CHAPTER 1

General Introduction

Staple strength is an important raw wool characteristic, which has a definite impact on processing performance and as a result is an important determinant of the price received by producers for their wool. Increased or controlled staple strength creates an opportunity for woolgrowers to increase the returns from their wool. It is therefore important to gain an understanding of the wool growth factors that may influence staple strength and the position of break. Staple strength is a complex trait and as a result understanding of this trait is far from complete.

Wool staple strength may vary due to many factors such as environmental conditions, differences in genotype and fibre growth characteristics. Fibre diameter varies throughout the year in accordance with the sheep's interaction with environmental conditions. The way in which the fibre diameter varies over one year of wool growth is referred to as a fibre diameter profile (FDP). This profile is therefore an indication of the way in which a sheep's wool growth responds to environmental conditions. It has been established that the characteristics of the FDP, that is the rate and extent of fibre diameter change throughout the wool growth period, are associated with staple strength. However, there is uncertainty as to the relative importance of each of these parameters within the profile in determining staple strength over different environments and genotypes. An improved understanding and quantification of these relationships may allow for improvements in staple strength.

The measurement of FDPs is time consuming and labour intensive, and subsequently expensive. As a result, it would be of benefit if research techniques could be modified or adapted, whilst still maintaining an acceptable level of accuracy, to reduce the time, workload and costs involved. If the FDP could be estimated without a full profile having to be measured, more staples and therefore more sheep may be able to be studied during a given time period. To conduct the genetic research that is required to properly evaluate the potential of FDP characteristics for breeding purposes it is essential to sample large numbers of animals. An improved technique is needed to make these studies feasible.

Research has shown that individual sheep within a mob respond differently to fluctuations in their environment, both in liveweight, body condition and wool growth, however, the biological mechanisms influencing these differences are not well understood. Under standardised environmental conditions there are differences in fibre diameter responses and therefore staple strength between sheep within a mob. Variation in fibre diameter along the staple can be manipulated through nutritional and possibly genetic means. The major unanswered question is whether reducing responsiveness of fibre diameter will increase staple strength? Variation in fibre diameter along the staple not only influences staple strength but also the position of break. Therefore reducing this variation should improve wool quality.

Staple strength has also been shown to be moderately heritable and therefore varies genetically between sheep. Suggestions have also been made that the characteristics of FDPs may also be genetically controlled. The identification of factors that are genetically related to FDP variation and/or staple strength may allow them to be exploited to improve wool quality. The problem for the sheep breeder is, how to cheaply identify animals that grow wool with less variation in fibre diameter throughout the year. If this is possible it may allow wool producers to select animals that are less sensitive to the environment. There are many identifiable factors that may combine to cause the variation between individual sheep within a mob. These factors will be discussed in this thesis.

Given these relationships the unifying hypothesis of this thesis is that differences between sheep in responsiveness of fibre diameter throughout the year can be utilised to improve staple strength.

CHAPTER 2

Review of Literature – Wool fibre diameter responses to environmental conditions and its relationship with staple strength

2.1 Introduction

Many nutritional and non-nutritional factors both individually and in combination modify wool growth and the characteristics of a sheep's fleece, most notably fibre diameter, staple length and staple strength. The factors that are capable of influencing wool growth include: sheep genotype, nutritional status, hormonal levels, climatic conditions, physiological state, age of dam, photoperiod, sheep health factors and their interactions. Wool growth is particularly affected by the availability of nutrients, either directly by the feed intake, composition of diet and metabolic efficiency of the individual animal (Allden 1979), or indirectly by factors such as pre-natal under-nutrition of the dam, rearing status or post-natal under-nutrition of the lamb (Corbett 1979; Kempton 1979).

Historically research has focussed on increasing the quantity of production per head. However in recent times research emphasis has shifted to improving product quality. This requires a move towards identifying and exploiting variation in physiological processes between animals and to integrate this approach with work on genetic selection to improve the efficiency and quality of production (Purser and Hogan 1992). There is inherent variability between sheep within a flock in almost every characteristic of economic importance. The identification of unique animals within a population for important traits is likely to remain an important source of genetic improvement of wool quality. Phenotypic variation in performance between individual sheep is attributed to both genetic and environmental components (Dickerson 1962). Management should recognise the variability imposed by the environment in which the sheep lives (climate, soil and feed resources) and must also account for the mechanisms the sheep uses to cope with their environment and the factors that interact with this environment (behaviour, animal health and physiological state) (Purser and Hogan 1992). The way in which an animal reacts to its environment will influence the quality of its wool, in particular the length, diameter and strength of the wool fibres produced. This chapter aims to identify the factors that may contribute to the level of environmental sensitivity of fibre diameter in sheep.

It has been established that the characteristics of a fibre diameter profile (FDP) are associated with staple strength. Factors such as fibre and staple structure, fibre shedding and sheep management also play a role in determining staple strength. Variation in the influence of these factors and the consequent individual response by animals contribute to the variation observed in staple strength between sheep and between mobs. Variation in any factor that influences wool growth has the potential to influence the variation in wool growth between individuals within a mob. Clean wool production is highly correlated (Stewart *et al.* 1961; Swan *et al.* 1995) with fibre diameter and therefore it is likely that any change in wool growth will have a resultant change in fibre diameter.

Staple strength as an objectively measured characteristics only became of economically important trait relatively recently and as a result the scientific literature focussing on staple strength is relatively limited. Associated with this a relatively large proportion of the information has also been published in the "public press", such as farm journals and research organisation newsletters.

The following review of literature will firstly explore the wool quality characteristic of staple strength. The constituent fibre properties that influence staple strength will then be investigated. Finally a discussion of the types of factors, and their mode of action on staple strength and FDP characteristics will be presented.

2.2 Definitions

Staple Strength	Staple strength is a measure of the level of load or work that is required to break a staple, corrected for the size (linear density) of the staple.
Tender Wool	Tender wool is wool that has low staple strength generally less than 30N/ktex and often having a "break" or localised weakness as a result of its low tensile strength.

Tenacity	The retentiveness or stubbornness of a fibre to withstand tensile stress.
Intrinsic Strength	The strength of the actual fibre material corrected for its cross-sectional area. That is, the inherent strength of the fibre material independent of the amount of fibre material present.
Position of break	The position of break (POB) is the position within the staple where the break occurs when it is subjected to longitudinal stress. POB is commonly measured on a percentage basis by weighing the two halves of the broken staple. POB is reported as a percentage of tip, mid or base breaks. Tip breaks are when less the 33% of the weight in the tip portion of the broken staple. Base breaks occur when the base section represents 33 or less percent. The remainders are mid breaks.
Flock	A group of sheep consisting of all the mobs of sheep on one farm.
Mob	A group of sheep of similar breeding, sex and age that have been run and managed together since the previous shearing.
Crimp	The wave or corrugation observed along the length of all wool fibres.
Crimp Definition	A measure of how closely the fibre crimp is aligned within the staple. In other words the degree to which the crimp pattern is clearly defined and regular along the length of the staple. It is also referred to as evenness of crimp or character.
Crimp frequency	The number of crimps per unit of length, ie. crimps per centimetre.
Fibre Curvature	The size of the curve in the crimp of the fibre. It is a measure of how much the fibre bends within each crimp.
Hauteur	The average fibre length in wool top.

2.3 Staple Strength

2.3.1 The importance of staple strength

Wool processors, with a goal of producing higher quality fabric, have prioritised the major wool quality characteristics. With the advent of sale by description and objective measurement, staple strength has emerged equally as the second most important raw wool characteristic determining variation in clean wool price after fibre diameter, for wool processed on both the worsted and woollen systems (Butcher *et al.* 1984; Teasdale 1985; Rogan 1994b). As a result of this, an increase in the staple strength of wool will increase the wool's value. In 1996, discounts for fine wools started at 36N/ktex (Adams and Oldham 1996) while currently discounts start at approximately 37N/ktex (Pricemaker May 2000). As a result there are large opportunities to improve wool quality through increases in staple strength.

The importance of staple strength as a quality characteristic of wool arises from wool processors. Staple strength is the second most important trait, after staple length, in determining the length of the fibres in wool tops (Hauteur) (Ross 1982; Rottenbury *et al.* 1986). The tensile strength of wool defines its ability to withstand the tension placed on it during the combing process (Harmsworth and Day 1990). Decreased fibre length also has detrimental effects on spinning performance, which is exerted through yarn breakage (Johnson 1995). No wool is able to yield 100% top and even wool with high staple strength will have at least 6% noil (Harmsworth and Day 1990; Reis 1992b). While staple strength can vary from approximately 0 to 90 N/ktex, it is at staple strengths below 45 N/ktex that a significant relationship between fibre length in the top (hauteur) and average staple strength is observed (Bigham *et al.* 1983).

Staple strength is a major problem at all levels of the Australian wool industry and affects a large proportion of sheep and wool. In the 1993/94 selling season approximately 28% of Australian Merino wool had a staple strength below 30 N/ktex, defined as tender and therefore attracting discounts (Thompson *et al.* 1995a; Huson 1996). Of this tender wool, 70% of the wool lots were under 21 micron. Low staple strength is particularly punishing on finer wools, which attract relatively greater penalties for tenderness than broader wools (Rogan 1994b). Consumer trends over the last two decades have been towards the wearing of lighter weight, softer to handle fabrics (Piper 1992). To achieve this processors require finer wool and therefore finer wools are attracting higher prices.

Staple strength is especially important in hogget wool as 60 to 70% of hogget wool grown in Western Australia is classed as tender. Similar trends are observed in the other wool growing states of Australia (Gherardi 1995). In monetary terms the Cooperative Research Centre for Premium Quality Wool estimated that reduced wool quality as a result of low staple strength is costing the Australian wool industry 50 million dollars each year (Purvis 1996). This estimation equates to a reduction of approximately 5% in the value of the wool clip annually.

The Australian wool industry needs to improve its productivity so as to maintain its share in the fibre market into the future where prices may have to drop for the industry to be sustainable (Ward 1997). One of wool's major disadvantages in comparison to cotton and synthetic fibres is that wool fibres are relatively weaker than many other textile fibres. Wool fibre also have high variability in length and diameter which has important implications in processing (Hall 1965; Orwin *et al.* 1986). An improvement in the strength of Australian wools should enable increased processing efficiency and therefore maintain and possibly improve wool's competitiveness and thereby the amount of textile fibre market share that is has compared to other natural and synthetic fibres.

The value of any wool with low staple strength will depend on the position of break. If staples break near the tip or base of the staple they may have sufficient length to permit economical combing. If the staples break in the middle they will usually not be able to be combed (Ritchie 1990).

2.3.2 Measurement of staple strength

Staple strength was traditionally estimated using subjective assessment (Baumann 1981; Reis 1992b) and this method is still used today by many wool classers. The test consists of pulling or plucking a taut staple and assessing how it withstands this treatment, estimating the strength by the "ring" of the staple when it is flicked between the fingers, or by the pull required to break it (Bigham *et al.* 1983). Subjective methods are limited in usefulness because the level of staple strength must be low before a fleece is appraised as tender, and as a result only discriminates at low levels of strength (Baumann 1981). Andrews and Lunney

(1982) reported that although only 5% of the wool was subjectively classed as tender, 65% of these samples exhibited an objective staple strength measurement below that which is considered to have some effect on processing performance. Another problem with this technique is that it is purely subjective and is therefore influenced by variation between assessors. Although having disadvantages this method is still used by producers today due to its convenience and relatively low cost.

To obtain a more accurate measurement of staple strength instruments have been developed to objectively measure staple strength. Only relatively recently has it become possible to routinely measure staple strength on large numbers of samples (Lewer and Li 1994). This objective test is the measurement of the maximum force or energy, in Newtons, required to break the staple, relative to its linear density in kilotex, where 1 kilotex is the linear density of a standard yarn weighing 1g/m (Bigham *et al.* 1983). The linear density is a direct measure of the staple cross-sectional area if specific gravity is constant (Reis 1992b). Staple strength is now expressed using Newtons / ktex (N/ktex).

Current procedures for measuring staple strength do not necessarily identify the specific characteristics of the fibres that determines their tensile properties. That is staple strength measurements do not differentiate between causes and as a result staple strength may be the same, but for different reasons (Lewer and Li 1994). These procedures also only detect the weakest point in the staple. This means that there could be two tender points in the staple of very similar strength but only one will be detected.

The fibre length distribution of the staple may also influence staple strength. Fibres within the staple being tested that do not span the gauge length between the clamps (such as shed fibres or shorter fibres) will influence staple strength. Such fibres make a contribution to the tex value (linear density) but bear no load and therefore reduce the staple strength independent of the linear density or the intrinsic strength of the fibres (de Jong *et al.* 1985; Thompson 1993).

The strength of a staple may also influence the way that it breaks. Heuer (1979) found that tender staples break at a plane of weakness, but stronger staples pull apart in a much less defined way. This creates some doubt as to where the break should be indicated because the fibres appear to be breaking at different points. The aim would be to indicate the point where the majority of fibres break.

2.3.3 Variation in staple strength

There is large phenotypic variation between animals in their staple strength, greater than that occurring between breeds or strains (Rottenbury *et al.* 1981; Bigham *et al.* 1983; Geenty *et al.* 1984; Hynd and Schlink 1992; Reis 1992b; Swan 1995; Swan *et al.* 1995). Therefore staple strength is a variable trait with the standard deviation estimates for this trait within flocks ranging between 6.4 to 10.4 over a number of research flocks (Rottenbury *et al.* 1981; Greeff 1997b). There is considerable variation between fleeces (61% of total mob variation) and this component is much larger than the variation between regions (4% of total mob variation) within a fleece (Rottenbury *et al.* 1981). This variation between sheep is high relative to other wool quality traits.

