GENETIC IMPROVEMENT OF APPAREL AND CARPET WOOL PRODUCTION

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SUMMARY

The genetic improvement of wool production is discussed in the context of four wool categories, namely: (i) fine; (ii) medium; (iii) coarse, and (iv) specialty carpet wools. Traits examined are: fleece weight, yield, fibre diameter (mean and variability), staple length (mean and variability), staple strength, colour, resistance to compression (or bulk), medullation, vegetable matter content, lustre and style. For each trait, the reasons for its importance are explained and the prospects for genetic improvement are examined. Recommendations are made on the desired direction of genetic change in wool traits for sheep breeds within the different wool categories.

INTRODUCTION

During the last decade several review papers on the genetic improvement of wool production have been published (Atkins, 1988; Binnie and Elliott, 1986; Burns, 1986; Cardellino, 1986; McGuirk, 1983; Rogan, 1984, 1988; Ross et al., 1982; Whiteley and Jackson, 1982; Wickham, 1984, 1985a,b; Wickham and McPherson, 1985). The approaches taken by the various authors differ and are often restricted in scope to a particular country or even to a particular breed within a country. However, considered collectively, these reviews provide information of value for the design of programs of genetic improvement of wool production in most parts of the world.

Naturally, since the above mentioned work was published there have been a number of developments. These have more to do with the refinement and implementation of measurement techniques, or with further genetic parameter estimates than with the substance of the recommendations one would make to practical sheep breeders. In this paper we summarize and update the findings reported in earlier reviews. We pay special attention to fibre attributes that influence processing performance, but we also mention characteristics that may be related to resistance to certain diseases and fleece protection against environmental degradation. We focus our attention on the genetic improvement of wool production, but flock owners usually also derive income from the sale of sheep products other than wool. Thus, in the development of a comprehensive breeding program, traits in addition to those affecting wool value (e.g., growth, reproduction, feed intake) need to be considered (Morris et al., 1982; Ponzoni, 1986).

WORLD WOOL PRODUCTION

The total amount of fibre produced annually in the world (approximately 35,000 million kg) is made up of similar proportions of natural and of man-made fibres (Australian Wool Corporation, 1989a). Wool represents 5.0 and 9.5 per cent of the total and natural fibre produced, respectively. During the last decade world wool production increased by 10 percent, whereas the production of cotton and of man-made fibres increased by 17 and 19 per cent, respectively. Thus, although wool is very important for some national economies, it is only a small fraction of all the fibres produced, and its production has grown at a slower rate than that of other fibres.

Table 1 shows that ten countries produce nearly 80 per cent of the world's wool. Australia is the leading country in terms of both sheep
numbers and size of the wool clip, followed by the U.S.S.R. The first five countries listed in Table 1 are the main exporters of wool in the world. Together, they have 26.7 percent of the sheep, produce 50.5 percent of the world's wool, and are all in the Southern Hemisphere. This contrasts with the pattern observed for wool consumption. If we consider the consumption of virgin wool by the textile industry at the spinning stage we find that the five major exporting countries consume only 4.6 percent of the wool. Japan and the European Economic Community consume 30 percent, while China and the U.S.S.R. consume 34.8 percent (see Table 6 of source cited in Table 1 of this paper). Thus, in broad terms, major wool producing and exporting countries are in the Southern Hemisphere, whereas major wool processing and consuming countries are in the Northern Hemisphere.

Table 1 World sheep and wool statistics (1987/88)

<table>
<thead>
<tr>
<th>Country</th>
<th>Number of Sheep</th>
<th>Greasy wool production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions</td>
<td>%</td>
</tr>
<tr>
<td>Australia</td>
<td>159.7</td>
<td>14.0</td>
</tr>
<tr>
<td>New Zealand</td>
<td>64.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Argentina</td>
<td>29.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Uruguay</td>
<td>25.5</td>
<td>2.2</td>
</tr>
<tr>
<td>South Africa</td>
<td>24.6</td>
<td>2.2</td>
</tr>
<tr>
<td>U.S.S.R.</td>
<td>140.8</td>
<td>12.3</td>
</tr>
<tr>
<td>China</td>
<td>102.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Turkey</td>
<td>48.8</td>
<td>4.3</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>40.9</td>
<td>3.6</td>
</tr>
<tr>
<td>India</td>
<td>40.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Other</td>
<td>463.4</td>
<td>40.6</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1,140.2</td>
<td>100.0</td>
</tr>
</tbody>
</table>


CLASSIFICATION OF WOOL ACCORDING TO END USE

It is convenient to group wools according to end use because not all fibre characteristics are equally important for different end uses. Table 2 groups major sheep breeds according to the category of wool they produce and the most common end use of that wool. Typical fibre diameter ranges for each group are given. The various wool categories differ in other fibre attributes, but (except for the specialty carpet group) fibre diameter is the main determinant of the wool's end use. Some of the breeds listed have fibre characteristics which are peculiar to them (e.g. lustre in Border Leicester and Lincoln, high bulk in Perendale), and these will be commented on later. Elliott (1985) and Binnie and Elliott (1986) give a more detailed classification for New Zealand sheep breeds.

