Animal (2007), **1:10**, pp 1414–1426 © The Animal Consortium 2007
doi: 10.1017/S175173110700078X

Industry benefits from recent genetic progress in sheep and beef populations

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(Received 14 November 2006; Accepted 14 August 2007)

An analytical model that evaluates the benefits from 10 years of genetic improvement over a 20-year time frame was specified. Estimates of recent genetic trends in recorded traits, industry statistics and published estimates of the economic values of trait changes were used to parameterise the model for the UK sheep and beef industries. Despite rates of genetic change in the relevant performance-recorded breeding populations being substantially less than theoretical predictions, the financial benefits of genetic change were substantial. Over 20 years, the benefits from 10 years of genetic progress at recently achieved rates in recorded hill sheep, sheep crossing sire and sheep terminal sire breeding programmes was estimated to be £5.3, £1.0 and £11.5 million, respectively. If dissemination of genetic material is such that these rates of change are also realised across the entire ram breeding industry, the combined benefits would be £110.8 million. For beef cattle, genetic evaluation systems have been operating within all the major breeds for some years with quite widespread use of performance recording, and so genetic trends within the beef breeds were used as predictors of industry genetic change. Benefits from 10 years of genetic progress at recent rates of change, considering a 20-year time frame, in terminal sire beef breeds are expected to be £4.9 million. Benefits from genetic progress for growth and carcass characters in dual-purpose beef breeds were £18.2 million after subtraction of costs associated with a deterioration in calving traits. These benefits may be further offset by unfavourable associated changes in maternal traits. Additional benefits from identification and use of the best animals available from the breeding sector for commercial matings through performance recording and genetic evaluation could not be quantified. When benefits of genetic improvement were expressed on an annual present value basis and compared with lagged annual investment costs to achieve it, the internal rate of return (IRR) on the combined investment in sheep and beef cattle was 32%. Despite a much higher rate of participation in performance recording, the present value of benefits and the IRR were lower for beef cattle than for sheep. The implications of these results for future national and industry investment in genetic improvement infrastructure were discussed.

Keywords: beef cattle, genetic improvement, sheep

Introduction

Sheep and beef cattle farming in the UK is characterised by many small- to medium-sized farms covering a wide range of environments and using a wide diversity of breeds (Pollott and Stone, 2006). Genetic improvement on commercial sheep and beef farms is largely realised through the purchase of breeding males (Simm *et al.*, 1994). These come from specialised flocks and herds where specific efforts are made to achieve genetic improvement of traits which maximise the saleability of breeding males to commercial farmers and, commonly, to other specialised breeders. The scale and dispersed nature of the beef and sheep breeding herds and flocks are very much in contrast with that in the poultry and pig industries. In these industries, there is a tendency for relatively few and very large seed stock companies to bring about genetic improvement in order to maximise their share of both domestic and international markets (e.g. Knap, 1998; Preisinger, 1998).

The large number of specialised male breeding units for the sheep and beef industries arise for several reasons. Firstly, there is a wide range of breeds that fit a large number of differing environments and farming structures. Secondly, relatively low reproductive rates relative to pigs

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and poultry mean that there are a large number of elite females required to generate breeding rams and bulls for sale, and there would be logistical issues associated with keeping the large numbers of elite females required within a small number of ownership units. Thirdly, there is a strong culture around the presentation and sale of elite breeding animals. This culture tends to support marketing approaches based on local reputation and visual appearance, rather than on scientific facts and figures promoted via publications, mail or over the internet. Finally, there are many more commercial ownership units for sheep and beef cattle farms than there are in the more intensive industries.

In many countries, there is typically a substantial degree of industry (via levies paid by farmers) or national (from general taxation) investment in the infrastructure that supports genetic improvement in extensive farming industries using sheep and cattle. In the UK, this does not extend to ownership of breeding programmes themselves; rather, it involves the provision of some assistance with performance recording, national databases, genetic evaluation systems, breeding objectives and evaluation of new technologies. Most of the costs of the breeding programmes are paid in the first instance by the specialised farmers who operate the breeding programmes. Motivation for this investment stems from price premiums and market share for sales of genetically improved breeding males.

The objective of this study was to quantify the extent of financial benefits to UK sheep and beef farmers that are expected to have arisen from recent genetic changes that have occurred in the flocks and herds from which breeding rams and bulls are sourced.

Material and methods

We first define an analytical model that translates genetic changes in a breeding herd into estimates of economic benefits in commercial herds. The model incorporates gene flow principles, and is driven by estimates of genetic trends in breeds and breeding programmes over recent years. We then define the parameterisation of the analytical model separately for sheep and beef. In addition to estimates of genetic trends, the model parameters include economic values of specific trait changes and statistics on the duration and extent of mating for commercial rams and bulls. Costs associated with genetic improvement are defined and considered both industry level investment in genetic improvement and also the costs paid by breeders for performance recording and genetic evaluation services.

Analytical model overview

The benefits of genetic progress in a breeding programme depend on a number of factors that determine the extent and time frame of expressions in commercial animals, of genes distributed from the breeding programme. For simplicity, it is assumed that only breeding males are used to pass genes to the commercial sector and this is via natural mating. Allowance for artificial insemination (AI) can be accommodated by increasing the average number of females mated per male from the breeding programme. If multiplier herds/flocks are to be considered, then it must be assumed that they achieve the same rates of genetic progress on average as that achieved by the breeding programme. The model developed here can be applied to breeding programmes varying in scale and magnitude, provided the key assumptions hold and the definitions are relevant.

Numbers of progeny of breeding programme sires

The breeding programme is taken to comprise c breeding females whose progeny have performance records collected on them in each year and where each generate b breeding males suitable for sale each year. Each breeding male is assumed to have a constant probability of surviving to breed again from one mating season to the next, λ, but with an upper limit u in the number of breeding seasons allowed for any individual breeding male. If each breeding male from the breeding programme is mated to f commercial breeding females per year, each of which generates p commercial progeny born (alive or dead), then the total number of offspring born per year that are sired directly by breeding programme sires for k successive sire mating years (o_k) can be calculated as

$$o_k = c \times b \times \lambda^{k-1} \times f \times p \quad \text{for } 0 < k \leqslant u.$$

Expressions of offspring genes

A single offspring born into a commercial herd and sired by a breeding male sourced from the breeding programme will express genetic superiority arising from genetic progress in the breeding population itself. It will also pass on this genetic superiority to descendants if it becomes a commercial replacement breeding female. Economic traits expressed by offspring at birth or slaughter are considered separately from those expressed by breeding females, because the time flows and numbers of expressions of these traits are different. Relative differences in numbers of expressions of genes by commercial offspring at slaughter *v.* at birth, and any time delays must be accounted for when specifying genetic trends in profitability (see below).

