19. Mate Selection for the tactical implementation of breeding programs

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Learning objectives

On completion of this topic you should be able to:

- Understand that specifying matings to be made covers a very wide range of animal breeding issues – technical, economic and logistical issues
- We now have evolutionary algorithms that can find the best mating set, or something close to best

Key terms and concepts

Mate Selection, Evolutionary Algorithm.

Introduction to the topic

Breeding program design can be pre-determined and implemented through sets of rules, or it can emerge as a consequence of decisions made at the level of individual matings. This latter approach is the tactical approach, with decisions made tactically in the face of prevailing animals.

Tactical implementation of breeding programs provides a practical means to integrate technical, logistical and cost issues facing animal breeders. Moreover, tactical implementation benefits from opportunistically optimal use of prevailing animals and other resources, resulting in better outcomes.

In any breeding operation, there is an almost infinite range of actions that can be made, involving decisions on issues such as animal selection, semen collection and purchase, and mate allocations. Each set of actions is predicted to have a given utility to the breeder - based on factors such as genetic gains, risk, costs and constraints satisfied. The tactical approach described in this topic works by searching across these possible routes ahead, and finding one that is predicted to suit the breeder’s needs, either the very best solution, or something sufficiently close to it. This has become possible because of the development of efficient computing algorithms that mimic evolutionary processes to approach the best solution.

The animal breeder must juggle many issues when s/he makes decisions resulting in implementation of the breeding program, including concerns about breeding objectives, genetic gains, crossbreeding, inbreeding, logistical constraints, and various types of operational cost. The classic approach is for the practitioner to try and follow sets of rules, as outlined in Topic 15:
Such rules are derived from generalised theories and concepts - and these are usually not well integrated with each other. For example, theories and rules about selection, crossbreeding and inbreeding have classically been developed largely in isolation from each other, such that it is difficult to mix them in real applications, and we are likely to miss the best overall strategy.

Mate Selection is an approach that can be used both to integrate all the key issues facing animal breeders, and to implement the program tactically using a tactical decision system. A simple example involving selection, crossbreeding and running costs is given in Topic 18. Mate selection incorporates decisions on animal selection and mate allocation. Because the best animals to select depends on pattern of mate allocation, and vice versa, we can best make these decisions simultaneously as mate selection - we just decide what mating pairs and groups to make.

Moreover, there can be added advantage in making decisions tactically, rather than following a pre-set strategy. This is because a tactical approach will make use of knowledge of the full range of actual animals available for breeding at the time of decision making, as well as other factors such as availability of mating paddocks, current costs of specified semen, current quarantine restrictions on animal migration, current or projected market prices, etc. Tactical implementation of breeding programs gives the power to capitalise on prevailing opportunities - opportunities that would often be missed when adhering to a set of rules.

### 19.1 The Mate Selection Criterion

This is the criterion that measures the overall value of a mating set. It is often call the Mate Selection Index (MSI), but this should not be confused with the Selection Index – and so we will use the word ‘Criterion’ to avoid confusion. The Selection Index pulls different traits into a single measure. The MSI pulls different animal breeding issues into a single measure. See Table 15.1 for a list of some key animal breeding issues.

In some cases, the consequences of a particular mating might be simple and quantifiable. For example, if the predicted merit of progeny from a mating is, say, 310Kg yearling weight, or +$12 in breeding objective units, then either of these figures constitutes an MSI for that mating. This can be done because the value of a mating in such a scheme is independent from what other matings might be made. However, in most progressive programs this is not the case - the value of a mating depends on what other matings are actually going to be made. For example, the value of a mating using a ‘new blood’ imported sire to help reduce inbreeding depends on how many other matings will be made using sires from the same outside source.

This means that for most applications the MSI cannot be specified at the level of individual matings - we can only calculate an overall MSI that characterises the combined value of all matings in the mating set. Examples of such an MSI are given by Kinghorn (1998, 2011), Shepherd and Kinghorn (1998) and Kinghorn et al. (1999), and another example will be given later in this topic.

### 19.2 Implementation of mate selection

The mate selection approach to breeding is driven by specifying desired outcomes. An outline of the approach is shown in Figure 19.1. For each mating set tested, the component outcomes evaluated constitute the overall Mate selection criterion (MSI). Each component should be evaluated on the same scale, typically the scale of the breeding objective in units of, for example, dollars profit per breeding cow per year. The MSI can be set to an arbitrarily low and uncompetitive value for mating sets that break a constraint - for example mating sets that imply migration against a hard quarantine barrier, or greater use of liquid funds than a limit specified by the breeder or group.