According to the classification proposed in Table 2, Australia and South Africa produce mainly fine wool (70 to 80 percent), whereas Uruguay's clip is predominantly (about 85 percent) of medium wool. Argentina produces similar proportions of fine, medium and coarse wool, whereas about 80 percent of New Zealand's clip is of the latter wool category.
<table>
<thead>
<tr>
<th>Wool category</th>
<th>Fibre diameter (µm)</th>
<th>Major breeds</th>
<th>End use of wool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>Up to 25um</td>
<td>Merino, Polwarth, other fine wool breeds or crosses</td>
<td>Apparel. Light weight high quality clothing fabric. High quality knit-wear. Processed mainly by the worsted system.</td>
</tr>
<tr>
<td>Medium</td>
<td>25 to 30um</td>
<td>Corriedale, other medium wool breeds, generally 50% Merino: 50% British breed</td>
<td>Apparel. Medium weight quality clothing fabric. Machine and hand knitting yarns. Processed by the worsted or by the woollen system.</td>
</tr>
<tr>
<td>Specialty carpet</td>
<td>Medullated, mean 40um</td>
<td>Drysdale, Tukidales, Carpetmaster, Elliottdales, Scottish Blackface</td>
<td>Carpet, upholstery, fillers. Specialty carpet woolens are blended with other wool types to produce heavy weight coarse yarns. Mostly used in floor-coverings, but also in furnishing fabrics and fillers. Processed mainly by the woollen system.</td>
</tr>
</tbody>
</table>
WOOL TRAITS AND THEIR IMPROVEMENT BY GENETIC MEANS

General

In this section we discuss major traits associated either with the quantity or the quality of wool produced. These are shown in Table 3, representing a minor modification of those given by Whiteley (1987) and Rogan (1988). Traits that could be measured and assessed in the fleece (or in a fleece sample) and thus used as a basis for selection were chosen. Quality traits are associated with processing performance, with the attributes of the resulting product, or both. Technological developments have enabled the objective measurement of many of these traits to be done routinely for wool marketing in some countries. Details of equipment and current state of development of the measurement techniques for the various traits are given elsewhere (Australian Wool Corporation, 1989b; Lunney, 1988; Maddever, 1990; Simpson et al., 1986; Simpson, 1989).

Table 3: Major traits associated with the quantity and quality of wool

<table>
<thead>
<tr>
<th>Trait</th>
<th>Unit of measurement (symbol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity of fibre</td>
<td></td>
</tr>
<tr>
<td>Fleece weight</td>
<td>kilogram (kg)</td>
</tr>
<tr>
<td>Yield</td>
<td>percentage (%)</td>
</tr>
<tr>
<td>Quality of fibre</td>
<td></td>
</tr>
<tr>
<td>Mean fibre diameter</td>
<td>micrometres (um)</td>
</tr>
<tr>
<td>Fibre diameter variability</td>
<td>micrometres (um)(^A)</td>
</tr>
<tr>
<td>Staple length</td>
<td>millimetres (mm)</td>
</tr>
<tr>
<td>Staple length variability</td>
<td>millimetres (mm)(^A)</td>
</tr>
<tr>
<td>Staple strength</td>
<td>Newtons per kilotex (N/ktex)</td>
</tr>
<tr>
<td>Colour</td>
<td>Tristimulus values (X, Y and Z)</td>
</tr>
<tr>
<td>Resistance to compression</td>
<td>kilopascals (kPa)</td>
</tr>
<tr>
<td>Medullation</td>
<td>percentage (%)</td>
</tr>
<tr>
<td>Vegetable matter content</td>
<td>percentage (%)</td>
</tr>
</tbody>
</table>

\(^A\) Assuming the standard deviation is the parameter measuring variability. If the coefficient of variation was used, variability would be expressed as a percentage (%).

The rationale behind the consideration of the quality traits listed in Table 3 as candidates in wool sheep selection programs is as follows. Wool is increasingly being measured objectively for a number of traits for marketing purposes. The aims of this practice are: (i) to increase the efficiency of the marketing process, and (ii) to provide buyers with sufficient specification to accurately predict processing performance, so that wool will increase its competitiveness with respect to synthetic fibres. Market price signals are already clear with regard to some attributes (e.g. mean fibre diameter) and it may be anticipated that they will become clearer in the future for other attributes. Thus, it is reasonable to examine the possibility of genetically improving raw wool quality traits.

We discuss each wool trait according to the following format: (i) why is the trait important in some or all wool categories? (ii) clarity of
market price signals, and (iii) prospects for genetic modification, including direct and correlated responses to selection. With regard to the latter aspect we drew upon the reviews of Mortimer (1987) and Rogan (1988) for fine wool sheep, and Rae (1982) and Wickham (1984, 1985a) for medium and coarse wool sheep. When appropriate we cite additional sources.