We define $d_{i,j}$ and $m_{i,j}$, respectively, as giving the expressions of direct (at birth) and maternal (at breeding) genetic superiority inherited from a breeding male sourced from the breeding programme by a single offspring born in year $i = 1$ and its descendants after a lag of i years from the time of birth of the offspring in successive generations j. These can be calculated recursively using

$$d_{1,1} = \frac{1}{2},$$

$$d_{\mathrm{i},1} = 0 \quad \text{for } i > 1,$$

$$m_{i,j} = \sum_{\mathrm{k}=1}^{\mathrm{i}} d_{i+1-k,j} w_k,$$

$$d_{i,j} = m_{i,j-1} \frac{1}{2} p \quad \text{for } j > 1,$$

where w_k is the probability of a commercial offspring becoming a replacement breeding female that is mated k years after birth. In this way, maternal genetic expressions are predicted from direct genetic expressions in the same generation after accounting for the lag from birth to breeding age. Values w_k can be readily calculated from a typical herd age distribution at mating and the probability that an offspring born becomes a breeding female mated at least once. Beyond generation *1*, direct genetic expressions are predicted from maternal genetic expressions in the previous generation.

The aggregate (over generations) expressions of genes of a breeding programme male per offspring born by the number of years since the offspring first expresses its own direct birth trait (i) can then be calculated as

$$\Sigma d_i = \sum_{j=1}^{j\max} d_{i,j}$$

for direct traits and

$$\Sigma m_i = \sum_{j=1}^{j\max} m_{i,j}$$

for maternal traits where $j$max is the maximum number of generations over which to count expressions.

Incorporation of genetic trend information

Let s_i be the expected genetic superiority (or inferiority) in aggregate currency units for traits expressed at birth or at slaughter (i.e. the direct traits), by an individual offspring of breeding males sold in year i, relative to that of those sold in year $i-1$. Also let a_i be the expected annual genetic responses in aggregate currency units for maternal traits expressed in one season by a breeding female. We define T as the number of years of genetic progress that is counted in the calculation of the overall commercial benefits from the breeding programme. Because of lags of expression, we allow for considering the effects of these benefits over a longer planning horizon H where $T \leqslant H$. Average direct and maternal genetic merit of breeding males sold from the breeding programme in year i, relative to those sold in year zero, y_i and z_i, can be computed over the planning horizon ($i = 1$ to H) as follows:

$$y_i = \sum_{j=1}^{i} s_j \text{ and } z_i = \sum_{j=1}^{i} a_j \text{ for } i = 1 \text{ to } T,$$

$y_i = y_T$ and $z_i = z_T$ for $i = T+1$ to H, such that over time, genetic benefits from previous years are accumulated along with those in the current year.

Aggregation to get total benefits

The economic benefits of genetic progress ($e_{i,j}$), where i is the year in which all genetically improved sires are mated for the first time in their own lives and j is the year that the benefits are realised within the commercial population, can be computed using the above derivations as follows:

$$e_{i,j} = \sum_{k=1}^{i} o_k \left[y_{i-k+1} \times \Sigma d_{j-i+1-x} + z_{i-k+1} \times \Sigma m_{j-i+1-x} \right]$$
$$\text{or } j - x \geqslant i,$$

where x is the lag between mating and birth of the offspring rounded to the nearest year.

Summing the economic benefits of genetic progress over years of first mating gives economic benefits v_j for the jth year of expression, in commercial herds as follows:

$$v_j = \sum_{i=1}^{H} e_{i,j}.$$

Finally, we define discount coefficients $q_j = (1/1+r)^{j+s}$, where $j = 1$ corresponds to the first year of mating of genetically improved breeding males, s is the lag between birth and first mating of breeding males and r is the discount rate.

The aggregate discounted benefits of genetic progress over a 10-year period counting 20 years (ε) from the time genetically improved males are first mated in commercial herds can then be computed as

$$\varepsilon = \sum_{j=1}^{H} q_j v_j.$$

A small example is used to illustrate the method in the appendix.

Benefits from a single year's genetic progress

The benefits of a single year's genetic progress can be computed using the above model by setting

$$y_i = s_i \text{ and } z_i = a_i \text{ for } i = 1 \text{ to } H$$

and then repeating all of the above calculations.

Breeding programme estimates of genetic trends

Averages of estimated breeding values by trait, breeding programme/breed and year were sourced from Meat and Livestock Commission (MLC)'s Signet Breeding Services, and genetic trends estimated by fitting a linear regression coefficient in all years of data available from the year 2000 onwards for sheep and from 1999 to 2003 for beef cattle. Depending on the breeding programme, averages of estimated breeding values for sheep were available up until either 2004 or 2005. The aim was to use sufficient data to obtain a consistent prediction of the trend, without relying too much on genetic changes that have occurred some time ago. These estimates of genetic trends in traits expressed in

Table 1 *Classification of breeds by species and breed role, their number of progeny born in recorded flocks and herds (average over five most recent years of data) from which genetic trends were estimated, and the estimated relative industry impacts† (within-breed role)*

Breed/breeding programme	Recorded progeny (average per year)	Relative impact†(%)
Hill sheep		
Scottish Blackface	8279	36
Welsh Mountain	5620	34
Beulah	1931	11
North Country Cheviot	4757	10
Welsh Hardy Speckleface	1374	6
Brecon Hill Cheviots	956	2
South Welsh Mountain	1578	1
Crossing sheep		
Blue Faced Leicester	795	33
Suffolk	10 911	31
Texel	11 360	25
Border Leicester	277	11
Terminal sire sheep		
Texel	11 360	44
Suffolk	10 911	42
Charollais	5088	14
Meatlinc	1316	<1
Hampshire Down	652	<1
Dual-purpose beef		
Aberdeen Angus	11 540	16
Hereford	3863	8
Limousin	16 817	55
South Devon	5663	3
Simmental	5662	18
Terminal beef		
Blonde D'Aquitane	2308	14
Belgian Blue	1522	28
Charolais	9582	58

†Percentages based on the total breed contribution to the numbers of sheep of each breed type on all UK farms by breed reported by Pollott and Stone (2006) but ignoring breeds not represented by any breeding programmes for sheep, and based on the total breed contribution to the numbers of births from British Cattle Movement Programme statistics in 2003 for all cattle (percentages within-breed role).

purebred populations were used as a direct prediction of genetic changes in the performance of commercial crossbred animals generated from matings by breeding programme sires and their descendents.