Compared to other fleece characteristics the systematic trends in staple strength over a fleece appear to be small and mid-side measurements are highly correlated with the fleece mean. However Rottenbury *et al.* (1981) found a highly significant interaction between fleeces and sites indicating that sheep do not exhibit a consistent pattern of variation of staple strength over sites of the fleece. As a result the mid-side region appears to be an appropriate sampling site for staples to be used to measure staple strength.

2.4 Constituent fibre properties in relation to staple strength

Staple strength can vary depending on several fibre and staple characteristics. These include, the minimum fibre diameter, the rate and extent of variation in diameter between and along the fibres, fibre shedding, the composition and intrinsic strength of those fibres, the variability in crimped length and extension at break of fibres within the staple (Ryder and Stephenson 1968; Reis 1992b; Thompson 1993; Lewer and Li 1994). Other factors such as pregnancy and lactation, parasitic challenge and blowfly strike influence fibre strength through competition for essential nutrients, however hormonal factors are also involved (Thompson and Curtis 1990). The way in which individual fibre and staple properties interact to influence staple strength is very complex.

Although there is conflicting evidence on the exact determinants of fibre strength it appears that the strength of wool fibres is primarily determined by cross-sectional area and the tensile properties of the keratinised fibre material (Woods *et al.* 1990). A variety of physiological and environmental factors influence the strength of wool fibres in varying ways. The most important factor appears to be nutrient supply which exerts a major influence via its effects on wool growth (Reis 1992b) as changes in the rate of wool growth cause variations in fibre diameter along-staples. There has been some debate as to whether minimum fibre diameter, rate of fibre diameter change and/or overall fibre diameter variation (mid-side CV) is the most important factor affecting staple strength. Staple strength is generally controlled by a lower level of strength at a specific point along its length, which corresponds to a particular growth period.

Therefore there is no single reason to explain low staple strength. The main determinants of staple strength fall into three main categories;

1. The variation of fibre diameter along and between fibres;
2. Incomplete fibres within a staple due to differences in growth rates and fibre shedding;
3. The strength of the fibre material associated with differences in the physical characteristics and composition of the fibre.

The published genetic and phenotypic correlations between FDP and wool quality characteristics with staple strength are summarised in Table 2.1.

2.4.1 Components of fibre diameter variation

Variation in fibre diameter within the fleece arises from a number of sources and therefore care needs to be taken to ensure the appropriate sources of variation are being studied. Fibre diameter variability is considered to affect many fleece characteristics and processing performance (Quinlivan 1990). Fibre diameter variability is a general term encompassing a wide range of variation. The variation within a fleece includes variation;

- between individual fibres within a staple
- along-fibres within a staple
- between staples with sites
- between sites within a fleece

Table 2.1 Summary of the published phenotypic and genetic correlations between the FDP characteristics, mid-side mean fibre diameter, mid-side fibre diameter variation and staple length with staple strength (SS)

FDP characteristic	Correlation	Reference	Comments
Minimum fibre diameter	0.64	Bigham *et al.* 1983	Mixture of NZ Long-wooled Breeds
	0.47 and 0.54	Fitzgerald *et al.* 1984	Mixed aged grazing Coopworth ewes and pen fed Romney ewes
	0.64 and 0.27	Hansford and Kennedy 1988	Pen fed Merino ewes with a number of nutritional treatments
	0.74	Orwin *et al.* 1988	Grazing and pen fed dry Romney ewes
	0.78	Peterson 1997a	SIFAN† 40 penned Merino wethers from SS selection flock in Western Australia (WA)
	0.81	Peterson 1997a	FDPs 40 penned Merino wethers from SS selection flock in WA
	0.13 to 0.59	Adams and Briegal 1998	Three strains of grazing Merino wethers
	-0.06 and 0.71	Adams *et al.* 1998	Pen fed Merino wethers from SS selection flocks from WA
	0.46	Peterson *et al.* 1998	Grazing Merino wethers measured with SIFAN†
	0.81	Thompson and Hynd 1998	Pen fed Merino wether weaners from WA SS selection flocks
	0.47	Yamin *et al.* 1999	Phenotypic correlation in South Australian (SA) Merino sheep
Maximum fibre diameter	0.19	Yamin *et al.* 1999	Phenotypic correlation in South Australian (SA) Merino sheep
Difference in fibre diameter (Range)	-0.72 and -0.41	Hansford and Kennedy 1990a	Pen fed Merino ewes with a number of nutritional treatments
	0.04 to 0.45	Adams and Briegal 1998	Three strains of grazing Merino wethers
	-0.39	Yamin *et al.* 1999	Phenotypic correlation in SA Merino sheep
FDP mean fibre diameter	0.26 and 0.28	Hansford and Kennedy 1990a	Pen fed Merino ewes with a number of nutritional treatments
	0.41	Yamin *et al.* 1999	Phenotypic correlation in SA Merino sheep
Along-staple variance	-0.30	Denney 1990a	Grazing Merino wethers and dry ewes
Along-staple CV of fibre diameter	-0.84	Peterson 1997a	SIFAN† 40 penned Merino wethers from SS selection flock in WA
	-0.71	Peterson 1997a	FDPs 40 penned Merino wethers from SS selection flock in WA
	-0.21 and -0.47	Adams *et al.* 1998	Pen fed Merino wethers from SS selection flocks from WA
	-0.71	Peterson *et al.* 1998	Grazing Merino wethers measured with SIFAN†
	-0.43	Yamin *et al.* 1999	Phenotypic correlation in SA Merino sheep
Along-staple SD of fibre diameter	-0.08 to -0.53	Adams and Briegal 1998	Three strains of grazing Merino wethers
	-0.62	Thompson and Hynd 1998	Pen fed Merino wether weaners from WA SS selection flocks
Rate of fibre diameter change (min to max)	-0.77 and -0.42	Hansford and Kennedy 1988	Pen fed Merino ewes with a number of nutritional treatments
	0.15	Yamin *et al.* 1999	Phenotypic correlation in SA Merino sheep

Rate of fibre diameter hange (tip to min)	-0.64	Peterson 1997a	FDPs 40 penned Merino wethers from SS selection flock in WA
	-0.67	Thompson and Hynd 1998	Pen fed Merino wether weaners from WA SS selection flocks
Mid-side mean fibre diameter	0.49	Orwin *et al.* 1988	Grazing and pen fed dry Romney ewes
	0.21	Denney 1990a	Grazing Merino wethers and dry ewes
	-0.29	Hansford and Kennedy 1990a	Pen fed Merino ewes with a number of nutritional treatments
	-0.23 ± (0.26) and 0.39 ± (0.20)	Lewer and Ritchie 1992	Genetic correlation for grazing Merino hoggets from a commercial and stud situation respectively
	0.15 and 0.25	Lewer and Ritchie 1992	Phenotypic correlation for grazing Merino hoggets from a commercial and stud situation respectively
	0.77 and 0.82	Earl *et al.* 1994	Phenotypic correlation for Merino grazing wethers
	0.31 ± 0.14	Lewer and Li 1994	Genetic correlation for grazing Merino hoggets
	0.22	Lewer and Li 1994	Phenotypic correlation for grazing Merino hoggets
	0.65 ± (0.05)	Bray *et al.* 1995a	Genetic correlation for grazing Romney SS selection lines
	0.44 ± (0.02)	Bray *et al.* 1995a	Phenotypic correlation for grazing Romney SS selection lines
	0.17 to 0.32	Greeff *et al.* 1995	A review of the phenotypic correlations estimated from the major Merino based research flocks
	-0.15 to 0.46	Greeff *et al.* 1995	A review of the genetic correlations estimated from the major Merino based research flocks
	0.08	Swan *et al.* 1995	Genetic correlation from grazing Merino sheep from CSIRO Fine Wool Project
	0.02	Swan *et al.* 1995	Phenotypic correlation from grazing Merino sheep from CSIRO Fine Wool Project
	-0.19 to 0.47	Adams *et al.* 1998	Pen fed Merino wethers from SS selection flocks from WA
	0.06 to 0.49	Adams and Briegal 1998	Three strains of grazing Merino wethers
	0.32	Yamin *et al.* 1999	Phenotypic correlation in SA Merino sheep
Mid-side CV of fibre diameter	-0.47	Hansford and Kennedy 1990	Pen fed Merino ewes with a number of nutritional treatments
	-0.82 and -0.89	Ritchie and Ralph 1990	Grazed Merino hoggets
	-0.59 ± (0.33) and -0.73 ± (0.22)	Lewer and Ritchie 1992	Genetic correlation for grazing Merino hoggets from a commercial and stud situation respectively (mini-core based sample)
	-0.70 ± (0.28) and -0.63 ± (0.21)	Lewer and Ritchie 1992	Genetic correlation for grazing Merino hoggets from a commercial and stud situation respectively (snippet based sample)
	-0.41 and -0.45	Lewer and Ritchie 1992	Phenotypic correlation for grazing Merino hoggets from a commercial and stud situation respectively
	-0.72 ± (0.11)	Lewer and Li 1994	Genetic correlation for grazing Merino hoggets
	-0.49	Lewer and Li 1994	Phenotypic correlation for grazing Merino hoggets
	-0.19 to –0.50	Greeff *et al.* 1995	A review of the phenotypic correlations estimated from the major Merino based research flocks

	-0.27 to –0.86	Greeff *et al.* 1995	A review of the genetic correlations estimated from the major Merino based research flocks
	-0.78	Swan *et al.* 1995	Genetic correlation from grazing Merino sheep from CSIRO Fine Wool Project
	-0.29	Swan *et al.* 1995	Phenotypic correlation from grazing Merino sheep from CSIRO Fine Wool Project
	-0.51	Greeff *et al.* 1997	Merino SS selection flocks from WA
	-0.35 to -0.53	Adams and Briegal 1998	Three strains of grazing Merino wethers
	-0.27 to -0.70	Adams *et al.* 1998	Pen fed Merino wethers from SS selection flocks from WA
	-0.44	Yamin *et al.* 1999	Phenotypic correlation in SA Merino sheep
Staple length	0.43	Orwin *et al.* 1988	Grazing and pen fed dry Romney ewes
	-0.07	Denney 1990a	Grazing Merino wethers and dry ewes
	0.56	Hansford and Kennedy 1990	Pen fed Merino ewes with a number of nutritional treatments
	0.10 and 0.10	Lewer and Ritchie 1992	Phenotypic correlation for grazing Merino hoggets from a commercial and stud situation respectively
	0.04 $\pm$ (0.29) and 0.19 $\pm$ (0.28)	Lewer and Ritchie 1992	Genetic correlation for grazing Merino hoggets from a commercial and stud situation respectively
	-0.06 to 0.21	Greeff *et al.* 1995	A review of the phenotypic correlations estimated from the major Merino based research flocks
	-0.11 to 0.80	Greeff *et al.* 1995	A review of the genetic correlations estimated from the major Merino based research flocks
	-0.16	Swan *et al.* 1995	Genetic correlation from grazing Merino sheep from CSIRO Fine Wool Project
	-0.03	Swan *et al.* 1995	Phenotypic correlation from grazing Merino sheep from CSIRO Fine Wool Project

[†] Calculated from individual fibre measurements using the Single Fibre Analyser

There have been a number of studies aiming to estimate the relative proportion of each of these different components of fibre diameter variation. The estimates of this variation in fibre diameter include;

1) Between fibres within staple

34% (McKinley *et al.* 1976),

60 - 80% (Quinnell *et al.* 1973; Whiteley 1987)

46% (Peterson 1997a).

2) Between sheep

20% (Dunlop and McMahon 1974),

9% (McKinley *et al.* 1976),

16% (Quinnell *et al.* 1973; Whiteley 1987),

13% (Peterson 1997a).

3) Between staples/sites within a fleece

4% (Quinnell *et al.* 1973; Whiteley 1987).

4) Along-fibres (seasonal)

34% (McKinley *et al.* 1976),

16% (Quinnell *et al.* 1973; Whiteley 1987),

42% (Peterson 1997a).

A staple is composed of many thousands of individual fibres (Schlink *et al.* 1996b), and it is not surprising that most of the variation in fibre diameter exists between fibres within individual staples. This variation between fibres constitutes approximately 2/3 of the total (Dunlop and McMahon 1973). Within a staple, variation in fibre diameter exists between fibres and along-fibres (Hansford and Kennedy 1988; Ritchie and Ralph 1990). Even over a small period of two days growth, the fibre diameter can vary by as much as 8μm (Schlink *et al.* 1996b). Quinnell *et al.* (1973) and Whiteley (1987) found that while variation in fibre diameter along-fibres accounted for 16% of the total variation in sound wool, in tender wool this along-fibre component increased to 43%. This supports the fact that variation along-fibres influences staple strength. The differences between the two estimates above for the proportion of variation along-fibres are most likely due to differences between environments where the wool was grown and the way in which each of these components were estimated.

Most wool traits have a tendency to vary over the body of the animal. These trends over sheep have been illustrated by Daws (1973), Cottle (1991) and Onions (1962). Mean fibre diameter generally increases from the shoulder to the breech. The mid-side region is generally used as a sampling point for all wool characteristics as it representative of the fleece as a whole (Cottle 1991; Hansford 1992). Due to these variations in fibre diameter between fibres, staples and between sites within the fleece, sampling method is an important consideration.

