formerly oilseed rape) has been produced on a widespread commercial scale only since 1971 and has undergone rapid and large scale expansion since 1990 (Table 3.4). It is now the largest oilseed crop grown in Australia. Australian commercial cultivars and hybrids are all *annual, spring* types of a single species, *Brassica napus* (Argentine or Swedish rape). This species has annual and biennial *and* spring and winter types, the latter with pronounced cold and LD requirements for floral initiation. Earlier maturing *B. campestris* cultivars were also grown in the 1970s, but were low yielding and are no longer commercially produced in Australia. Production is different to that in most other countries, spring types with no cold requirement being sown in autumn and harvested in late spring. Although they have no cold requirement, vernalisation speeds up flowering (Walton *et al.,* 1999). Sown area initially expanded rapidly, but then fluctuated markedly from year to year as a result of poor grower experience, removal of wheat quotas, seasonal conditions and the impact of blackleg disease. Blackleg decimated Western Australian crops in the mid-1970s and still remains the major disease problem (Howlett *et al.,* 1999). Production since then has stabilised in the better rainfall temperate moist regions of the New South Wales, Victorian, South Australian and Western Australian wheat belt. In New South Wales it has extended into the higher rainfall areas of the Tablelands, the drier Northwest Plains, and, since 1998, the Liverpool Plains of northern New South Wales. Production has also expanded into southeast Queensland and this development is expected to continue to steadily increase. The recent release of suitable *B. napus* hybrids has also extended production in all areas, including the better rainfall wheat districts of southeast Queensland. Although produced almost entirely as a rainfed crop to date, irrigated production is increasing steadily along the western river systems of New South Wales and in flood years, on western lakebeds and river flood plains as floodwaters recede (Colton *et al.,* 2001). Distribution of canola production areas is shown in Figure 3.6. Production in the southern areas of Western Australia, South Australia, Victoria and southern New South Wales has been markedly affected by the incidence of blackleg disease and the development of resistant cultivars has been a high priority in breeding programs. The disease, however, remains as a major production limitation in high rainfall and southern areas and all cultivars carry a blackleg resistance rating published by the Canola Association of Australia.

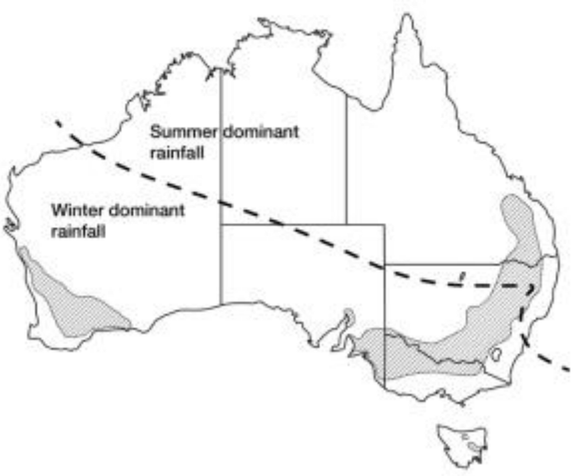


Figure 3.6 Australian canola production areas (after Kelleher,1994 and Colton,1994a)

Cultivars with a low rating are restricted to northern regions, where the disease risk until recently has been very low. Production in Western Australia, the largest producing state in the mid to late 1970s, fell to almost negligible levels by 1985, but has steadily recovered since then and had the largest sown area in 2000. Yields in Western Australia, however, are consistently lower than in New South Wales, averaging 1.04 t/ha compared to 1.72 t/ha over the 1995 to 2000 crop years. Several hybrids and genetically modified cultivars have been released from private and public breeding programs, and 36 cultivars in four maturity groups (early, early-mid, mid and mid-late maturing) were available to growers in 2001. Of these, 19 were 'regular' (non-genetically modified) and 17 were genetically modified, comprising 10 triazine tolerant (TT) and 7 imidazolinone tolerant (IT) lines. TT and IT cultivars are generally lower yielding than the regular ones, but are well suited to weedy situations where regular cultivars can not be economically produced (Colton *et al.*, 2001).

Growth and seed yield are almost always limited by water availability to the crop, at least up until maturation (Walton *et al.,* 2001). Canola has a higher water demand than temperate cereals, and both seed and oil yield are severely depressed by water stress during flowering, a major cause of poor yield performance in drier areas of the wheat belt. In these areas, Indian mustard (*Brassica juncea)* shows promise as a replacement for canola and commercial cultivars that produce canola quality (low glucosinolate, low erucic acid) oil are under development (Oram *et al.*, 1999) and nearing release. Cultivars with these oil characteristics are expected to be in commercial production in the drier margins of current canola growing areas by 2004 (GRDC, 2002). As well as better adaptation to drier areas, they also have better seedling vigour and less pod shattering than canola.

Crop growth rate is closely related to solar radiation interception by the leaf canopy, with leaf area index (LAI) increasing slowly through autumn and winter, then rapidly in spring to a maximum at flowering, with an LAI of about 4 required to intercept 90% of incident radiation. Leaves senesce rapidly from late flowering, but at full flowering, the majority of radiation is intercepted by the flowers themselves, leading to a photosynthate deficit during seed filling. The pod layers at the top of the crop then provide a dense photosynthetic surface up until mid pod-filling (Walton *et al.,* 1999). Canola is slightly frost sensitive in the early rosette stage, but damage is generally negligible. Flowering is indeterminate and extends over 30 to 40 days. Frosts can severely reduce yield if they coincide with the main period of flowering, particularly in northern production areas where mild winter conditions can promote rapid development and flowering while spring frost risk is still high. In this region, risk of yield loss from spring frosts during most of the flowering and grain filling period is now seen as a key constraint on canola production. Late frosts after flowering, with seed water contents of around 60%, cause severe pod losses, as do water deficits after anthesis that result in seed loss through pod abortion (Robertson *et al.,* 2001). In general terms, early planting (in low rainfall areas, as early as late March) of mid-late maturing cultivars, given normal seasonal conditions and crop development, results in higher yields. Normal planting times for rainfed crops in the main wheatbelt areas are mid-April to late-May. If late autumn breaks occur, planting can be delayed until late June but results in a yield penalty of up to 10% per week of delay (Sykes, 1992). High temperatures during flowering and grain filling cause significant reductions in yield and have adverse effects on oil content and quality.

In addition to its commercial value as an oilseed crop, canola is a valuable disease break crop in cereal rotations, providing an effective break in soil borne cereal diseases, particularly take-all and cereal cyst nematode. The breakdown products of *Brassica* roots include isothiocyanates, which are toxic to soil borne fungal pathogens in particular and result in soil bio-fumigation (Kirkegaard *et al.,* 1998). It is one of the most profitable crops available to southern Australian grain growers, and more intensive rotations incorporating canola have been developed in recent years. These, however, may pose problems of herbicide use, disease carryover and increasing potential of blackleg in existing cultivars (Norton *et al.,* 1999). Recent outbreaks of a new pest species, diamond back moth, were devastating in some Western Australian crops in 2001, causing estimated yield reductions of up to 90% in some cases, and research into its control has a high priority (GRDC, 2001).

LINSEED/LINOLA

Linseed is the seed of the flax plant (*Linum usitatissimum*) and is produced for its industrial quality oil, which contains 45 to 60 per cent linolenic acid, making it unsuitable for human consumption. Its restriction to industrial use and competition from synthetics caused a major decline in market demand and it is now a minor crop, with negligible plantings since 1983. It has been commercially grown as an oilseed in Australia since 1947, prior to which it was grown on a fairly large scale for flax from 1938 to 1945, with total sown area exceeding 25 000 ha in 1945. Production for flax utilised tall cultivars with little branching and seed production, and continued on a small scale, in parallel with that for linseed, until 1964. A new flax industry began on the Darling Downs in Queensland in 2001, with the purchase by a farmer group of a decorticator, which extracts flax fibre from linseed straw. Crop returns from seed and flax fibre are reported to be up to double those from wheat or barley. Production as an oilseed began in the 500 to 700 mm rainfall zones of the northern New South Wales and Queensland wheatbelt, and quickly expanded to over 20 000 ha. Subsequently the principal area of production shifted south into the central western and southern Slopes of New South Wales, the western district of Victoria, and Western Australia. Area and production fluctuated widely from year to year with market demand. The crop had a resurgence in the early 1970s with the onset of wheat quotas, but has declined to negligible levels since 1983. More recently, Wolfe (1998) promoted Linseed/Linola as the most promising crops to broaden the base of winter oilseed rotation crops beyond its current limitation to the *Brassica* species Canola and, in future, Indian mustard. This will allow improved herbicide and disease break strategies for existing cereal/Canola/pulse rotations, particularly in southern areas.

The crop is small seeded and exhibits limited seedling vigour, which, combined with its sparse leaf canopy, make it a poor competitor with weeds. As a result, plantings should be restricted to land where broadleaf weed populations have been reduced to low levels. Linseed can be planted from late autumn to early spring, depending on cultivar, seasonal rainfall and frost incidence. It is very sensitive to frost throughout flowering and seed setting, and later planting times are required to reduce the risk of damage during this phase. If spring planted, higher temperatures result in a short growing period of 120 days, compared to 210 days for late autumn plantings. The shorter growing period results in smaller plants with lower yield potential (Sykes and Green, 1988). Flowering and capsule maturation occur over a protracted period, and if soil moisture levels are adequate the crop may undergo a renewed period of flowering, leading to uneven maturity but potentially high yields. The small root system predisposes it to spring water stress, although it can withstand relatively dry conditions during vegetative growth (Matheson, 1979). Water stress during flowering, seed set and seed filling causes severe yield reduction, making it unsuitable for areas with low or unreliable spring rainfall. Dry conditions are essential at harvest because the crop has tough stems, and wet weather induced secondary growth and flowering may require crop desiccation before harvest. High temperatures and low humidity from flowering to seed maturation reduces seed yield and oil content, and adversely affects oil quality. Dry, hot conditions after maturity, however, facilitate harvesting (Sykes and Green, (1988). It is intolerant of waterlogging for prolonged periods and performs poorly in wet seasons - irrigated plantings should be restricted to well-drained land (Wightman, 1984).

Like canola, linseed is a valuable disease break crop in cereal rotations, and the development by CSIRO of a totally new oilseed, linola, in the 1980s has created an opportunity for renewed interest in the crop (Green, 1992). Linola was developed from linseed using induced mutation, and produces a modified oil containing only 1 to 2% linolenic acid and 60 to 70% linoleic acid, making it a high quality edible oil similar to that from sunflower. Two cultivars have been released for commercial production in areas suited to linseed (Coombs, 1994).

SAFFLOWER

Safflower (*Carthamus tinctorius*) has been commercially grown in Australia since the 1950s, and was mainly restricted to the Darling Downs and Central Highlands of Queensland, the northwest slopes and plains and upper-central western plains of New South Wales and the northern wheat belt of Victoria. The crop is also produced under irrigation in the Ord River region of northern Western Australia. Annual sown area has fluctuated widely from almost nil to 40,000 ha in response to disease problems, market fluctuations, drought and comparative returns from competing crops. Production in Queensland has declined markedly since 1985 and Victoria has been the major producer since 1990 (Figure 3.7). In southern areas, the crop was often sown in spring following either a late onset of the autumn-winter rainfall break or a wet winter, which prevented sowing of a winter cereal crop (Colton, 1988). Like linseed/linola, it offers a further opportunity to diversify southern cereal/canola/pulse rotations where disease break and herbicide resistant weeds have become problematic.

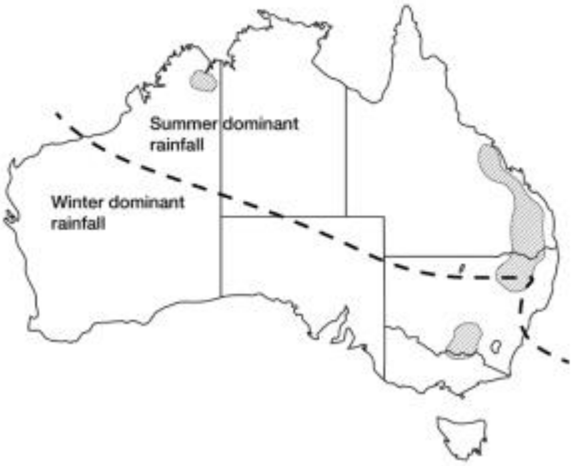


Figure 3.7 Australian safflower production areas (after Colton, 1994)

Most of the New South Wales production comes from opportunity cropping on drying floodplains and lake beds of the Darling Basin in the far west of the state, after seasonal floodwaters recede. It is considered drought tolerant because of its deep taproot, which can exploit subsoil water in dry periods. Safflower is also a useful disease break crop in cereal rotations on suitable soils, but its late maturity and deep soil water extraction, at the expense of the following crop, limit its use for this purpose (Beech and Leach, 1989). Its deep rooting habit and intolerance to waterlogging limits successful production to fertile, deep soils with good internal drainage and water holding capacity, the most suitable being the black, brown and grey cracking clays. Soil water availability during spring flowering is the most critical factor governing crop yield and quality. It matures 4 to 8 weeks later than wheat in the same environment, exposing it to greater risk of water and high temperature stress during this critical phase. In the northern summer rainfall areas, a full moisture profile to at least one metre depth is a prerequisite to planting to reduce this risk as far as possible (Colton, 1994).

Commercial prospects have been severely hampered by very limited cultivar availability, with only one late-maturing cultivar, Gila, available for Australian production until 1989. The 1989 release of Sironaria and Sirothora (CSIRO-developed cultivars resistant to *Alternaria* and *Phytophthora* respectively) was a significant advance, but both are agronomically similar to, and slightly later maturing than, Gila, and their major contribution is to enable more reliable production in existing dryland production areas where safflower is traditionally grown. A number of local and newer overseas cultivars are currently under evaluation in Victoria (Wachsmann *et al.,* 2001). Safflower has a significantly higher water requirement than wheat for satisfactory grain yields and is grown almost entirely as a rainfed crop. Irrigated production is minor and is limited to its use as a rotation crop with cotton, its deep taproot effectively breaking up compacted subsoil layers. Under wet conditions, particularly if waterlogging occurs at any stage on poorly drained soils, significant yield reduction can result from *Phytophthora* root rot, while rainfall during or after flowering can promote germination in the head and outbreaks of *Alternaria carthami* causing substantial yield loss (Harrigan, 1987). It is also temperature sensitive, low soil temperatures causing emergence failure and poor establishment, while frost damage during stem elongation, flowering and grain filling can severely reduce yields (Matheson, 1976). Frost avoidance at flowering requires mid-winter (May-June) planting, which predisposes the crop to late maturity under high temperature and water stress in summer (December-January). High summer temperatures and rainfall in northern New South Wales and Queensland predispose the crop to severe outbreaks of *Phytophtora cinnamomi* and *Alternaria carthami* and to seed germination in the head (Colton, 1994). High but not excessive temperatures (26-29^{0}C) at and after flowering also have deleterious effects on seed yield and oil content.

Temperate Grain Legumes (Pulses)

Temperate grain legumes or pulses are winter-growing, large-seeded legumes produced for their high protein grain. Six species are commercially important in Australia: lupins, field peas, chickpeas, faba beans, lentils and vetch. All are recent developments as commercial crops throughout the southern croplands of New South Wales, Victoria, South Australia and Western Australia. Lupins and field peas were established as an industry in the early 1970s, followed by chickpeas and faba beans in the mid-1980s and lentils and vetch in the mid 1990s. Interest in these crops as alternatives to, or as rotation crops with, the temperate cereals, particularly wheat, has accelerated since 1984. This was stimulated by fluctuating market prospects for the cereal grains, recognition of the value of grain legumes as effective cereal disease-break crops that improve soil nitrogen levels, and a favourable market outlook for legume grains. Lupins, faba beans and vetch are grown primarily for the stockfeed trade, while chickpeas and lentils are produced mainly for culinary purposes, but must meet stringent quality standards for this trade – lower grades are used for stock feed. Field peas are produced for both the culinary and stock feed markets. Future prospects for all are closely linked with export markets. Seed quality in all species can be seriously downgraded by handling damage, and the use of augers for grain transfer should be kept to a minimum.