We refer to heritabilities as being low, moderate or high when they fall in the ranges of lower than 0.15, 0.15 to 0.30 or greater than 0.30, respectively. Similarly, we refer to correlations (negative or positive) as being very low, low, moderate, high or very high when they fall in the ranges 0.0 to 0.2, 0.2 to 0.4, 0.4 to 0.6, 0.6 to 0.8 or 0.8 to 1.0, respectively.

Fleece weight

This is a sheep trait rather than a wool trait, and its economic importance is immediately obvious. The fleece as shorn contains grease, dust, vegetable matter and other impurities, as well as fibre. However, the genetic correlation between greasy and clean fleece weight is very high (Bigham et al., 1983; Mortimer 1987). Measured at about 15 months of age the heritability estimates of both greasy and clean fleece weight are high for fine wool sheep and moderate to high for medium or coarse wool sheep. There is an unfavourable low positive genetic correlation between fleece weight and mean fibre diameter. This is particularly undesirable in fine wools, in which there is a substantial economic premium for fineness. However, if selection is based on an appropriate index combining information on fleece weight and mean fibre diameter, it is possible to genetically improve fleece weight and mean fibre diameter simultaneously (Ponzoni, 1986). The problem is less critical in medium wool breeds because the premium for fineness in their diameter range is small compared to that in fine wools, and it is of little relevance in coarse and in carpet wool sheep breeds, in which there is little justification to maintain or reduce mean fibre diameter.

Fleece-rot is a major skin and fleece disease which leads to blowfly strike. Raadsma and Rogan (1987) report a very low positive genetic correlation between clean fleece weight and fleece-rot incidence in Australian Merino sheep. If their value was confirmed by other studies there would be no problem in the simultaneous improvement of both traits.

There is no clear evidence of other serious genetic antagonisms with fleece weight. Selection for greasy fleece weight will not necessarily change yield, but selection for clean fleece weight will increase it. The genetic correlation with staple length is very low to high positive (i.e. favourable). In fine and coarse wool sheep a low to moderate negative genetic correlation with resistance to compression (or bulk) has been found (James et al., 1990; Watson et al., 1977; Bigham et al., 1985). The economic significance of resistance to compression is discussed later. Selection for fleece weight may result in a favourable correlated response in staple strength and resistance to cotting in coarse wool sheep (Wickham 1985a).

Yield

Yield is the amount of clean fibre that can be obtained from greasy wool, expressed as a percentage. Wool buyers are interested in the amount of fibre present in a given lot of wool, and will pay accordingly, either assessing yield subjectively or on the basis of an objective measure of a representative sample.
Yield is influenced by the environment (e.g. generally, it is lower in dustier areas), but within an environment heritability estimates for yield are high, the majority being in the range of 0.3 to 0.6 (Mortimer, 1987). The genetic correlations between yield and greasy fleece weight are low negative to very low positive (Mortimer, 1987; Bigham et al., 1983), but they are moderate to high positive with clean fleece weight and low to high positive with staple length. Greater yield is also genetically associated with low resistance to compression (or bulk) and greater whiteness of the wool in both fine wool and coarse wool breeds (James et al., 1990; Bigham et al., 1983).

Performance recording schemes for wool sheep typically include clean fleece weight (calculated as the product of greasy fleece weight and yield) in the breeding objective. By using this composite trait we are abdicating the formal control of its components. An exaggerated increase in yield (and thus probably a reduction in wax) as a correlated response to selection for clean fleece weight could lead to reduced protection of the fleece against water and dust penetration (Hayman, 1953; Charlesworth, 1970) and possibly to increased fleece-rot (Raadsma and Rogan, 1987). It would be better to specify both greasy fleece weight and yield as traits in the breeding objective in order to more easily monitor the change in both traits, and if necessary, to establish maximum permissible yields for particular areas. To our knowledge no schemes reported to date feature such an option.

Mean fibre diameter

Mean fibre diameter is a major determinant of the end use of wool (Table 2). It influences the spinning performance, the handle and the weight of the resulting products. Generally, finer wools enable a better spinning performance and impart a softer handle.

Studies of the relationship between mean fibre diameter and wool prices indicate that it varies according to the wool category considered (Cardellino, 1986; Elliott, 1986). The association is strong for fine wools, much less important for medium wools, and virtually non-existent for coarse wools. Fibre diameter is important in fine wools (up to 25 um) because high spinning performance and soft handle are essential in the production of apparel goods. Soft handle, while still desirable, is not as important in goods manufactured with medium (25 to 30 um) wools. In addition, medium wools are often spun well below the spinning limit. These two factors weaken the association between mean fibre diameter and wool price in medium wools. Finally, considerations of soft handle and spinning performance have little relevance for wools of 30 um or greater mean fibre diameter, hence the lack of association between this trait and price in coarse and in specialty carpet wools.