An efficient algorithm for finding the best mating set is required. The computing challenge is to find the mating set that gives the best MSI, or something close to it. For this purpose, an evolutionary algorithm was developed (Kinghorn, 1998), based on Differential Evolution (Price and Storn, 1997).
19.3 An example Mate Selection Criterion

The following example MSI pays attention to genetic gain, long-term inbreeding, short-term inbreeding, crossbreeding effects, running costs and logistical constraints. This section is included for completeness. It adds little in concept to what is shown in Figure 19.1, and so this section can be skipped by those not wanting to know more about the nuts and bolts of an MSI. You will not be asked to reproduce this material in an exam, but understanding it will help you to master this area.

For any given mate selection set (list of matings to be made):

\[
MSI = x'G + \lambda \frac{x'Ax}{2} + \phi F + \chi C - \text{cost}
\]

... when no logistical constraint is broken, or ...

\[
MSI = \text{a very low value when a logistical constraint is broken. This low value is sufficiently low to ensure that the mating set is not the solution of the mate selection algorithm.}
\]

- \(x\) is a vector of genetic contributions to be made from each candidate, over both sexes. Each sex contributes half the genes to the next crop of progeny and so, for each sex of candidate, the elements of \(x\) are restricted to sum to \(\frac{1}{2}\). In practical application, using number of matings as elements of \(x\) is useful, in which case the overall sum is not 1, but twice (two sexes) the number of matings to be made. Restrictions on the maximum value of each element of \(x\) are made as described later. Vector \(x\) could also be extended to accommodate predicted future contributions from existing juveniles and adults (see section 17.2).

- \(G\) is a vector of selection index values for candidates based on multi-trait EBV's, typically in dollar units.

- \(x'G\) is the weighted mean EBV of selected parents - it is in fact an estimate of the mean genetic value of progeny arising from the mating set.

- \(\lambda\) is a weighting factor on mean coancestry for selected parents (see next item). \(\lambda\) is typically negative, to discourage low effective population sizes. Meuwissen (1997) calculates \(\lambda\) to give a constrained value of coancestry \(x'Ax/2\). However, different values of \(\lambda\) can be chosen,
effectively giving different index weights on genetic gain (1) and long-term inbreeding (λ), to
give a range of results for these two factors.

- A is the numerator relationship matrix for candidates.

- \( \frac{x'Ax}{2} \) is the weighted mean coancestry of selected parents. This reflects long-term
  inbreeding, reliability of predicted selection response, and risk of poor response achieved. Just as
  the numerator relationship between two animals is twice the inbreeding predicted in their progeny,
  this value relates to (but is not quite equal to) the rate of inbreeding, ΔF.

- φ is a weighting factor on predicted progeny mean inbreeding coefficient. A small negative
  value for φ is often sufficient to have a notable effect to reduce progeny inbreeding. This can also
  be true even when there are competing mate allocation issues in the MSI. Higher values of φ will
  affect which animals are selected, as well as mate allocation (Kinghorn et al., 1999).

- F is predicted progeny mean inbreeding coefficient for the mating set under consideration.

- χ is a weighting factor on predicted progeny mean crossbreeding value C. A sensible value for
  χ is 1 - this is the implied weight on the genetic gain component \( x'G \), and both these components
  have direct effects on progeny merit, making them of equal importance if merit of later descendants
  does not feature in the objective.

- C is predicted progeny crossbreeding value - the value predicted using information on breed
  genotype alone. This is typically predicted using a dominance model of heterosis, incorporating
  direct and maternal components of both additive and dominance effects. Use of χC aims just one
  generation ahead. A more involved approach is required in order to aim further ahead (Shepherd
  and Kinghorn, 1999), making investment matings (eg. to generate first cross females) as well as
  realisation matings (eg. terminal sire by first cross female). If χC is included in the MSI then EBVs
  in G should be given as deviations from breed genotype effects, to avoid double counting of these
  effects.

- Cost is the cost of the mating policy implied by χ. This can include costs of AI and MOET. It
  can be calculated to discourage solutions that, for example, nominate allocation of just a few
  females to a natural mating male, as well as giving both genetic and economic consideration to use
  of reproductive manipulation. Figure 19.2 gives a simple example for females. In one mode of
  operation, the price of reproductive techniques used to drive Figure 19.2 can be decreased until
  reproductive technology starts to feature in the best mating set, and this illustrates a break-even
  price for use of that technology. Cost can include other components such as seedstock purchase
  prices and transport costs, expressed in the same units as the dollar EBV’s in G (see Topic 18 for a
  simple example).