LUPINS

Although grown extensively in the southern wheat belt (especially in Western Australia) for many years as green manure and forage crops, development as a grain crop suitable for livestock consumption began only in 1969 with the release in Western Australia of low alkaloid cultivars of *Lupinus angustifolius* (narrow-leafed lupin). These were the world's first true crop cultivars of this species. Subsequent release of improved narrow-leafed cultivars has resulted in this species accounting for over 90% of Australian production. Other species for which low alkaloid commercial cultivars have been developed are the sandplain lupin (*L.cosentinii*), the white lupin *(L.albus)* and the yellow lupin *(L.luteus)*. Cultivars of a large seeded species, *L.atlanticus*, were released in the late 1990s. Grain from the latter is in demand for the premium priced snack food market, particularly in the Middle East. Development of lupins as a low alkaloid grain crop has resulted in Australia being the largest lupin grain producer in the world, with substantial and expanding export markets.

Production areas extend throughout the southern croplands of Western Australia, South Australia, Victoria and New South Wales (Figure 3.8).

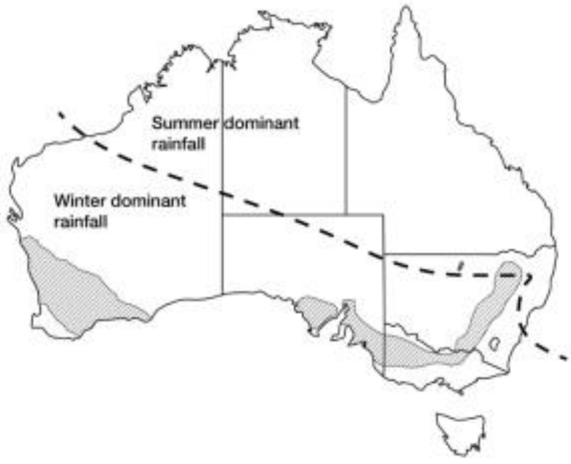


Figure 3.8 Australian lupin production areas (after Kelleher, 1994; Grain Pool of WA, 1994; and Pulse Australia, 2001)

Western Australia dominates production, averaging over 86 and 82% respectively of Australian sown area and production from 1995 to 2000. Average yields over the same period were 1.05 and 1.09 t/ha for Western Australian and total Australian lupin crop plantings respectively. Higher yields of 1.5 t/ha or more are achieved in better rainfall areas, although the severity of *Anthracnose* damage in infected crops is considerably higher in those areas. With the exception of New South Wales, where production extends into the semi-arid zone, lupins are limited to the dry summer, temperate areas with reliable winter rainfall. They are well adapted to low fertility, lighter acid soils, but perform best on well drained, fertile sandy loams. They grow poorly on heavier clay soils, particularly those that are poorly drained or alkaline - cultivars of *L.atlanticus* have been developed specifically for these soils in Western Australia.

All species are best adapted to mild temperate Mediterranean climates with reliable winter and spring rainfall, with water availability during the reproductive phase critical to grain yield (Palta *et al.,* 2001). They are classified as LD plants, but the degree of sensitivity to daylength varies between species and cultivars. Some have a cold requirement that must be met before they become daylength sensitive, but this has been largely eliminated in commercial cultivars. Development through the vegetative phase is controlled by temperature, with more rapid leaf emergence and development as temperature rises. This response is accentuated by long days, which will further accelerate development for a given temperature. The crop is sensitive to temperature at flowering, where values outside the range 11-25^{0}C will cause flower and seed loss and reduced yield. Early (April-May) sowing of early to mid-season cultivars will result in early flowering and frost damage, causing flower loss, seed abortion or inhibited seed filling. This may be offset to some extent by their indeterminate flowering habit (Dracup and Kirby, 1996). Length of the growing season, based on rainfall, ranges from 4 months in marginal low rainfall areas to 6 months in the better rainfall zones. Successful grain production ideally requires a growing period of at least 5 months free of moisture stress, coinciding with rainfall totals of 450 to 500 mm per annum in the main production areas. Early maturing cultivars are required for the marginal rainfall areas (Anon., 1994). Further expansion of production on a wider range of lighter soils in northern New South Wales and southeastern Queensland is feasible, but has to date been limited. Breeding programs focusing on developing cultivars with higher yield potential, greater resistance to lodging, disease resistance, reduced branching and pods borne higher from the ground will have a major influence on the extent of future expansion of the crop.

FIELD PEAS

Field peas are the most widely adaptable of the winter grain legumes and the best suited to areas with low rainfall and short springs. They have been grown for almost 100 years as a rotation crop with cereals in the southern areas of the wheat belt in Western Australia, South Australia, Victoria and Tasmania. While well suited to the Western Australian environment, they are dominated there by lupins, which are better adapted to the light sandy acid oils typical of the cereal belt in that state. Production in Western Australia is limited to the medium to heavy, neutral to alkaline soils that are not suited to lupins (Soedetjo *et al.,* 2001). During the 1980s production extended rapidly into the southern and central wheat belt of New South Wales on a substantial scale (Figure 3.9). Australian sown area peaked at 456,000 ha in 1989, but has since declined to a fairly stable annual total area of around 310,000 ha. Victoria and South Australia are the major producers, with South Australian crops consistently outyielding Victorian ones by approximately 0.5 t/ha. Average yields were 1.37 and 0.94 t/ha respectively for South Australia and Victoria over the period 1995 to 2000. Field peas may be grown as a specialty grain crop, but are most frequently grown as a rotation crop with cereals, providing both soil nitrogen build-up and a break against soil-borne cereal diseases, particularly cereal cyst nematode and take-all. As an alternative to lupins in cereal rotations, field peas are better suited to late sowing, to a wider range of soils (particularly heavy soils), and have better winter growth. There is also a wider range of herbicides registered for field peas, enabling more management options for weed control (Simmons, 1989). Field peas have an additional advantage in being well suited to conservation as hay in the event of a dry spring and poor finish as a grain crop.

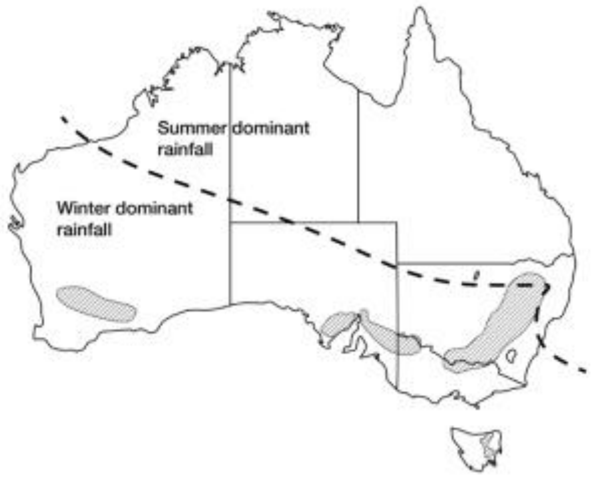


Figure 3.9 Australian field pea production areas (after Pulse Australia, 2001)

They also have advantages over chickpeas and faba beans as planting times are later, and harvesting times earlier, than those for the main cereal crops (Moore, 2001).

As a cool temperate crop, field peas are confined in Australia mainly by the 375-500 mm rainfall isohyets across the southern wheat belt and are best adapted to latitudes 34°S and higher. They are adapted to cool temperate winter rainfall areas with a long, cool growing season, making better cool season growth than other grain legumes. Annual rainfall requirements for good yields range from 500 mm in warmer areas to 400 mm in cooler regions such as the tablelands and slopes of southern New South Wales. The timing of rainfall is more important than total amount received, yields of 2 t/ha having been achieved in the Mallee region of Victoria (300 mm annual rainfall) when rainfall coincides with flowering and grain filling. While adapted to a wide range of soil types, including heavier alkaline soils, they cannot tolerate poorly drained conditions. They are replaced by lupins on acid soils with pH values below 5.5, where nodulation problems severely constrain their growth and yield. Commercial production is concentrated on neutral to alkaline loam or clay soils in medium rainfall areas, where the risk of waterlogging is low (Smith and Mahoney, 1994). The crop is frost tolerant during vegetative growth, but frost during flowering or pod development can cause heavy loss of pods and yield. Sowing time for any locality should be the same as for a mid-season wheat, and can vary from May to as late as August in more elevated, cool temperate areas (Simmons, 1989). High temperatures, particularly during flowering and pod development, can cause a significant reduction in yield, particularly when combined with low water availability. Field peas are also susceptible to damage from hail after flowering and from rain on a ripe crop, causing a substantial reduction in quality. Current production is constrained by the limited adaptation of the major cultivars available and their susceptibility to diseases such as *Mycosphaerella*, *Ascochyta* and bacterial blights, all of which are favoured by cold wet conditions and poor drainage. Earlier maturing lines are continually being evaluated for yield and disease resistance, and improved cultivars may initiate wider interest. The release of the cultivar Kiley in 2001 offers growers in the northern region a high yield potential (up to 2.5 t/ha in trials) alternative to chickpeas and faba beans (Moore, 2001). By maturity, field peas are normally prostrate on the ground, which considerably accelerates wear and tear on harvesters that must skim the ground to pick up the crop. The release of leafless and semi-leafless, semi-dwarf types, to improve crop standability for harvest, has not resolved this problem and it continues to be a deterrent to many growers. New cultivars with much better standability and larger grain size are expected to renew interest in the crop for the southern region. Intercropping field peas with canola improved the productivity of both crops in Western Australia compared to the yields of either crop sown in pure stands (Soedetjo *et al.,* 2001), and this was attributed to support for the field pea canopy by the more erect canola plants. Future expansion will reflect market outlook, the current utilisation of the Australian crop being 55% for domestic stock feed, 20% exported for stock feed and 25% exported for human consumption.

CHICKPEAS

Chickpeas (*Cicer arietinum*) are a recent commercial crop in Australia, and are showing considerable promise as a substitute for field peas in cereal rotations on alkaline soils unsuitable for lupins, particularly where high temperatures occur at flowering. Two major groups are produced: the *desi* types*,* which have small (1-2.5 g/100seeds), angular shaped seeds and the *kabuli* types with their larger (2-6g/100seeds) round seeds. Both are produced for human consumption. Almost the entire New South Wales and Queensland crops are of the *desi* type, but *kabuli* cultivars are also produced in the other states (Knights, 1994). Commercial production began in 1979 on a small scale in Victoria, and has since expanded rapidly into New South Wales and Queensland. The total Australian area planted in 2000 was 233,000 ha, with 90,000 ha in each of New South Wales and Queensland. They are grown as rotation crops in a wide range of farming systems from broadacre, rainfed production in the Mediterranean-type environments of the southern wheatbelt, to intensive irrigation systems in the sub-tropical northern regions. The recent extension into Queensland occurred on the alkaline black cracking clays of the Darling and Western Downs, the Dawson Valley and the Central Highlands. A significant area is also grown in Western Australia, with plantings of 45,000 ha in 2000 on the neutral to alkaline, fine textured soils of the low rainfall eastern sector of the crop belt, largely as a replacement for field peas (Turner *et al.,* 2001). The main production areas are shown in Figure 3.10.

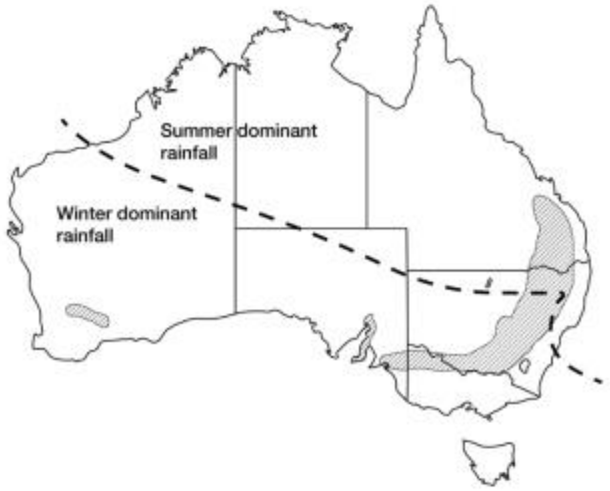


Figure 3.10 Australian chickpea production areas (after Knights, 1994; and Pulse Australia, 2001)

They have an advantage over field peas as they stand well at harvest and do not pose the same harvesting problems, so that further substitution is likely in all suitable production areas. In both southern and northern areas, chickpeas are grown as a valuable cash crop in rotation with temperate cereals. In the northern region, they may also be grown in a rotation following summer crops such as maize, sorghum or sunflower, provided soil water content at planting is adequate to support the crop through spring flowering and grain filling (Knights, 1994). The crop is best suited to the heavier soils of the wheat belt, provided they are well drained, while nodulation problems limit their production on soils with pH below 5.2 (Macrae, 2002). If grown under irrigation, even short periods of waterlogging can result in severe damage and yield loss (Slatter and Lucy, 2002). On a world scale, chickpeas are the most important grain legume crop of semi-arid regions. They are adapted to dry, short season environments and set seed successfully under moderately high temperatures, enabling later sowing than the other temperate grain legumes. Chickpeas also suffer less from flower drop and pod abortion during hot spring weather (Simmons, 1991) and are able to maintain pod and leaf photosynthesis even under terminal drought (Turner *et al.,* 2001). Research at a number of sites in Queensland has shown that chickpeas can emerge from sowing depths as deep as 15 cm without yield penalty. This will enable the crop to be sown on time, into stored soil moisture, rather than wait for rain in a dry autumn, and could provide a crop opportunity in an otherwise adverse season such as 2002. Planting time ranges from April to August and early sowing times produce the highest yields, but predispose the crop to a higher risk of *Ascochyta* blight outbreak. Although only recently (1996) reported in Australia, *Ascochyta* blight is now the most serious disease of chickpea in all production areas, particularly in Western Australia. Several new potentially resistant lines of both *desi* and *kabuli* types are currently under evaluation, but it will be some years before commercial cultivars are released

(GRDC, 2002a). Chickpeas are particularly sensitive to *Phytophthora* root rot in wet years in the northern region, although three resistant cultivars are now commercially available. The foliar diseases *Botrytis* mould, *Sclerotinia* stem rot and *Phoma* blight cause serious problems under high rainfall in the southern areas. Control or avoidance involves cultivar selection, clean seed, fungicide seed treatment, paddock selection, residue management including isolation from the previous year's chickpea paddocks, and application of foliar fungicides. All of these strategies, except foliar fungicides, have to be implemented before sowing (Knights, 1994). Fungicides are applied as a preventative 3-4 weeks after emergence, before the disease becomes established, and regular follow-up applications are necessary if the disease becomes evident or if wet conditions develop during or after flowering. Early harvest, with the aid of desiccation (spraying out when 50-60% of pods will rattle), will minimise the risk of rain damage, improve seed colour and help spread the time of harvest. If harvest is delayed (the crop has traditionally been harvested after the wheat crop), significant yield and quality deterioration can occur from weathering, resulting in pod drop, tougher pods that will not thresh, increased lodging, grain cracking if dried below 13% moisture, and grain quality downgrading through discolouration of seed coats (Birchall *et al.,* 2001).