Despite the clear economic incentive for finer wools some Australian Merino breeders choose to maintain mean fibre diameter unchanged, fearing that a finer fibre may not withstand the rigours of some environments. This attitude is based on traditional views about adaptation of Merino strains to different environments, but there is no scientific evidence to support or refute it.

The heritability of mean fibre diameter is moderate to high, the majority of estimates falling in the latter class (Mortimer, 1987; Rae, 1982). The genetic antagonism between mean fibre diameter and fleece weight
is stronger in coarse wool breeds than in medium or fine wool breeds (Mortimer, 1987; Bigham et al., 1983).

In fine wool sheep moderate positive genetic correlations exist for mean fibre diameter with staple strength (Rogan 1988) and resistance to compression (James et al., 1990; Watson et al., 1977) and very low negative to moderate positive with staple length (Mortimer, 1987). There is a moderate positive genetic correlation between mean fibre diameter and fibre diameter variability measured as the standard deviation of diameter (James et al., 1990; Rogan, 1988).

In coarse wool breeds mean fibre diameter could change as a correlated response to selection for other traits such as bulk or colour (Bigham et al., 1985) but this would be of little consequence given that mean fibre diameter is relatively unimportant in this category of wool.

Fibre diameter variability

In wool from a group of animals of a given breed or strain, and managed together, there will be variation in mean fibre diameter. The coefficient of variation of fibre diameter in lines of Merino fleece wool may range from 19 to 25 per cent. Australian researchers have shown that 60 to 80 per cent of the observed fibre diameter variability is due to variation between individual fibres within staples (Australian Wool Corporation, 1989b). However, the influence of fibre diameter variability on processing performance and product quality is minor compared to that of other traits. Noted effects are in yarn thickness variation and in 'prickle' of wool fabrics when worn against the skin. At present, variations in the price paid for wool are not associated with fibre diameter variability. Thus, there is little reason for modifying the low priority currently assigned to the inclusion of this trait in the breeding objective of wool sheep.

Heritability estimates for fibre diameter variability are high (see review by James et al., 1990). The genetic correlation with mean fibre diameter depends on the measure of variability. It is moderate positive between mean fibre diameter and standard deviation of fibre diameter, whereas it is effectively zero between mean fibre diameter and the co-efficient of variation of fibre diameter (see James et al., 1990 for detailed discussion on this topic). Another, more interesting, genetic association is that of fibre diameter variability with susceptibility to fleece-rot and body strike in Peppin Merino sheep (Raadsma and Rogan, 1987). The use of fibre diameter variability as an indicator character in a breeding program to reduce fleece-rot and body strike susceptibility may be justified in some circumstances. Note that selection for reduced fibre diameter variability would take place not because it is economically worthwhile per se, but because it would reduce susceptibility to fleece-rot as a correlated response.

Staple length

There is an association between staple length and fibre length in raw wool, but the relationship of these characteristics with mean fibre length in the top (hauteur) and with length after carding, is not straightforward (Australian Wool Corporation, 1989b; Simpson et al., 1986). Other factors such as staple strength, mean fibre diameter and vegetable matter content also have an important influence. Australian researchers (TEAM, 1988) have generally found that in multiple regression equations predicting hauteur the order of importance of the independent variables is: staple length, staple
strength, mean fibre diameter and vegetable matter content. This finding has stimulated the promotion of the objective measurement of staple length in wool sales, and has led to suggestions that staple length could be an additional trait in the breeding objective of Australian Merino sheep.

It is our perception that the case for the inclusion of this trait in the breeding objective is not clear-cut. While accepting that the measurement of staple length may be of assistance in offering wool for sale with a greater degree of specification, we contend that it does not necessarily follow that we should try to increase it genetically. Currently, under the Australian Minimum Reserve Price Schedule for the season 1989-1990 a small premium is paid for greater staple length whether objectively or subjectively assessed. However, before embarking upon the genetic improvement of staple length the cause for some wools being short (and thus penalised in price) should be established. If it were because of shearing with less than 12 months of wool growth or because of other environmental influences, then there would be little reason to consider improving the trait genetically. Generally, in well managed South Australian Merino flocks staple length is above the threshold under which a price penalty would be incurred. On the other hand, excessive staple length could create difficulties during processing. The trend in this area is to develop equipment capable of efficiently processing shorter wools, not longer wools.

Nevertheless, there could be flocks or other fine wool breeds in which the value of the wool could be improved by increasing staple length by genetic means. For example, Wickham (1985a) states that in New Zealand there are premiums for length in apparel wools. There are also premiums for length among coarse wools from sheep shorn more often than once per year. He concludes that staple length should be part of the breeding objective in fine woolled and in coarse wool sheep shorn more than once per year. At the time, lower prices for wool less than 100mm long made staple length in Romneys a major determinant of wool price.

Specialty carpet wool breeds such as Drysdales can produce staple lengths of 200 to 250mm in 12 months. Fibres longer than 175mm can cause problems in processing (Wickham, 1985b) and the preferred range is 75 to 125mm. Thus, such sheep have to be shorn twice a year.