Hansford (1992) found a similar wool growth response (FDPs) from all sites of the fleece however there were no statistical analysis of the FDP characteristics between sites. Denney (1990) also observed that the variance of fibre diameter along-staples was highly repeatable between duplicate staples within the mid-side sample from the same sheep. However the technique used by these authors only utilised 10 snippets per staple which may not provide a good estimate of the true FDP.

The variation in the fibre diameter within a staple has been directly related to reduced staple strength of that wool from sheep run together in field conditions (McKinley *et al.* 1976).

However, it must be remembered that the causes of the reduced fibre diameter cannot be differentiated. That is, reduced fibre diameter at particular points in time can be due to a number of causes.

A number of characteristics have been used to evaluate differences in the level of fibre diameter variation within a fleece. There appears to be genotype by environment interactions in the relative importance of each of these characteristics in determining staple strength. The influence of the various components of variation in fibre diameter within a fleece on staple strength will be examined individually.

2.4.1.1 Fibre diameter distribution

Depending of the method used, this measure of fibre diameter variation incorporates variation along-fibres, between fibres and between staples. The level of fibre diameter variation within a mid-side sample is related to staple strength. Mid-side coefficient of variation in fibre diameter explains approximately 50 - 80 % of the phenotypic variation in staple strength of wool from Merino sheep, irrespective of mean fibre diameter (Ritchie and Ralph 1990; Hansford 1992; Hynd and Schlink 1992; Butler and Head 1993; Peter *et al.* 1994; Lewer and Li 1994). These traits are also genetically related. Negative genetic correlations of between -0.18 and -0.86 have been observed between staple strength and coefficient of variation of fibre diameter (Lewer and Ritchie 1992; Lewer and Li 1994; Gifford *et al.* 1995; Greeff *et al.* 1995; Swan 1995; Greeff and Windsor 1996). This relationship suggests that coefficient of variation of fibre diameter may be able to be used for indirect selection for staple strength. The fact that staple strength has been shown to be moderately to highly heritable (0.3 - 0.4) supports the possibility of selection. As a consequence of these strong relationships a small change in the coefficient of variation of fibre diameter can result in large change in staple strength (Greeff *et al.* 1997). Adams (1998) estimated that a genetic reduction of coefficient of variation in fibre diameter by 5% might increase staple strength by 8 to 16 N/ktex.

2.4.1.2 Variation along-fibres

Variation in fibre diameter along-fibres in response to fluctuating environmental conditions is normally largely nutritional in origin and therefore is greatly influenced by management practices. The way in which a sheep reacts to an environment will also influence its mean fibre diameter and fibre diameter variation along-fibres. The level of variation in fibre diameter along-fibres has been shown to be associated with staple strength (McKinley *et al.* 1976; Denney 1990a; Bow and Hansford 1994; Greeff *et al.* 1997; Peterson 1997a). The characteristics of the FDP can also be directly related to the characteristics of the fibre length distribution in the top, (Hansford 1994). The prediction of Hauteur can be improved by utilising information derived from the FDP (Hansford 1997). Hawker and Littlejohn (1989) also found that Romney ewes growing fleeces of low staple strength had a more pronounced seasonal pattern of wool growth than ewes growing sound fleeces however this result may be complicated by the seasonal rhythm of wool growth exhibited by Romney sheep.

2.4.1.2.1 Fibre diameter profiles

The way in which the fibre diameter varies over one year of wool growth is referred to as a FDP and is an indication of the along-staple variation in fibre diameter. FDPs are modified by temperature and light (Hutchinson 1962; Williams and Schinckel 1962) however the main determinant is nutritionally based. Unlike Romney sheep, Merino sheep exhibit little seasonal rhythm in wool growth (Reis and Shlu 1994). Environmental conditions throughout the year are not constant, and exhibit periods of stability and periods of change, some of which occur abruptly. As a result there is substantial seasonal variation in the quality and quantity of wool grown by grazing sheep, particularly in the Mediterranean environment. Therefore, for healthy sheep, FDPs represent overall responses of fibre diameter to changes in nutrition, nutritional demands, temperature, light and management. The fibre diameter of the wool varies throughout the year in accordance with the sheep's interaction with these environmental conditions. Variation along-staples still occurs even when animals are fed at maintenance for long periods (Hansford 1992). The mean fibre diameter of a standard mid-side wool sample often masks wide variation in fibre diameter along the fibres.

FDPs are the phenotypic response of sheep to their environment (Hansford 1994) and therefore can be used to evaluate differences between animals in their response to the environment. At present there has only been one study examining the genetic variation between animals in FDP characteristics (Yamin *et al.* 1999). This study suggested that absolute fibre diameter and overall fibre diameter variation along and between fibres is moderately heritable, while the rate of fibre diameter change was not heritable.

A sheep will normally have seasonal variation of fibre diameter along the staple due to the normal seasonal variation in feed quality and quantity, temperature and other factors. This variation over the year can vary from as little as 2 microns to as much as 10 microns (Ross 1990a). Variation in fibre diameter along the staple may arise from any one or more of the physiological and environmental factors that influence wool growth individually or as a compounded effect. Every animal will respond differently to a given set of environmental conditions. The difficulty at this point in time is the accurate identification of animals with greater ability to cope with nutritional surpluses and deficits while producing fibres with less variation in their FDPs.

The FDP of a wool staple is measured by way of fibre diameter profiling (Hansford *et al.* 1985). To obtain a FDP, staples are cut into consecutive 2mm length snippets for the entire length of the staple and these are measured for fibre diameter. Therefore, if a staple is segmented into a series of snippets and the mean fibre diameter of each segment measured, the outcome is a picture of the average fibre diameter changes throughout the entire fibre growth period, called the FDP. This FDP can then be described by calculating a number of characteristics, including the maximum and minimum fibre diameter points and the difference between these points. The rates of fibre diameter change between the points of maximum and minimum fibre diameter and the level of along-staple variation in fibre diameter can also be calculated. Perhaps the best measures of FDP variation is the coefficient of variation in fibre diameter along FDPs which is the level of variation in fibre diameter along the staple corrected for the average fibre diameter of the staple. Although staple profiling is very informative it is time consuming and expensive and presently only suitable for research applications. The OFDA2000 (Brims *et al.* 1999) has been recently released which has the capability of rapidly measuring FDPs in greasy and clean staples, however at present there has been inadequate validation of this equipment to enable its routine use.

2.4.1.2.2 Minimum fibre diameter

In general it can be assumed that fibres will generally break at their thinnest point, that is at the smallest cross-sectional area (Bigham *et al.* 1983; Ross 1990b). This has been confirmed by the strong correlation between minimum fibre diameter and position of break ($r= 0.97$) (Hansford and Kennedy 1990a). Thompson and Hynd (1998) also observed that minimum fibre diameter determined by measuring dyebands inserted at 28 day intervals throughout the growth period accounted for 66% of the variation in staple strength. When a sheep is stressed nutritionally the fibre becomes thin and, in extreme cases, follicles may shut down completely and fibres shed. The lower number and lower fibre diameter of fibres at a distinct point in the staple is believed to be the primary cause of reduced staple strength (Huson 1996). There have been considerable investigations into the effects of reductions in fibre diameter, both at the POB and the rate of change in fibre diameter. If the minium fibre diameter is increased by 1 micron the staple strength can be increased by up to 4 to 5 N/ktex (Bray *et al.* 1993; Adams 1998, Thompson and Hynd 1998).

If wool fibres break at the point where fibre diameter is at its minimum, factors, which influence minimum fibre diameter, will influence staple strength, for example, breed, strain of sheep, age, level of feeding and reproductive status (Bigham *et al.* 1983). Other factors include flystrike and acidosis.

Not all of the variation in staple strength is determined by the minimum fibre diameter. Wool fibres of the same fibre diameter have varying breaking loads and do not always break at the point of minimum fibre diameter (Schlink and Hynd 1994). In New Zealand wools minimum fibre diameter only accounts for approximately 25 - 50% of the variation in staple strength (Bigham *et al.* 1983; Hunter *et al.* 1983). Fitzgerald *et al.* (1984) found, in Romney and Coopworth mixed-aged ewes, that despite a high correlation ($r = 0.95$) between position of break and minimum fibre diameter, less than 30% of the variation in staple strength within each flock could be accounted for by variation in fibre diameter at the position of break. There was also a poor relationship between staple strength and fibre diameter at the position of break ($r = 0.54$). Associated with this Orwin *et al.* (1980) found in Romney sheep that about 85% of the tender and 70% of the sound wool fibres when tested broke at the thinnest point. This suggests that factors other than fibre diameter may be involved, such as fibre structure and compositional differences. However these results may have little relevance to Merino sheep due to the photoperiodically determined annual wool growth cycle exhibited by Romney and Coopworth sheep (Gourdie *et al.* 1992).

These relationships have also been observed in Merino wethers. Peterson (1997a) found that the minimum fibre diameter from both single fibres and staple FDPs were highly correlated with staple strength, $r = 0.78$ and 0.81 respectively. While the minimum fibre diameter did not significantly improve the prediction of staple strength, the fibre diameter at the position of break did and was highly correlated with the minimum diameter (r= 0.91). However once again these characteristics did not explain all the variation in staple strength. Yamin *et al.* (1999) also observed in South Australian Strongwool Merino sheep that minimum fibre diameter was phenotypicaly correlated with staple strength (r= 0.47).

The strength of each individual fibre is predominantly determined by the minimum diameter and due to differences in the rate of fibre length growth between fibres these points of minimum fibre diameter occur at different positions within the staple. When these individual wool fibres are combined into a wool staple the position of break will be determined by where all the individual fibres weak points average out. These factors are most likely the reason for Hansford and Kennedy (1990a) finding that the position of break of a staple was generally at or around the point of minimum mean fibre diameter.

2.4.1.2.3 Rate of fibre diameter change

The rate of change of fibre diameter along the staple has also been shown to be associated with staple strength (Hansford and Kennedy 1988; Hansford 1992; Peter *et al.* 1994; Peterson 1997a). In an examination of the variation of fibre diameter along a staple, Hansford and Kennedy (1990a) found that the minimum fibre diameter, range in fibre diameter and the rate of change in fibre diameter along the staple were all significantly correlated with staple strength, r= 0.37 to 0.69, -0.72 to -0.41 and -0.77 to -0.42 respectively. However rate of change in fibre diameter along the FDP was the characteristics that explained a greater proportion of the variation in staple strength than mean fibre diameter, minimum fibre diameter or the range in fibre diameter. Peterson (1997a) also observed that the rate of change in fibre diameter from the tip of the staple towards the minimum was negatively correlated with staple strength (r= -0.64).

Although research has illustrated associations between rate of fibre diameter change, minimum fibre diameter and staple strength no biological or physiological explanation for these relationships has yet been developed (Schlink and Hynd 1994). It would be anticipated that these effects would arise from changes in the fibres cross-sectional area, fibre composition and intrinsic strength.

2.4.1.2.4 Overall along-staple fibre diameter variation

Along-staple variation in fibre diameter measured as a variance and standard deviation of fibre diameter along the staple or reported as coefficient of variation are measures of the overall variation in fibre diameter along-staples. These characteristics are related to the FDP characteristics previously mentioned and along-staple variation in fibre diameter is also related to staple strength. Denney (1990a) estimated a moderate negative correlation of -0.30 between along-staple variation in fibre diameter and staple strength. Quinnell *et al.* (1973) also demonstrated this relationship by comparing the components of the fibre diameter variation between tender and sound fleeces. Peterson (1996) found that the most important factor influencing staple strength of the wools studied was the variation in diameter along-fibres ($r= -0.84$) using the SIFAN (Single Fibre Analyser) to measure single fibres. The along-staple variation in fibre diameter from the staple FDPs from this experiment were also associated with staple strength ($r= -0.71$). Greeff *et al.* (1997) also found that the lines of Merino sheep selected for high staple strength grew wool with less variation of fibre diameter along the staple than the selection line with low staple strength. Lower levels of variation in the cross-sectional area profiles along individual fibres were observed by (Bray *et al.* 1995a) in the Romney sheep selected for high staple tenacity compared the line selected for low staple tenacity.

2.4.1.3 Between-fibre variation in fibre diameter

Although there are estimates of the level of variation in fibre diameter between fibres excluding the variation along-fibres, its relationship with staple strength has not been extensively studied. At a phenotypic level variation in fibre diameter between fibres is negatively associated with staple strength, $r=-0.30$ (Yamin *et al.* 1999). It is known that wool fibres grow at a relatively constant L/D ratio (Reis 1991) and as a result of this relationship a staple from an animal with increased variation in fibre diameter between individual fibres is likely to have increased variation in the length of the fibres. Increased fibre length variation influences the way in which fibres come into tension during measurement of staple strength (de Jong *et al.* 1985; Bray *et al.* 1995a; Peterson 1997a; Peterson *et al.* 1998). In opposition to these theories, Schlink *et al.* (1998) observed no significant relationship between fibre length variation and fibre diameter variation. However the method used to estimate fibre length variation in this study has not been validated against standard fibre length measurement techniques.