FABA BEANS

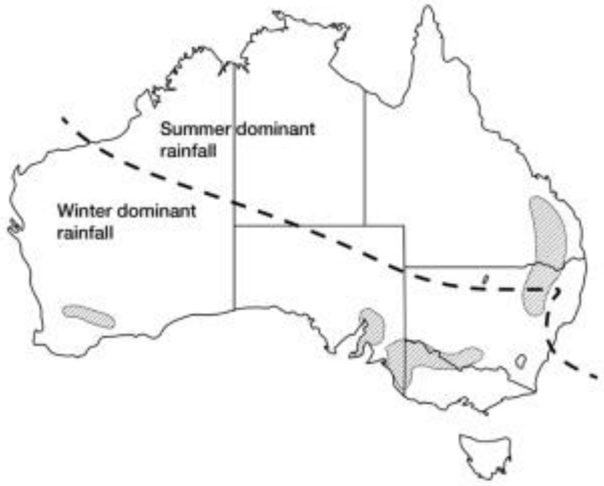


Figure 3.11 Australian faba bean production areas (after Hawthorne, 1994; and Pulse Australia, 2001)

There are two types of commercial crops produced from the species *Vicia faba*, the large seeded broad bean and the smaller seeded faba bean. Broad beans have been produced on a small scale as a culinary crop for many years and are a common home garden vegetable. Commercially, they are produced on a limited scale for the canning and fresh markets, but were initially restricted by the limited adaptability and disease susceptibility of the single available cultivar, Aquadulce. Over 80% of Victorian production is now exported for human consumption, with the principal cultivar for this purpose, Ascot, having excellent seed coat quality but lower yields than the more disease susceptible cultivars such as Fiesta (Raynes, 2002). In the northern region only 35-40% of harvested grain meets the human consumption grade criteria (Serafin *et al.,* (2002). Faba beans are smaller seeded types that are moderately tall, erect and easy to plant and harvest with conventional cereal machinery. They are the most tolerant of the grain legumes to heavy but well drained soils prone to temporary waterlogging, and are the best suited to irrigated production. They are well adapted to neutral to alkaline soil types and perform poorly on acid soils of pH 5.2 or less, because of nodulation failure (Macrae, 2002). High yields have been obtained on the alkaline cracking clays of the northern New South Wales and southern Queensland wheat belt, where faba beans are now well established in rotations with both winter and summer crops. Soils with compacted, acid or alkaline subsoil layers that limit taproot penetration result in poor root development and water and nutrient stress, particularly in dry springs (Hawthorne, 1994). Initial interest in the crop was centred on heavy alkaline soils in the South Australian wheat belt, where trial plantings showed high yield potential and led to the registration and release of the cultivar Fiord in 1982. This was the only commercial cultivar available until the mid-1990s and its late maturity and disease susceptibility resulted in low yields, particularly in the northern region, where its poor adaptation to high spring temperatures and water stress was a major constraint. Total Australian area sown in 2001 had increased to 175,000 ha, producing 268,000 t at an average yield of 1.53 t/ha with South Australia (70,000 ha, 1.71 t/ha) Victoria (55,000 ha, 1.45 t/ha) and New South Wales (37,000 ha, 1.48 t/ha) the major producing states (Figure 3.11). South Australian yields were consistently higher than the other states over the 5 years 1997-2001.

Interest in the crop for fine textured, more alkaline soils in Western Australia has been renewed by the availability of cultivars with multiple resistance to the main diseases (Hawthorne, 1994). Industry development in the early years was limited by crop failures through disease, particularly Chocolate Spot (caused by a complex of *Botrytis cinerea* and *B.fabae*), *Phytophthora* root rot and *Ascochyta* blight in all production areas, while rust and viral diseases have also been significant constraints in the more recent northern growing areas. Expansion was initially limited to low to medium rainfall areas where these diseases were less prevalent, and subsequent spread throughout the southern wheat belt and into the northern summer rainfall region has been possible only through improved cultivars, better agronomic management and intensive use of fungicides.

The release of the first cultivars with resistance to either Chocolate Spot or *Ascochyta* blight in 1998 stimulated renewed interest in the crop and two cultivars with moderate resistance to both now account for the majority of sowings. New cultivars with good to high resistance to both diseases are likely to be released by 2003 (GRDC, 2001). Early sowing produces the highest potential yields but greatest danger from virus diseases and Chocolate Spot, as vigorous early vegetative growth produces dense canopies that are most at risk in spring, because the microclimate within the crop canopy is more important than ambient temperature in triggering outbreaks (Hawthorne, 1994). Excessive vegetative growth, wet conditions and suitable temperature (15-20^{o}C) and relative humidity (>70%) favour outbreaks, as do stem frost damage and inadequate fertiliser. Disease control requires preventative sprays beginning 4-8 weeks post-emergence, with 4-6 sprays typical for commercial crops. Late sown crops are typically short with low yields and small grain size, but are less limited by disease. Wet weather at crop maturity will cause grain discolouration and quality downgrading. Actual planting time is a compromise between yield potential and the growers' attitude to disease risk management. Early (May) sowing is necessary, however, in low rainfall areas, on wetter soils and on soils of low fertility or acid reaction, in all cases to allow sufficient crop development to maximise yield potential (Serafin *et al.,* 2002). Because the crop is cross-pollinated, grain yield can be boosted by the presence of bees during flowering. High temperatures and water stress during flowering and grain filling can severely limit yield, and early sowing in areas prone to these conditions in spring is essential to limit yield loss. Tolerance to frost, cold wet weather and waterlogging is superior to that of field peas, lupins or chickpeas, and faba beans are an effective substitute for those crops under these conditions (Hawthorne, 1994).

LENTILS

Lentils (*Lens culinaris*) are a relatively new commercial crop to Australia and the industry is expanding steadily as new and better adapted cultivars become available. Planted area has grown from 2400 ha in 1994 to 190,000 ha in 2001, with 100,000 of this in Victoria and 80,000 in South Australia (Figure 3.12). Much smaller areas of around 5000 ha each were planted in southern New South Wales and Western Australia. Production in 2001 increased by over 60% on the total 2000 crop.

The most successful production area to date has been the Wimmera region of Victoria. Yields have been very variable and grower acceptance of the crop was slow until new cultivars and better definition of suitable production areas has occurred. Disease management and yield stability is still the major focus for lentil improvement in Australia. Market opportunities exist for both import replacement and a sizeable potential export trade. The crop is produced primarily for human consumption and its low yields and premium prices largely preclude its use in stockfeed, other than with low quality grain.

There are two distinct lentil types, based on seed size and colour, grown in Australia:

- green lentils, also known as large or Chilean lentils, which have a green seed coat, yellow cotyledons and seed size from 6 to 8 mm in diameter and weight of 6-8 g/100 seeds. Laird, a very late maturing Canadian cultivar, was the basis of the initial green lentil industry. Green lentils are cooked whole;
- red lentils, also known as small or Persian lentils, are sold as a split product for cooking and have red cotyledons. Seed size is smaller (4-6 mm diameter, 3-4 g/100 seeds) and the main cultivars Callisto and Kye, on which the local industry has been based, are both selections from imported material (Hawthorne, 1994).

Early growth is erect but slow and the crop is a poor competitor with weeds, particularly broadleaves, for which limited herbicide options are available. Broadleaf weed control should begin well before lentils are to be sown to minimise infestation, and paddocks with a history of broadleaf weed infestation should be sown to other crops. Lentils branch profusely, are thin stemmed and typically lodge in spring. Because of their small size and lodging, they should only be sown in paddocks with a flat surface free of stones and trash (Materne and Brouwer, 1996). Pods are carried on most of the above ground plant and harvesting has to be done with the comb on the ground to pick up all of the plant, resulting in accelerated wear and tear on machinery (Reithmuller *et al.,* 1999). They are indeterminate and flower over a protracted period where spring moisture conditions permit. Individual plants as a result simultaneously bear the whole range from developing flower buds through to mature, two seeded pods. Late spring moisture stress will terminate further flowering, enabling harvest of mature pods without delay. However, in wet springs, flowering may continue and growers may have to windrow or desiccate the crop to enable harvest. If not, harvest delays will result in yield loss through shattering of mature

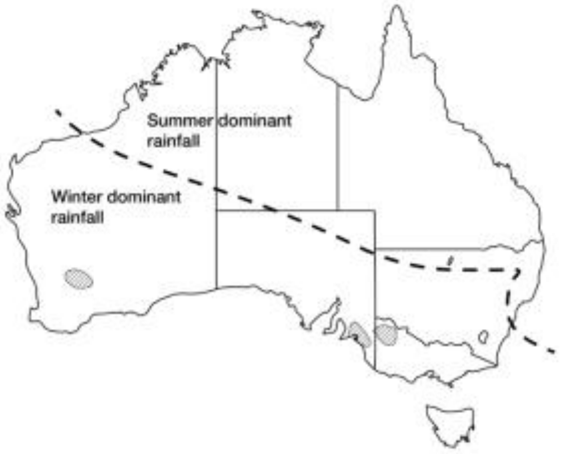


Figure 3.12 Australian lentil production areas (after Pulse Australia, 2001)

pods. Rain on mature pods can cause seed discolouration and downgrading to stockfeed grade. Lentils are best suited to medium rainfall (400-500 mm) areas and are poorly adapted to drier or wetter environments. In low rainfall areas, growth is limited and the resulting plants are often too small to be effectively harvested. In wetter areas, disease and waterlogging can result in complete crop failure. They are intolerant of waterlogging and require well drained loams to clay loams with a pH range of 6 to 8. They are poorly adapted to acidic (pH<5.5) and light sandy soils (Hawthorne, 1994).

Lentils are susceptible to a range of diseases which can cause complete crop failure. The most important are caused by *Ascochyta lentis* and *Botrytis cinerea*, the latter in common with faba beans. Botrytis Grey Mould (BGM) is the major disease, with yield losses in some South Australian areas exceeding 50% in 2001. Three new cultivars with better resistance to BGM have been commercially released, but effective control requires, in addition, a management package that includes seed treatment, not planting near lentil, vetch or faba bean stubble, a range of sowing times, and delayed sowing and reduced sowing rate, in each case to constrain vegetative growth and biomass production pre-flowering (GRDC, 2002a). Rust, the root rot complex caused by *Phytophora/Pythium/Sclerotinia* and viral diseases can also be devastating. Insect pests, particularly *Helicoverpa* during podding in spring, require close monitoring and timely spraying to limit yield loss. The recent release of two new, better adapted red lentil cultivars for Western Australia is likely to stimulate grower interest in the crop on heavier, neutral pH soils in suitable rainfall areas and production is projected to rise to 10,000 tones by 2005.

VETCH

Three species, *Lathyrus sativus, L.cicera and L. ochrus* show potential as grain and forage crops in rainfed farming systems in the Mediterranean-type climatic zone of southern Australia. Early studies in southern Australia showed that all three species had good adaptation and produced greater grain yields than a locally grown vetch, *Vicia sativus*. They also had slower winter but higher spring growth rates than field pea, producing up to 12 t/ha of biomass. All have a long history of production in Asia, North Africa, the Middle East and southern Europe as forage and grain crops (Siddique and Loss, 1996). Australian production to date has been mainly for hay and as green manure, although a new cultivar, Morava, is showing potential as a high protein pig feed grain. Of the three, *L.sativus* (grasspea or common chickling) has considerable potential as a grain crop for both human consumption and stockfeed. It is a particularly hardy legume, resistant to drought and tolerant of waterlogging during the vegetative phase. The grain contains a neurotoxin (ODAP) that causes a condition known as lathyrism, a paralysis of the lower limbs in animals and humans when the grain is consumed as a major part of the diet for 3-4 months (Siddique *et al.,* (1996). Recent research in Western Australia has resulted in the development and release of the first low-ODAP *L.cicera* cultivar, and it is expected that a low-ODAP cultivar of *L. sativus* will be released in the near future. Current lines of *L. cicera* are early flowering, endowing them with wider adaptability in water limited environments than the later flowering *L.sativus*. Agronomy of the crop has been studied in Western Australia, South Australia and Victoria in low to medium rainfall environments, to which it appears well adapted (CLIMA, 2001). Australian production has increased since 1994 from 26,000 ha to 62,000 in 1999, then declining to 32,000 in 2001. The grain produced has largely been for stock feed and as seed for forage, hay and green manure crops, but the increasing availability of low ODAP cultivars will enable production as a stock feed grain and, potentially, as a grain for human consumption.

Tropical and Sub-Tropical (Summer) Crops

Production principles for summer crops also focus on frost escape, water availability throughout the growing period, and minimization of water and high-temperature stresses during flowering and grain filling. The principal production strategies to minimise climatic constraints are cultivar selection, planting time and, to a lesser extent, planting rate. The growing season is generally delimited by temperature, coinciding with the end of the frost period and a soil temperature rise to 12 to 16^{0}C, depending on species adaptation, for successful establishment. The end of the growing season is determined by the onset of autumn frosts and, provided grain has reached physiological maturity, subsequent frosts may actually assist in hastening grain drying and crop ripening for harvest. Species vary in their low-temperature tolerance - sunflower, for example, is frost tolerant up to the eight leaf stage, while rice is much more low-temperature sensitive, with a minimum temperature tolerance of 13^o-15^{o}C during the critical panicle initiation stage, and a total production period considerably shorter than the frost-free period for the location. All are typically SD plants, but with the exception of soybeans, cultivars of all species exhibit little photoperiod response. Hence the suitability of any environment is set by the length of the period of suitable temperatures for growth and development, provided adequate water is available. The absolute length of the growing season is set by the frost-free period, but the actual length is usually less than this because of the lag in spring soil temperature rise to the minimum required for establishment. The temperature delimited growing period in southern regions is generally too short for production of all but early maturity cultivars with relatively low yield potential. The large scale production of summer crops for grain is thus, even under irrigation, generally restricted to areas north of the New South Wales-Victoria border.

Seasonal Conditions and Production Strategies

Summer crops grown in Australia are generally well adapted to the seasonal production environment (Table 3.7). They are planted from early spring to mid-summer and undergo vegetative growth in long days and warm to hot temperatures through summer. With the exception of soybeans, floral initiation occurs after accumulation of the necessary heat units for the cultivar. Subsequent inflorescence development occurs under declining daylength, temperature and solar radiation through late summer and early autumn. Pollination (anthesis) and grain development subsequently occur under a combination of declining temperatures and, frequently, increasing water stress. Within this environment, production strategies are governed by water availability for planting, adaptation of the species and cultivar being grown, length of the frost free period, suitable soil temperatures for establishment, suitable ambient temperatures for growth and development, and average seasonal rainfall and temperature conditions for the production period. A typical production calendar is shown in Table 3.7.

Crop and cultivar selection. All commercially produced summer crop species have a range of cultivars varying in maturity from early (typically 3 to 3.5 months) to late (5 to 6 months). Cultivar selection is based on average seasonal temperature patterns, expected water availability during critical stages of development, and other factors such as land preparation in multiple cropping or row-crop systems. Irrigation availability greatly increases flexibility in cultivar selection and in general allows the use of late maturing, full-season cultivars with higher yield potential than shorter season ones.

Table 3.7. Typical calendar of operations and development stages for summer crops in Australia.

SPRING			SUMMER			AUTUMN		
Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
PLANTING							HARVESTING	
Establishment				Flowering				
	Vegetative Growth					Grain Filling		
			Floral Initiation				Maturity	

In these situations, the length of the growing season is defined by temperature conditions. Cultivar selection is based on the timing of grain filling, to avoid frost prior to physiological maturity in late autumn/early winter. In temperate southern New South Wales and northern Victoria, the higher yield potential of full-season cultivars may be offset by harvesting difficulties resulting from late autumn-early winter rainfall, and earlier cultivars may be chosen to minimise this risk. Earlier cultivars may also be used in multiple cropping systems, where the changeover between summer and winter crops constrains both planting and harvest times for each. Under dryland (rainfed) conditions, summer crops are often grown on an opportunity basis, particularly in the northern region of New South Wales and Queensland. In these areas, inadequate fallow-stored soil water for planting of winter crops in autumn may result in the fallow being maintained through to late spring and a summer crop being sown instead, provided the soil moisture profile has filled in the extended fallow. Cultivar selection for the summer crop then depends on soil water availability: if still inadequate in late spring-early summer (November-December), early to mid-season maturity cultivars would be needed for a successful crop finish before the onset of autumn frosts. In these dryland situations, cultivar selection reflects the availability of soil water and, if this is inadequate in early spring, the timing of effective planting rains and thus length of the potential growing season.

Planting time. The planting time for summer crops is determined by a combination of cultivar maturity, soil water availability, frost risk, soil temperature and ambient temperature.

