Multiple Land Management Unit pastoral optimisation model

J M Rendel[1,3] (john.rendel@agresearch.co.nz)

A D Mackay[2] (alec.mackay@agresearch.co.nz)

P Smale[1] (paul.smale@agresearch.co.nz)

A Manderson[2] (MandersonA@landcareresearch.co.nz)

[1] AgResearch, Private Bag 50034, Mosgiel 9053, New Zealand

[2] AgResearch, Private Bag 11008, Palmerston North 4442, New Zealand

[3] Corresponding author

1 Abstract

A new generation, INtegrated grazing Farm Optimisation and Resource allocation Model (INFORM) for pastoral livestock farms is described and initial evaluation completed. It is an annual-steady-state model combining a financial budget, a feed budget and livestock reconciliation. The feed budget must balance within each individual land management unit (LMU), as must the farm livestock reconciliation. The model advances the use of Linear Programming in farm systems modelling and decision making by departing from the use of whole farm and average data, to the integration of independently obtained biological data from LMUs within a farm system. This allows the responses to inputs or constraints to be isolated to that unit on the farm, as part of the optimization routine. The user supplies pasture growth rates, minimum and maximum acceptable pasture covers for each LMU, animal performance, farm costs and market prices. The linear programming equations formed by INFORM can be divided into a single objective and a number of constraints. Additional constraints can be placed on individual LMUs. The optimization routine uses this information to identify the mix of production enterprises and management regimes that maximises profit for the business and also creates the capacity to interrogate the expected returns from specific on-farm investments targeted at specific LMUs on the whole farm business. The initial evaluation of INFORM was conducted using a live-case farm consisting of five distinct LMUs, each with a different pasture growth rates, running a mixed sheep and beef livestock operation in New Zealand. The model framework had sufficient flexibility to be able to integrate the independently entered biological data from each LMU and specified livestock performance to derive a feasible livestock policy. Little difference in the livestock policy or EBITDA was found when INFORM was run for the five individual LMUs, as a single area weighted LMU or when constrained to carry the number of cows and ewes currently farmed on the live-case farm. The ability of the model framework and optimisation routine to mimic the live-case farm system gives confidence the model provides plausible solutions. To this sensibility test against expert knowledge and the ability of the model to mimic reality, was added an initial sensitivity analysis, which allowed further testing of the robustness of the model.

Keywords: Farm systems design, pastoral farm, land management units, optimisation, linear programming.

2 Introduction

Like pastoral farms throughout the world, New Zealand sheep, beef and deer farms are rarely found on a single soil type-landscape-continuum. Farms are more often than not an assemblage of multiple landscapes that include a mix of topographies and range of different soil types, both of which influence pasture and crop production, and importantly responses to inputs and practices. The biophysical features of farms land resources often dictate the enterprise mix and the amount of infrastructure required in the pursuit of sustained profit.

The concept that a farm is made up of individual land management units (LMU) is not new (Mackay *et al.* 2001). LMUs are (near) contiguous areas of land that can be farmed or managed in a similar way due to underlying physical similarities. They represent a static snapshot of how the land is currently used, or an insight into how land could be used if all physical opportunities were realised. The separation of the farm into individual LMU's according to their productive characteristics and response to inputs and practices provides a basis for the differential management of the farms biophysical resources (http://beeflambnz.com/lep/). Gillingham *et al.* (1999) investigated a differential approach to nutrient management, found adjusting nutrient inputs to the individual requirements of each land unit resulted in net gross margin improvements of 7 to > 40%, compared with treating all landscape units that made up a farm the same. The disaggregation of a farm to LMUs in recognition of difference in current and potential production also assists in separating out some of the annual pasture growth rate variability that is invariably included with the influence of climate.

The emergence of geospatial systems and remote sensing technologies offers the land manager options for collecting discrete geospatial referenced farm performance data and vehicles for the delivery of differential management practices. Currently, however, there are few analytical farm systems models with the capacity to explore and optimise the contribution individual land units make to farm outcomes. Existing farm systems models are often constrained to exploring the influence a change in practice on one land unit has on the whole farm systems through an analytical approach that requires the user to select and impose the necessary farm systems changes. A critical component of any new analytical approach would be a flexible model framework that can integrate independently obtained biological data from individual land management units, so responses to inputs or constraints can be isolated to that part of the farm. Further, the model framework would need to contain an optimization routine to link this biophysical variability into a combined financial objective function to search the solution space for alternative farm system configurations. It is possible to represent or closely approximate biological and dynamic relationships described by skilled practitioners using linear programming (Morrison *et al.* 1986). To date its application and use in farm systems decision making is very limited, in part because of the considerable experience required to develop models that adequately describe the relationships that exist within an agro-ecosystem and adequately analyse the outputs (Nuthall 2011a; Pannell 1997).