The heritability of staple length is high among breeds of all wool types (Mortimer, 1987; Rae, 1982). Estimates of genetic correlations between staple length and fleece weight (greasy or clean) are positive but vary from very low to very high, indicating that, generally, in breeding programs emphasising fleece weight, staple length will increase as a correlated response. The genetic correlations with yield and mean fibre diameter are mainly positive, but moderate to high negative with resistance to compression or bulk (Watson et al., 1977; Bigham et al., 1983, 1985).

Staple length variability

The coefficient of variation of staple length has only a small influence on the processing performance of wool to the spinning stage (Turpie, 1979; Andrews et al., 1985). By contrast, the coefficient of variation of fibre length in the top may affect yarn properties, but this characteristic is largely determined by factors affecting fibre breakage during carding and combing, such as staple strength and vegetable matter content. Currently there are no price premiums or penalties associated with staple length variability for any type of wool. This, coupled with the lack of genetic

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parameters, make the inclusion of this trait in a breeding program extremely difficult to justify.

**Staple strength**

Traditionally wool has been classified subjectively for staple strength as, for example, part tender, tender and very tender. Now, it is possible to measure staple strength objectively. The thinning of fibre diameter at a point along the fibre is responsible for the reduction in staple strength. This may occur due to seasonal variation in the rate of fibre growth, stress, or because of both factors interacting. In extreme cases fibre growth ceases, resulting in a break of the fibre and cotting. It appears that cotting is a more frequent problem among coarse and carpet wool breeds than among medium and fine wool breeds.

Wool is subjected to strong extension forces during carding and combing, and staple strength is known to be important in both the worsted and woollen processing systems, affecting hauteur and length after carding, respectively. At high spinning speeds greater hauteur is associated with greater spinning efficiency (fewer breaks). Fibre length after carding affects yarn regularity, strength and extensibility.

In addition to staple strength per se, the position of the break along the staple is of interest. In general, if the position of the break occurs near the tip or near the base of the staple it will reduce fibre length in the processed product less than if it occurs near the middle of the staple, but it will result in greater fibre wastage (of very short fibres). When the fibre weakness occurs regularly at a particular time of the year, the position of the break along the staple may be modified by changes in shearing date.

The subjective assessment of staple strength by wool buyers and valuers establishes a limit of about 20 to 30 Newtons per kilotex, below which the wool is deemed tender. In general, the market has penalised tender wools, but pays no premiums for wools of staple strength above 40 Newtons per kilotex. In the Australian Minimum Reserve Price Schedule for the season 1989-1990 a small premium which continues to increase above 40 Newtons per kilotex is paid for tensile strength. It is yet to be determined whether wool buyers will respond favourably and do the same in the future.

An early estimate of the heritability (0.58) of staple strength in coarse wool sheep raised optimism about the prospects for genetic improvement of this trait (Bigham et al., 1983). However, more recent estimates in both fine wool and coarse wool sheep have been considerably lower, about 0.2 (Rogan, 1988; Newman et al., 1990a). This latter value seems more realistic than the former.

Despite its moderate heritability the genetic improvement of staple strength poses another problem, which, though not exclusive to this trait, could be especially serious in this case. If staple strength were recorded in the context of a breeding program, typically, it would be recorded in young rams and ewes before they would be used for reproduction. Since much of the wool is produced by breeding ewes, the expectation would be that by selecting for staple strength in non-breeding sheep we would achieve a favourable response in breeding ewes. However, breeding ewes are under the stress of pregnancy and lactation, whereas young rams and ewes are not. Thus, staple strength measured in one class of sheep may not necessarily be exactly the
same trait as that measured in the other class. Newman et al. (1990b) found a genetic correlation of 0.64 for staple strength measured in hoggets and in adult Romney ewes. Such non-unity genetic correlation compounded with the low heritability would make the genetic improvement of this trait difficult.

Colour

The colour of wool after scouring can limit its dyeing potential. Wool must be bright and white if it is to be dyed light colours. However, most wool is marketed and evaluated for colour in a greasy state. Greasy wool colour is determined by the colour of the fibre itself plus dirt, grease, suint and vegetable matter present. It is not possible to accurately predict the colour of scoured wool from an assessment of greasy wool colour (Pattinson and Whiteley, 1984). This has led the Australian Wool Corporation to encourage the objective assessment of scoured wool colour on wool sale lots. Average yellowness is measured as Y-Z, where Y and Z are 'tristimulus' values representing the green and blue components of the light spectrum reflected from a wool sample. Australian wool is generally of very good colour, with an average yellowness in the range 1 to 4 (higher values indicate greater yellowness). Yellowning is a common problem in humid environments, particularly if it is also hot (Burns, 1986).

When the market signals are clear, the inclusion of scoured wool yellowness as a trait in the breeding objective may be justified.