(i) *Cultivar maturity* Cultivar maturity is an important determinant of planting date as it establishes the length of the growing season required before low temperatures or frost limit or curtail growth. With full-season (late maturing) cultivars, planting must be done in the early part of the season to enable the crop to reach physiological maturity before the onset of autumn frosts. Early maturing cultivars provide much greater flexibility in planting date and can be planted up until January, if seasonal conditions dictate.

(ii) *Frost risk* Most summer crops are frost sensitive at all growth stages, and in general terms the production period is delimited by the length of the frost-free period. Some species such as sunflower are frost tolerant in early growth and can be planted 6 to 8 weeks before the average date of the last severe spring frost, without yield penalty. Maize also shows some tolerance early in growth, where the stem apex appears to be insulated by the soil and basal pseudostem in the early stages of growth.

(iii) *Soil temperature* With the exception of sunflower, which can germinate at soil temperatures as low as 8^0C, all summer crops require minimum soil temperatures of 15-16^0C for rapid germination and successful establishment. Planting may often be delayed well beyond the average date of the last severe frost, because of the lag time for soil temperature to rise to acceptable levels. The planting of temperature-sensitive crops such as cotton is delayed until soil temperature reaches 16^0C *and is rising* – a brief period of hot weather sometimes triggers a 'false start' and a subsequent drop in soil temperature post-planting may result in patchy establishment and the necessity to replant. The standard for soil temperature measurement is the 8.00 am EST reading at 10 cm soil depth.

(iv) *Ambient temperature* The length of the growing season for many summer crops is set by the length of the period of suitable temperatures for active growth, rather than the frost-free period. For the start of the season, this factor is usually less important than soil temperature in determining the planting time, but can be a factor where cool weather follows a hot early season period, where soil temperature may have allowed planting. Slow growth under subsequent cooler temperatures may result in patchy establishment and slow crop development.

(v) S*oil water status* Starting soil water availability is critical to successful crop establishment. Under rainfed conditions, planting may be considerably delayed by inadequate soil-stored water and erratic early season rainfall. Routine determinations of available soil water may be made with hand probes or sensing systems and, where significant delays occur, a change to an earlier cultivar may be necessary. In some cases, the summer crop plans may be abandoned and the fallow extended through to autumn in preparation for a winter crop. Under irrigation, a pre-sowing watering is often used to establish sufficient water reserves for crop establishment. This practice is preferable to that of 'watering up' by post-sowing irrigation, particularly on soils prone to surface crusting.

Summer Cereals

The summer cereals grown in Australia are maize, sorghum, rice and millet. Rainfed maize, sorghum and millet production are largely restricted to the summer-dominant rainfall zones of northeastern New South Wales and southern Queensland, although maize is also grown under irrigation throughout the irrigated inland areas of Queensland, New South Wales and northern Victoria. Irrigated Victorian maize is largely limited to sweet corn for human consumption and to silage for the dairy industry. Rice is grown only in the Riverina region of southern New South Wales and northern Victoria. Although less important in a national sense than the winter cereals, all have significant regional importance. All four are annual, summer-growing grasses of tropical origin and can generally be regarded as modified SD plants, with limited photoperiod response evident in commercial cultivars.

MAIZE

Maize is a relatively minor crop in Australia, ranking 14th in order of sown area of field crops in 2001, when 89,000 ha were sown. While the area sown has steadily declined from a peak of 168,000 ha in 1910, production has not fallen to the same extent, with New South Wales yields in 2001 more than three times those of 1910. A significant area (up to 10,000 ha) is also sown for silage for the dairy and feedlot industries, while silage is an option for grain crops threatened by severe water stress after anthesis.

Production is almost entirely restricted to New South Wales and Queensland, with small areas (1-2000 ha) sown in Victoria and in the Ord River Irrigation Area of northern Western Australia in 2001 (Figure 3.13). Production areas have remained stable since 1996, averaging 27,000 and 33,000 ha for New South Wales and Queensland respectively. Yields from New South Wales crops, however, are more than double those of Queensland, averaging 7.4 t/ha compared to Queensland yields of 3.3 t/ha over the 1997-2001 period. The main production areas are the Riverina, central Macquarie Valley, North West Slopes (particularly the Liverpool Plains) of New South Wales, and the Darling Downs, South Burnett and Atherton Tablelands of Queensland. Production in New South Wales has shifted significantly since 1988, with rainfed production on the North Coast declining rapidly with rationalisation of the coastal dairy industry, where it was traditionally grown as an on-farm feed grain (Colless, 1994). Production is now centred on inland irrigation areas, with the Riverina and Liverpool Plains now accounting for the majority of New South Wales output (Grain Yearbook, 2002).

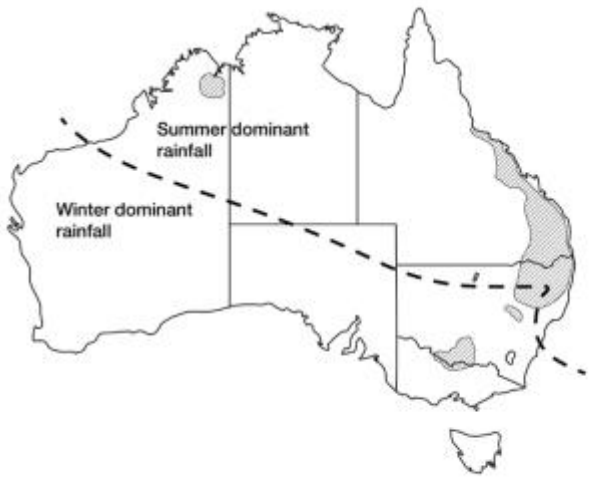


Figure 3.13 Australian maize production areas (after Kelleher, 1994; Colless, 1994 and Grain Yearbook 2002)

Maize exhibits a diversity of types that enable its adaptation to a wide range of climatic conditions, although the main production areas are typified by warm to hot days and cool to warm nights. Production in Australia is limited by high temperatures combined with low relative humidity post-anthesis, rather than by the length of the temperature-delimited growing season. Rainfed production is conducted in the better rainfall eastern areas of the northern slopes, the eastern coastal and tableland areas of New South Wales and Queensland, and to irrigated inland areas. Rainfed maize is typically replaced by sorghum in the drier, hotter, western areas of the northern region. Successful establishment requires a minimum soil temperature at 8 am EST of 12°C for 3 days and rising. Emergence at 12°C will take up to 14 days, compared to 4-5 days at 25°C. The rate of development from planting to anthesis is governed almost entirely by growing point temperature, which is determined by soil temperature for more than half the vegetative growth phase, as the growing point remains at or below the soil surface. Subsequent growth and progression through development is governed by ambient air temperature when the growing point extends above soil level. Maximum yield potential is attained where warm days of 25 to 30°C are combined with cool nights, resulting in a moderate rate of development and thus a long growth period, large plant size and high yield potential (Duncan, 1975). In hotter areas, accelerated development results in smaller plants, earlier maturity and lower resultant yield potential. Where high temperatures (up to 38°C) coincide with low relative humidity during the critical tasselling and silking (anthesis) phase, seed set and yield can be substantially reduced by pollen and silk destruction. The crop is cross pollinated, and the extruded stigmas and air borne pollen are very susceptible to desiccation (blast). For this reason, sowing strategies aim at avoiding the timing of anthesis between late-December and mid-February, when these conditions are most likely in the main production areas. This is achieved by sowing early to mid season cultivars either early (soil temperatures permitting) so that anthesis occurs before mid-December, or late, so that anthesis occurs after mid-February and the crop can still mature before autumn frosts. Full-season hybrids are sown in spring, as early as soil temperatures permit, and require adequate water availability throughout the production cycle. Maize is a SD plant, but as daylengths in the main production areas are less than the critical daylength of between 14 and 15 hours, no evident response to photoperiod occurs and development is controlled by temperature. As a C_4 plant, photosynthesis accelerates as light intensity increases up to very high levels. Shading can limit yield, and can be caused by interplant competition in dense canopies, or by cloudy conditions in northern summer rainfall areas. Cloud cover and reduced light intensity may in fact limit photosynthesis and growth rates on the Atherton Tableland. The crop is sensitive to water stress throughout the growing cycle, with substantial yield reductions (6-8% per day of stress) from stress during flowering and pollination. The effects of later stress are smaller but still significant, right through to physiological maturity (Colless, 1994).

The interval from anthesis to harvest maturity varies widely between cultivars, with considerable variation in length of the anthesis to physiological maturity and physiological maturity to harvest ripeness stages. The latter essentially involves grain drydown, and its duration depends on temperature and humidity. Declining autumn temperatures, combined with moderate to high humidity, often significantly delay drying and harvest into late autumn-early winter, particularly in the southern Riverina region. Wet soils may also seriously hamper harvesting operations, particularly in inland irrigated areas (Dale and Colless, 1990). While grain drying is weather dependent, there is also considerable genetic variation in the rate of grain dry-down under the same conditions.

Production in Australia until the 1950s utilised tall, locally adapted open-pollinated cultivars, with moderate yields but high yield stability. Introduction of the first hybrid from the US in 1947, and subsequent establishment of both public and private hybrid breeding programs in New South Wales and Queensland, led to the rapid transition to hybrid cultivars in all production areas. Little open-pollinated maize is grown today. Two distinct hybrid types were developed, namely:

- tall, late maturity (24 to 28 weeks) types resistant to a range of diseases and insect pests endemic to the humid coastal production zone. These were developed from the adapted open-pollinated cultivars on which production was originally based;
- short, high yield potential, early maturing (20 weeks) hybrids of US origin, or developed in Australia from US inbred parents. These are grown in the inland areas of New South Wales and Queensland, where their early maturity matches the frost-free growing season. Production of these types in coastal regions is limited by their susceptibility to endemic diseases and pests.

The latter now account for the great majority of maize produced, with the substantial decline of the coastal maize industry (Colless, 1994).

GRAIN SORGHUM

Almost the entire sorghum crop is produced in Queensland and New South Wales, with Queensland the dominant producer in terms of area sown (500,000 and 270,000 ha respectively for Queensland and New South Wales in 2001), but not in terms of yield, Queensland and New South Wales averaging 1.95 and 3.00 t/ha respectively over the period 1996-2000. The lower yields in Queensland reflect the drier environment compared to that in the main New South Wales production areas. Annual sown area over the same period averaged 395,000 ha in Queensland and 181,000 ha in New South Wales, and remains reasonably stable over time, fluctuations between years reflecting seasonal and market conditions. Production is centred on the Central Highlands and Dawson Callide regions of central Queensland, the Lockyer Valley, Burnett/Northern Downs, Central and Western Downs of southern Queensland and the northwest Slopes and Plains, including the Liverpool and Breeza Plains, of New South Wales. Small areas of 1-2000 ha are also grown in the Ord River area of Western Australia (Grainco, 1994). It is also grown on a limited scale under irrigation in inland areas, where it provides an effective disease break crop in cotton rotations (Figure 3.14).

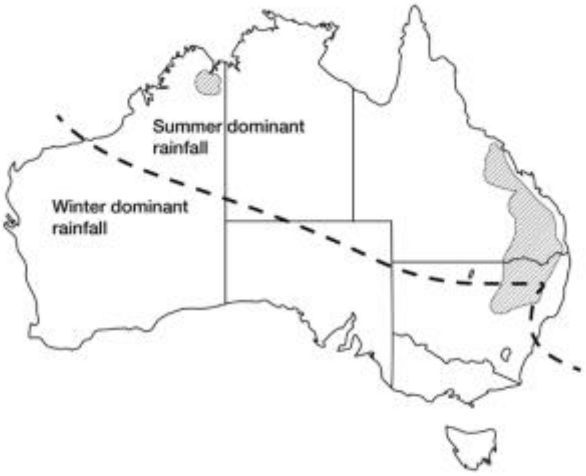


Figure 3.14 Australian sorghum production areas (after Kelleher, 1994; and Grainco, 1994)

Sorghum is a crop of tropical origin which has long been renowned for its tolerance of high temperature and water stress (Doggett, 1970), although the bulk of the crop has been produced in sub-tropical and temperate regions from adapted hybrid cultivars developed by intensive breeding and selection programs (Anderson, 1979). Adaptation to temperate environments has resulted in a significant loss of photoperiod (SD) sensitivity. As a result, the rate of development is largely governed by temperature, and accelerates as temperatures increases from 20^0C to 35^0C, reducing the duration of individual development phases as well as that of the total growing cycle. Commercial cultivars are sensitive to temperature extremes, low soil temperatures (<16^0C) at sowing inhibiting germination and emergence, while high temperatures (>38^0C) at panicle emergence and anthesis, particularly when combined with low atmospheric humidity, result in reduced pollen viability and a substantial reduction in seed set and potential yield. Some degree of acclimation occurs in sorghum in continuously high temperatures, such that the effects of short-term heat waves, which have severe effects on plants grown in temperate regions, are not so pronounced.

Sorghum is more tolerant of water stress than maize, which it replaces in the hotter, drier inland margins of the main production areas (Hayman *et al.,* 2002). It is grown largely under rainfed conditions, where water stress occurs frequently, and develops an extensive root system which, depending on soil physical properties, may extract water down to a depth of one metre. It has both sensitive stomatal control, which enables effective internal control of transpiration water loss, and a C_4 photosynthetic pathway that enables photosynthesis to continue even when its stomates are partly closed. Its high photosynthetic efficiency under stress, combined with an extensive root system, enable it to successfully exploit the often limited available soil water in the rainfed environments where it is grown world-wide (Doggett, 1970). Dryland production occurs in the semi-arid zones of northern New South Wales and southeastern Queensland

It is frequently grown as an alternative opportunity crop to wheat in northern areas, when inadequate fallow water storage prevents or significantly delays wheat planting. It is also grown as a summer rotation crop to control major weeds of wheat, particularly wild oats. In recent years it has become the most important summer crop component of strip cropping systems that are rapidly substituting for broadacre production of wheat and other crops in erosion-prone summer-dominant rainfall areas. US hybrids were first introduced in the early 1960s and resulted in a rapid increase in sown area, particularly in Queensland. Despite their high yield potential, average yields in Australia, at less than 2 t/ha, are erratic and low. This has been attributed to expansion into previously unsuitable marginal areas with low yield potential and low water availability (Henzell *et al.,*1985). Within the extensive maturity range of hybrids available in Australia, early to mid-season maturity lines have proven most successful because of limitations on length of the growing season imposed by water, temperature, disease and insect pests.

Besides its production as a grain crop, forage sorghums and sorghum-sudan grass hybrids (e.g. Sudax) are an extremely important source of forage and are widely grown beyond the grain production areas for forage, silage and hay, particularly in the coastal areas of New South Wales and Queensland.

MILLETS

Millets are grown on a fairly small scale in Australia for the production of grain and forage. The term ‘millets’ embraces a range of species (Table 3.4) that feature considerable tolerance to heat and water stress when compared to other cereals. Pearl millet (syn. bulrush millet) in particular produces good grain yield in regions too hot and dry for other crops. They have potential in the northern grain belt for their adaptation to semi-arid areas as a result of their early maturity for forage, grain, or both (George and Buljan, 1998). Australian production for grain with a range of species (Table 3.4) is essentially for the birdseed market, and is unlikely to expand significantly beyond current production areas. Forage species, particularly Japanese millet and Shirohie, a selection from Japanese, have been grown as an early-spring sown crop in coastal districts for many years. Acceptance of pearl millet as a forage crop was limited until the release of semi-dwarf hybrids, which combine high productivity and easy grazing management, in the mid-1980s. They have gained acceptance as an alternative to the highly productive, but prussic acid containing, forage sorghums and sorghum-sudan grass hybrids in the main New South Wales and Queensland croplands.