Other MSI components not in this example include penalties on variation in progeny trait
expression, attention to connection between flocks and optimising QTL expression in progeny.
Figure 19.2 An illustration of one way to formulate costs for female matings. Calculated costs are summed over all candidates, of both sexes, to contribute to the component cost in the MSI.

Logistical constraints are simply applied by examining each contending mating set and applying an MSI value of low value, or an overriding penalty, if any constraint is broken. A related strategy is to apply a moderate penalty - this means that mating sets that break a constraint but are otherwise of high merit can contribute to finding the best solution. However, the penalty must be applied in such a manner that the final solution contains no broken constraints. Here are some example constraints:

- Nominated maximum number of matings for each candidate. This might be, for example, 40 matings for males that cannot have semen taken from them, 1000 for males that can have semen taken, 1 for females that cannot enter a MOET program and 8 for females that can. The figure for dead males might be the number of semen doses available. Minimum numbers can also be set, where a minimum number of semen doses per animal must be purchased. Of course zero is an accepted value in such cases.

- Migration constraints include not permitting young rams to migrate from flock of birth, and restricting older natural mating rams to be used in just one flock alone. Quarantine barriers can also be set in a simple manner.

- Any factor in the MSI can be included as a constraint instead of an index component. For example, long-term inbreeding can be included as a constraint by using a simplified MSI, (MSI = $x^T G + \phi F + \chi C - cost$) and penalising any mating set for which $\frac{x^T Ax}{2} \sim \Delta F$ exceeds a predetermined value.

Calculation of optimal values for MSI index weights $\chi$, $\phi$ and $\lambda$ would be a complex undertaking. However, these can be manipulated to give a desired outcome. An example of this is shown in Figure 19.3, where several factors, including progeny trait distributions have been managed in a dynamic manner. In this case the frontier has not been drawn by varying $\lambda$, but setting the top-right of the frontier in Figure 19.3 as 0 degrees, with full emphasis on progeny index, and the bottom-left as 90 degrees, with full emphasis on lowered parental coancestry. Any position on the frontier can be targeted as shown in the appendix of Kinghorn(2011). The solution in Figure 19.3 has settled on the frontier at the 25 degree 'target degree' line (see also ‘Dynamic control of desired outcomes’, later in this topic).
Figure 19.3. Screen shot showing trait distribution management. Trait 2 has variation reduced, Trait 3 has a minimum boundary set, and Trait 5 targets bimodality (e.g. in marbling, for two market end-points). These outcomes are achieved, together with moderate pressure against progeny inbreeding, without deflecting significantly from the desired balance between progeny index and parental coancestry.
19.4 Finding good solutions

Optimisation across a wide range of technical, logistical and cost issues is a task that can in fact be achieved, thanks largely to the advent of stochastic optimisation algorithms, such as evolutionary algorithms and genetic algorithms (see, for example, Price and Storn, 1997, and Mayer et al. 2005). The days of struggling with strong-arm mathematical approaches to optimising more complex problems, such as dynamic programming, are now over. Stochastic algorithms ‘breed’ better solutions to the prevailing problem over a number of generations.

In the evolution of life, DNA of a given configuration can express its fitness through the performance of the organism that hosts it. It is not necessary to ‘calculate’ what is the best configuration of DNA – this can be evolved through expressions of fitness and a system of breeding. Evolutionary and genetic algorithms do the same thing. It is not necessary to ‘calculate’ what is the best configuration of input parameters – these can be evolved through expressions of fitness (value on an objective function) and a system of breeding (better solutions being selected as parents, to mix and pass on their attributes at random).

This means that if we can evaluate any set of input parameters on the prevailing objective function, then an appropriate evolutionary algorithm can carry out the rest of the optimisation task for us. The input parameters are typically representations of selections and mate allocations for the prevailing solution, and the objective function is a comprehensive evaluation of the outcome(s) predicted for the prevailing input parameters. Kinghorn (2011) describes this process in detail.