Table 1 shows the breeds and breeding programmes for which data were available, and the average number of progeny born in the participating recorded flocks and herds. Estimates of the relative genetic contributions to the respective commercial farming industries are also shown in Table 1. These reflect the ultimate industry impact of the various breeds within defined industry roles, and are used below in the aggregation of genetic trend estimates for different breeds. For the sheep breeds, they were based on statistics reported by Pollott and Stone (2006). For the beef breeds, data on cattle births reported by breed or breed cross in 2003 recorded by the British Cattle Movement Programme (BCMS) were used. These breeds are classified by their respective roles, e.g. hill, crossing and terminal sheep breed types. However, some breeds serve more than one role. In particular, Texels and Suffolks can effectively be considered as both terminal and crossing breed types based on recent statistics reported by Pollott and Stone (2006). Crossing breeds are typically mated to hill breeds to generate crossbred breeding ewes, which do not generate their own replacements. Beef breeds are divided into maternal and terminal breed types.

Linear genetic trends for sheep breed types are summarised in Table 2, and for beef breed types in Table 3. For litter size, several of the hill sheep breeding programmes evaluate the number of lambs reared, rather than the number of lambs born. For these programmes, trends were converted to a number of lambs born equivalent by multiplying by 1.25. Weighted average trends were taken across breeds within species and breed type. Taking averages reduces the necessity for multiple runs of the cost benefit model to achieve the same results, reduces sampling errors of individual estimates and preserves confidentiality of commercially sensitive information. The weighting factors were based on average numbers of recorded progeny across the years the trends were estimated (from Table 1) for both sheep and beef. Additional weighting systems were also used, whereby weighting was based on the relative industry impact of the breed (from Table 1).

In 2001, a foot and mouth disease (FMD) outbreak in Britain resulted in a significant drop in both recorded and commercial cattle and sheep. A fall of approximately 30% in the annual trend that was observed for several important beef traits in the 2002 birth year may have had a small impact on the overall beef trait trends estimated across 5 years from 1999 to 2003. No fall was observed in genetic trends for the sheep breeding programmes around the time of the FMD outbreak. The absence of an effect in sheep may be because genetic progress in cattle breeding programmes is likely to be more dependent on use of elite males through AI than in sheep breeding programmes. Farm access by AI technicians was severely restricted during the FMD outbreak.

Economic consequences of trait changes

The analytical model described above relies on estimates of the expected genetic change in profitability for each breeding female, and also for each animal born. No account for discounting based on gene flow principles is required when specifying the economic values. These factors are accounted for directly in the analytical model described above.

For hill sheep, estimates of trait economic values were taken from Conington *et al.* (2004). It was necessary to adapt these before they could be applied to genetic trends, because some of the trait definitions used by Conington *et al.* (2004) are not consistent with the trait definitions in

Table 2 *Weighted average linear annual genetic trends from 2000 onwards in traits affecting farm profitability for sheep breed types*

Trait	Hill breeds		Crossing breeds		Terminal breeds	
	Rec	Imp	Rec	Imp	Rec	Imp
8-week live weight (kg)	0.052	0.059	0.143	0.114	0.153	0.146
Mature live weight (kg)	0.195	0.220	0.011	0.013	0.007	0.007
Litter size (lambs born† per ewe lambing)	0.006	0.006	0.003	−0.001	0.004	0.004
Live weight at scanning (kg)	0.137	0.145	0.300	0.241	0.336	0.317
Maternal live weight at scanning (kg)	0.032	0.037	0.000	0.000	0.001	−0.002
Muscle depth (mm)	0.073	0.074	0.088	0.095	0.128	0.110
Fat depth (mm)	−0.001	−0.007	0.002	0.011	−0.011	−0.009
Lean weight (kg)	NA	NA	NA	NA	0.123	0.114
Fat weight (kg)	NA	NA	NA	NA	0.046	0.040

Weightings are by numbers of recorded progeny (Rec), and alternatively by relative impact of the breed on the industry (Imp) as specified in Table 1. Estimated breeding values used to derive the trends were taken from the MLC Signet database from 16 hill breed breeding programmes, four crossing breed breeding programmes and five terminal sire breeding programmes.
†Two of the hill sheep breeding programmes have breeding values estimated for lambs reared per ewe lambing as opposed to lambs born per ewe lambing. Their trends for numbers of lambs reared were adjusted assuming 0.8 lambs reared per lamb born.
NA = not applicable.

Table 3 *Weighted average linear annual genetic trends in traits and sub-indexes affecting farm profitability for periods 1991 to 1995 and 1999 to 2003 for two types of beef breeds*

Trait or sub-index	Terminal breeds		Dual-purpose breeds	
	Rec	Imp	Rec	Imp
1991–1995				
Beef value (£ per calf born)	0.354	0.329	0.506	0.333
Calving ease (% unassisted)	−0.368	−0.295	−0.123	−0.096
Gestation length (days)	0.073	0.065	0.016	0.012
1999–2003				
Beef value (£ per calf born)	0.719	0.672	0.667	0.681
Calving ease (% unassisted)	−0.305	−0.277	−0.095	−0.094
Gestation length (days)	0.020	0.029	0.044	0.033

Weightings are by numbers of recorded progeny (Rec) and alternatively by relative impact of the breed on the industry (Imp). Estimated breeding values used to derive the trends were taken from the MLC Signet database for each breed.

the MLC Signet genetic evaluation system. Specifically, the economic value of a change in lambs reared of £17.00 per ewe from Conington *et al.* (2004) was adjusted downwards to £13.60 to correspond to litter size, based on the assumption that additional lambs come as twins (not triplets), and that lamb deaths average 10% in singles and 15% in twins. The economic value of fat depth (mm) was derived as −£0.064 per lamb born and counts benefits accrued by other farmers who have purchased lambs from the hill flock for finishing. An economic value for fat class for a semi-intensive hill flock was taken from Conington *et al.* (2004) and the theory of genetic regression of the goal trait on the recorded traits (James, 1981) was applied incorporating genetic variances and covariances for the two traits reported by Conington *et al.* (2001). The economic value for scanning weight for a semi-intensive hill flock was calculated from Conington *et al.* (2004) as £0.31, assuming a genetic correlation of 1 between scanning weight and carcass weight, a killing out proportion of 0.43 and the same heritability of carcass weight and scanning weight. This same value was used for maternal scanning weight. No economic value was applied to muscle depth, as Conington *et al.* (2001) reported very low correlations between muscle depth and traits not already included in the breeding objective. An economic value of £0.13 per kg of mature weight per ewe was based directly on Conington *et al.* (2004).