It is known that total variation in fibre diameter within a staple accounts for a large proportion of the variation in staple strength between sheep although the reason for this relationship is not completely understood. Variation in fibre diameter between individual fibres accounts for a large proportion of the overall fibre diameter variation. Therefore increased variation in fibre diameter between-fibres must influence staple strength in additional ways other than increasing fibre length variation. The following are some possible explanations of how increased between-fibre variation in fibre diameter may influence staple strength;

1. An increased proportion of larger diameter fibres that are more prone to fibre diameter variation along the fibre which reduces staple strength (Bow and Hansford 1994),
2. An increased proportion of finer fibres that are more prone to fibre shedding (Hynd and Schlink 1992; Thompson 1993) which also influences staple strength (Schlink and Dollin 1995; Thompson et al. 1995a; Peterson 1996),
3. An increased incidence of finer fibres which have a reduced cross-sectional area to bear the load which may not be entirely corrected for by linear density.

As mean fibre diameter increases with improved nutrition and if all fibres increase in diameter by the same magnitude (Dolling et al. 1994), the response of the smallest follicles to nutritional change is relatively greater. That is, the finer fibres within a staple have a greater proportional change in fibre diameter than the thicker fibres. Therefore if this theory is correct, the actual level of variation between fibres within a staple may influence the responsiveness of the staple to changes in nutrition. Variability in fibre diameter may influence the fibre diameter response of the fibres population and staple strength however Ansari-Renani and Hynd (1996) found that variability of fibre diameter did not affect the incidence of follicle shut down.

2.4.2 The Intrinsic Strength of Wool Fibres

If wool fibres had the same intrinsic fibre strength, the strength of any individual fibre would be simply determined by its fibre diameter. However, like all other fibre properties, intrinsic fibre strength varies between fibres and between sheep (Orwin *et al.* 1985; Thompson *et al.* 1996). The fact that the FDP characteristics previously mentioned do not account for all of the variation in staple strength suggests that other factors are involved in the production of wool with low staple strength. Although it appears that minimum fibre diameter and variation between fibres in diameter are the major factors causing reduced staple strength, some evidence exists to suggest that the fibre material is also physically weaker. The intrinsic strength of wool fibre may differ due to differences in internal structure, and the protein composition of their complex components.

Intrinsic strength is the strength of the fibres within the staple per unit of cross-sectional area. The fibre diameter and the breaking extension of keratin are variable along the length of the fibre (Orwin *et al.* 1980) and as a result it would be expected that the actual point of break would be a function of both these factors.

The chemical and physical characteristics of wool fibres are responsible for 20 to 30% of the differences in average intrinsic fibre strength between Merino sheep (Peterson 1995). Differences exist between fibres in the form of protein composition, physical structure, cell structure and composition, nature of the cortex, cortical components (ortho-, meso- and para-cortex), cystine content and chemical composition (Orwin *et al.* 1980; Orwin *et al.* 1985; Hansford and Kennedy 1990b; Reis 1991; Gourdie *et al.* 1992; Reis and Shlu 1994; Peterson 1995; Huson 1996; Thompson *et al.* 1996). These studies all observed different effects on fibre strength. Gourdie *et al.* (1992) postulated two causes of this disagreement: difficultly in accurately measuring the stress-strain properties of wool fibres and insufficient experimentation examining the possible sources of variation in intrinsic fibre strength. Recent research by Scobie *et al.* (1996) and Peterson *et al.* (1998) demonstrated a non-significant relationship between intrinsic fibre strength and staple strength while Bray *et al.* (1995a) found that individual fibre tenacity did not significantly differ between high and low staple strength selection lines of Romney sheep.

Using staples of different strength but matched for average fibre diameter, Huson *et al.* (1996) found that fibres from the tender region of the staple are intrinsically weaker than those from the sound region. These results suggest that there may be differences between the intrinsic strength of fibres. In contrast recent research in both New Zealand and Western Australia with both Merino and Romney sheep has shown that there is almost no variation along and between fibres in the strength of the keratin itself (Peterson 1997b).

There is some disagreement as to whether the physical strength of fibres differs genetically. Much speculation has been made because the actual factors determining intrinsic fibre strength are not fully understood. There is potential genetic variation between breeds and individual sheep in the many proteins that make up the wool fibre (Schlink *et al.* 1992). The differences between sheep in intrinsic strength may arise from cell structure together with the composition and arrangements of the protein molecules in the various ultra-structural components of the wool fibre (Jones 1997). If an understanding of the biology and genetics determining fibre breakage can be gained it may lead to a reduction or an elimination of low staple strength.

Individual fibre strength is a component of staple strength (de Jong *et al.* 1985; Scobie *et al.* 1996). Although the breaking load of fibres increases with fibre diameter (Anderson and Cox 1950), it would expected that the physical strength (intrinsic strength) of the material within that fibre to have a significant effect on staple strength. Individual fibre strength is a function of intrinsic strength and fibre diameter. Individual fibre strength increased approximately linearly with fibre linear density accounting for 90% of the variation in fibre strength (Smuts *et al.* 1981). Individual fibre strength is also, as expected, highly correlated with peak force and staple strength (Hunter *et al.* 1983; Gourdie *et al.* 1992; Thompson *et al.* 1995a). The significant differences in wool fibre strength between sheep and its relationship to staple strength may provide some explanation for low staple strength. However fibre strength is not the only determinant of staple strength (Peterson 1996), with fibre characteristics such as fibre extension, evenness of crimp and fibre length variation playing a role in determining staple strength.

2.4.3 Fibre Shedding

At certain times of the year wool follicles can dramatically reduce or cease fibre production resulting in extreme thinning or a period of time where no fibre is produced, such that the fibre may dislodge from the follicle. This process is referred to as fibre shedding. In some instances a proportion of fibres may cease production, or there may be fundamental changes in the wool substance (Rottenbury *et al.* 1981). Research has confirmed the fact that fibre shedding is an important determinant of staple strength. However fibre shedding only appears to be important in wools with low staple strength, below 30 N/ktex in Mediterranean environments (Schlink *et al.* 1996c). The rate of fibre shedding is also highly variable between sheep (Schlink 1997).

Schlink *et al.* (1992), Schlink and Dollin (1995), Thompson *et al.* (1995a), Peterson (1996), Hynd *et al.* (1997) and Thompson *et al.* (1998) have all presented evidence that indicates that the incidence of fibre shedding is significantly correlated with staple strength in a range sheep breeds and of varied ages. Follicles that shut down and cease fibre production create discontinuous fibres within a staple. Although the proportion of shutdown follicles has been shown to significantly explain variation in staple strength, Thompson *et al.* (1998) and Schlink *et al.* (1996a) found that the rate of fibre shedding did not differ significantly between the sheep bred for high and low staple strength. Associated with this the fibre shedding failed to remove any variance in staple strength additional to that already attributed to along- and between-fibre changes in diameter. It is anticipated that the influence of fibre shedding on staple strength will be associated with environmental conditions during the wool growth period. The extent to which fibre shedding determines staple strength in the Tableland environment is yet to be determined.

Under normal conditions the incidence of shedding in Merino sheep is less than 1% (Ryder 1962; Ryder and Stephenson 1968). Fibres appear to shed when there has been drastic reduction in fibre diameter (below 8 - 12um) (Schlink *et al.* 1992; Schlink and Dollin 1995).

The incidence of fibre shedding may vary between secondary and primary follicles as they respond differently to changes in nutrition. Secondary follicles are more affected than primary follicles with adverse nutrition (Lyne 1964; Ryder and Stephenson 1968) and are therefore more susceptible to fibre shedding. This therefore suggests that sheep differing in S/P ratio will differ in their sensitivity to fibre shedding.

The exact cause of follicle shutdown or the susceptibility of different sheep to environmental stress is not known (Ansari-Renani and Hynd 1996). Schlink *et al.* (1996c) discussed experiments aiming to separate the effects of nutrition and stress on staple strength by administering cortisol, a stress hormone. Sheep gaining weight did not have a shedding response however, in sheep losing weight, staple strength declined. This decline was solely due to an increase in the number of fibres shed and not due to changes in fibre diameter.

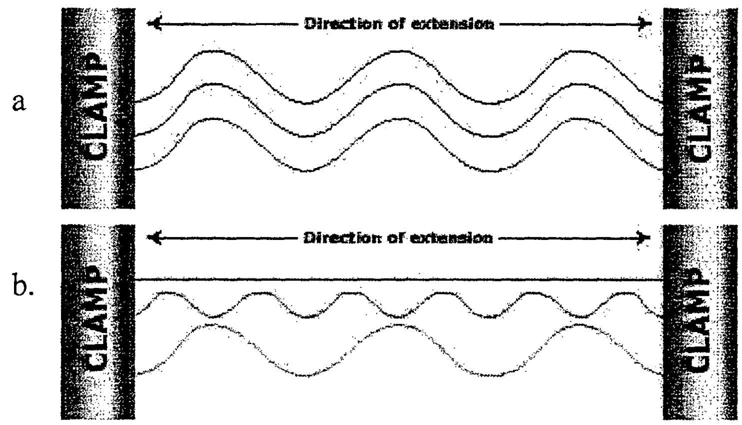
Nutritional management, including stocking rates and supplementary feeding strategies (Schlink 1995) can manipulate shedding rates and staple strength (Hughes *et al.* 1996).

It is not presently known whether shedding rates are a characteristic of the sheep, a response to the environment or a combination (Schlink *et al.* 1996c). If some sheep could be identified as having a lower incidence of fibre shedding, and if they could be selected it may lead to an improvement in staple strength. Ansari-Renani and Hynd (1996) observed that in the period after the cortisol injection the fine wool sheep had fewer shutdown follicles than strongwool sheep. The follicles of these fine wool sheep also recovered more quickly than the strongwool sheep after completion of cortisol injections. These results support the theory that there may be genetic differences in susceptibility to follicle shutdown. However, Hughes *et al.* (1996) found that genotype, strong versus fine wool sheep, did not affect follicle morphology. Although there are large differences between sheep in the rate of fibre shedding and proportion of discontinuous fibres under similar nutritional conditions (Thompson *et al.* 1995a) the physiological and follicular mechanisms which determine the sensitivity of individual sheep to follicle "shut down" are at present not understood.

2.4.4 Fibre Length variation

Variation in fibre length growth rate, and hence fibre length, influences when and how much any individual fibre is strained under extension (Thompson 1993; Swan 1994; Bray *et al.* 1995a; Schlink *et al.* 1998b). The strength of a staple is determined by the sum of all fibres under strain at the peak of the extension curve (Peterson 1997a). The more uniform the fibres are the more fibres will be strained at this point. If a staple has a reduced variation in fibre length and crimp (Figure 2.1a), when the staple is pulled taut under staple strength testing, the fibres within the staple should take up the strain more evenly than a staple with uneven crimp and therefore variations in length. Staples with an increase in the variation in fibre length within the staple will take up the load and break over a longer period in time and thus result in a lower staple strength (Figure 2.1b). The crimps are straightened out when the fibres are tensioned but there is major effect on the staple stress-strain curve because the length of the more crimped fibres between the jaws is greater than the length of the less crimped fibres within staple (Carnaby 1986). Swan (1994) simulated this in a hypothetical example, in which increasing the amount of fibre length variation resulted in a decrease in the peak force required to break the staple. That is, even if all the fibres within a staple have identical breaking strength but varying lengths, the shorter fibres will be broken first followed by the longer fibres. This will have an effect on the peak force required to break this staple (de Jong *et al.* 1985; Swan 1994; Scobie *et al.* 1996) and therefore staple strength. This also suggests that for two staples with identical mean fibre diameters the staple with decreased variation in fibre length growth rate would have greater staple strength. The influence of fibre length variation on processing performance is yet to be determined.

Figure 2.1 The extension of wool fibres during staple strength measurement (Source Peterson 1997b)



2.4.5 Fibre Crimp and Curvature

The configuration of the fibres within the staple is likely to be an important factor determining staple strength (Carnaby 1986). Distinctness, definition of, and evenness of crimp are strongly related to the wool quality characteristic of "character". Although this trait is not measured objectively some producers regard this as a very important wool quality characteristic.

Crimp definition is negatively correlated with fibre diameter (r= -0.30 to -0.20) and fibre diameter variation (r= -0.37 to -0.33) (Lockart 1958; Lax *et al* 1995) at the phenotypic level and genetically, r= -0.21 and -0.52 respectively (Lax *et al* 1995). That is, wools with very distinct crimping tend to have a lower fibre diameter and lower coefficient of variation in fibre diameter. Fibre length growth rate and fibre diameter are closely related (Cottle 1987; Hynd 1992; Reis 1992a) and therefore it is likely that the relationship between definition of crimp and fibre diameter variation is in fact most affected by evenness of length growth rate. As a result, a staple with greater crimp definition should have fibres that are grown at a more uniform rate, have a more even length and therefore have reduced variation in fibre length.

The relationships of crimp definition with fibre length variation and staple strength are yet to be determined.

Follicle curvature and alignment influence crimp characteristics. Nay and Johnson (1967) observed that animals with straight type follicles had lower crimp frequency. These authors also noted that the animals ranged from the two extremes - highly tangled follicles growing fibres with higher crimp frequency and very straight follicles growing fibres with a much reduced crimp frequency. Fibre curvature is also correlated with follicle curvature (Nay and Johnson 1967; Nay and Hayman 1969). Average curvature of fibres within the staple and top is highly related to crimp frequency, with average curvature accounting for approximately 90% of the variation in staple crimp frequency (Swan 1994; Smuts *et al.* 1995; Lamb 1997; Hansford and Humphries 1997; Nimbs *et al.* 1998).