Greasy wool colour has a high heritability in Merino sheep (James et al., 1990; Pattinson and Whiteley, 1984), but estimates range from low to high in Romneys (Rae, 1982; Newman et al., 1990a). The genetic improvement of greasy wool colour per se, is not a worthwhile endeavour since it is scoured wool colour that is important from a processing point of view. However, greasy wool colour may be of use as an indicator character of susceptibility to fleece-rot, given the low to moderate positive genetic correlations found by McGuirk and Atkins (1980) and James et al. (1987) between greasy wool colour and this trait. James et al. (1990) obtained a very high genetic correlation between yellowness in greasy and in scoured wool. If that estimate were confirmed by other studies it would have useful practical implications. Wickham (1985a) cites a high genetic correlation between greasy and clean colour for Romneys.

The heritability of scoured wool colour is high in Merinos (James et al., 1990; Pattinson and Whiteley, 1984) but low to moderate in Romneys (Bigham et al., 1983; Newman et al., 1990a). In Merinos the genetic correlations of scoured yellowness with greasy and clean fleece weight, and with yield are moderate to high negative, but very low positive with mean fibre diameter. In Romneys they are low to moderate positive with greasy and clean fleece weight, and with mean fibre diameter, but moderate negative with yield. Note that very few estimates of genetic parameters for objectively measured scoured wool colour are available because the technological developments enabling its measurement are rather recent. The heritability estimates suggest that response to selection is possible for this trait, but likely to be easier in Merino than in Romney sheep. Further studies are required before we can have confidence in the genetic correlations with other traits.

Note that we have not dealt with the problem of presence of dark fibres in white wool. Rogan (1988) reviewed the topic, and Dr P. Sponenberg is
Resistance to compression or bulk

Resistance to compression is the force per unit area required to compress a fixed mass of wool to a fixed volume, and it is expressed in kilopascals (kPa). Bulk is the volume a sample fills under a given compression, and it is expressed in cubic centimetres per gram (cm³/g). Australian wool scientists measure resistance to compression, whereas New Zealand scientists measure bulk. The two measures are related, but the correlation between them is not perfect (Teasdale, 1986).

Resistance to compression affects both the processing performance of the wool and the characteristics of the end product. Wools of low resistance to compression suffer lower processing losses and produce softer handling fabrics (Hunter et al., 1984; Kurdo et al., 1986). Given the end use of fine wools (Table 2) it appears that low values of this trait would be generally preferred. However, high resistance to compression (or bulk) is desirable in some knit-wear, in wool-filled products, and, particularly, in carpets, where research has shown that the use of bulkier wools results in a product of better appearance and wearing performance (Wickham, 1985b). Thus, whether resistance to compression (or bulk) is a wool property to be increased or reduced depends on the end use of the wool under consideration.

Elliott (1986) discusses the relationship between bulk and price for New Zealand wools. It is not possible to discern a clear pattern from which decisions about genetic improvement within a breed can be made. However, he cites an instance in which a premium could be demonstrated for Perendale wools of greater bulk (Elliott, 1984).

Australian wool is not routinely measured for resistance to compression so the analysis of this trait in relation to price is not possible. Given our current state of knowledge it seems that processors may benefit from knowledge about resistance to compression (or bulk) in the wools they are buying, but the desired direction (as suggested by market signals) of genetic change within a particular breed is far from clear.

Nevertheless, if genetic change in resistance to compression (or bulk) were of interest, it could be achieved, either in fine or in coarse wool sheep since the heritability is high (Watson et al., 1977; James et al., 1990; Bigham et al., 1985). The last named authors indicate the possibility of a gene of large effect for bulk being present in Perendale sheep. The genetic correlations of resistance to compression (or bulk) with clean fleece weight and with yield are in broad agreement in fine wool and in coarse wool sheep, being low to moderate negative with the former, and moderate to very high negative with the latter trait. The genetic correlations are moderate positive with mean fibre diameter in fine wool sheep, but estimates have been very variable among coarse wool sheep (very low negative to moderate positive).

Medullation

Medullation is the presence in a fibre of a core of large fragile cells within a sheath of normal dense cortical cells. Medullated fibres affect the dyed appearance of wool and cause end products to have a crisp (as opposed to soft) handle and a hairy or ‘rough’ appearance.
Generally, medullation is undesirable in fine and medium wools, but the incidence of this trait is very low in sheep breeds producing such wool. Cardellino (1977) notes that in Uruguay (where 85 per cent of the clip is medium wool) wool processors considered medullation a totally unimportant wool characteristic. By contrast, medullation is desirable in carpet wool blends, where it is believed to give the carpet better appearance retention, soil-hiding properties and a crisp handle. For this reason manufacturers include a proportion of wool from a specialty carpet breed (e.g. Drysdale, Scottish Blackface) in carpet wool blends. The proportion may vary between 15 and 30 per cent. Thus, the presence of medullation may be regarded as desirable or undesirable depending on the end use of wool.

In some breeds medullation is controlled by a single gene of major effect (Wickham, 1984).