For crossing sheep breed types, the economic value of a change in litter size was taken as zero, reflecting the fact that crossbred progeny of these breed types are close to commercial optimum for this trait. Any modest deviation from the optimum litter size is inconsequential to this study, because of the very small genetic trends for litter size in the crossing breed types. Economic values for ewe mature weight, maternal scan weight and fat depth were also ignored because of the very small genetic trends for these traits in the crossing breed types. The same economic values as for hill sheep were assumed for live weight at scanning and muscle depth.

Economic values used for terminal sires were derived from Jones *et al.* (2004), assuming 0.85 lambs slaughtered per lamb born from a terminal sire. The values were £2.66 per kg of carcass lean per lamb born, and −£1.76 per kg of carcass fat per lamb born. The value for fat is currently more negative than in indexes used in the industry (Simm *et al.*, 2002) but observed genetic trends in carcass fat were very small, so this should have minimal impact.

Over recent years, there has not been any substantial change in the economic values of beef carcass traits (Roughsedge *et al.*, 2005a). For this reason, the genetic trend in the Beef Value sub-index using carcass trait economic values as derived by Amer *et al.* (1998a) was used to quantify the value of genetic progress in carcass traits. In contrast, estimates of the economic value of calving ease have increased dramatically. For this reason, economic

Table 4 *Dissemination parameters by sire breed type*

	Symbol	Hill sheep	Crossing sheep	Terminal sheep	Dual-purpose beef	Terminal beef
Breeding males sold per female in a performance-recorded flock or herd	b	0.3	0.4	0.3	0.34	0.34
Breeding male probability to breed again	λ	0.8	0.8	0.8	0.8	0.8
Maximum male breeding years	u	4	4	4	4	5
Commercial females mated per male	f	40	40	40	30	30
Offspring born per commercial female	b	1.1	1.7	1.7	0.92	0.92
Replacement females kept per offspring born		0.45	0.45	0	0.24	0

values derived by Roughsedge *et al*. (2005a) were applied to gestation length (−£1.00 per day) and calving ease (£2.47 per % unassisted calving) for dual-purpose beef breeds. Estimated breeding values for many of the maternal traits described by Roughsedge *et al*. (2005a) are only just becoming available to the industry, and so only traits relevant to calves were considered for dual-purpose beef breeds. The economic value for calving ease for terminal sire breeds was derived under the assumption that terminal sires in general are not mated to cows with a high risk of calving difficulty. It was assumed that a 1% decrease in assisted calvings when mating across cows of all ages in a typical herd would translate to a 0.25% decrease in a group of older cows of lower calving difficulty risk, where the overall incidence of assisted calvings would be much lower in the first place. To reflect this, the economic value for calving ease from Roughsedge *et al*. (2005a) was multiplied by 0.25 to give £0.62 per % unassisted calving.

Dissemination parameters

The analytical model described above requires inputs that characterise the timing and extent of dissemination of genetic progress from within the purebred breeding sector of the industry to the commercial sector. The key parameters as defined in the analytical model description and used in the calculations are in Table 4. These assumptions are averages across the industry segments and are consistent with standard industry practices and performance (e.g. Scottish Agricultural College, 2001; Pollott and Stone, 2006). Considerable variation across flocks within industry segments is likely for these values. The breeding herd/flock age distribution also affects the rate of dissemination of genes through replacement breeding females that are direct descendants of sires from the breeding programmes considered. The values assumed for breeding herd/flock age distributions are shown in Table 5.

Sensitivity analysis

Many of the parameters used in this model have a linear relationship with the predictions of the value of genetic improvement. For example, changing the numbers of breeding males sold per recorded female, the number of commercial females mated per male, and the number of offspring born per commercial female has a directly proportional impact on the predictions. No detailed sensitivity analysis was carried out to test the effects of changes to estimates of economic trends, as any proportional change in them also results in an equal proportional change in the estimated financial returns from genetic improvement. A sensitivity analysis was used to determine the effect of breeding male probability of survival to breed another year, the maximum breeding male age, the proportion of commercial females born that are kept as replacements and the age structure of commercial breeding females on the predictions. Sensitivity was tested for the dual-purpose beef breeding industry sector only by observing the proportional change in the estimates of financial benefits, when each parameter being tested was changed by a specified proportion.

Table 5 *Assumed age structures for commercial breeding females that are daughters* of the three breed types that produce commercial replacement females

Age (years)	Hill sheep	Crossing sheep	Dual-purpose beef
2	0.3	0.26	0.2
3	0.25	0.23	0.16
4	0.2	0.2	0.14
5	0.15	0.16	0.12
6	0.1	0.11	0.1
7	0	0.04	0.08
8	0	0	0.06
9	0	0	0.05
10	0	0	0.04
11	0	0	0.03
12	0	0	0.02

Accounting for costs of genetic improvement

The costs of genetic improvement are best characterised in terms of investments made for a single years genetic improvement. This is because rates of adoption of new breeding technologies developed from public or private research effort are quite difficult to quantify, and because many of the breeder-incurred costs to achieve genetic improvement remain relatively static over time. Table 6 summarises annual costs associated with the genetic improvement programmes for the sheep and beef industry corresponding to the year 2000. The costs considered include the annual expenditure on underpinning research into genetic evaluation by the MLC, the costs associated with a full-time geneticist position within the MLC whose activities are spread over sheep and beef cattle breeding, costs of a young bull proving scheme and the costs of CT scanning sheep. In addition, subscription costs to MLC Signet's performance-recording service include breeder assistance with weighing, ultrasonic measurement and visual scoring of carcass trait predictors in live animals. MLC Signet is the technical division of the MLC, which has been responsible for delivering breeding evaluations to the sheep and beef sector throughout the UK. It was not possible to break the costs down within breed type, because, for example the same genetic evaluation software has been used across breed types within species.