Differences in crimp frequency between the 12 bloodlines in the CSIRO Fine Wool Project are only small (Purvis 1997b). Crimp frequency (Purvis 1997b) and crimp definition (Lax *et al.* 1995) are both moderately heritable with approximately 30% of the phenotypic variance due to genetic differences between animals.

Crimp definition is also related to fibre curvature. Swan (1994) found that approximately half of the variation in staple crimp definition measured by a style instrument was related to variation in the level of alignment of the fibres within the staple. Therefore a staple with a larger variation in curvature between fibres is likely to have a poorer staple crimp definition. Reduced crimp definition could also be a result of uneven length growth rate creating unaligned crimps. Alternatively it may be that a more distinct crimp has fibres within in that have deeper crimps. It could also be a combination of these two factors. Furthermore visual assessed crimp definition has also been shown to be negatively associated with variation in fibre curvature at a phenotypic level (Crook *et al.* 1999).

The influence of fibre curvature and alignment on staple strength has not been directly investigated, however, Barnett *et al.* (1996) observed a significant genetic correlation between staple strength and crimp definition in Merino sheep of 0.65 ($\pm$0.29).

2.5 Factors that influence staple strength and FDP characteristics

A vast range of factors influence wool growth and therefore the shape of the FDP. Any factor that influences wool growth has the potential to influence the characteristics of a FDP. These factors include feed availability and quality, nutritional requirements, climatic conditions, parasite infestation, wool type, skin and follicle characteristics, genetic differences and sheep management. An underlying assumption of this discussion is that all animals within a mob are of similar breeding and subjected to the same environmental factors to same degree. The actual responses by sheep to all these factors will vary between individual animals (Hansford 1994). The possible cause of this variation in responsiveness between sheep within the mob may due to differences in a range of characteristics. These characteristics will be discussed in more detail below. Many of these differences between sheep have not been investigated in relation to variation in fibre diameter along the FDP.

2.5.1 Environmental Influences

2.5.1.1 Susceptibility to environment

The environment can be defined as a collection of forces that have an influence on and therefore interact with the sheep. A detailed description of these factors is given by Purser and Hogan (1992). Grazing sheep are disadvantaged in that they need to produce wool over a wide range of environmental conditions that cannot easily be controlled. If these environmental interactions could be controlled or manipulated like intensive industries the efficiency of wool production would improve (Adams *et al.* 1996a). Some environmental factors affecting wool growth can be manipulated such as lambing date, shearing date and nutritional management while most environmental factors such as soil type, rainfall and climatic conditions cannot be controlled by management. An alternate approach is to breed sheep that are better able to cope with these environmental conditions.

Some sheep appear to be more susceptible than others to fluctuations in fibre diameter in response to changes in nutritional and other environmental variations (Hynd 1992). Sheep grazing under the same nutritional and environmental conditions show similar patterns of wool growth however the degree in which they responded to these environmental conditions varies (Hansford 1992; Hansford 1994; Hansford 1997b) which results in a considerable range in fibre diameter and staple strength between sheep (Thompson 1993). These differences can be seen in their FDPs and are related to the variation in staple strength within a mob (Hansford 1994). Differences in wool growth responses may relate to genetic differences in susceptibility to environmental stresses (Hynd and Schlink 1992) and may also be influenced by an interaction between genotype and the environment for this trait.

Differences in the susceptibility to seasonal and environmental effects have been observed between lines of Merino sheep selected for high or low fibre diameter (Jackson and Downes 1979), between individual sheep within selection lines (Jackson and Downes 1979), between sire groups (Denney 1990a) and between bloodlines (Hansford 1994). These differences in susceptibility to seasonal effects resulted in lower variation in fibre diameter along-staples for these animals. This suggests that there is a genetic component involved in determining the susceptibility of sheep to environmental change. Although these authors have observed differences between sheep in the degree of variation in diameter along the fibre in response to their environment, it is not known to what extent these differences were genetic. Although needing further study, Jackson and Downes (1979) and Denney (1990a) found that there are individual animals and selection lines for which the variance of fibre diameter along the staple is lower leading these authors to conclude that potential exists to reduce this variation through selective breeding. Considering the phenotypic correlations observed in Table 2.1 such a selection strategy may improve staple strength.

Therefore it would be beneficial to establish why individual sheep respond differently when exposed to the same environmental conditions. There is a range of environmental factors that have potential to influence an animal's responsiveness of fibre diameter.

2.5.1.2 Nutrition

The large effects of nutrition on the quantity and quality of the fibre produced by a sheep are well-documented (Allden 1979; Faichney and Black 1979; Purser 1979; Reis 1979). The rate of wool growth is generally positively related to the level of nutrition. This may include the previous as well as the current nutrition of the sheep (Sharkey *et al.* 1962).

There are a number of main nutritional factors that may impinge on wool production. These include;

- level of feed intake, rate of feeding and the ability and willingness to consume forage
- diet selection and composition
    - level and type of protein intake, especially the type and amount of sulphur amino acids in the protein,
    - level and type of energy intake (eg. starch, fat, carbohydrate),
    - feed digestibility, amount of dietary protein degrade in the rumen and how much of the un-digested protein is absorbed from the gastrointestinal tract,
- amount of protein available for microbial degradation and digestion/absorption (eg. the presence of binding lignins, phenols etc.),
- rumen metabolism and efficiency and composition of microbial protein synthesis,
- efficiency of energy use and fat deposition,
- efficiency of conversion of amino acids to wool,
- interactions between these components, especially that between the level of energy and the level of protein.

The pattern of liveweight and wool growth, staple length and fibre diameter, closely follow the quantity and quality of feed on offer (McManus *et al.* 1964). As changes in fibre diameter are associated with changes in the nutrient supply, rapid alterations in nutrient availability increase the rate of change in fibre diameter and reduce staple strength. In the Mediterranean environment staple strength is strongly related with changes in liveweight (Gherardi and Masters 1996a) and therefore by maintaining liveweight, fibre diameter variation along the FDP is reduced and staple strength increased (Bogdanovic *et al.* 1990) compared to that produced both by animals gaining and losing liveweight. It has not been confirmed if this relationship between staple strength and liveweight change is as strong in the Tableland environments of Eastern Australia.

Nutrition of sheep in relation to wool growth involves a consideration of a number of major areas, including feed intake, diet selection, rumen metabolism, the quantities of nutrients absorbed and their utilisation. Alteration in these mechanism results in differences in the quantity and quality of feed ingested and the efficiency of its use, all of which influence wool production (Allden 1979; Williams 1979; Hawker 1986) and therefore potentially the characteristics of the FDP.

2.5.1.2.1 Voluntary feed intake

The quantity and quality of feed on offer that the grazing sheep can select a diet from has a major influence on the quantity and quality of wool produced by the sheep (James 1963; Arnold *et al.* 1964; Langlands 1969; Allden 1979; Lee *et al.* 1995a). The quality and quantity of feed available to the sheep unavoidably varies throughout the year. Restrictive nutrient intake is probably the major factor limiting production from grazing animals (Hodgson 1981).

Diet quality is also influenced markedly by selective feeding which makes prediction of animal performance difficult (Doyle and Thompson 1992). Selective grazing is a complex of interacting factors and a detailed discussion of these principles is beyond the scope of this review. Arnold (1964), Allden (1979) and Weston (1979) have discussed selective grazing in detail.

Feed acquisition may be pursued under a wide range of environmental conditions which impose climatic, psychic and disease stresses. It has been established that the environment has different effects on individuals within a mob of sheep and as a result this will create differences in feeding habits between individual sheep. Not only are there differences between species of grazing animals in selection preferences but there is considerable variation between individuals within a mob (Arnold 1964; McBride *et al.* 1967; Langlands 1969; Lee *et al.* 1995b). Differences in the nutritive value of the diet selected by animals grazing together may be an important source of variation in digestible nutrient intake and hence their wool production (Langlands 1969). Therefore it is possible that the sheep in the same mob or flock could be ingesting very different diets creating differences between individual sheep in their FDP characteristics.

The regulation of voluntary feed intake in sheep involves a range of physiological processes and is very complex (Weston 1979). Therefore there are many possible factors that give rise to variation in the total amount and quality of digestible organic matter consumed (Purser and Hogan 1992). Voluntary feed intake is determined primarily by two factors, the digestibility of the forage and the intake capability of the animal (Dulphy and Demarquilly 1994). The satisfaction of appetite is further determined by interactions of behavioural responses with characteristics of the plant community from which the diet has to be selected and with environmental factors, particularly weather (McBride *et al.* 1967). Many other factors have been suggested to influence voluntary feed intake and the nutritive value of intake. These include; the botanical and morphological composition and structure of the feed on offer, palatability, physiological state, stomach capacities, ruminal degradation of feed particles, disposal of end products of digestion, heat dissipation and conservation, accessibility of water, diseases and climatic conditions (McBride *et al.* 1967; Wilson *et al.* 1969; Weston 1979; Arnold 1981; Donnelly *et al.* 1974; Hodgson 1985; Henry *et al.* 1996). Slight variations in any of these processes or mechanisms may influence voluntary feed intake, digestion and therefore nutrient partitioning to wool follicles. This may result in variations in wool growth and therefore FDPs between sheep.

In addition to the well-documented influence of the current nutrition, the nutritional condition that the animal experienced during early life may influence its future wool production. These effects could arise during pregnancy, lactation and post weaning due to differences in grazing experience and grazing preferences (McBride *et al.* 1967; Arnold and Maller 1977; Green *et al.* 1984; Denney 1990b; Distel *et al.* 1994). The effects of the differences in younger life on latter life production are not conclusive. Individual animals within a mob are likely to vary in their ability to cope with new feeds and/or changes in feeds. This therefore may affect wool growth and changes in fibre diameter over this period.

Competition between animals is an additional factor that may influence the variation between animals in voluntary feed intake through competition to obtain a satisfactory diet (Hawker 1986), however this subject has not been sufficiently researched.

Feeding habits and therefore voluntary feed intake may be a heritable trait (Lee *et al.* 1995a). Estimates of the heritability of feed intake of ruminants vary from 0.1 to 0.7 (Newton and Orr 1981; Archer and Parnell 1995; Lee *et al.* 1995b; Lee and Atkins 1997). However, information on the genetic and environmental variation in feed intake and the genetic relationships of feed intake with other important wool growth traits is limited. Lee *et al.* (1995b) found that digestible organic matter intake had a heritability of 0.12 ($\pm$0.07) in pasture intake of grazing sheep. However, Williams (1979) found that variation in voluntary feed intake did not contribute to genetic variation in wool growth when selection lines were compared. Differences between bloodlines and individual animals in feed intake appear to be small (<10%) when adjusted for liveweight (Lee and Atkins 1997).

As pasture supply can often be inadequate, especially in the drier and cooler months of the year and in drought, supplementation of pasture supply with additional feed sources can be quite common. Supplementation can have varying effects on wool quality depending on nutrient source, time and quantity of supplementation and nutritional demands of the sheep (Thompson and Curtis 1990; Gherardi *et al.* 1996). When animals are supplemented they may respond differently in terms of supplement intake and pasture intake. Within a mob of sheep offered supplements, variation between individuals in their supplement intake can be appreciable (Lobato *et al.* 1980; Dove 1994; Nolan and Hinch 1997).

It is also possible that some sheep within a mob change their feeding and watering habits more dramatically than others when they are all exposed to extremes of temperatures and other environmental conditions which may result in greater differences in wool growth between individuals.

All these factors combine to suggest that the pattern of voluntary intake is an important determination of the characteristics of the FDP. It may therefore be possible that differences in feeding behaviour are an important source of variation between sheep in wool growth responses and staple strength, however these relationships have not been examined to date.

2.5.1.2.2 Metabolism and nutrient partitioning

The supply of nutrients to the sheep from its diet depends upon many factors. The function of a tissue or organ also depends upon an adequate delivery of nutrients to it via the vascular system. The actual rate of wool growth rate in any particular situation, including length growth and fibre diameter is influenced by;

- the amounts and the relative availability of nutrients digested and absorbed,
- the partitioning of these absorbed nutrients into tissues of the body, maintenance and productive functions
- and the level of competition between biochemical processes due to changes in hormone levels and physiology of the animal (Faichney and Black 1979; Doyle and Thompson 1992).

Although wool growth is mainly dependent of the availability and composition of protein to the intestine, particularly sulfur-amino acids (Kempton 1979), it is also influenced by supply of energy. The lack of high quality protein, protected from degradation in the rumen, can be a major limitation to wool growth (Gherardi and Masters 1996b). In addition to the effect on the overall amount of wool produced, nutrition also influences the rate of fibre length growth to that of diameter change, fibre strength and fibre composition (Reis 1991).

Absorbed substances, both nutrient and non-nutrient, are disposed of in pathways of synthesis, oxidation and excretion. Rate limiting steps in these metabolic pathways may directly impose limits on feed intake and nutrient partitioning. Possible limitations include; the rate of nutrient use in pathways of production and impairment of metabolic pathways due to nutrient deficiencies and/or toxicities of dietary origin (Weston 1979). It would be expected that wool growth has a lower priority for available nutrients than do foetal development and milk production (Hawker and Kennedy 1978). The flow of nutrients into liveweight gain may be independent to the flow of nutrients to wool growth and the partitioning of nutrients between these two areas may be influenced by many other factors including specific nutrient limitations and compensatory growth (Adams *et al.* 1994). Furthermore, animals may vary in their inherent capacity to partition nutrients to wool growth at times where feed is scarce (Adams *et al.* 1994) resulting in differences in wool growth response at these times.