RICE

Essentially a tropical crop, rice (*Oryza sativa*) is grown over a wide latitudinal range throughout the world, ranging from 49ºN to 35ºS, the latter extreme in southern New South Wales. Rice was produced in two distinct zones, the temperate, winter rainfall, semi-arid Murrumbidgee and Murray River valleys of the Riverina region in southern New South Wales and the tropical, wet summer, Burdekin River delta in northeastern Queensland. Production in the latter region ceased in the early 1990s and the industry is now limited solely to the Riverina (Figure 3.17). Total Riverina rice plantings in 2001 totalled 150,000 ha, for a total production of 1,200,000 t at an average yield of 8 t/ha. Grain yields are on average closer to

9 t/ha, among the highest in the world, and increased by approximately 20% from 1990 to 1997 (Farrell *et al.,* 1998). Eighty per cent of the rice produced is of medium grain *japonica* cultivars, while the remainder is of long grain *indica* cultivars, including fragrant rice. Short grain types are also produced specifically for the Japanese market (Lewin, 2002). Attempts to establish a commercial rice industry at other sites in the tropical and semi-arid regions of northern Australia, notably on the coastal plains east of Darwin and the Fitzroy and Ord River systems of northwestern Western Australia, have failed for a number of reasons, most of them being agronomic. Production is entirely under irrigation, with locally developed high yield potential cultivars well adapted to intensive cultivation. Highest rice grain yields are typically obtained in temperate zones, where dry summers with little cloud cover and high solar radiation levels are followed by mild early-autumn temperatures during ripening.

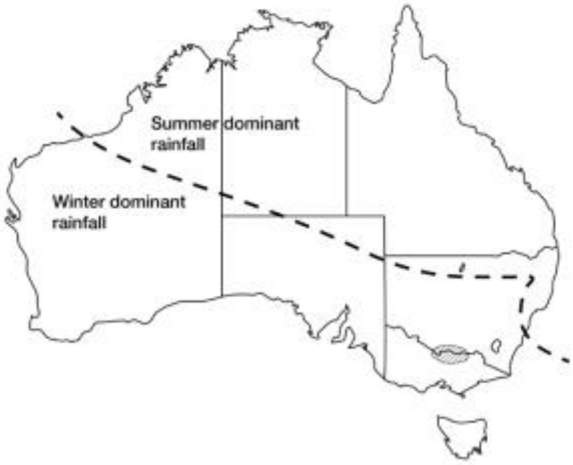


Figure 3.15 Australian rice production areas (after Kelleher, 1994)

Record and average yields in the Riverina are typically greater than those in the tropics, where summer rainfall and associated heavy cloud cover reduce solar radiation receipts. Although the high radiation received is conducive to high yields, the major control of growth and development, and ultimately grain yield, is the length of the growing season delimited by low spring and autumn temperatures. This problem is common to other temperate zone rice production areas of the world. Although rice is a crop of primarily tropical adaptation, it has a C_3 photosynthetic pathway, in contrast to maize, sorghum and millets. It requires relatively high (25^{0}C to 30^{0}C) temperatures for growth and development, although temperature requirements vary between growth stages. Low spring temperatures in the Riverina cause slow germination and distorted seedling growth, while temperatures in excess of 30^{0}C during establishment can restrict root penetration and anchorage. Minimum night temperatures of 15^{0}C or less, particularly if extended over 2 to 3 days during the panicle initiation to flowering period (December to early February in southern New South Wales), result in reduced panicle branching and massive pollen and floret sterility (Williams and Lewin, 1998). The type and extent of damage depends on the minimum temperatures attained and their timing relative to the critical development stages of the crop from panicle initiation through to flowering (Gunawardena *et al.,* 1998). In contrast, low temperatures during grain ripening are conducive to high grain yields through extension of the grain filling period, although evidence on this point is conflicting. The development of low temperature tolerant rice is a major focus of the New South Wales rice breeding program for the Riverina region.

The average length of the low temperature delimited growing season in southern New South Wales is 180 to 200 days, although that in the Murray Valley to the south is even shorter. In these areas, management strategies (in particular aerial seeding, which allows more rapid establishment and 10 to 14 days earlier maturity) have been used to shorten the crop growing season. Intensive plant breeding efforts have resulted in release of very early

(130 to 140 days) maturity cultivars, which are better adapted to the colder, shorter season Murray Valley and to the entire southern rice growing area, where the season is further limited by erratic spring and autumn rainfall (Coombs, 1994a). Erratic rainfall in spring may significantly delay ground preparation and sowing, while in autumn it may prevent machinery access for harvest. Consequently, cultivars with a shorter duration crop cycle impart greater flexibility and allow more reliable production. Recent research has shown 20% higher Radiation Use Efficiency (RUE) (conversion of intercepted solar radiation to biomass) in lines from the International Rice Cold Tolerance Nursery compared to Australian cultivars. Incorporation of higher RUE into Australian short season cultivars may enable higher productivity per day to compensate for the shorter growing season, so that current high yields could be maintained even with shorter growing seasons (Farrell *et al.,* 1998).

Summer Oilseeds

The summer oilseed crops grown in Australia are soybeans and sunflower. Two other summer crops, cotton and peanuts, are important sources of vegetable oils, although grown primarily for the cotton fibre and confectionery trades respectively. For convenience, peanuts have been included in this section as summer oilseeds. Production of summer oilseeds is restricted almost entirely to eastern Australia, in rainfall zones ranging from uniform distribution to summer dominant, with sunflower plantings extending into the drier inland margins.

SOYBEANS

Soybeans are a legume crop, well adapted to most soil types and to warm to hot areas with either reliable summer rainfall or the availability of irrigation. They were originally a relatively minor crop, restricted to rainfed production in the South Burnett and Darling Downs areas of Queensland, where sowings totalled less than 2000 ha per annum until 1968. Sown area subsequently expanded rapidly in both Queensland and New South Wales, peaking at 71,000 ha in 1989, but by 2000 it had fallen again to 48,000 ha. New South Wales is the major producer, with average plantings of 33,000 ha over the period 1996-2000, compared to the Queensland average of 19,000 for the same period (Figure 3.16). Small areas (2000 ha) are also planted in northern Victoria under irrigation. Yields are similar for all three states, averaging around 2 t/ha. The decline in soybean plantings since 1989 reflects competition from irrigated cotton and vegetable crops, (particularly in Queensland), the limited areas available with suitable temperature and either irrigation or reliable summer rainfall, and the lack of cultivars adapted to lower rainfall (Colton and Coombs, 1994). Replacement by cotton, as a more profitable irrigated crop in the northern region, has resulted in the southern New South Wales Riverina region becoming the

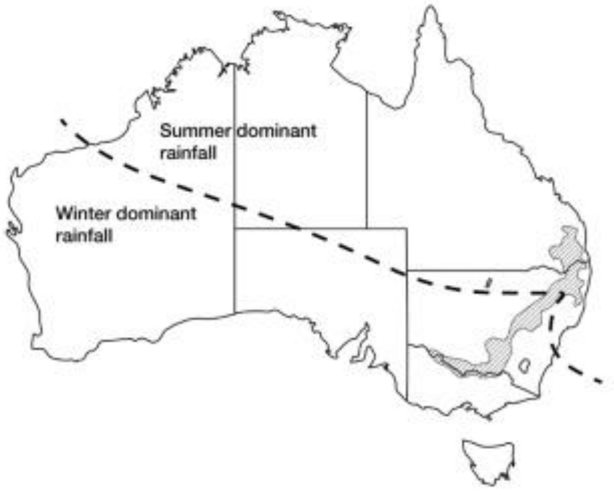


Figure 3.16 Australian soybean production areas (after Colton and Coombs, 1994)

dominant production area since the early 1990s. Production is predominantly under irrigation, the only significant rainfed production areas being on the summer-rainfall North Coast and Tablelands and Northwest Slopes of New South Wales. Rainfed production requires fallow stored soil water, with a full profile at planting, to offset unreliable autumn rainfall when crops are in the critical flowering-pod-filling phases. Intensive breeding programs have been conducted since the early 1960s in Queensland and the mid-1970s in New South Wales. The major focus of the New South Wales program was the development of early maturity, indeterminate cultivars for dryland production (Rose *et al.,* 1987). While that remains a major focus, more recent breeding programs are also concentrating on development of high value culinary lines, for which strong export market demand, approaching that for the oilseed crushing market, has developed. Breeding advances in Queensland using semi dwarf germplasm and the strategic deployment of maturity and long juvenile genes, indicate that the yield potential of irrigated soybeans can be doubled, to *c.* 7t/ha, and the optimum planting window widened to include all planting dates that allow 110 days of frost-free growth (James *et al.,* 1996).

The soybean plant is particularly sensitive to photoperiod, commercial cultivars being classified into 10 maturity groups on the basis of their relative SD requirement. In general, the photoperiod requirement is the critical factor in cultivar selection and requires correct matching of cultivar daylength requirements to that of the latitude and sowing date. Temperature is also a critical consideration in selection, with development controlled both by daylength and a complex daylength-temperature interaction. Successful cultivar adaptation occurs where flowering begins approximately 60 days after sowing. When sown north of its adapted region, a cultivar will flower early, producing a small plant with low-set pods with low potential, as well as harvestable, yield. The harvestable yield is set by the proportion of pods carried high enough above ground level to be picked up by the harvester. If sown south of its adapted region, it will flower late in autumn, produce excessive vegetative growth, and have a low yield recovery if subjected to killing frosts prior to maturity. These crops are also very prone to lodging and as a result harvest is slow and often very difficult. Cultivar selection on the basis of daylength requirement can also be modified by sowing date, planting arrangement and temperature, an interaction investigated on a wide latitudinal basis in eastern Australia. Because of their daylength sensitivity, new cultivar development tends to be regionally based and latitude specific, rather than the broader adaptation approach typical of breeding programs for other crops that show only moderate responses to daylength. As a result, individual soybean cultivars tend to be limited to a narrow latitudinal range (Colton and Coombs, 1994).

Soybeans require a reliable water supply from establishment until physiological maturity, followed by dry weather for grain drydown and harvest. They are highly sensitive to water stress, particularly during flowering, pod development and pod filling. Even with adequate soil moisture supply, high temperature-low humidity conditions can cause severe flower and pod abortion. Rainfall during grain drydown can cause disease problems, harvest delays and deterioration in grain quality. They are adapted to a wide range of soil types and require good drainage, but will tolerate temporary waterlogging although a yield penalty will usually result. Production on poorly drained soils predisposes the crop to *Phytophthora* root rot, to which it is particularly sensitive, and severe infestations can result in complete crop loss.

Temperature also imposes strict controls on growth and development, with minimum soil temperatures for germination and emergence of 13 to 15^0C, although values of 19^0C are desirable. Optimum temperatures for growth are 27 to 32^0C, while those during floral initiation, flowering and pod filling are complicated by interactions with daylength. It is tolerant of mild frosts at establishment and during grain ripening. Soybeans are well adapted to zero-tillage production, enabling opportunity dryland cropping as an alternative to fallow in favourable summer seasons in northern New South Wales.

Research priorities for the crop include better resistance to *Phytophthora* root and stem rots for inland areas, better tolerance to acid soils and pre-harvest weathering for coastal areas, earlier maturity for southern areas, and drought resistance and early maturity for lower rainfall rainfed production (Colton and Coombs, 1994). Development of well adapted culinary lines for human consumption to supply the high value export market is a recent high priority for all major production areas.

SUNFLOWERS

Sunflowers (*Helianthus annuus*) are a relatively recent commercial crop in Australia, the industry beginning in the early 1970s following the imposition of wheat production quotas in 1969. They quickly became the most widely grown oilseed crop, with record plantings of 295,000 ha in 1972, but then declined and are now ranked second to canola in annual sown area. Production is restricted to New South Wales and Queensland, with Queensland the dominant state (Figure 3.17). Queensland plantings in 2001 were lower than average at 64,000 ha, with 38,000 ha sown in New South Wales. Average sown area for Queensland and New South Wales over the period 1996-2000 was 85,000 and 39,000 ha respectively, with average yields of 0.93 t/ha in Queensland and 1.18 t/ha in New South Wales. Smaller rainfed areas are also planted in South Australia and northern Victoria and it is also grown under irrigation in the Riverina district of southern New South Wales. Sunflowers are adapted to a wide range of environments and were initially grown as rainfed crops throughout the northern New South Wales and Queensland cropping region, but the main production areas have now contracted to the Liverpool Plains of northern New South Wales and the Darling and Central Downs of Queensland, where production is almost entirely dryland.

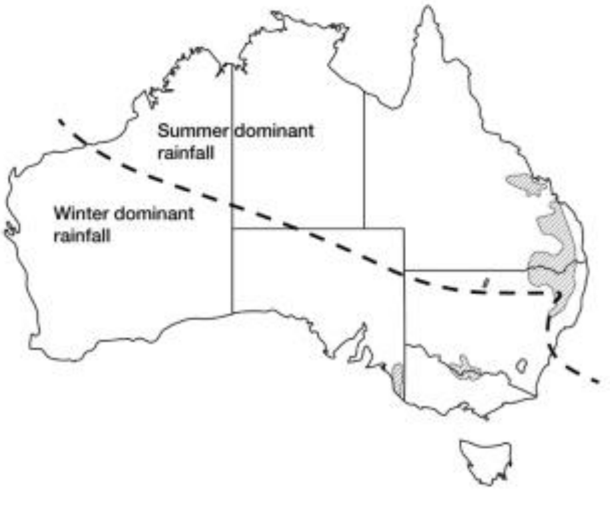


Figure 3.17 Australian sunflower production areas (after Colton and Coombs, 1994)

In these areas they are grown as rotation crops with rainfed cotton and sorghum, providing both a disease break and some soil physical conditioning by the deep taproot. They are also grown as opportunity crops when rainfall constraints result in a short summer growing season (Colton and Coombs, 1994). The industry is based on hybrid cultivars that were developed from mainly imported germplasm, and which show little daylength response,. The length of the growing period ranges from 80 to 160 days, and is almost solely controlled by temperature, provided adequate water is available. Variation in total length of the growth cycle is closely related to the cumulative Degree Days (°D) experienced. Summer plantings, where daily mean temperatures are considerably in excess of base temperature (1-7^{o}C, depending on cultivar), result in accumulation of the required ^{o}D in a shorter period than with spring plantings. Hence the length of the growing cycle is much shorter for summer-sown than for spring-sown crops. Individual cultivars exhibit relatively constant ^{o}D totals for development from sowing to maturity. Total ^{o}Ds required are the sum of those for the individual development stages sowing to emergence, emergence to head visible, head visible to first anther, first anther to last anther, and last anther to maturity (Dale, 1984). The longer growing period of early planted crops results from an extended emergence to head visible stage, such that very early (late winter) sown crops do not flower very much in advance of later (spring) sown crops. Sunflowers will germinate at relatively low (5-8^{0}C) soil temperatures, although emergence is retarded and may take up to 30 days, compared to 4 days at 24 to 27^{0}C (Shaw, 1991). Newly emerged seedlings are frost tolerant, withstanding temperatures as low as –6^{0}C at ground level. Frost tolerance is retained until the six to eight-leaf stage, although some leaf damage may occur. The ripening seeds are also frost tolerant, but between this stage and the young seedling stage the crop is frost sensitive. This frost tolerance at both ends of the growth cycle enables sowing to be carried out over a long period, allowing sowing when soil water conditions are most favourable. Sunflowers tolerate high temperatures during vegetative growth, but hot conditions at and after flowering can adversely affect pollination, oil yield and oil quality. Crops maturing in midsummer under high temperatures will suffer penalties in both oil yield and oil quality, the latter through a marked reduction in linoleic acid content of the oil. Production in better rainfall areas is mainly from medium to late maturity hybrids, planted either early (October) or late (December-January) to avoid flowering and grain filling during the high risk heat stress period (mid-January to late February). Late sown crops may be predisposed to *Sclerotinia* damage and should not be sown later than February. Short season cultivars are grown in areas with lower and less reliable rainfall. Optimum taproot development requires deep, well drained, medium to fine textured soils with good waterholding capacity and structure. Soils should be fertile and have pH values above 5.5 (Colton and Coombs, 1994). The crop is particularly sensitive to water stress during anthesis and early grain development, which will significantly reduce grain and oil yields. It has lax stomatal control and low water-use efficiency under restricted water conditions, but considerable progress has been made in developing more drought tolerant cultivars for Australian conditions. The research is based on incorporating higher Transpiration Efficiency (TE – biomass per unit of water transpired) germplasm into hybrid breeding programs and, to date, high TE hybrids have outyielded low TE ones by as much as 35% in drought stressed environments (Lambrides *et al.,*1999). Yield is closely correlated with photosynthetic leaf area during seed filling, and is adversely affected by water stress during the period 2 to 3 weeks before flowering as upper leaf expansion, and ultimately photosynthetic area during seed filling may be severely inhibited (Colton and Coombs, 1994). Earlier water stress has little effect on yield provided establishment was not affected. Successful dryland production thus depends on adequate water availability for establishment, and for the entire period from 3 weeks before flowering through to physiological maturity of the seed. A fully charged, deep soil profile, wet to 1.5 m depth, is the ideal prerequisite to planting, particularly in areas with unreliable later summer-early autumn rainfall (Dale, 1984). Good weed control is essential, as sunflowers are poor competitors, especially in the first 4 weeks after establishment. Although a C_3 plant, the deep taproot and high temperature tolerance during vegetative growth makes sunflowers a suitable replacement for maize in drier, hotter inland areas of the main production regions, where it provides an alternative to sorghum in the rotation. The small amount of crop residue remaining after harvest is a limitation in northern conservation farming systems, as it affords little soil protection against erosion during the subsequent fallow period.