For each type of investment, a lag is assumed between the time of expenditure and the time the expenditure would have an impact on sale of breeding males. These lags are then used to discount forward the research investments into a present value corresponding to the year that improved breeding animals are first sold from the breeding programme and mated in commercial herds.

The net present value of the overall discounted benefits and discounted costs associated with genetic progress in performance-recorded flocks and herds were then calculated for a range of interest rates. In addition, an internal rate of return (IRR) was calculated, which gives the discount rate that results in a net present value of zero.

Table 7 summarises assumptions and calculations used to quantify the purchase costs paid for breeding males by commercial sheep and beef farmers to performance-recording breeders. Prices of breeding males are based on unpublished summaries prepared by MLC Signet's breeding specialists. It is expected that these prices largely reflect the costs faced by breeders because competitive forces among ram breeders will mean that average profitability on rams sold will be modest. These calculations are of interest because they reflect an economic transfer from commercial farmers to performance-recording breeders, but they were not considered in the calculations of net present values because performance-recording breeders and commercial farmers jointly make up the UK sheep and beef farming industries.

Results

Genetic trends in profitability

The derived genetic trends in profit per lamb born and profit per breeding ewe are in Table 8 for the three sheep breed types, hill, crossing and terminal. These were used to specify the elements of vectors **y** and **z** in the analytical model. The change of profit per breeding ewe was slightly higher than the change in profit per lamb born for the hill breed type. For crossing sires, the economic benefits per lamb born

Table 6 *Summary of calculations of the net present value of investment in sheep and beef genetic improvement by performance recording sheep and beef cattle breeders in the UK*

	Sheep	Beef	Total	Lag before animal sold	Discount factor†	Discounted total	% of total
Underpinning investment including R&D by MLC (£)	32 100	55 200	87 300	5	1.40	122 443	13.54
Young bull proving by MLC (£)	0	16 000	16 000	3	1.23	19 601	1.31
MLC geneticist (£)	10 000	10 000	20 000	3	1.23	24 501	1.64
Signet membership (£)‡	439 450	1 422 500	1 861 950	1	1.07	1 992 287	80.90
CT scanning (£)§	60 000	0	60 000	1	1.07	64 200	2.61
Net present value of investment in genetic change (£)						2 223 031	

†A discount rate of 7% was assumed for calculation of a discounting multiplier to translate the investment cost to the time breeding males are sold.
‡Signet membership costs were calculated assuming average charges of £8.50 per ewe in a recorded flock and £25.00 per cow in a recorded herd.
§Based on 600 ram lambs scanned per year at a cost of £100 per lamb scanned.
Abbreviations are: MLC = Meat and Livestock Commission; CT = computed tomography.

Table 7 *Summary of assumptions used to calculate the total annual costs to commercial farmers from purchasing breeding rams and bulls from performance recorded breeding programmes in the UK*

	Dual-purpose beef sires	Terminal beef sires	Hill sheep	Crossing sires	Terminal sheep sires	Total
Breeding females in recorded herds	43 500	13 400	25 000	4200	22 500	
Males sold per recorded breeding female	0.34	0.34	0.3	0.4	0.3	
Males sold	14 790	4556	7500	1680	6750	
Price to commercial farmer buying a breeding male (£ per animal)	3000	3000	300	300	300	
Total costs to commercial farmers for male purchases (£M)	44.37	13.67	2.25	1.50	2.03	62.82

Table 8 *Weighted average annual genetic trends in profit per ewe and profit per lamb from 2000 onwards for sheep breed types*

Trait	Hill breeds		Crossing breeds		Terminal breeds	
	Rec	Imp	Rec	Imp	Rec	Imp
Profit per lamb born (£)	0.04	0.04	0.09	0.07	0.24	0.22
Profit per breeding ewe (£)	0.07	0.06	0	0	0	0

Weightings are by numbers of recorded progeny (Rec) and alternatively by relative impact of the breed on the industry (Imp).

Table 9 *Sizes of relevant breeding and commercial populations and ewes mated and expected value of genetic progress in five sire breed types over a 20-year planning horizon from 10 years for genetic improvement with penetration of genetic merit restricted to the recorded population, or extended to all breeders supplying rams to the relevant sector of the commercial population*

	Hill sheep	Crossing sheep	Terminal sheep	Dual-purpose beef	Terminal beef
Recorded breeding females (000)	25	4.2†	22.5	43.5	13.4
Females mated by males from recorded flocks/herds (000)	886	198	1063	1311	404
Industry females mated by this ram/bull type (000)	3886	2200	7000	1311	404
Direct benefits from recorded population (£000)	5342	1026	11546	18192	4992
Benefits if progress disseminated to all breeders (£000)	23 291	11 387	76 061	18 192	4993

†Note that it was assumed that only 14% of crossing sheep types coming from the terminal sire breeds (Texel and Suffolk) have a high proportion of their daughters kept as replacement breeding females.

were approximately double those of hill sheep, reflecting the greater rate of genetic progress for live weight at scanning (Table 2). There was no trend in maternal traits that have a meaningful impact on the profitability of crossbred ewes out of crossing breed sires (Table 2). Terminal sire breeds showed six times the annual trend in profit per lamb born of hill breeds, and three times more than that of crossing breeds. Weighting average genetic trends by number of recorded progeny, *v.* by each breeds' contribution to commercial animals, had quite modest influences on the estimated rate of genetic trend in profitability. For all subsequent calculations, the lowest of the values obtained from the two weighting approaches for the sheep breeding programme genetic trends are used here.

Trends in profitability due to changes in traits expressed by calves at birth and slaughter were obtained by multiplying economic values for gestation length and calving ease by the appropriate trait trends and adding them to the trends in the beef value sub-index. The resulting trends were £0.42 and £0.47 per year per calf born for dual-purpose beef breeds and terminal sire beef breeds, respectively. Comparative values when weighting by the breed number of recorded progeny born per year were £0.40 and £0.51 per year, respectively. For beef, averages weighted by each breeds contribution to commercial animals were used in subsequent calculations.