Factors such as the efficiency of microbial protein synthesis, degradability of forage protein and nutrient partitioning may also be important determinants of variations in wool growth between sheep. It is possible that higher producing sheep have more efficient metabolic capacities allowing for a greater quantity of limiting nutrients being available (Williams 1984). This may be due to differential partitioning of nutrients with some sheep having greater push or pull for nutrients. Reduced push may be due to reduced demand from other tissues and organs or increased supply (pull) from increased blood flow or nutrient concentration. These relationships are also further influenced by pregnancy and lactation (Hawker and Kennedy 1978).

The inherent variation between individual sheep in terms of metabolism, nutrient portioning and blood flow to the wool follicles may contribute to the variation between individual sheep in their FDPs. It has been shown that changes in the quantity and quality of nutrient supply influence not only wool growth but also FDPs and staple strength (Hansford and Kennedy 1990a; Doyle *et al.* 1994). However, nutrient supply and the balance of nutrients available to the tissues is difficult to control in the paddock.

2.5.1.2.2.1 Follicle nutrition

Nutritional changes in wool growth arise from changes in the activity of wool follicles. Both nutrition and nutritional status have an important influence on the regulation of wool follicle function. The supply of amino acids available to the wool follicle can exert a considerable effect on the rate and characteristics of wool growth (Kempton 1979). A number of these amino acids are essential for "normal" fibre production and are required for maintaining wool growth (Reis 1979; Reis 1991). As a result of this if a sheep is lacking one of these amino acids or is a less efficient user of an essential amino acid it will have reduced wool growth relative to another sheep in that mob. The ability to convert non-essential amino acids and internal recycling of nutrients may have an important role in the efficiency of follicle function (Williams 1979) and therefore variation between individual sheep in wool growth.

Higher follicle densities are associated with smaller follicles and fibre diameter, which suggests that competition exists between follicles for available nutrients (Fraser and Short 1952; Short 1955a; Purvis and Swan 1997b). It would also be expected that follicle efficiency and skin blood flow might influence these relationships between follicle density and wool growth. Competition between follicles may also influence sensitivity of sheep in terms of fibre diameter to seasonal changes in nutrition (Kelly and McLeod 1991).

Changes in the nutrition of animals are known to influence follicle activity. Declining nutrition from maintenance to a 100 g/day weight loss increased fibre shedding from 1 to 9% (Schlink *et al.* 1996a). Fibre shedding is a response of the wool follicle to large reductions in follicle activity. Variations in the proportions of active to resting follicles can alter fibre production appreciably (Reis and Shlu 1994) and staple strength (Schlink and Dollin 1995; Peterson 1997a). Although nutrition has important effects on wool follicles and therefore fibre production and characteristics (Hynd 1989) the only explanation of the effect of follicle nutrition on staple strength is its effect on follicle shutdown. Follicle shutdown leads to fibre shedding and therefore discontinuous fibres that contribute to staple tex value but not peak force. Therefore staples exhibiting greater proportions of follicle that shut down having reduced staple strength.

In most situations sheep have unavoidable changes in body weight and body composition. The skin is a large tissue, which accounts for approximately 5 to 10% of liveweight of an adult sheep (Williams and Morely 1994). Although the influence of nutrition on the skin has been understudied it has been shown that the skin weight per unit of area shows similar trends to that of body weight (Hutchinson 1957; Lyne 1964; Williams and Morley 1994; Murray 1996; Schlink *et al.* 1996c). These changes in skin weight are reflected in the rate of wool growth with reduction in wool follicle bulb diameter and fibre diameter. As a result of these trends it has been suggested that skin thickness is an indication of an animals body condition and composition. Skin thickness may also influence wool growth (Williams and Thornberry 1992). Sheep that are more able to maintain skin thickness with decreases in body condition may be able to maintain an improved skin and therefore follicle nutrition and wool growth. There is also evidence to suggest that there are genetic differences in skin thickness (Williams and Morley 1994).

The level of blood flow at the skin is related to wool growth (Williams 1987; Hocking Edwards and Hynd 1991; Williams 1991; Hocking Edwards and Hynd 1994; Thompson and Hynd 1994). Differences in wool growth may be associated with changes in the supply and/or uptake of nutrients from the blood, and/or efficiency with which absorbed nutrients are utilised by follicles, all of which may be influenced by skin blood flow (Harris *et al.* 1994; Thompson and Hynd 1994). The function of any tissue or organ is dependent upon an adequate supply of nutrients to it through the vascular system. Based on this it is logical to expect that animals which have greater blood flowing through the skin would have follicles that receive a greater supply of nutrients, which if the follicle can utilise would result in greater wool production.

Large variation has been observed between sheep in the amount of vascular tissue in the skin (Hocking Edwards and Hynd 1994). This large variation does not appear between bloodlines. It would be expected that animals with greater amounts of vascular tissue present in the skin would also have greater levels of blood flow through the skin. However, Hocking Edwards and Hynd (1994) found that only 0.2% of the variation in blood flow was accounted for by the amount of vascular tissue present. There was also no relationship between follicle density and the amount of blood vessels present suggesting that follicle nutrition was not improved.

2.5.2.3 Physiological state

Pregnancy and lactation cause a reduction in wool growth in the magnitude of 20 to 45% for pregnancy and 12 to 60% during lactation (Corbett 1979). These reductions in wool growth have direct influences on wool quality in terms of fibre diameter, fleece weight and staple strength (Hansford and Kennedy 1988; Thornberry *et al.* 1988; Masters *et al.* 1992). Corbett (1979) reviewed the effects of both pregnancy and lactation on wool growth in detail. It is beyond the scope of this thesis to examine the influences of reproduction on wool growth in any detail. The following is a brief discussion on the possible sources of variation in wool growth between animals due to the effects of reproductive processes. For a more detailed discussion on the effects of reproduction on wool growth see Corbett and Furnival (1976), Corbett (1979), Hawker and Kennedy (1978), Foot and Russel (1979), Oddy and Annison (1979), Fitzgerald *et al.* (1984), Weston (1988), Williams and Butt (1989), Masters (1992), Masters *et al.* (1992), Reis 1992a, Masters *et al.* (1993), Gherardi and Masters (1996) and Robertson *et al.* (1996).

Ewes react very differently to the physiological stresses imposed by pregnancy and lactation (Thornberry *et al.* 1988) and it may therefore be possible that reproducing ewes partition their nutrients in different ways and therefore have different responses in terms of their FDP.

Pregnancy and lactation can also influence the grazing and therefore feeding behaviour of ewes and possibly the wool growth of the offspring. During pregnancy and lactation major quantitative and qualitative changes occur in the nutrient demand. To meet this increase demand the animal is required to make adjustments to its voluntary feed intake and possibly digestion and metabolism. The intake of the ewe can also be effected by litter size (Lee *et al.* 1995a), supplementation strategies (Holst *et al.* 1996) and previous nutrition (Lee *et al.* 1995a). This effect may be due to changes in appetite or physical decreased gut size due to the foetuses. Differences in voluntary feed intake between ewes rearing singles and twins can also persist until after weaning (Lee *et al.* 1995a). Variation in any of these factors may lead to variation in liveweight, wool growth and FDPs in both the ewe and its offspring.

2.5.2.4 Weather Conditions

Weather conditions such as heat stress, cold exposure and wind-chill have been shown to influence wool growth (Bottomley 1979). Other climate factors such as photoperiod may also influence wool production (Butler and Head 1993; Bray *et al.* 1995b; Murray 1996; Pearson *et al.* 1996; Winder *et al.* 1996). The effects of weather and environmental conditions may increase or decrease wool growth directly through physiological effects by influencing metabolism at the follicle and nutrient partitioning or indirectly by affecting pasture quality and quantity and voluntary feed intake.

Most sheep exhibit a seasonal pattern of wool growth associated with changes in their environment throughout the year. Seasonal patterns in wool growth occur as a result of several seasonal factors. These factors include genotype, photoperiod, quality and quantity of feed supply, physiological changes, temperature, parasitism and diseases (Wodzicka 1960a; Hutchinson 1962; Lyne 1964; Stevens 1988; Williams and Butt 1989; Butler and Head 1993). This seasonal variation in wool growth rate is less pronounced in Merinos than in British breeds of sheep (Butler and Head 1993). It would be expected that the variation the susceptibility of sheep to these environmental effects results in variations in seasonal patterns of wool growth between sheep.

2.5.2 Wool type

Research has indicated that the type of wool grown by the sheep influences its responsiveness of wool growth to environmental change. The most important factor appears to be fibre diameter, however evidence suggests that high producing sheep also have greater changes in wool production with changes in environmental conditions (Butcher *et al.* 1984; Williams and Morley 1994). Sheep with a lower fibre diameter show smaller fluctuations in diameter with changes in nutrition than those with a higher fibre diameter (Jackson and Downes 1979; Thompson 1993; Earl *et al.* 1994; Murray *et al* 1994). Selection of sheep with lower fibre diameter and preferably a higher length growth results in sheep with smaller and less rapid changes in fibre diameter and possibly high staple strength (Thompson 1993; Baker *et al.* 1994; Earl *et al.* 1994). This indicates that the way in which a sheep will react to an environment will be influenced by its mean fibre diameter.

Murray *et al.* (1994) observed greater changes in fibre diameter in Bungaree animals than Peppin animals with changes in nutrition. The Bungaree animals had greater mean fibre diameter at the start and throughout the experiment. The results also demonstrated that the four groups of sheep maintained their ranking over three differing levels of nutrition. However no comparisons were made of the differences between animals within each of these strains. The physiological reasons for these differences are unknown. However, it is known that as mean fibre diameter increases variation between and along individual fibres also increases (Bow and Hansford 1994). Both these components have been shown to be associated with staple strength and as a result it is expected that these differences in fibre diameter change will influence staple strength.

In contrast to these previous relationships it has been suggested that reducing fibre diameter also reduces staple strength due to reduced cross-sectional area to bear the load and the fact that fine fibres may be more susceptible to fibre shedding. The woolgrower has economic incentives for reducing fibre diameter however this might lead to reductions in staple strength which attracts discounts. The positive phenotypic and genetic correlations illustrated in Table 2.1 support these trends and highlights the need for improvements in staple strength.

2.5.3 L/D ratio

The number, diameter and length of fibre produced by the sheep determines the amount and characteristics of the wool produced. The L/D ratio is commonly used experimentally to examine changes in wool fibre growth between two points in time. There are large differences between sheep in the average fibre diameter, length, L/D ratio and degree to which L/D changes when wool growth rates increase or decrease (Woods and Orwin 1988; Hynd 1992; Thompson 1993). L/D ratios range between approximately 10:1 and 30:1 and may be related to the between sheep variation in FDPs (Thompson 1993). The extent of this relationship and to what degree it influences staple strength of sheep has not yet been investigated.

The effects of many environmental and genetic factors on wool production are well studied however their specific effects on fibre diameter and length growth rate in combination are not well understood. This is partly due to the fact that at present the measurement of these fibre characteristics is expensive and very time consuming.

Nutritional changes in wool growth are a result of three main components. These are the total number of follicles producing fibre, the average length of fibres, and their average diameter (Williams 1976). The contribution of fibre diameter and length to wool production varies between fibres, over time and between sheep. A change in one of these components will result in a change in the amount of wool grown. During nutritional changes the volume of fibre produced per unit of time changes rapidly. Some follicles achieve fibre growth through changes in fibre diameter while others change fibre length growth preferentially. As a result of this, the ratio of fibre length growth to fibre diameter is an important consideration for changing wool growth and therefore the characteristics of the fibre grown. As L/D ratio influences fibre growth characteristics, it also has the potential to influence wool quality characteristics such as staple strength.

It is also not known if the large differences between sheep in L/D ratio are genetically controlled. If there are large genetic differences in the L/D ratio between sheep, and these differences were related to variation in fibre diameter along-fibres and staple strength, it may be possible to improve these traits through selection.

2.5.3.1 The response of L/D ratio to nutritional change

L/D ratio was historically thought to be independent of nutrition (Downes 1971; Williams 1976; Cottle 1987; Cottle 1991; Reis 1992a) and therefore remain nearly constant with changes in the rate of wool growth (Reis 1991). However, L/D ratio has been found to change under some specific situations.

There is conflicting evidence as to the effects of changes in nutrition on the L/D ratio. Downes (1971) and Downes and Sharry (1971) found with both Corriedale and Merino sheep under varying nutritional conditions, that L/D ratio increased by no more than 10%. Recent research has indicated that L/D ratio in grazing sheep varies throughout the year (Purser 1981; Woods and Orwin 1988; Hynd 1989; Reis *et al.* 1990; Hynd and Schlink 1992). The seasonal trend in L/D ratio is inverse to that of fibre diameter and length, feed availability and photoperiod cycle (Woods and Orwin 1988; Schlink *et al.* 1996a). Schlink *et al.* (1998b) also observed a significant decline in the L/D ratio in a line of Merino sheep selected for low staple strength. At this point in time there is no explanation for these trends that are observed, however it has been suggested that the mechanisms determining these growth parameters in the follicle are complex (Woods and Orwin 1988). The characteristics of these seasonal trends (amplitude and rates of length and diameter change) have also been shown to vary between sheep (Woods and Orwin 1988).