Because the incidence of medullation is negligible in breeds in which it is undesirable (e.g. Merino, Corriedale), whereas it is present at a satisfactory level in breeds in which it is desirable, there is little point in trying to modify genetically the incidence of this trait within particular breeds.

Vegetable matter content

The vegetable matter content of wool indicates its degree of contamination, rather than describing a property of the fibre itself. The removal of vegetable matter during processing is costly, and thus, severely contaminated wools will usually be subject to large price penalties.

Mortimer (1987) presents a heritability estimate of 0.1 for vegetable matter content in Merino sheep. This is the only estimate we are aware of for this trait. We believe it would be unrealistic to seek a solution to a problem of high vegetable matter content in wool by modifying the animals genetically. It would be more sensible to try to modify the environment. Thus, despite its large effect on wool value vegetable matter content is not worth considering in the breeding objective of wool sheep.

Other Traits

There are, of course, a number of other wool traits not included in our discussion. Lustre (a type of light reflectance of the fibre's surface) is one such trait, present in some breeds (e.g. Lincoln, Border Leicester). Lustrous wool is used in blends to produce special effects. However, lustre is a disadvantage when bulk is required (Wickham, 1985b). As some breeds already produce lustrous wool, there is little justification to consider this trait in other breeds.

Another quality trait not discussed in previous sections is wool 'style'. Style grades are used in the Australian wool marketing system in an attempt to further describe the processing (top making) potential of raw wool (e.g. Spinners, Best topmaking, Good topmaking, etc.) (Australian Wool Corporation, 1989b). This subjective classification of the wool occurs in addition to measurement of variables such as mean fibre diameter, yield, vegetable matter content, and possibly staple length, staple strength and colour. It is based on an aggregate of traits including crimp definition and regularity, dust penetration, staple tip appearance and greasy colour, and it is regarded as a relatively important wool attribute by industry. Style influences the price of wool but, it alone is less important than other
traits, such as fibre diameter. Some of the component traits mentioned above receive attention in the subjective and informal selection programs of Merino breeders (Scott, 1987). However, Winston (1988) notes that recent work indicates that style has a minor effect on wool processing performance. Work is in progress to identify the components of style that influence processing performance, and once this is clear we will be able to focus our attention on them.

RECOMMENDED DIRECTION OF SELECTION

Table 4 shows a recommended direction of selection and relative emphasis to be placed on wool traits according to the category of wool produced. The rationale behind the recommendations is given in the preceding sections. The recommendations are to be interpreted as broad guidelines only, and particular cases have to be studied carefully. To implement an effective breeding program it is not enough to establish qualitatively that certain traits are more important than others. A quantitative assessment, using procedures such as those described by Morris et al. (1982) or Ponzoni (1986) is required, but that is beyond the scope of the present paper.

Not all traits are equally important in breeds producing different categories of wool. Mean fibre diameter is the best example, its consideration being very important among fine wool breeds, but not justified among coarse and carpet wool breeds. A special case is that of breeds or strains in a border-line situation. It may be worth while intensely selecting a 'heavy cutting fine' Corriedale flock for fineness to 'move' it to the fibre diameter range of fine wools and thus benefit from greater wool prices. However, such intense selection may not be the most appropriate course of action for a flock of the same breed, but with coarser fibre diameter.

PRACTICAL BREEDING PROGRAMS

Rogan (1988) discusses the importance of raw wool characteristics in the context of breeding objectives for wool sheep. His comments are currently valid, and this section is complementary to his. Table 4 lists wool traits which could be candidates for inclusion in the breeding objective of wool sheep. Even though only traits considered to be of importance in the foreseeable future were included, the list is long for any particular group (e.g. nine traits for fine wool sheep). It would be difficult to accommodate formally such a large number of traits in a practical breeding program, and most likely, selection will focus on a sub-set of traits.

In Australia, for example, while it is generally accepted that Merino breeders will carry out some selection based on a subjective appraisal of wool attributes such as 'dry' wool, harsh handle or poor wool colour, the only wool traits included in the breeding objective of WOOLPLAN, the national performance recording scheme for wool sheep (Ponzoni, 1987), are clean fleece weight and mean fibre diameter. If breeders follow the recommendations made by WOOLPLAN advisers, most of the selection pressure concerning wool traits will be on these two traits. Breeders have the right to ask about the genetic consequences of such a simplification. Satisfactory answers to this kind of question may come from experimental evidence enabling the calculation of direct and correlated responses to selection in industry flocks, or from predictions based on selection theory and current knowledge of genetic parameters for the traits involved.
Table 4 Recommended direction of selection and relative emphasis placed on wool traits