Industry benefits

The parameterised analytical model described above gives the expected benefit over a 20-year planning horizon from a period of genetic progress for 10 years starting at year 1 of the planning horizon (ε). Thus, neither benefits of genetic change in the breeding programme prior to the onset of the planning horizon nor the benefits of genetic changes that occur in the breeding programme from year 11 onwards are counted. Table 9 summarises the breeding and commercial populations affected, and the sizes of benefits from the rates of genetic progress identified in this study. For sheep, benefits are computed either assuming that the recorded population genetic progress is only captured by commercial farmers purchasing rams directly from the breeders involved or, alternatively, assuming that the same rate of genetic progress is being achieved across all purebred breeders. In the latter situation, breeding flocks not participating in the breeding programmes for which we had genetic trend estimates (both performance-recording, and non-performance-recording flocks) are assumed to be either acting as multipliers of genetic progress achieved within the recorded breeding population or on average achieving the same rates of genetic progress in their own right.

Sensitivity analysis

A reduction in the breeding male probability of survival to breed another year from 0.8 to 0.7 resulted in a 15% reduction in the average working life of breeding dual-purpose bulls (i.e from 2.95 to 2.53 years) and a 13% reduction in the estimated industry benefits from genetic progress. Reducing the upper limit on male breeding age from 4 to 3 years reduced the average working life of bulls to 2.44 years (i.e. by 17%), resulting in a 14% reduction in the estimated industry benefits. A proportional increase in the number of replacement females kept per offspring born by 50% resulted in a 20% increase in predicted benefits. Changing the breeding female age structure so that cows in the commercial breeding herd were on average 4% older resulted in a 2% change in the estimated industry benefits.

Table 10 *Discounted costs and benefits and aggregate net present values (£000) associated with 1 year of genetic progress within the currently recorded sheep and beef populations of the UK*

	Discount rate			
	2%	5%	7%	10%
Benefits				
Hill sheep	1818	1209	937	655
Crossing sheep	279	198	160	120
Terminal sheep	19 461	14 123	11 614	8877
Total sheep	21 558	15 531	12 712	9651
Dual-purpose beef	5401	3731	2967	2155
Terminal beef	1354	961	778	580
Total beef	6755	4692	3744	2735
Total sheep and beef	28 314	20 222	16 456	12 386
Costs				
Sheep combined	555	577	592	614
Beef combined	1539	1594	1631	1688
Total sheep and beef	2095	2171	2223	2303
Net present values				
Sheep combined	21 003	14 954	12 120	9037
Beef combined	5216	3098	2113	1047
Sheep and beef	26 219	18 051	14 233	10 084

Annual net present values

Table 10 summarises present values of annual benefits *v.* annual investments for the range of discount rates considered. Net present value results are combined across breed types within species because of the overlap in research costs for the different species (Table 6). At low discount rates, the net present values of benefits were very high relative to the present values of investments. There was a very noticeable reduction in the present value of benefits as discount rate increased, reflecting the long time frames for dissemination of benefits from genetic improvement. The IRR on annual investments in performance recording and genetic improvement was 52% for sheep and 15% for cattle. The IRR on investment combined over sheep and cattle was 32%.

Discussion

The paper has demonstrated that historical rates of genetic progress have yielded, and will continue to yield, substantial financial benefits to the UK sheep and beef industries. These benefits are an order of magnitude higher than the ongoing investments required to achieve them, although they do take a long time to accumulate. Key factors influencing the realised benefits of genetic improvement in the sheep industry include the proportion of rams used by all purebred breeders that come from performance-recorded populations, the proportion of rams sold to commercial farms that are coming from the purebred populations involved in performance recording as well as associated multiplier flocks, and the genetic response within the recorded populations. These factors were less important for estimation of benefits to the beef industry, because of the high levels of performance recording in the beef industry.

The observed genetic trends are moderate to high, relative to theoretical maximums for terminal traits within the recorded terminal sire sheep populations. Simm *et al.* (2002) predicted changes in lean weight and changes in fat weight of 0.233 and 0.96 kg per annum in a selection population, approximately double the values observed in the breeding programmes modelled here. For the crossing breed programmes, responses in carcass traits are less than those for terminal sheep breeding programmes, but are significant. The crossing breed programmes are still in the process of finalising selection index weights and there are economically important maternal traits (e.g. ewe mature size, ewe longevity) that are not widely recorded and are more difficult to evaluate using performance recording and genetic evaluation systems. Using results from Roughsedge *et al.* (2005a), the best 5% of selected bulls should be superior by approximately £5.60 per calf born than the average of those available. Assuming that bulls used within the recording breeding population are on average sourced from the best 5% across the industry, ignoring genetic progress from the selection of females, and assuming a generation interval of 4 years, a reasonable annual rate of genetic progress would be £0.70 per calf born per year. This is comparable with the £0.42 and £0.47 per year, respectively, that have been achieved in both terminal and dual-purpose beef breeds.

Recent studies have shown that there are substantial opportunities for the UK sheep and beef industries to benefit from improvement in traits more directly affecting maternal performance such as litter size, calving interval, longevity and mature body weight of breeding females (Conington *et al.*, 2001; Roughsedge *et al.*, 2005a). Nevertheless, the inherent problems of selecting for sex-limited traits with low heritability and expressed quite late in life appear to have precluded quantifiable genetic improvements in maternal traits, at least until very recently. Instead, recent genetic progress appears to have come from improvement in terminal sire traits, such as growth rate, and to a lesser extent, carcass composition.

It is questionable whether genetic progress for growth and carcass traits in dual-purpose beef breeds is of significant net financial benefit, given that there is a strong likelihood of antagonisms between improvements in these traits and the maternal performance and profitability of breeding cows (Roughsedge *et al.*, 2005b). Failure of sheep hill and crossing sire breed types to match the genetic progress seen in terminal sheep breeds may be an explanation in part for the increasing retention of terminally sired females as breeding flock replacements. There is a risk though that replacement breeding ewes sired by terminal sire breed rams may under-perform if the improvements in carcass merit of their progeny are outweighed by having higher maintenance and health costs and/or fewer lambs reared for sale. The UK beef industry has also seen an increase in the numbers of replacement females bred from breeds originating from continental Europe, which tend to be superior to traditional British breeds for growth and carcass characteristics, but which are generally not superior for maternal characteristics (Roughsedge *et al.*, 2001).