Summer Fibre Crops

COTTON

Although cotton (*Gossypium hirsutum*) is grown primarily as a fibre crop, the seed after ginning (lint removal) is also a major source of edible vegetable oil, ranking second to soybeans in world oilseed markets. It has been produced in Australia since the early 1920s, initially only as a dryland crop in Queensland, where it reached a peak planting of over 30,000 ha in 1932. Since the early 1960s rapid expansion of irrigated plantings, to 116,000 ha in Queensland and 315,000 ha in New South Wales in the 2000-2001 crop year, has occurred (Figure 3.18). Dryland plantings peaked at 52,000 and 79,000 ha in Queensland and New South Wales respectively in 1998-1999, but subsequently declined to 40,000 and 42,000 ha in 2000-2001 (Dowling, 2001a). New South Wales is the largest producer, with around 75% of total plantings. The largest production areas are the Gwydir, Namoi, Macintyre and Macquarie River valleys of New South Wales. Highest yields are obtained in the northern region, from the Namoi in New South Wales to St George in Queensland. Earlier industries in the Murray-Murrumbidgee Irrigation Area of southern New South Wales and the Ord River valley of northwest Western Australia ceased production in the mid-1970s. The southern New South Wales industry failed because research yields were not achieved commercially, short growing seasons restricted production to short staple lines that had limited market demand, suitable soils with good internal drainage were lacking, production and transport costs were very high, and government funding for cotton research in the region was withdrawn (Dowling, 2001). Recent analyses showed ^{o}D summations for Hillston, in the Lachlan River Valley in southwestern New South Wales, were similar to those for Gunnedah, in the northern Namoi Valley. The combination of short season management techniques with the availability of new short season cultivars, suited to cooler regions, led to new interest in the crop from southern farmers and commercial plantings began at Hillston in the 1998-1999 season.

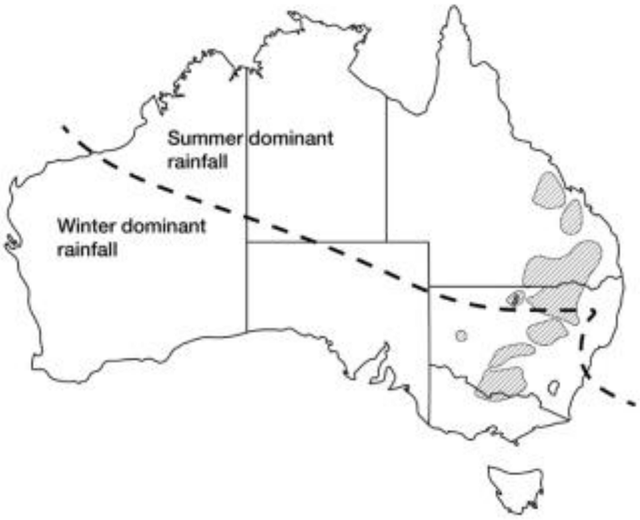


Figure 3.18 Australian cotton production areas (after Australian Cotton Yearbook, 2001)

High production costs and insect pressure led to closure of the industry in the Ord, but the release of transgenic Ingard cotton cultivars, together with new rotations with irrigated cotton as a dry season crop, will enable the industry to be successfully re-established there (Yeates and Constable, 1998). The high capital costs of land development for irrigated production led to renewed interest in rainfed production in northern New South Wales during the 1980s, and the dryland area sown has increased slowly but steadily. Excellent yields of over 5 bales/ha in the 1990/91 season stimulated confidence, but subsequent plantings have fluctuated with seasonal conditions, sown area falling from 131,000 ha in 1998-1999 to 82,000 ha in 2000-2001. Better yield performance under rainfed conditions has been shown to be associated with okra leaf type, but not with early maturity (Stiller *et al.,* 1998). Under irrigated conditions, however, cultivar maturity rating has a large effect on yield, accounting for up to 70% of the variation in lint yield in a series of experiments at Narrabri. Yield increased by 34.4 kg lint/ha for each day of increase in maturity, with later cultivars showing higher harvest index (HI), greater plant height and more nodes before the first fruiting branch. A full season okra leaf type extracted more water from deeper soil layers and had 20% greater water use efficiency (kg lint ha/mm evapotranspiration) than an early maturity normal leaf type (Stiller and Constable, 2001).

Cotton is well adapted to warm to hot, arid environments where it produces high yields as long as adequate water is available. Provided the water needs of the crop are met, growth and development are controlled almost entirely by temperature. Within limits, the higher the average seasonal temperature, the higher the growth rate and potential yield. Cotton is a C_3 plant, however, and temperatures can be too high for active growth and development. When daily maxima exceed 35°C, growth and development may actually be retarded and the linear relationship assumed between growth and temperature between 12 and 35°C no longer holds. Retardation of growth and development in situations where daily maxima frequently exceeds 35°C results in a higher total °D requirement (and longer growing period) than in locations with more moderate temperatures. For example, °D requirements from sowing to appearance of the first square vary from 510 to 695, with the higher values recorded in crops in hotter regions, particularly the Ord River in northwestern Australia (Milroy *et al.,* 2000). The base temperature for °D calculations is 12°C, below which all growth stops, and 'cold shocks' occur when temperature falls below 11°C.

Chilling injury or cold shock is of most importance during establishment and approaching squaring (flower bud formation) – when daily minimum temperatures fall below 11°C, growth and development the next day are retarded, regardless of the maximum temperature reached on that day. Development is thus delayed and yield potential significantly reduced. The probability of this occurring increases from north to south, southern areas having a much higher incidence of cool nights during the season (Constable and Shaw, 1988). On average, the accumulated °D summation required for flowering to occur is increased by 5.2 for each occurrence of a cold shock. Cold shocks are more frequent in the southern areas around Hillston than in the north, and can seriously retard establishment. For most production areas, they can even occur in mid-summer, in the middle of the growing season (Milroy *et al.,* 2000). The absolute length of the growing season is delimited by the average dates of last spring and first autumn frosts, but the major spring factor determining start of the season is soil temperature. Successful establishment requires a minimum soil temperature (10 cm soil depth, 8.00 am EST) of 14°C maintained for at least 3 days. At this temperature, complete emergence at Narrabri took 17 days and only 73% of seed produced surviving seedlings. At 18°C, results improved sharply to 5 days and 90% survival (Constable and Shaw, 1988). The development of the crop can be predicted from temperature data by °D summations, using a base temperature of 12°C (Table 3.8).

Table 3.8 Total ^{o}D for some phases of cotton development:typical values (after Constable and Shaw, 1988)

Phase	Total degree days	Days at 28/20^{0}C*
Sowing to final emergence	80	7
Sowing to squaring	505	42
Sowing to flowering	777	65
Flower to open boll	750	63
Total	2112	177

*Day/night temperatures

In general terms, length of the growing season and thus yield potential increases with distance north from the current southern limit (Hillston, in the Lachlan Valley) to the Queensland production areas. Planting time is critical in New South Wales, with a substantial and progressive yield penalty for crops planted beyond mid-October. Safe planting time then becomes a trade-off between waiting for favourable soil temperatures and planting before mid-October, with most New South Wales cotton plantings beginning in mid-September. Preliminary research on Ultra Narrow Row cotton (UNR), which was the focus of considerable research in the southern Murray and Murrumbidgee Valleys in the 1970s, has shown significant advantages over the conventional row crop systems on which the industry is based. UNR uses 38 cm row spacings compared to the conventional 90 cm, with double the plant population (160-195,000 plants/ha cf 86,000 for conventional). Trials on the Breeza Plain south of Gunnedah showed UNR to have much faster canopy closure, 21 days earlier maturity and similar yields when compared to conventional. Development of UNR in the US is focused on considerably reducing production costs, but the benefits of early maturity may improve crop performance in southern areas and enable extension of cotton into new, short season areas. It may also enable late planting with less yield penalty in wet years (Hickman, 1998).

Besides the benefit of high temperatures and radiation receipts, semi-arid areas offer the best production environment, as water supply to the crop can be controlled without waterlogging or interruptions to production operations by rainfall. Irrigation management aims to avoid severe water stress at any stage of development, particularly during squaring (flower bud formation), flowering and boll filling. Cotton has high water requirements, ranging from 600 to 900 mm for the growing season, the actual amount depending on cultivar maturity, radiation, temperature, rainfall and evapotranspiration during the season. Daily water use increases from 1 to 2 mm in early growth to a peak as high as 8 mm during late flowering and early boll fill, then declines to 4 mm from late boll filling to maturity. Cotton is most sensitive to water stress during the peak demand period, which in New South Wales occurs in late January-early February. Growing a crop with restricted water supply requires limiting water and nitrogen availability during early growth to restrict plant and canopy size, and thus peak demand. Available water should be saved until the peak demand period to maximize water use efficiency and lint yield. If adequate water is available for full irrigation, soil moisture depletion between irrigations should be limited to 50% of available water before irrigating again (Browne, 1984). Irrigation scheduling with neutron probes is routine in the industry, and has markedly improved irrigation efficiency and cost-effectiveness since its introduction in the 1970s (Cull, 1992). Erratic rainfall can be a major problem in some seasons, wet weather causing delayed land preparation and planting, interference with weed and pest control operations, waterlogging, lint damage and harvest delays from secondary growth, inaccessibility to machinery and retarded maturity (Thomson, 1986). Floods in some years have caused total crop loss in some regions such as the Namoi Valley. Shortages of irrigation water, through inadequate recharge of major storage systems in dry years, impose serious constraints on production in some years. Pre-season projected allocations have been restricted in some years to as low as 5% of licensed quotas. Water availability for irrigation and market conditions are the two principal determinants of the area of cotton planted in any season. While continuous cotton growing on the same land has been common practice to offset the high infrastructure and establishment costs of irrigated cotton production, serious pressure from soil borne diseases caused by *Fusarium, Phytophthora* and *Verticillium* has led to the increasing use of rotations, particularly with wheat and triticale, as disease break crops over the last decade. Grain legumes such as chickpea and faba bean have also been used successfully, although allelopathic effects of grain legume residues on cotton emergence, growth and lint yield have been reported (Hulugalle *et al.,* 1998).

Summer Grain Legumes

Crops in this group are cowpeas (Poona peas), mung beans, navy beans and pigeonpeas. The first three have been produced on a relatively small scale for many years, while pigeonpea came into commercial production in 1982. All are grown as grain crops in the summer rainfall areas of northern New South Wales and southeastern Queensland.

COWPEAS

Cowpeas (*Vigna sinensis*) are grown as a dryland summer crop in northwestern New South Wales and southeastern Queensland. The grain produced is mainly used as planting seed for production of cowpea forage crops. Substantial production increases are unlikely, as further expansion would be at the expense of sunflower and sorghum in the drier rainfed northern areas. The recent release of a new culinary grain cultivar resistant to stem rot (*Phytophthora vignae*), however, is a major advance, as production of the two commercial culinary cultivars was seriously limited by this disease in wet years. Expanded grain production would be largely reliant on development of the high protein grain market in the stock feed trade. Cowpeas are adapted to a wide variety of soils from light to heavy texture, but will not tolerate waterlogging. They require a soil temperature of 18^0C for successful establishment, and planting in the main production areas is delayed until mid-October in the earliest areas to mid January in the latest. The crop is well adapted to semi-arid regions and can withstand prolonged water stress better than most other crop species. The crop is better than mung bean under water limited conditions, and is useful for grazing and hay if water availability is inadequate to finish a grain crop.

MUNG BEANS

Mung beans (*Vigna radiata* ssp. *aureus* [Green Gram] and *V. radiata* ssp. m*ungo* [Black Gram]) are small, short-season (60 to 120 days), erect or semi-erect summer-growing legumes. They are best adapted to the drier tropical and subtropical regions with growing season rainfall totals of 300 to 400 mm, where summer rainfall is too low for other crop legumes. Production areas are shown in Figure 3.19.

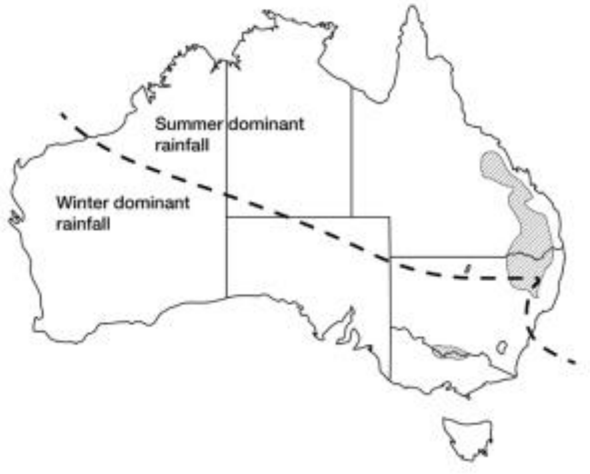


Figure 3.19 Australian mungbean production areas (after Pulse Australia, 2001)

Yields are usually low (0.5-1.0 t/ha), often because of water stress at flowering and grain filling, while wet weather during this phase can also significantly reduce yields and quality (Lawn and Imrie, 1994). Potential areas of production encompass existing cowpea areas, extending to the north into high rainfall areas of central and coastal Queensland, and to the south into the irrigation areas of northern, central and southern New South Wales where they would compete directly with soybeans, cotton, maize, sorghum and rice. Mung beans are adapted to hot environments and require soil temperatures for sowing of 18^{o}C at 10 cm soil depth, 8.00 am EST. Their short growing season enables production as an opportunity crop, as well as a set rotation crop with winter cereals in the northern region. When grown as an opportunity crop, they enable extension of the cropping phase, while making a valuable contribution to soil nitrogen status. Premium quality grain is germinated to produce bean sprouts for human consumption and lower quality grain is used as stock feed. Close crop monitoring and control of sucking insects from budding onwards is essential for good yields. The commercial release of a new cultivar with superior seed size, sprouting performance and improved disease resistance for 2003 planting will enable access to the higher priced international market for premium grade sprouting beans (GRDC, 2002). The low yields obtained under rainfed conditions make financially viable production of the crop dependent upon the grain produced meeting export quality sprouting standards. The Australian domestic market is limited in size and is unlikely to expand rapidly, making further industry growth dependent on export sales, particularly to the considerable Asian market.

NAVY BEANS

Navy beans (*Phaseolus vulgaris*) are produced in the South Burnett, Darling Downs and Atherton Tablelands regions of Queensland. They have also been grown in northern New South Wales, northern Victoria and Tasmania. Early maturing cultivars have shown high yield potential in Tasmania, where they are in demand for processing, and a small but expanding industry is developing there. They are widely adapted, provided water availability is not limited, and are commercially produced from Queensland to Tasmania (Figure 3.20).