19.5 Application of the mate selection approach

The mate selection approach outlined here has been implemented in the software systems Total Genetic Resource Management (TGRM, commercially delivered by Xprime Pty Ltd), GenMate (within the Pig Improvement Company) and MateSel available free as part of Pedigree Viewer (http://www-personal.une.edu.au/~bkinghor/pedigree.htm). Information to implement these systems includes parameters that describe conditions and desires, and data on animals. You should get a feel for how they work in a practical session. This section gives a more formal description that should help.

Parameters that describe conditions and desires

These include:

- Number of matings to be made, across all breeding units in the analysis
- Whether costs are to be applied
- Information on costs
- Initial MSI weights

Plus, as required:

- Direct and maternal breed and heterosis effects
- Effects of quantitative trait loci, for which genetic markers are available
- Mating constraints
- Constraints to be applied to trait expression
- Any other constraints

Data on animals

If possible, pedigree data should be extensive, including all relatives of all animals that are candidates for breeding. This helps when calculating the numerator relationships among candidates.

Additional information should be provided for animals that are potential candidates for breeding:

- Sex of the animal. This is required in order to separate male and female candidates.
• EBV of the animal, or some other criterion of genetic merit. This is usually the multi-trait EBV calculated from a BLUP run followed by application of economic weights.

• Candidate status of the animal. This is the maximum number of matings that can be made by the animal, and reflects natural mating versus use of reproductive boosting (AI, MOET etc.). For sheep and beef, these values are typically higher for males (25 to 1000+) than for females (1 to 8+). Candidate status defines a limit, and does not mean that the animal will automatically be used for that number of matings.

Other information on each animal can be included as required, for example:
• Information on individual traits, in order to place restrictions on progeny expression of these traits, or simply to report expected outcomes in terms of these individual traits.

• Information on breed genotype of the animal, in order to accommodate crossbreeding effects.

• Information on the animal’s genetic markers for known genetic defects or quantitative trait loci.

Output and reporting
The mean value of key variables for the chosen mating set is reported, such as predicted genetic merit of progeny, long-term rate of inbreeding, progeny inbreeding, progeny heterosis and program costs.

The sires selected are listed together with their number of matings and distribution of these matings across flocks/herds.

The part of the report to be acted on is the mating list. This lists the male and female to be used for each mating, together with predicted merit, inbreeding etc. for progeny from each mating. This mating list constitutes decisions on all the breeding issues addressed in the mate selection run.

Dynamic control of desired outcomes
As the mate selection analysis is running it is possible to view key aspects of the currently best solution in a visual manner, as in Figure 19.3. This means showing predicted progeny trait merit, trait distributions, inbreeding, heterosis, costs and structural components, such as the pattern of use of sires over flocks, using real-time graphical output. The user can then change weighting factors and constraints during the analysis so that these outcomes change in desired directions. This approach gives great flexibility to learn about the potential outcomes and to optimally balance them.

Using this approach, we do not have to make theoretical calculations about what weighting factors to use for the different components of the MSI. We can discover what weightings bring us to the most satisfying solution. This makes sense when we consider that we cannot calculate what is the best direction to go in without first discovering how far we can go in each direction, given the prevailing scenario. This aspect should become clear in a practical session.

This approach is similar to the desired gains selection index approach, except that here the index (MSI) covers much more ground than selection alone. See Kinghorn et al. (2002) for a more detailed description.

Use over multiple stages
It is possible to carry out mate selection runs to make culling decisions well before joining time. In this way it is possible to undertake, for example, relatively heavy culling by castrating males, at a relatively early stage, while accommodating concerns about (lack of) relevance of early measures of merit, inbreeding, cost savings, etc.

A separate run can also be made well before mating for the purpose of identifying semen, embryos and seedstock to purchase. A later run for the main mating round will benefit from knowledge of purchases made and any change in the candidate status of other animals. A further run can be
made to make backup mating decisions in the light of knowledge of which females did not conceive.

Dispersal of breeding males to commercial units
A mate selection analysis can be run over both commercial and stud operations, such that it solves the problem of dispersal of bulls or rams to commercial units, simultaneously with selection of bulls or rams into the stud(s) (Figure 19.4). The competition between commercial units for bulls or rams can be handled in a manner that optimises overall profit, in harmony with bull or ram selection for the breeding operation, and all the components in the MSI.

As the value of prospective progeny is calculated specifically for the herds or flocks in which they will be born, the benefits will be highest where the commercial units have different breeding objectives, as in Figure 19.4. Moreover, where crossbreeding is practiced in some commercial units, the range of terminal and maternal attributes of candidate sires can be well accommodated via their EBVs and knowledge of their breed genotype and that of their prospective commercial mates. This also holds when the commercial destinations involve different end-uses (eg. fully terminal versus ‘daughters may be bred’).