L/D ratio of a sheep may influence the way in which sheep respond to changes in nutrition (Hynd 1989; Hynd 1992; Hynd and Schlink 1992; Thompson 1993). Hynd (1992) investigated these relationships using South Australian strongwool Merino sheep and found that sheep with higher L/D ratios had lower fibre diameter increases and greater changes in fibre length relative to diameter change. Associated with this, sheep with higher initial fibre diameter on a low plane of nutrition had greater increases in fibre diameter and lower changes in the ratio of change in fibre length to change in fibre diameter. The L/D effect however appears to be independent of its relationship with initial fibre diameter. A comparison of sheep with similar fibre diameter also indicated that those with a high fibre length had lower fibre diameter increases. In support of these relationships, Woods and Orwin (1988) noted that in Romney sheep it was possible to find fibres in every sheep that had the same mean fibre diameter but significantly different mean fibre length growth rates and vice versa. As a result the volume of fibre produced varied both between and along-fibres. Direct or indirect selection of sheep with high L/D ratio should have the desirable outcomes of greater fibre length and reduced fibre diameter variability (Hynd 1992).

2.5.3.2 L/D ratio and other environmental influences

Factors including temperature, thyroxine status, growth hormone status, cortisol status and amino acid balance have in certain situations been shown to alter the L/D ratio (Woods and Orwin 1988; Hynd 1991; Hynd and Schlink 1992). Hynd (1989) and Reis *et al.* (1990) found in some situations that fibre length might be stimulated slightly more than fibre diameter at high levels of nutrient supply. The L/D ratio may also change with an unbalanced mixture of amino acids (Reis and Colebrook 1972). Supplementation of lysine resulted in increased length growth rate while reduced fibre diameter (Reis 1989).

2.5.4 Skin and follicle characteristics

The number, shape, arrangement and function of the follicle population in the skin (Nay and Jackson 1973; Jackson *et al.* 1975; Schlink *et al.* 1996a; Hughes *et al.* 1996; Crook 1997;

Hynd *et al.* 1997) partly determines the fibre diameter and length of the wool, grown by any sheep. Other wool quality characteristics such as crimp frequency and definition are also associated with the characteristics of the follicle population (Crook 1997). The characteristics of the skin are heritable and therefore can be modified through selection. Crook (1997) summarised the published heritabilities for the major skin traits (Table 2.2). It is possible that characteristics such as follicle density, S/P ratio and skin thickness, may also be related to fibre diameter profile characteristics, however these relationships have not been investigated.

Table 2.2 Summary of heritability estimates for skin traits from Crook (1997)

Trait	Heritability
Follicle density	0.18 – 0.62
S/P ratio	0.21 – 0.52
Skin thickness	0.60
Follicle depth	0.37
Follicle curvature	0.40
Skin biopsy weight	0.17
Bulb area	0.25 – 0.26
Variation in bulb area	0.09 – 0.22

2.5.4.1 Follicle density

Follicle density refers to the number of follicles present per unit are of skin. Follicle density varies between sheep but there is some inconsistency as to its effects on wool production (Kelly *et al.* 1996; Hill *et al.* 1997a; Purvis and Swan 1997b; Skerritt 1995; Hocking-Edwards *et al.* 1996). It has also been established that follicle density is moderately heritable (Purvis and Swan 1997b). Additional research involving follicle density has concentrated on its genetic and phenotypic relationship with other wool quality traits. Strong genetic correlations have been observed between follicle density and clean fleece weights of 0.54 (Hill *et al.* 1997a) and between follicle density and mean fibre diameter of -0.68 to -0.70 (Davis and McGuirk 1987; Purvis and Swan (1997b). Hill *et al.* (1997a, b) also established that follicle density was strongly negatively related to crimp definition (-0.62) and skin biopsy weight (-0.74). Furthermore, Purvis and Swan (1997) estimated a genetic correlation between follicle density and staple length of -0.31 and between follicle density and body weight of -0.26. The relationships observed between density and fibre diameter and density and staple length suggest that there is some level of competition between follicles. Given these relationships it is possible that follicle density is related to fibre diameter profile characteristics.

2.5.4.2 S/P ratio

Two main types of follicles are present in the skin of sheep. These are the primary and secondary follicles which both differ in morphology (Lyne 1965; Cottle 1991) and are present in varying proportions between sheep. Differences in the secondary to primary ratio (S:P ratio) are normally used as an index of the variation in the population of secondary follicles between animals. Wool production in Merino sheep can be significantly influenced by the S:P ratio (Hocking Edwards *et al.* 1996; Kelly *et al.* 1996) and therefore differences in these characteristics may influence the variation in wool growth between sheep.

There have been suggestions that the reactions of primary and secondary follicles may differ in their responses to changes in nutrition, with the evidence suggesting that secondary follicles are more sensitive to these influences than the primary follicles (Lockart 1956; Onions 1962; Quinnell *et al.* 1973). Given these relationships it would be expected that differences in S/P ratios between sheep would result in sheep having differences in responses to nutritional change. For example, if more of the small fibres, presumable from secondary follicles, were affected by adverse nutrition this may result in lower fibre diameters and possibly increased fibre shedding (Lyne 1964) which in turn would result in lower staple strength. However, Lockart (1956) found that the evidence available at the time suggested that the primary and secondary follicles do not respond differently to nutritional change. S/P ratio is moderately heritable (Purvis and Swan 1997b) and as a result S/P ratio would respond to selection.

It has also been suggested that S/P ratio is associated with the level of variation in fibre diameter between fibres. Primary fibres tend to exhibit a greater variation in diameter than secondary fibres and as a result a lower S/P may produce greater variation in overall fibre diameter (Quinnell *et al.* 1973).

These relationships therefore suggest that sheep differing in S/P ratio will differ in respect to their degree of fibre growth, fibre shedding and wool quality.

In addition to the genetic influences on S/P ratio, it is also influenced by other factors such as foetal follicle development and postnatal nutrition (Schinckel 1953; Short 1955a; Schinckel and Short 1961; Lax and Brown 1967; Sumner and Wickham 1970; Quinnell *et al.* 1973; Jackson *et al.* 1975; Kelly *et al.* 1994; Skerritt *et al.* 1994; Hocking-Edwards *et al.* 1996; Reis and Shlu 1994; Kelly *et al.* 1996). Variation between sheep in pre and post-natal development may influence S/P ratio and future wool production.

2.5.4.3 Skin thickness

Differences between sheep in skin thickness may be associated with differences in wool production. Skin thickness is genetically related to clean fleece weight (0.39, s.e. 0.13), mean fibre diameter (0.20, s.e. 0.11) and staple length (0.35, s.e. 0.12) (Gregory 1982b). Sheep selected for high fleece weight had thicker skin than those selected for reduced fleece weight (Williams and Thornberry 1992). This result was not related to the differences in liveweight between the two groups. However, when individual animals from these groups where pen fed these differences were not observed.

Differences in skin thickness between animals may be associated with differences in the environmental responsiveness of wool growth. As skin thickness is a heritable trait with estimates of heritability ranging between 0.22 to 0.79 (Gregory 1982a) this trait would respond to selection. Furthermore as suggested previously sheep that are more able to maintain skin thickness with decreases in body condition may be able to maintain a higher level of skin and therefore follicle nutrition and wool growth.

2.5.5 Genetic Differences in staple strength and FDP characteristics

There are large phenotypic and genetic differences in the rate of wool growth between breeds, strains, and individual sheep within a mob run under similar environmental conditions (Hocking Edwards and Hynd 1992; Swan *et al.* 1995). The reasons for the differences in wool growth per unit of skin area and on a per follicle basis remain undetermined. Many such factors have been investigated including; feed intake, digestive efficiency, metabolic efficiency, hormonal and follicle characteristics and morphology but these factors appear to be of minor importance.

Genetic effects can operate at 4 main levels: breed, strain, flock and individual sheep within flock differences. There are genetic differences between all sheep in their capacity for wool growth. Ryder and Stephenson (1968) illustrated four possible causes for these genetic differences in wool production between sheep;

- the supply to the follicles of substances required for fibre growth,
- the effectiveness of the follicle group in utilising the precursors supplied,
- the relative productivity of the different follicle types within the follicle group,
- competition between follicles.

Considering that staple strength is an important determinant of raw wool quality, it would be expected that great benefit would be gained if staple strength could be incorporated into breeding programs. The benefits of such a breeding and selection program have been recently illustrated by Greeff *et al.* (1995) and Greeff and Karlsson (1998). The phenotypic and genetic variation in staple strength between individuals in a flock is higher than for most wool characteristics (Reis 1992b; Greeff *et al.* 1995; Swan *et al.* 1995). This is promising as genetic variation is essential (Franklin 1997) to achieve genetic progress, however it would be expected that genotype by environment interactions will have a significant impact on the actual expression of this trait.

Staple strength is a heritable trait with estimates ranging between 0.17 and 0.51 (Bigham *et al.* 1983; Rogers *et al.* 1990; Lewer and Ritchie 1992; Reis 1992b; Greeff *et al.* 1995). Staple strength has a similar heritability to that of greasy fleece weight (Greeff and Windsor 1996) and therefore it would be expected that significant genetic progress could be made. Lewer and Ritchie (1992) produced the most definitive evidence of genetic variation by establishing three selection lines that had similar fleece weights, fibre diameter and staple length but with significant differences in staple strength. These selection lines in Western Australia have consistently showed that it is possible to improve staple strength while holding other wool traits constant (Thompson *et al.* 1995a; Greeff 1997a, Greeff *et al.* 1997).

Despite large variation in staple strength between individual animals within bloodlines variation in staple strength between bloodlines is small (Swan 1995). These trends in staple strength were examined between 11 bloodlines, comprising superfine, fine and medium-fine bloodlines (Swan 1995). Other genetic studies show that different bloodlines have a similar incidence of tender wool during good or average seasonal conditions (Butcher *et al.* 1984;

Piper 1992) but that some lines are better able to maintain staple strength than others when adverse conditions prevail (Butcher *et al.* 1984).

Staple strength is both phenotypically and genetically correlated with a range of economically important traits including clean fleece weight, mean fibre diameter, fibre diameter variation and staple length (Table 2.1). As a result single trait selection on staple strength would result in inevitable indirect responses in other wool quality traits such as mean fibre diameter and fibre diameter variation (Lewer and Ritchie 1992). With these correlated traits being important determinants of the price of wool it is important to include these traits in breeding objective along with staple strength.

Recent research suggests that there are different determinants of genetic differences in staple strength compared to those induced by differences in nutritional conditions. Genetically induced differences in staple strength appear to be related to differences in the level of variation in fibre diameter between fibres (Adams *et al.* 1997; Peterson 1997a; Thompson and Hynd 1998). Merino staple strength selection flocks in Western Australia (Adams *et al.* 1997; Greeff *et al.* 1997; Peterson 1997a; Thompson and Hynd 1998) and Romney staple strength selection flocks in New Zealand (Bray *et al.* 1995; Woods *et al.* 1995) have consistently demonstrated that the groups with higher staple strength have a lower variation in fibre diameter between fibres. Some of these studies have also shown that the sheep selected for staple strength produce FDPs with less variation in wool growth and/or fibre diameter throughout the year (Bray *et al.* 1995; Woods *et al.* 1995; Greeff *et al.* 1997; Adams *et al.* 1997).

At present the genetic components of variation in FDP characteristics between sheep have not been extensively studied. Yamin *et al.* (1999) estimated heritabilities for FDP characteristics in 650 South Australian Strong wool Merino ewes. Along-staple variation and range in fibre diameter were lowly heritable, being 0.17 (s.e. 0.10) and 0.20 (s.e. 0.10). The absolute fibre diameter values within the FDP were moderately to highly heritable, with the heritabilities for mean, minimum and maximum fibre diameter being 0.55 (s.e. 0.16), 0.47 (s.e. 0.15) and 0.57 (s.e. 0.16) respectively. Variation between fibres was highly heritable (0.59, s.e. 0.16), however rates of fibre diameter change was not heritable. No genetic correlations were reported from this study. The FDPs used in this study were also generated using a 10 segment profiling technique which may not provide accurate estimates of the original FDP.

There are differences in FDPs from different sheep breeds, strains and bloodlines (Hansford 1994). However, individual sheep within a flock of similar genotype also respond differently when subjected to the same environmental conditions (Jackson and Downes 1979; Denney 1990a; Hansford 1994). Differences in the level of along-staple variation in fibre diameter have also been observed between selection lines and sire groups (Jackson and Downes 1979). The predominance of certain strains of Australian Merino in particular regions is due either to their adaptation to the area or to anecdotal evidence that a particular strain is best suited to that area. It is most probable that this adaptation factor will influence the FDPs of sheep. However, within a flock it would be expected that the sheep will be adapted to that environment to a similar extent.

The general objective of any breeding program is to modify the genotype of the population as rapidly as possible to improve performance under the environmental conditions that prevail. The wool growth of grazing sheep will be largely dependent on its genetic capacity and how this capacity reacts with all the environmental factors that it encounters. In support of this, Eady *et al.* (1990) found that under severe nutritional stress, the sheep introduced to North-Western Queensland showed a significantly greater decrease in staple strength than locally bred sheep. The locally bred sheep had lower wool production but were more capable of maintaining staple strength in the face of adverse seasonal conditions. The effect of rearing or pre-weaning environment may be an important determinant of a sheep's future wool production (Eady *et al.* 1990) and may have permanent effects that influence lifetime productivity (Denney *et al.* 1986). It also may be an indication that the locally bred sheep were less susceptible to fibre diameter change throughout the year, which in turn increased or maintained staple strength. These results also suggest that FDP characteristics and staple strength are influenced by interactions between genotype and the environment.