They are grown for the premium edible dry bean and canning (baked beans) trade, which requires high grain quality standards – staining by rainfall during grain maturation is a major cause of downgrading. Navy beans had limited commercial acceptance until 1950, with the release in the late 1960s of higher yielding, bush type, disease resistant cultivars that were better adapted than the US ones on which the industry was founded in 1941 (Collett *et al.,* 2000).

With favourable market conditions, peanuts are the main competitor for land, as they have similar soil and climatic requirements (Wood *et al.,* 1994). The short growing season (90-100 days) enables summer production of navy beans as a double crop with wheat and barley. Production as edible dry beans in New South Wales has largely lapsed because of the high risks of weather damage and downgrading by autumn rainfall. Bush types are produced commercially, as they carry pods higher than vine types, allowing faster grain drydown and less risk of rain damage. Navy beans are intolerant of frost and require soil temperatures at sowing of 18^{o}C (at 10 cm soil depth, 8 am EST) while ideal temperatures for growth and development are similar to those of peanuts. While a range of soil types are suitable, they must be well drained yet have good water-holding capacity, as the crop is very susceptible to water stress, particularly from flowering to physiological maturity. They do not perform well on heavy textured, alkaline clay soils (Collett *et al.,* 2000). They are shallow rooted and best suited to irrigated production, but when grown as a rainfed crop require regular but moderate rainfall, and minimal water stress, from sowing to physiological maturity. Quality can be severely downgraded by rainfall on crops close to maturity and harvest, while high temperatures (36^{o} or above) at or near flowering will result in flower and pod abortion. Grain quality and crop value can also be seriously reduced by harvest and handling damage, incurred through aggressive machine settings, particularly if grain is allowed to dry below 14% before harvest, as severe seed coat damage and grain cracking will result.

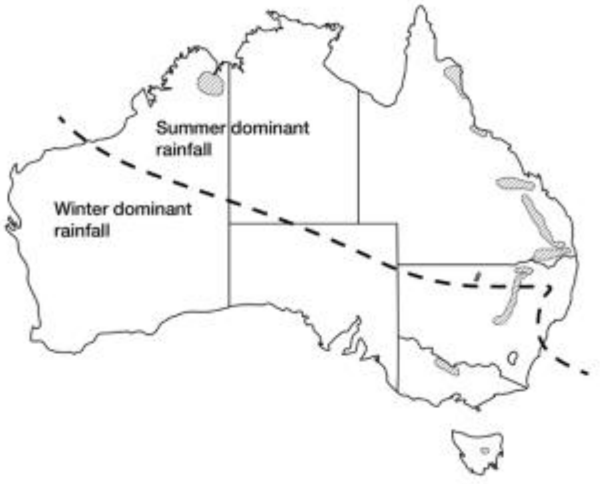


Figure 3.20 Australian navy bean production areas (after Heit, 1994)

PIGEONPEAS

Pigeonpeas (*Cajanas cajan*) are frost-sensitive, short-lived perennial legumes grown widely in the tropics and subtropics, where the grain is mainly used for human consumption. The plant is drought tolerant, and production is climatically best suited to areas currently producing sorghum, where they are a useful summer rotation crop. Production in higher rainfall areas is possible only where dry autumn conditions permit seed maturation without rain damage and secondary growth. Severe water stress causes significant delay in flowering and reduction in yield. The plant requires warm to hot temperatures for active growth, while frost will defoliate and even kill it. It is adapted to a wide range of soil types, but will not tolerate poor drainage. Successful establishment requires soil temperature at planting of 19^{0}C or more (Holland and Byrnes, 1986).

Pigeonpeas have only been grown commercially in Australia since 1985. Initial success led to rapid expansion to 9000 ha in Queensland and New South Wales in 1986-7, with almost 8000 of this in the Moree and Narrabri districts of northern New South Wales. The crop is basically an export prospect, and market development will be the key to its future (Brinsmead, 1994).

MISCELLANEOUS CROPS

Summer Crops

The important commercial crops in this category are peanuts, sugar cane and tobacco. Peanuts and tobacco are adapted to a range of climatic conditions and can be grown from temperate southern Australia to the sub-tropical north, but their commercial distribution is relatively limited. Sugar cane has a much more limited adaptation and is restricted to the high rainfall sub-tropical and tropical northeastern coastal regions of New South Wales and Queensland.

PEANUTS (GROUNDNUTS)

Peanuts (*Arachis hypogea*) are legumes that have traditionally been grown in Australia on the friable red volcanic clay loams of the South Burnett and Atherton Tablelands in Queensland. A small industry on red kraznozem soils near Lismore in northern New South Wales closed down in the mid 1970s. Australian plantings in 2001 were 21,000 ha, all in Queensland (Grain Yearbook, 2002) (Figure 3.21).

An almost complete failure, through drought, of a 38,000 ha Queensland crop in 1997 was compensated for by a ’one-off’ planting of 22,000 ha in northern Victoria, but no further Victorian sowings have been reported. The crop is now also being grown under irrigation in central Queensland and the Ord River district in northwestern Western Australia. Recent research has shown that yields of up to 7 t/ha are obtainable under irrigation in South Australia and commercial production is possible there, provided they can be harvested before the autumn rainfall break. Current cultivars require an average 150 days to maturity, and the future prospects of a southern industry will be enhanced by a current breeding program that aims for development of early (110 day) cultivars. Current Australian production is less than domestic demand, so there are good opportunities for industry expansion. The majority of current Australian production is under rainfed conditions, where drought can severely limit both yield and quality and this has led to problems in continuity of supply for established markets. Terminal drought has also been shown to favour development of aflatoxins, toxic factors produced by the fungus *Aspergillus* that lead to severe downgrading of harvested peanuts. Simulation modelling has shown that for the Kingaroy region in Queensland, cultivars maturing 20 days earlier than current commercial ones would produce higher yields, with lower aflatoxin levels (Wright, 1998).

There are two main botanical groups, based on branching patterns, seed dormancy and maturity rating. The Virginia group flowers on the lateral branches, has some seed dormancy and is late maturing. It has both erect and runner (prostrate) types. The Spanish group has erect types only, flowers on both central and lateral branches, has no seed dormancy and is early maturing. Virginia types typically produce higher yields under favourable conditions. The crop cycle varies from 16 to 22 weeks, depending on group, cultivar, and temperature conditions during growth. Cultivars from both groups are grown commercially, but Virginia types dominate the industry (Hatfield, 1994).

They are adapted to a wide range of climatic conditions, provided the soil type is suitable, but are completely intolerant of frost at any growth stage and require relatively high temperatures throughout the growing season. Minimum soil temperature for germination is 18°C at 50 mm soil depth. Research in Queensland has shown extreme sensitivity in many commercial cultivars to low night temperature (<20°C), resulting in reduced rates of photosynthesis on the following day (Bell and Cruickshank, 1996). They are drought sensitive at all growth stages, having rather lax stomatal control, and require crop season rainfall between 500 and 635 mm during the growing season. This restricts production to areas of moderate to high, regular summer rainfall. Flowers are borne in the leaf axils, and after pollination the flower stalk elongates, bends down and penetrates the soil, where the pod develops. Flowering is indeterminate and despite a high moisture demand, rainfall requirements for optimum yield are rather specific. The ideal rainfall environment has low rainfall during early flowering, followed by a short period of heavy rainfall to stimulate rapid flowering and a single crop of pods, and culminating in dry weather at harvest, the latter to facilitate pod separation from soil and allow adequate pod curing in open air stacks (Saint-Smith *et al.*, 1969). This aids production of seeds of uniform size and quality. Consistent rainfall throughout the growing period is undesirable as it stimulates continuous flowering, producing pods with a wide range of size and maturity, making prediction of harvesting time for maximum yield of mature pods difficult. Peanuts are day neutral and the length of the growing period is determined primarily by temperature (Bagnall and King, 1991). A range of soil types ranging from sandy loams to friable clays and duplex soils are suitable, provided the surface is well drained and friable and adequate calcium is available for pod development. Heavy clay or hard setting soils are unsuitable, as they do not release pods freely at harvest and are untrafficable in wet weather. Harvest delays are critical, as mature pods will be shed in the soil after one week if not harvested. Soil colour is also important and red soils are favoured to minimise pod staining for the whole-pod confectionery market. Rotations with cereals are also a key management strategy to minimize buildup of weeds, diseases and insects.

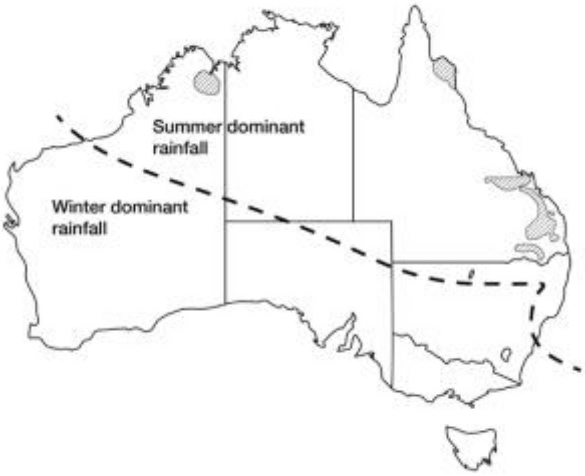


Figure 3.21 Australian peanut production areas (after Hatfield, 1994)

SUGAR CANE

Sugar cane (*Saccharum officinarum*) is a C_4 tropical grass and production is confined to the narrow northeastern coastal strip of New South Wales and Queensland, in the wet sub-tropical and tropical climatic zones.

A perennial, it requires high temperatures (21^0 to 36^0C) throughout the growth period, and takes from 8 to 24 months to produce a crop. Cane is planted in Queensland in autumn and harvested during the dry winter of the following year, a production period of 15 months (one-year cane). In the southern producing areas in New South Wales, the production period is 20 to 24 months (two-year cane). Here winter temperatures delay sowing until spring and the crop subsequently grows through two summers, before harvest in winter of the second year. The crop can be allowed to regrow following harvest, producing a lower yielding second or ratoon crop some 18 to 20 months later (Williams, 1975). Water requirements are very high, approximating and even exceeding pan evaporation rates during active growth. Irrigated crops in Queensland require up to 2000 mm of water per year, while successful dryland production throughout the world is limited to areas with a summer rainfall of 1250 to 1625 mm. Rapid summer growth at high temperatures slows down considerably with the onset of cool temperatures in the following autumn and winter, and sucrose is stored in the stem during this cool period. Water deficits during this period result in reduced sucrose storage and lower crop value, and supplementary winter irrigation is used in the northern regions to prevent this (Bull and Glasziou, 1979). Intense summer cyclone activity in northeastern Queensland is a significant hazard to crop production in some seasons, high winds causing extensive mechanical damage. Yield decline under long term sugarcane monoculture has been a serious problem for the industry for many years. Research into breaks to the traditional monoculture using other crops or pastures and bare fallow resulted in yield increases over monoculture cane ranging from 14 to 84%. Yield increases varied with type and length of break (Bell *et al.,* 2001). Well managed peanut and soybean crops, either grown as legume grain crops or green manure, increased sugarcane yields by 20-30% in subsequent plant, first and second ratoon crops (Garside *et al.,* 2001).

TOBACCO

Tobacco (*Nicotiana tabacum*) production is a highly specialised industry and has been conducted over a fairly wide latitudinal range, from the Atherton Tableland in northeast Queensland to northern Victoria, reflecting the wide climatic adaptation of the crop. Production is linked to a declining market demand, while distribution largely reflects the availability and suitability of both irrigation water and soil types, the best-quality leaf being obtained on chemically poor soils, where close control can be maintained over crop nutrition. Successful production requires a hot, humid environment with a frost-free period of 100 to 150 days and, particularly, freedom from strong winds and hail. Ambient temperature requirements during the initial 6 to 10 weeks seedbed period are 24^0 to 26^0C, followed by average temperatures after transplanting of 26^0 to 27^0C. The crop is sensitive to water supply at all growth stages, leaf quality being reduced by growth checks from water stress, while excess rainfall and waterlogging can cause root damage. Precise irrigation control is essential to minimise both water deficiency and excess throughout the growth cycle. Both low humidity and excessively high temperatures are detrimental to leaf quality during ripening in autumn, the finest tobaccos in the world being produced in areas with climates subject to maritime influences. Harvesting requires dry weather, picking of mature leaves generally being delayed until two or three fine days after rain, enabling sufficient photosynthesis to restore adequate leaf carbohydrate levels. Some degree of cloud cover throughout the growing season also appears desirable, since excessively high solar radiation levels can blemish leaves and reduce crop quality (Martin *et al.,*1976).

In general, production is closely controlled by water availability during the growing season, and it is likely that production will continue to be restricted to irrigation areas that have an acceptable water quality. Summer temperatures throughout the areas where production is now concentrated appear quite suitable.

Potential Alternative Crops

There are many crop species that have potential as new industries for Australia, and some 4500 species have been identified by the Australian New Crops Association (Fletcher, 2000), while at least 220 are being considered for development as new crops (Fletcher, 1999). Reviews of many of these species, their adaptation and potential as new crop industries in Australia, can be found on the Association website (http://www.newcrops.uq.edu.au). Earlier reviews by Matheson (1979), Marshall (1992) and Imrie *et al.,* (1994) also provide valuable information on alternative species.

The following briefly outlines the adaptation and industry status, where known, of crops that have been grown on a small scale and that show potential for further commercial development.

SESAME

Sesame (*Sesamum indicum*) is adapted to the tropics and subtropics, where summer temperatures during the growing season average 27^0 to 32^0C. Research in the early 1990s identified cultivars with climatic adaptation from the tropical Northern Territory to southern New South Wales, as well as suitable agronomic management practices. Sesame is indeterminate and as the plant matures, capsules borne in the leaf axils progressively ripen from the base of the plant upwards. As capsules mature, they split open, dispersing the seeds. As a result, cultivar development for mechanical harvesting requires greater synchrony in flowering and seed retention in capsules (Imrie, 1997). The potential for rainfed production is highest in Queensland and northern Australia, although severe disease and harvesting problems may be encountered under high temperature-high humidity conditions. Irrigated production is most likely to be successful in cotton growing areas in New South Wales, Queensland and northwestern Western Australia where it would compete directly with cotton. The major problems of uneven maturity and seed shattering will have to be overcome before it becomes a successful new crop industry. Seed is utilised both for oil and the confectionery trade.

BUCKWHEAT

Buckwheat (*Fagopyron esculentum*) is a summer-growing, short-season (70 to 84 days) plant best adapted to cool moist temperate climates. It is very susceptible to temperature extremes, being completely intolerant of frost at all growth stages and extremely sensitive to high temperatures at flowering. At the other extreme, it is tolerant of low soil fertility and poor seedbed preparation, although yields are considerably enhanced by fertiliser application and thorough seedbed preparation. At present it appears best adapted to spring plantings on the higher tablelands of central and southern New South Wales and in Tasmania. Market prospects are limited on the domestic scene, but the Japanese market offers potential for some development as a commercial crop. Grain is used both for drug extraction and as a source of specialty flour for ‘buckwheat cookies’ in the US and Japan. Trial commercial plantings in Tasmania and in the Orange district of New South Wales have been made under contract to Japanese processors.

CASSAVA

Cassava (*Manihot esculenta*) is a tropical species confined to areas in a broad belt between 30^{0}N and S latitudes. Cassava is a perennial shrub that is cultivated primarily for its starch-rich tuberous roots, which when dried and pelleted provide a high energy carbohydrate source (Wood *et al.,* 1996). The crop appears limited to Australian regions in which the lowest winter (July) temperature is 13^{0}C, confining potential production areas to a narrow strip in northeast Queensland and extending across northern Australia to the west coast of Western Australia. It is regarded as drought tolerant, but commercial yields require growing season rainfall of 1000 mm, with a distribution spread ideally over 9 to 10 months of the year. Suitable areas for production require a summer Moisture Index of 0.8 or higher (De Boer and Forno, 1975). Additionally, high-protein meal produced from the leaves and stems could be competitive with fishmeal in the domestic stock feed market. Starch manufacture for domestic markets is limited, with the major competitors being maize, wheat and potatoes. Major restraints at present are the isolated nature of suitable production areas, the high costs of mechanisation for production, and the need to establish expensive drying and pelleting plants to process roots for the EEC market. Increasing competition from wheat as a source of starch has also been a negative factor in the development of a starch based cassava industry (Imrie *et al.,* 1994).