<table>
<thead>
<tr>
<th>Category of wool</th>
<th>Trait</th>
<th>Fine</th>
<th>Medium</th>
<th>Coarse</th>
<th>Specialty Carpet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fleece weight</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Yield</td>
<td>++ or ?</td>
<td>++ or ?</td>
<td>++ or ?</td>
<td>++ or ?</td>
</tr>
<tr>
<td></td>
<td>Mean fibre diameter</td>
<td>--</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Fibre diameter variability</td>
<td>? or -</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Staple length</td>
<td>+ or ?</td>
<td>+ or ?</td>
<td>+ or ?</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Staple strength</td>
<td>+ or ?</td>
<td>+ or ?</td>
<td>+ or ?</td>
<td>+ or ?</td>
</tr>
<tr>
<td></td>
<td>Colour B</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Resistance to compression (or bulk)</td>
<td>0 or ?</td>
<td>0 or ?</td>
<td>0 or ?</td>
<td>0 or ?</td>
</tr>
<tr>
<td></td>
<td>Medullation</td>
<td>M or 0</td>
<td>M or 0</td>
<td>- or M or 0</td>
<td>M</td>
</tr>
</tbody>
</table>

A Selection direction and emphasis: -- intense negative; - moderate negative; M maintain at present level; + moderate positive; ++ intense positive; ? debatable or will depend on circumstances; 0 ignore.

B Assuming lower values correspond to whiter wools.
The work of Hynd et al. (1989) is an example of answering questions with experimental evidence. Lax et al. (1988) warn that sheep selection programs emphasising clean fleece weight could result in fleeces with high fibre diameter variability. It is sometimes argued that the problem will occur even if at the same time fibre diameter is reduced or maintained, as is the case in WOOLPLAN indices. In the 'Anama' stud (Messrs Ryves and James Hawker, Clare, South Australia) a selection program with South Australian Merino sheep has been conducted since 1978 based largely on an index in which clean fleece weight and fibre diameter are the only wool characteristics formally considered (see Hynd et al. for details). At the same time a randomly bred control flock was maintained. This provided an opportunity to check the hypothesis advanced by Lax et al. (1988). Hynd et al. (1989) found that the selection program conducted in the 'Anama' stud resulted in favourable responses in greasy fleece weight and yield (and hence clean fleece weight), mean fibre diameter and hogget live weight. They also found that this was accompanied by a reduction in fibre diameter variability, and not an increase. Thus, concerns about the long-term impact of WOOLPLAN indices on fibre diameter variability appear unwarranted, a finding which is further supported by theoretical and numerical work (Atkins, pers. comm.).

The calculation of correlated responses in traits that are not formally accommodated by existing performance recording schemes, but that are or may be in the future of some importance, can provide useful information. The most commonly used selection index in WOOLPLAN (Brien, pers. comm.) includes clean fleece weight and mean fibre diameter, with index coefficients 18.4 and -4.4, respectively. Using 'acceptable' genetic parameter values, assuming that the best 6 per cent of rams on index were selected, that there was no selection among ewes, and that the average generation interval for males and females was 3 years, we calculated the genetic change in a number of traits after 10 years of selection. Using trait means appropriate for a South Australian Merino flock, we found that clean fleece weight and mean fibre diameter would change from 3.5 to 3.9 kg, and from 22.5 to 21.0 um, respectively. These changes would be accompanied by correlated responses in yield (66.0 to 67.4 per cent), standard deviation of fibre diameter (5.0 to 4.8 um), staple length (95.0 to 97.5 mm), staple strength (32.5 to 31.9 N/ktx), scoured wool yellowness (1.50 to 1.05 on the Y-Z scale), and resistance to compression (7.32 to 6.71 kPa). All correlated responses are of small magnitude, but favourable, with the exceptions of staple strength, in which case the change is in an unfavourable direction but of very small magnitude, and resistance to compression, where the small change would be considered favourable or unfavourable depending on the end use of the wool. Assuming the genetic parameter values used were correct, one may conclude that the WOOLPLAN index studied, while resulting in changes in a desirable direction in clean fleece weight and mean fibre diameter, will not lead to the deterioration of the wool quality traits studied.

The estimation of genetic change (James, 1987) and the prediction of correlated responses in traits not formally accommodated by performance recording schemes should be considered an integral part of the service provided to breeders by such schemes. The work involved requires only modest funding and the results may add to the credibility of the schemes or act as a warning, serving a useful purpose in either case.

CONCLUDING REMARKS

Our approach to the issue of genetic improvement of wool production has, no doubt, been influenced by our working experience in Australia, and to some
extent, due to our proximity and professional contacts, by developments in New Zealand. No breeder, adviser or scientist should follow our recommendations without carefully assessing the relevance of these to his or her particular situation. There may be prosperous wool industries based on local consumption, and for which the market requirements are not the same as for Australian wool. Note that, because a wool trait can be measured, it does not necessarily follow that it should be modified genetically in all wool categories.

In the planning of genetic improvement of wool production the speculative nature of breeding programs should be born in mind. When selection decisions are made today, it is with the hope that they will result in more profitable animals in the next generation, that is, some time in the future. Thus, we must consider not only the present market requirements, but more importantly, those likely to be in force in the foreseeable future.

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