These results suggest that the characteristics of the FDP vary genetically between individual sheep within a flock and may be heritable. Accurate estimates of genetic parameters for these traits would therefore be beneficial to quantifying these relationships. These results will also determine the usefulness of these characteristics to indirectly select for improved staple strength.

2.5.6 Sheep Management

Staple strength and the shape of the FDP are influenced by many sheep management factors through their influence on the wool characteristics described above. These factors include nutritional management, lambing date and shearing date. These decisions are further influenced by the type of environment in which the wool is being grown.

Staple strength is generally controlled by a lower amount of staple tex or material to bear load at a specific point along its length, which corresponds to a particular growth period. Therefore it is important that management practices and specific environmental conditions are identified that cause this period of reduced fibre growth. As staple strength is determined in part by the changes in fibre diameter around the position of break the nutritional management at this point in time is especially important in determining the strength of the wool (Doyle *et al.* 1994). The nutritional management of sheep has a large impact on the health and performance of sheep.

Time of shearing and lambing have a major influence on wool growth and fleece characteristics through their alterations of patterns of nutrient demand in relation to feed availability. These two dates are very important and need to be considered with factors such as feed availability, climate, susceptibility to sheep diseases and parasites such as flystrike, and other management processors and the environment (Foot and Vizard 1992; Masters *et al.* 1997). The date of lambing influences the wool growth of the ewe as both pregnancy and lactation have a significant effect on wool growth rate and fibre diameter. If a ewe is pregnant or lactating during a period of low nutrient supply, such as winter in the Tableland environment, the effect on wool growth will be more significant than if there was plentiful feed. The choice of a shearing date will also have important ramifications for sheep health and wool quality. Woolgrowers can manipulate staple length, fibre diameter, staple strength, position of break, wool colour, contamination and sheep condition, by choice of shearing time (Baker *et al.* 1994; Masters *et al.* 1997).

The Mediterranean environment accounts for over 60% of Australian wool production (Masters *et al.* 1997). Reduced staple strength is a major problem for Merino wool grown in Mediterranean environments. The major factor causing this reduced staple strength is the large seasonal variation in quantity and quality of feed available to sheep during the year (Bellotti *et *al.* 1992). The Mediterranean environment generally consists of cold wet winters and hot dry summer/autumn periods (Doyle and Thompson 1992; Adams *et al.* 1994). This results in an abundance of green feed in spring, deteriorating feed quality and quantity over summer and autumn until the break in the season in late autumn/winter. This relatively large variation in the quantity and quality of feed creates large variation in liveweight, wool production and therefore fibre diameter throughout the year. The seasonality of the environment in which the wool is grown has a large influence on the way that wool producers manage their flocks.

While the staple strength problem is greatest in Australia's Mediterranean environment, it is also important in all the other wool growing areas of Australia. The New England region is a large wool growing area and the environment is considerably different to that of the Mediterranean environment. The Tableland environment consists of warm wet summers with cold drier winters. The rainfall is actually close to diurnal in nature. Pasture growth in winter in this environment is generally influenced by temperature more than rainfall. As a result of this climate the pasture is plentiful from late spring and dies off going into the autumn - winter period. There is generally a shortage of native pasture feed during winter due to the cold and heavy frosts.

2.5.7 Other factors

2.5.7.1 Sheep behaviour

The behaviour of grazing sheep in the paddock and in experimental plots has an important effect on feed intake and diet selection. Differences in grazing patterns have been observed between sheep within the one mob of four hundred sheep grazing approximately 500 acres (Lynch 1967). Environmental conditions strongly influence the flocking habit in Merinos (McBride *et al.* 1967) and will be further modified by topography and vegetation.

Other behavioural factors, such as peck orders, may also effect the feed intake and diet selection of both grazing, supplemented and housed sheep. This particular example would be more important where the animals were being fed supplements or in a group fed situation.

2.5.7.2 Sheep health

The health of sheep is influenced by many factors that in turn influence wool growth and fibre diameter in different ways. It is again beyond the scope of this thesis to examine in detail the influence of sheep health on wool growth. The following is a brief discussion of the major health factors influencing sheep and how they may influence the variation in wool growth between individual animals.

2.5.7.3 Disease

Diseases have a significant impact on the wool produced by sheep and can be infection, metabolic, deficiency and parasitic based. These diseases can have a dramatic influence on both wool growth and quality. Cottle (1991) reviewed the influence of disease on wool growth in detail. The influence of disease on wool growth may be due to decreased voluntary feed intake, increased stress and hormone levels and altered nutrient metabolism.

Individual animals within and between mobs of sheep vary in their susceptibility to fleece rot (Copland and Chenoweth 1984) and mycotic dermatitis (Gherardi *et al.* 1984). As a result if an outbreak of such a disease occurs it could be expected that the influence on wool growth and staple strength will vary between sheep. An acute disease state could influence the FDP and therefore the fibre length distribution of the top (Hansford 1997a).

2.5.7.4 Internal and external parasites

Internal and external parasite burden influences the quantity and quality of wool produced by the sheep (Onions 1962; Besier 1992; Reis 1992). Fibre diameter, staple length and staple strength are all reduced with worm infestations (Barton and Brimblecombe 1983; Besier 1992). The role of parasites in staple strength was reviewed by Besier (1992). Although differences in wool growth occurred between anthelmintic treatment regimes, Barton and Brimblecombe (1983) found that there was no influence on the seasonal variation of wool growth characteristics.

As a general rule, more parasites result in less wool being produced, which, as well as being finer, may also have a lower staple strength (Barton and Brimblecombe 1983; Besier 1992).

The reduced production due to worm infestations may result from a reduction in appetite, inefficient protein utilisation and energy metabolism and stress due to hormonal influences. The net result of this is a reduced availability of amino acids for protein synthesis and hence reduced body and wool growth (Besier 1992; Reis 1992). The effect of internal and external parasites may have their most important reduction in wool production when they are superimposed on top of other stresses such as pregnancy and lactation.

It has been shown that within a mob of sheep, subjected to the same worm control program, that there are variations in worm resistance to drench, sheep resistance to parasites and therefore the degree of worm infestation (Gray *et al.* 1987; Leathwick *et al.* 1995; Stear *et al.* 1995; Pralomkarn *et al.* 1997; Barger 1999; Vlassoff *et al.* 1999). There is also small genetic variation between animals in their resilience to internal parasites and their ability to maintain production while subjected to parasitism (Bisset and Morris 1996; Woolaston and Baker 1996; Knox and Steel 1999). This may result in differences between sheep in wool production and therefore FDPs.

Fly strike (Onions 1962; Butcher *et al.* 1984; Butler 1994) and severe lice infestation (Butler 1994) have been shown to significantly reduce wool production and staple strength.

2.5.7.5 Mineral and vitamin balance

A number of vitamins and minerals are essential for wool growth and therefore an adequate supply of vitamins and minerals is important to achieve optimum wool growth (Reis 1991). Although of the trace elements only copper, zinc, folic acid, and pyridoxine appear to be directly required for the process of wool growth (Purser 1979) the supply of some vitamins and minerals may also indirectly influence wool growth and its properties by influencing rumen metabolism and feed intake (Reis 1992a).

Sub-clinical deficiencies of some minerals, such as selenium, cobalt and copper, have been associated with reduced wool production and wool quality (White and Fortune 1992). Some deficiencies reduce the amount of wool grown, such as copper (Reis 1991) and others can also influence wool quality. For example, zinc deficiency can cause extreme tenderness and fibre shedding (Reis 1991). Mineral deficiency can also alter fibre composition. Wool from sheep with copper deficiency is not only weaker but has been found to contain less of the sulphurrich protein fraction from the keratin (Ryder and Stephenson 1968). Copper deficiency also causes a reduction in the crimp due to its effects on keratinisation (Cloete *et al.* 1994; Lee *et al.* 1999; Leon *et al.* 2000). Cottle (1991) reviewed the influence of minerals on wool production in detail and concluded that the effects of dietary mineral content are largely non-specific, that is influencing feed intake and/or rumen function, which influence nutrient supply.

There are also genetic differences between and within breeds in the level of trace elements in blood and tissues (Judson *et al.* 1994). As a result, differences between individual sheep in the vitamin and mineral nutrition and their tolerances for toxicities and/or deficiencies would be expected to cause differences in wool growth and quality and therefore FDPs.

2.5.7.6 Age

As a sheep ages the quality and quantity of the wool produced changes. These effects of age on fleece weight, fibre diameter and other wool traits are well documented (Brown *et al.* 1966; Foot and Vizard 1992; Cottle *et al.* 1995; Hickson *et al.* 1995). Wool production is highest between 2 and 4 years of age and then declines with an associated decline in the number of follicles and fibre production rates (Foot and Vizard 1992). After 5 to 6 years of age a proportion of the secondary follicles cease production resulting in coarser fleeces (Foot and Vizard 1992). There have been no studies on the relationship between age and FDP variation and / or environmental susceptibility. Associated with this, information is limited on the effects of age on staple strength.

It is known that the wool produced by Merino sheep tends to increase in fibre diameter as they age. This process has been referred to as micron "blow-out" (Hickson *et al.* 1995). Micron "blow-out" and fibre diameter stability varies genetically and has an estimated heritability of 0.23 (Atkins 1990; Hickson *et al.* 1995). Therefore there is potential to improve this trait through selection. Micron "Blow-out" does not occur at specific times or ages and varies between individual sheep. Therefore it is possible slight variations in age within a flock and variation between the way in which this micron "blow-out" operates within individual animals may influence the FDPs within individual sheep.

The age of sheep may also influence the incidence of fibre shedding. Fibre shedding rates are higher in weaners than adult sheep (Schlink *et al.* 1996c; Thompson *et al.* 1998) which may then influence staple strength. This may also be one of the causes for increased fleece tenderness in young sheep (Foot and Vizard 1992) as a result the nutritional regime and management stress which they are subjected to during there first year of life. Within a mob, sheep are usually born within a six to eight week period therefore producing small variation in age within a mob. The difference in age within a mob influence body weights and the amount of wool produced at 18 month and 30 month shearings (Mullaney and Brown 1967; Lax and Brown 1967). The level of these differences varied between the characteristics being investigated. Associated with this, the age at weaning may also influence the growth rate of lambs. Lambs weaned earlier grow more slowly than those weaned later, especially when their mothers were on restricted diets (Gibb *et al.* 1981). Although the long-term effects of these differences have not been examined it would be expected that as animals age these differences would reduce. There is variation in the response of animals when they are subjected to stresses such as weaning. It is likely that these differences would lead to differences in wool growth, fibre diameter profiles and staple strength.

2.5.7.7 Sex

This discussion is primarily concerned with differences that may exist between sheep with a mob. A mob is defined as a group of sheep of the same breeding, sex and similar age that have been run and managed together since the previous shearing. Therefore sex should not have an influence on any possible variation within the mob. However it is worthwhile to note that the sex of a sheep may influence wool growth and therefore FDPs (Pitchford and Ch'ang 1990).

2.5.7.8 Hormones

Hormonal and environmental stresses can effect the continuity of wool growth (Peter *et al.* 1992; Adams *et al.* 1996b), staple strength and fibre shedding (Schlink 1997), especially during pregnancy and lactation when hormonal factors may play a role in the reduction in wool growth rates (Reis 1992). However, Wallace (1979) concluded that the endocrine status of animals in a similar environment was unlikely to contribute to variation in wool growth between individuals.

Thyroxine is required for normal wool growth. Thyroidextomised sheep have significantly greater amounts of inactive wool follicles and significantly lower wool fibre growth (Hynd 1994c). Thyroid hormones and cortisol do not act directly on the follicle (Hynd 1994b). As cortisol reduces wool growth at the systemic and local level (Scobie and Hynd 1995) it would be expected that differences between animals in the level of cortisol production would also influence wool growth. Linder and Ferguson (1956, cited by Ryder and Stephenson 1968) indicated that sheep given adrenocorticotrophic hormone, another stress hormone, produced a break in the wool. There have been no studies investigating the relationships between differences between sheep in hormone levels with FDP characteristics or environmental responsiveness of wool growth.

2.6 Conclusion

It can be concluded the characteristics of the FDP are associated with staple strength. Other factors such as fibre composition, intrinsic strength, fibre shedding and staple structure influence staple strength. However there is no definite agreement as to how all these individual fibre and staple characteristics combine to influence staple strength. It appears as though the relationships between all these factors and staple strength are variable between genotypes and environments and it is not known how environment and genotype combine to determine the relationship between FDP characteristics and staple strength.

There is a large number of factors that influence wool growth and that the effect on wool growth will vary between sheep. These factors therefore have the potential to influence the variation between sheep in environmental responsiveness of wool growth and FDP characteristics. It is not known to what extent these differences may be related to staple strength.

The first experimental chapter that follows will examine a number of potential techniques to reduce the workload required to estimate FDP characteristics. Using one of these profile prediction techniques the variation in the FDP characteristics between environments, bloodlines and sire groups will be examined. These FDP characteristics were then examined in relation to mean mid-side fibre diameter, mid-side fibre diameter variation, staple length and staple strength. A field experiment will then be described which investigates the relationships between the FDP characteristics, mid-side sample measurements of fibre diameter and staple length, body traits and fibre growth characteristics collected from 16 grazing Merino sheep during a 12 month experiment. The final experimental chapter examines several potential methods to measure and predict fibre length and fibre length variation in dyebanded staples.