JOJOBA

Jojoba (*Simmondsia californica*) is a bushy, evergreen perennial shrub that grows to three metres and is native to desert, as well as coastal, regions of Central and South America. It usually grows on hillsides and is well adapted to arid situations with an annual rainfall of 100 to 300 mm. It has a deep taproot and is capable of survival under extreme and prolonged drought conditions (Imrie *et al.,* 1994). Plants are usually dormant in winter, commencing spring growth with flowering, followed by fruit development and ripening in early to mid-summer. Vegetative growth continues through summer and autumn whenever water is available. Late winter flowering may occur, but buds and developing fruit are sensitive to frost damage. There are separate male and female plants; one in ten plants must be male for successful pollination. Plants mature sexually at 2 to 3 years of age, but may not mature fully until 8 years. They prefer deep, well-drained, fertile soils of sandy to medium texture and pH of 5.5 or above. The ripe seed contains about 50% by weight of a liquid wax that has similar properties to sperm whale oil and is in demand for high-grade cosmetics and lubricants. Consistent trial yields from mature plants in central New South Wales of 0.7 t/ha rainfed and 1.6 t/ha under irrigation would produce gross returns of $3150 and $7500/ha respectively at 1996 prices. The release of adapted cultivars, together with further development of an agronomic management package, should ensure the crop a sound future as a new industrial crop (Milthorpe, 1996).

FENUGREEK

Fenugreek (*Trigonella foenum-graecum)* has been grown in Australia since the mid-1980s and the area sown in the Victorian Wimmera region has increased since 1998 because of high prices and the impact of *Ascochyta* in chickpeas. The crop has potential as an alternative legume to chickpeas and lentils in southern areas, and can be used for green manure, as a specialty grain crop for niche Asian condiment markets, or for forage. In trials in the Victorian Wimmera, fenugreek performed similarly to other grain legumes grown in the area (field pea, faba bean, lentil, vetch and medic) (McCormick *et al.,* 2001).

LIMA BEANS

Lima beans (*Phaseolus lunatus*) are a summer crop with a narrowly defined sowing time in November-December, up to a month earlier than navy beans in southern Queensland. Varieties have been identified that are 20-40% higher yielding than navy beans and that are of acceptable canning quality. They are likely to be better adapted than navy beans to rainfed production in the Burnett region of Queensland. They have a wide range of seed sizes and colours, but the predominant market class in Australia is the Baby Green type, with green to white seeds averaging 30-40 g/100 seeds. They may offer growers an attractive alternative to navy beans, particularly in drier areas, as a quick maturing (100-110 days) crop for midsummer planting in the drought prone Burnett districts (Redden and Wright, 1998).

Case Studies

The following case studies describe three farms, typical of their regions, in eastern Australia. They range from the Mallee region of Victoria with low, winter dominant rainfall, through the Liverpool Plains of New South Wales with higher, uniform to summer dominant rainfall (supplemented by irrigation) to the Western Downs/Maranoa region of southern Queensland, with a similar annual rainfall to the Liverpool Plains farm, but pronounced summer dominance. These farms have been chosen to illustrate the effects of the contrasting rainfall and soil environments on crop options and production strategies. The farm locations are shown in Figure 3.22.

The Mallee Region of Northern Victoria

The farm has an average annual rainfall of about 325 mm, with pronounced winter dominance, resulting in growing season (April-October) rainfall averaging around 240 mm. The low summer rainfall precludes production of summer crops, unless irrigation is available. Soils are sandy loams underlain by clay, in contrast to the sandy soils with poor water retention properties in the central and northern Mallee. Soil pH on the better soils averages around 8.5 in water.

Figure 3.22 Case study farm locations

There are numerous constraints on crop production, but low water availability is by far the most dominant. Water limitations arise from failure of autumn and winter rains, or from rainfall in these seasons arriving in events that are too small to be of agronomic value. The low summer rainfall restricts the prospects of fallow water accumulation between winter crops, so that production is almost entirely dependent on crop season rainfall. The sometimes sodic and high boron subsoils present a further limitation on water availability to crops, as they prevent roots extracting otherwise available water from the full soil profile. Timing of rainfall is particularly important, with an early autumn break required for crops such as canola or faba beans to be successfully grown. Frost is sometimes damaging, with field pea the worst affected crop.

Crop options currently available are bread wheat, malting barley, feed barley, triticale, oats, field peas, desi chickpeas, lentils, vetch, faba beans and canola. Durum wheat is grown by a very small number of growers but is a possible future crop. Lupins are not possible because of soil type, but there are patches of suitable, lighter soils in the area. The current rotation is based on wheat, feed barley, canola and lentils.

Crop choice for any year is a very complex question, as it is so dependent on water availability. If the climate outlook is poor, the areas of canola and pulse crops are reduced because of their greater vulnerability to water stress. Ideally, canola and lentils would be grown on paddocks with stored moisture, but then only when the seasonal rainfall break comes before mid-May. Disease incidence in both cereal and broadleaf crops is also a major factor in crop selection. The focus with cereals has been on cultivars that are resistant to cereal cyst nematode (CCN) as this has been a major problem in the Mallee. Other cereal diseases of note are take-all, *Rhizoctonia* and crown rot, and successful cereal production requires rotation with broadleaf crops, either pulses or canola. Rotations with cereals are also necessary to minimise the impacts of blackleg in canola and fungal diseases (*Ascochyta, Mycosphaerella, Phoma, Pythium* and *Botrytis*) in lentils and field peas. Weeds can affect crop choice because they are generally difficult to control in-crop and herbicide resistance, particularly in annual ryegrass, is becoming a significant problem. The major weed problems other than annual ryegrass are great brome (controlled in wheat, but not in barley, with herbicides), Indian hedge mustard in conventional canola and medic in lentils. Crop choice can also be constrained by herbicide residues, particularly from use of Group B herbicides, which degrade slowly on these alkaline soils and have a long plant back for pulses.

The Liverpool Plains of Northern NSW

The Liverpool Plains is a region where grain growers typically produce a diverse range of summer and winter crops, both rainfed and irrigated, on a large scale. On the case study farm, average annual rainfall is 600 mm, with a slight summer dominance. Soils are grey and brown cracking clays of high native fertility, but years of cropping have resulted in the need for high fertiliser inputs, especially nitrogen. These soils have excellent water holding capacity but have a narrow working window in terms of moisture content, being very hard when dry and sticky and untrafficable when wet. Winter and spring frosts can be very severe and late spring frosts have caused substantial damage to flowering winter crops in the past. As a result, sowing dates are conservative and later than optimum for the district. No-till farming is practised on a controlled traffic (permanent wheel track) system. In good rainfall years, double cropping with both winter and summer crops is practiced, while in dry years double cropping is restricted to irrigated areas only. Decisions on whether to plant a winter or a summer crop on rainfed areas depends entirely on the availability of soil water at planting time in autumn or spring, with a target of ideally 1 metre of wet soil for planting. Both rainfed and irrigated winter crop options are wheat (bread and durum), faba beans and barley, with bread wheat, faba beans and barley generating average gross margins of $400-$600/ha. Both durum and bread wheats yield an average of 4 t/ha under no-till, with 2001 yields of over 8 t/ha and the potential for even higher. The higher value durum returned gross margins up to $1200/ha in 2001. Both are planted in late June-early July, later than optimum because of spring frost risk. Typical crop sequences in the past were wheat direct drilled into maize or sorghum stubble (providing the autumn soil water profile allowed), then either a 10 month long fallow from wheat harvest until the following spring, when maize or sorghum was planted. Long fallow could extend up to 18 months into autumn of the third year, when wheat was planted. A severe outbreak of *Fusarium* head blight in recent years, particularly in durum cultivars, decimated wheat yields and quality. Maize is an alternative host for the disease and outbreaks typically occur when rainfed maize is severely water stressed. The disease carries over on maize stubble, infecting the following wheat crop. As a result, only barley and faba beans are now double cropped into corn stubble, while wheat is double cropped only after sorghum. Barley is mainly double cropped into maize or sorghum stubble and has an estimated yield potential of 6 t/ha – yields in 2001 were 5 t/ha. Only malting cultivars are grown, so that in years with a good spring finish, much higher returns are made if the grain meets malting standards. Faba beans are also double cropped into corn or sorghum stubble, but yield potential (estimated at 5 t/ha) is severely reduced by planting later than May. If corn or sorghum harvest is delayed by wet autumn weather, barley is substituted as the following winter crop. Current faba bean yields average 2.5 t/ha, with a gross margin of almost $600/ha. Chickpeas have also been tried as an alternative winter crop, but were not viable because of low grain and stubble yields, severe *Ascochyta* outbreaks, and limited nitrogen contribution. Canola has been considered, but is not grown because of concerns about biofumigation effects on soil vesicular arbuscular mycorrhizae (VAM). As a double crop after maize or sorghum, in a wet autumn with a full soil profile, the high costs of nitrogen and sulphur fertilisers for canola would result in lower gross margins than from either barley or faba beans. Faba beans in particular have considerably lower production costs than Canola.

Summer crops grown are maize, sorghum and, more recently, black-eye peas. Sorghum has an estimated yield potential of 10 t/ha, with current rainfed yields averaging 6 t/ha under no-till. Previous yields under conventional cultivation averaged 4 t/ha. Sorghum is planted in the last week of October, about two weeks earlier than the ideal, but this avoids a clash with the start of winter crop harvest. Grass weeds are a major problem and higher soil temperatures, with a later planting, promote their more rapid germination and better herbicide control. Maize is planted in early October and has a rainfed yield potential estimated at 8-10 t/ha, with current yields averaging 6 t/ha. Experience has shown that rainfed maize is much more severely affected by late summer drought than sorghum. Under irrigation, yield potential is estimated at 13-14 t/ha, with 2002 harvested crops yielding over 12 t/ha. Maize requires about twice as much nitrogen as sorghum, and production costs are about three times those for sorghum. A recent development has been contracts for high moisture (28-32%) maize, which is harvested in February, 60-90 days earlier than the normal maize harvest at 14% moisture or less. This allows double cropping into faba beans in May, the ideal planting time. Black-eye peas are a recent introduction, with yields in 2001 averaging 1.1 t/ha from a crop with establishment problems, so there are good prospects of reaching potential yields (estimated 2 t/ha) with this crop. The premium market has strict grain quality requirements, but prices range up to $1200/t for clean, bright, unstained white grain. Besides high value, the crop is a low production cost, short season (90 days) option yielding gross margins up to $800/ha on current prices, with grain cleaning the major cost item.

Other summer crop options are sunflower, which could be planted from early October through to late January. However, the major deterrents are low prices, lack of stubble and poor competition with grass weeds. Experience has shown that grass weeds are difficult to control in the later stages of sunflower growth, resulting in a grass weed buildup that may take years to bring under control. Cotton has been trialed in the past, but low yields and quality resulting from weather damage, together with high infrastructure and production costs, make sorghum a financially much better option.

At present, faba beans and black-eye peas are the only broadleaf crops being produced, and introducing more broadleaves, particularly summer legumes, is a current management objective. However the available options considered so far, including mung beans, are not financially competitive with the current crops being grown.

Western Downs/Maranoa Region of Queensland

This property is 500 km west of Brisbane in the Western Downs/Maranoa farming belt. Average annual rainfall is 550 mm, with an 80% summer dominance. The soil types are Brigalow/Belah clay loams, to about one metre deep. Most crops are produced using fallow stored soil moisture, with no set rotation. The variable rainfall and extreme seasonal conditions often mean crops are planted on an opportunity basis, depending on estimated gross margin and projected returns. Because of lower yields, sorghum is not planted if market price indications are less than about $120/t.

Winter crops are wheat, both bread (Prime Hard (PH) cultivars with a target protein content of 14%) and durum, chickpeas, faba beans, and canola in the winter. Summer crops include sorghum, sunflowers, and mung beans. Mung beans are not so popular because of insects and marketing difficulties. Lucerne will be grown on part of the property in a 3 year rotation with crops, depending on seasons and market prospects for both. Cattle provide about 30% of the farm income, but are not run on cultivation areas unless seasonal conditions are extremely dry. The SOI (Southern Oscillation Index) and APSRU (Agricultural Production Systems Research Unit) models are used to assist in planning crop mix for the year ahead. Sorghum and sunflowers were planted for the first time in summer 2001, followed by a double crop to wheat and chickpeas.

Zero till and controlled traffic have made a huge difference to the crop production system. The challenge is to continue refining the system to minimise the most limiting factor. Disease control, crop rotation and crop nutrition are the key considerations in management. For example, salt at depth is an issue on some soil types, so sorghum is the preferred crop to make better use of in-crop summer rain. Currently under consideration is planting chickpeas and faba beans in alternate runs to aid IPM (Integrated Pest Management). Also under consideration to combat salinity is to plant chickpeas on one-meter skip rows, to allow the plants access to more moisture above the salinity layer. Yields are steadily increasing, with wheat 2 t/ha, sorghum 2 t/ha (3 t/ha in 2001), faba beans 1 t/h and chickpeas 0.8 t/ha, with room for improvement.

PRINCIPLES

- Adaptation of a crop species is reflected in its responses to the combined environmental, edaphic and biotic features of its growing environment
- Adaptation reflects the heritable features of a plant that enable it to survive, reproduce, or both, in a given environment.
- Acclimation reflects the non-heritable modifications to the plant phenotype caused by exposure to environmental stresses that enable it to tolerate further and more severe stress.
- Growth is an increase in plant biomass over time, and is determined by the level of availability of all factors necessary for normal plant metabolism and function.

- Development is the progression of a plant through the successive stages of its normal life cycle.
- Economic performance in grain crops is dependent on the successful completion of all development phases from establishment to harvest maturity.
- Development in most modern crop cultivars is dependent more on temperature than daylength and is accelerated by high temperatures, resulting in a shortened life cycle.
- The outcomes of competition reflect the relative adaptation of competing plants in optimising their capture or use of essential factors for growth that are in limited supply.
- Competitive ability in modern crop cultivars is a function of area, activity and distribution in space and time of absorptive surfaces (roots for water and nutrients; leaves for light and CO_2) in crowded, productive situations.
- Water supply and temperature, sometimes aided by the buildup of pests and diseases, determine the maximum length of the growing season, the range of crops that can be grown, their optimum duration and likely yield.
- Adaptation to temperature is a major factor governing the natural distribution of plants, and is a principal determinant in the selection of crop species for any location.
- The adaptation of crop species to harsh environments has depended more on changes in the length and timing of their life cycles that allow avoidance of harsh conditions, than to changes in their tolerance to those conditions.
- Reducing daylength dependence in crop cultivars increases the flexibility of their life cycles, allowing greater manipulation of their planting dates, flowering times and growing periods.
- Under water limited rainfed conditions, earlier flowering and maturity can be critical to yield performance, as they enable flowering and grain fill before available water is exhausted.
- Production principles for rainfed temperate crops reflect strategies to capitalise on available water during the growing period, while minimising frost risk at flowering and high temperatures and water stress during grain filling.
- Production principles for rainfed summer crops focus on frost escape, water availability throughout the growing period, and minimisation of water and high-temperature stresses during flowering and grain filling.
- The principal production strategies to minimise the impact of climatic constraints are cultivar selection, planting time and, to a lesser extent, planting rate.
- Late planting of most crops results in accelerated development, a short vegetative phase, low biomass at anthesis and reduced yield potential.
- The optimum planting time for any crop is determined by the combination of cultivar adaptation, soil temperature and available soil water.

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