This can be done without individual information on commercial cows or ewes, by considering each cow herd, or part thereof, as a single individual in the analysis with a large number of matings required - one ‘nymphomaniac cow’ for each commercial herd.

Figure 19.4 The fate of stud born bulls. Mate selection can be used to make decisions on dispersal of breeding males to commercial units, simultaneously with stud selection decisions.

19.6 Getting the most out of the tactical approach

This tactical approach to breeding is driven by specifying desired outcomes. Although mate selection analysis is a very powerful computing tool, the results that it gives are closely aligned to the ‘outcome instructions’ that it receives. This means that the breeder can have a high degree of control, not by specifying which animals should be selected, but by specifying desires in terms of direction of genetic change, maintenance of genetic diversity, limits in money spent, constraints to be satisfied etc. Don’t fiddle with the solution itself – just move the goal posts!

Using the tactical approach is like driving a good car in a competitive race. We have control of the steering wheel, accelerator and brakes, and we can drive in a manner that is fast, yet safe, economical and in the proper direction. We no longer need to have our head under the bonnet, monitoring every piston beat, and missing opportunities to overtake or avoid crashes. There is plenty of opportunity to do test laps of the circuit before committing to a decision - if it does
something we do not like, we need to adjust the way we steer it, rather than getting out and pushing it round the track. Here are some examples of how we can give mate selection room to manoeuvre:

- Pre-culling of animals should be restricted to ‘definite culls’. The mate selection approach will only use competitive animals, but benefits from a bigger pool of candidates (but adds costs in maintaining animals that will ultimately be culled).

- It is worth considering the numerical scoring of important visually classed traits. This will permit the use of information from relatives to make faster progress in these traits and monitor their genetic change. It also gives more opportunity to make corrective matings.

- Consider a wide range of outside sires. These can help increase gains, lower inbreeding levels, and provide connections to outside seedstock sources that will result in better gains in the longer term.

- Include all key costs. These can include costs of semen, transport, quarantine holding and even fencing for natural mating paddocks. Limits on finances available can also be set.

- Make flock size variable. By factoring in the cost of maintaining breeding females, flock size could be an outcome of the analysis. This can provide a way to give controlled reduction of flock size through periods of drought or financial hardship, with parallel accommodation of concerns about genetic gains, inbreeding, etc.

- Select sires for commercial units as well as breeding units. This is likely to work well in large enterprises in which the breeding objectives differ between commercial units. This means that the fate of stud males can be: use in the stud, use in any one of several production units, or culled.

- There is power to constrain trait outcomes. For example, it could be declared that all progeny should be expected to be genetically below a given fat thickness or diameter micron. This is most relevant to breeding operations in which the value of product is high.

- Drive outcomes using a production model. Mate selection could usefully be driven by a dynamic production model, with each mating set evaluated on profit from the optimal production and processing pathway(s) for prospective progeny.

Readings


Summary

In any breeding program there is a very large number of decisions and actions that can be made, and the way these actions and decisions are handled determines the design of the breeding program. The design of a breeding program can be pre-determined by the implementation of sets of rules, or it can tactically implemented with decisions made at the individual mating level. Tactical implementation of breeding programs gives the power to capitalise on prevailing opportunities - opportunities that would often be missed when adhering to a set of rules.

Mate Selection incorporates decisions on animal selection and mate allocation and is an approach that can be used both to integrate all the key issues facing animal breeders, and to implement the program tactically.
References
Kinghorn, B.P. 1998, 'Managing genetic change under operational and cost constraints', 36th National Congress of the South African Association of Animal Science, University of Stellenbosch 5-8 April, pp. 9-16.

Glossary of terms

<table>
<thead>
<tr>
<th>Evolutionary algorithm</th>
<th>A method that can be used to find a good (possibly best) mating set</th>
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<td>Inbreeding Coefficient</td>
<td>A measure of the amount of inbreeding defined as the probability that two alleles at any locus are 'identical by descent'</td>
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<tr>
<td>Mate selection</td>
<td>Simultaneous decision on selection and mate allocation</td>
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<tr>
<td>Mate Selection Criterion</td>
<td>A measure of value of a mating set</td>
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<tr>
<td>Stochastic algorithm</td>
<td>A model that incorporates a random component even when given an identical set of initial conditions</td>
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