Along with the complexity of the analytical model used in this study, there are a large number of assumptions required to parameterise it. The assumptions dealing with the economic benefits of specific trait changes have largely been drawn from the published literature. The estimates of genetic trends have been obtained from quite large recorded populations, and so any errors in them will be either because of error in the genetic and phenotypic parameters used in the BLUP genetic evaluation models or because of correlations of less than one between animal performance in recorded populations *v.* crossbred commercial populations (i.e. a genotype by environment interaction). Substantial errors in the genetic parameters are unlikely for the key traits in which economic progress has been achieved, because there have been many detailed studies to estimate the parameters using field data. While genotype by environment interactions probably exist, they tend to be modest in their impact (e.g. Lewis *et al.*, 1996).

The most uncertainty for model projections of benefits will be for sheep. For sheep, it is unclear what impact the co-operative breeding programmes have on the commercial sector of the industry. We have had to rely on assumptions that determine the penetration rate of these programmes into the commercial industry. The assumptions of 0.3 to 0.4 of males sold per breeding female per year have therefore been conservative to protect against a gross overestimate of benefits. These rates, as well as the number of commercial females mated per year, are also consistent with the relative proportions of purebred flocks, breeding rams and ewes mated as reported by Pollott and Stone (2006). It has also been impossible to determine the extent to which genetic progress achieved in breeding programmes for which genetic trends were available has been transferred to other breeder flocks through exchange of rams.

No account was taken of the benefits from the commercial use of the AI of semen from elite beef bulls to disseminate genetic progress widely across the commercial beef and dairy industries. However, AI of commercial cows does not affect the rate of genetic progress; rather, its successful application to facilitate widespread use of economically elite bulls provides a lift in genetic merit which is sustained but not compounded over time. Thus, there are likely to be benefits to both the UK sheep and beef industries that arise from the existing recording and genetic evaluation structures that result from better commercial use of genetics from the available populations. This study has focused exclusively on the benefits from the rate of genetic progress from year to year. The benefits of better use of genetics available at any one time are very difficult to estimate without knowledge of the sires that have been sold to commercial herds/flocks, as opposed to those that have been culled, and for this reason they have been ignored.

The combined purchase prices of breeding males paid by commercial farmers to sheep breeders represent a substantial transfer of revenue within the UK farming industry. Indeed, the annual cost of these breeding males is well in excess of the benefits of the genetic progress associated with them. However, it is not appropriate to subtract this cost of breeding males from the benefits of genetic improvement. For extensive industries relying heavily on natural mating, breeding males serve the critical purposes of heat detection and insemination, over and above the delivery of superior genetic merit. To achieve this successfully, they need to be selected critically from a group of animals to make sure that they are structurally and reproductively sound at a time just prior to first mating age. In a commercial cross-breeding situation as is widespread in the UK sheep and beef industries, purchased breeding males are necessary to maximise heterosis in the commercial herd. For these reasons, retention of surplus commercial males that might otherwise have been slaughtered is not recommended, and is not common practice on UK sheep and beef farms. Thus, the prices paid for breeding males would, to a large extent, need to be incurred anyway, irrespective of whether or not they were genetically superior. Premiums for performance-recorded males over non-performance-recorded males tend to be modest on average, and reflect the additional costs associated with performance recording, and the fact that only a select proportion of male progeny in a performance-recorded flock or herd is sold as breeding males.

No attempt has been made in this study to describe the long run beneficiaries of the calculated economic benefits. With competitive industries and markets, the distributions of benefits of genetic improvement can spread across different farmers depending on whether or not they are leaders, followers or laggards on the technology-adoption treadmill, and also to intermediate processing and retailing segments of the industries, and to consumers (Amer and Fox, 1992). Because a considerable majority of sheep meat and beef produced in the UK is consumed within the UK, we can assume that it is unlikely that the benefits we have computed have been captured by consumers outside the UK. Characterisation of the distribution of benefits from different types of genetic trait changes in the UK sheep and beef industries would be a valuable addition to, but was beyond the scope of, the current study. There may also be substantial additional benefits from the genetic progress we have characterised both to the meat processing industries and possibly to consumers, due to meat yield and eating quality benefits associated with trait changes not being fully reflected in the market payment systems used to define their economic values.

The comparison of recent genetic trends in beef breeds with those from an earlier time period indicates that at least for beef cattle, the rates of genetic progress in growth and carcass traits have been accelerating (Table 3). While the associated deterioration in calving ease appears to be less pronounced in the genetic trends over the more recent time period, there is still deterioration in both dual-purpose and terminal beef breed types.

Likely deterioration in calving ease and maternal trait performance due to breed substitutions and within-breed selection may become of increasing concern for European consumers of livestock products. It appears that current price signals, technology availability and technology adoption patterns are driving these genetic changes. A future challenge for the national government and industry bodies that provide the funding that underpins the genetic improvement structures supporting the UK beef and sheep industries will be to provide a means with which the dual interests of commercial farmers and consumers can be met. In reality, this is most likely to be via the 'supply side' of genetic improvement (Amer *et al*., 1998b) or alternatively via the strict regulation of farmer activities and selection decisions. Regulation of farmer activities might be enforced through legal obligations or by supply restrictions enforced by retailers and meat processing companies with strong product claims attached to their marketing brands.

This study has shown that a substantial proportion of UK sheep and beef breeders have responded effectively to a demand for lower cost, leaner meat by society and the resulting price signals. If society wants the industry to produce a different product under different circumstances, then improvements in traits such as meat quality, disease resistance and animal welfare can be delivered by UK sheep and beef breeders, provided the right signals are in place, and the breeding industry has the appropriate recording and genetic evaluation tools available. Relatively low penetration rates of performance recording in the sheep breeding industries suggest that substantial additional benefits could be achieved with higher adoption rates.

References

Amer PR and Fox GC 1992. Estimation of economic weights in genetic improvement using neoclassical production theory: an alternative to rescaling. Animal Production 54, 341–350.

Amer PR, Crump R and Simm G 1998a. A terminal sire selection index for UK beef cattle. Animal Science 67, 445–454.

Amer PR, Mpofu N and Bondoc O 1998b. Definition of breeding objectives for sustainable production systems. In Proceedings of the Sixth World Congress on Genetics Applied to Livestock Production, Armidale, NSW, Australia, 11–16 January, 1998, vol. 28, pp. 97–104.

Conington J, Bishop SC, Grundy B, Waterhouse AW and Simm G 2001. Multi-trait selection indexes for sustainable UK hill sheep production. Animal Science 73, 413–423.

Conington J, Bishop SC, Waterhouse AW and Simm G 2004. A bioeconomic approach to derive economic values for pasture-based sheep genetic improvement programs. Journal of Animal Science 82, 1290–1304.

James JW 1981. Index selection for simultaneous improvement of several characters. In Proceedings of the 14th International Congress on Genetics (ed. D Belyaer), pp. 221–228. MIR Moscow, USSR.

Jones HE, Amer PR, Lewis RM and Emmans GC 2004. Economic values for changes in carcass lean and fat weights at a fixed age for terminal sire breeds of sheep in the UK. Livestock Production Science 89, 1–17.

Knap PW 1998. Internationalisation of pig breeding companies. In Proceedings of the Sixth World Congress on Genetics Applied to Livestock Production, Armidale, NSW, Australia, 11–16 January, 1998, vol. 26, 143–146.

Lewis RM, Simm G, Dingwall WS and Murphy SV 1996. Selection for lean growth in terminal sire sheep to produce leaner crossbred progeny. Animal Science 63, 133–142.

Pollott GE and Stone DG 2006. The breeding structure of the British sheep industry 2003. DEFRA, London.

Preisinger R 1998. Internationalisation of breeding programmes – breeding egg-type chickens for a global market. In Proceedings of the Sixth World Congress on Genetics Applied to Livestock Production, Armidale, NSW, Australia, 11–16 January, 1998, vol. 26, pp. 135–142.

Roughsedge T, Thompson R, Villanueva B and Simm G 2001. Synthesis of direct and maternal genetic components of economically important traits from beef breed-cross evaluations. Journal of Animal Science 79, 2307–2319.

Roughsedge T, Amer PR, Thompson R and Simm G 2005a. Development of a maternal breeding goal and tools to select for this goal in UK beef production. Animal Science 81, 221–232.

Roughsedge T, Amer PR, Thompson R and Simm G 2005b. Genetic parameters for a maternal breeding goal in beef production. Journal of Animal Science 83, 2319–2329.

Scottish Agricultural College 2001. Farm management handbook 2001/2002. SAC, Edinburgh.

Simm G, Conington J and Bishop SC 1994. Opportunities for genetic improvement of sheep and cattle in the hills and uplands. In Livestock production and land use in hills and uplands (ed. TLJ Lawrence, DS Parker and P Rowlinson), pp. 51–66. BSAP occasional publication no. 18. BSAP, Edinburgh.

Simm G, Lewis RM, Grundy B and Dingwall WS 2002. Responses to selection for lean growth in sheep. Animal Science 74, 39–50.

Appendix. A simple example

A breeding programme of 100 breeding ewes generates sires sold to commercial sheep farms that have 2300, 1610 and 1127 progeny born from their first to third matings, respectively. Thus

$$o_k = \begin{bmatrix} 2300 \\ 1610 \\ 1127 \end{bmatrix}.$$

The probability of each commercial lamb surviving to become a breeding female in successive years after birth is

$$w'_k = \begin{bmatrix} 0 & 0 & 0.24 & 0.2 & 0.16 & 0.12 & 0.08 \end{bmatrix}.$$

With each breeding female producing P=1.1 lambs born (alive or dead) per year, direct and maternal expressions of a breeding programme's sire's genes per lamb born in the year after birth of the offspring (rows) in the first three generations (columns) are

$$d = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0.066 & 0 \\ 0 & 0.055 & 0 \\ 0 & 0.044 & 0.009 \\ 0 & 0.033 & 0.015 \\ 0 & 0.022 & 0.018 \end{bmatrix} \quad \text{and} \quad m = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.12 & 0 & 0 \\ 0.1 & 0 & 0 \\ 0.08 & 0.016 & 0 \\ 0.06 & 0.026 & 0 \\ 0.04 & 0.032 & 0.002 \end{bmatrix}.$$

Summing over generations to obtain genetic expressions by year gives

$$\Sigma d' = \begin{bmatrix} 0.5 & 0 & 0.066 & 0.055 & 0.053 & 0.048 & 0.04 \end{bmatrix}$$

and

$$\Sigma m' = \begin{bmatrix} 0 & 0 & 0.12 & 0.1 & 0.096 & 0.086 & 0.074 \end{bmatrix}.$$

Annual genetic progress in the breeding programme over 5 years is worth £0.2 per direct trait expression and £0.1 per year per maternal trait expression and if we are to consider benefits over a planning horizon of 7 years then

$$y' = \begin{bmatrix} 0.2 & 0.4 & 0.6 & 0.8 & 1 & 1 & 1 \end{bmatrix}$$

and

$$z' = \begin{bmatrix} 0.1 & 0.2 & 0.3 & 0.4 & 0.5 & 0.5 & 0.5 \end{bmatrix}.$$

If we ignore the lag between mating and birth of an offspring (i.e. $x = 0$), then the economic benefits of genetic progress by year in which genetically improved rams born from the breeding programme are mated for the first time (rows) and by year that the benefits are realised (columns) are

$$e = \begin{bmatrix} 230 & 0 & 58 & 48 & 46 & 42 & 35 \\ 0 & 621 & 0 & 156 & 130 & 125 & 113 \\ 0 & 0 & 1125 & 0 & 283 & 236 & 226 \\ 0 & 0 & 0 & 1628 & 0 & 410 & 342 \\ 0 & 0 & 0 & 0 & 2132 & 0 & 537 \\ 0 & 0 & 0 & 0 & 0 & 2406 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 2519 \end{bmatrix}.$$

Summing over years of first use of genetically improved rams gives cumulative benefits by year of expression of both direct and maternal genetic improvements

$$v' = \begin{bmatrix} 230 & 621 & 1183 & 1833 & 2592 & 3219 & 3772 \end{bmatrix}.$$

With a discount rate $r = 0.07$ and assuming that breeding rams sold from the breeding programme are first mated at 2 years of age, then

$$q' = \begin{bmatrix} 0.816 & 0.763 & 0.713 & 0.666 & 0.623 & 0.582 & 0.544 \end{bmatrix}$$

and the discounted sum of cumulative benefits from the 5 years of genetic progress in direct and maternal traits for the 100 ewe breeding flock over a 7-year planning horizon is £8266.