One of the advantages of using a linear programming approach is it provides an optimum solution as a reference point, from which input can then be altered, the system re-optimised, and the solutions compared. This was part of the underlying philosophy in the development of MIDAS (Model of an Integrated Dryland Agricultural System), a whole-farm model jointly describing biological, managerial, financial and technical aspects of dryland farming in the Merredin region of Western Australia (Kingwell 1987). Kingwell (2007) pointed out later that a linear programming approach creates the “opportunity to capture the elusive enterprise interactions often missed or poorly captured by gross margin analysis.” In a recent review of the use of Linear Programming in farm systems analysis Robertson *et al.* (2012) found that, spatial heterogeneity was a feature of only two of the industrialised agricultural applications. They noted that MIDAS allowed up to eight land management units (or soil types) to be specified. In most cases the use of Linear Programming has been limited to optimisation the farm as a single unit to consider a single change (Doole 2010; Doole & Romera 2013; Miller 1982; Ridler *et al.* 2001; Ridler *et al.* 1988). For example (Miller 1982) developed a Linear Programming for a dairy farm system to investigate the link between per cow production nitrogen fertiliser inputs and wilted silage. Ridler *et al.* (1988) used Linear Programming to quantify the value and feasibility of including Prairie grass into the farm system (dairy, dairy with bull beef and bull beef only). McCall *et al.* (1999) developed a Linear Programme to determine optimal feeding regimes in dairy grazing systems. This was further developed by Doole (2010) to investigate nitrate pollution from New Zealand dairy farms, while (Doole & Romera 2013) applied the same approach to the modelling of dairy grazing systems.

A feature missing from all these Linear Programming based pastoral farm systems models is the flexibility in the model frameworks to integrate the contribution individual LMUs that differ in their ability to support livestock production and response to inputs and practices. Further these models lack flexibility to integrate the contribution of independently obtained biological data from individual land management units so the responses to inputs or constraints can be isolated to that unit on the farm as part of the optimization routine. In this paper a new-generation INtegrated grazing Farm Optimisation and Resource allocation Model (INFORM) offering a far reaching alternative to more fully explore the dynamics of biophysical and financial performance of the farm is described and the findings from an initial sensibility evaluation on a sheep and farm system live-case study presented and discussed.

3 Model framework

Conceptually INFORM (Integrated Farm Resource allocation Model) is not complex (Figure 1). In constructing the model the farm is split into LMU's along with the pasture performance data for each unit. The LMU's are divided into those that can be used to produce pasture and winter crop or those that can only produce pasture. The area of crop and its location is decided by INFORM. The pasture can either contribute to the existing feed pool or added to the supplementary feed pool, if it is feasible to make supplementary feed on that LMU. The supplementary feed pool can be added to the feed pool when required.

The feed pool supports livestock (sheep, beef cattle, deer, and dairy grazers). Livestock can move between LMUs and can also be sold (e.g. as store at weaning, prime across the year or as culls). Livestock sales and supplementary feed sales are sources of income for the farm system and the costs are those associated with running the livestock and making and feeding supplementary feed.

Importantly the costs associated with land (e.g., fertiliser, repairs and maintenance, weed and pest, etc.) or those associated with running the enterprise (e.g., communication, accountancy, etc.) are not included in the costs of running an animal (e.g., animal health, labour, etc.), rather they are attributed to each LMU (as the land costs) or to an overall cost to run the enterprise. The measure of profit is Earnings Before Interest, Tax, Depreciation and Amortisation (EBITDA) (FFSC, 2011). INFORM solution space also includes the number of animals (type, age class, performance level) on each of the LMUs, animal sale dates (and numbers) along with movements between LMUs. It also identifies the amount of supplementary feed made and when, on which LMU(s) it is made and fed out, along with amount sold.

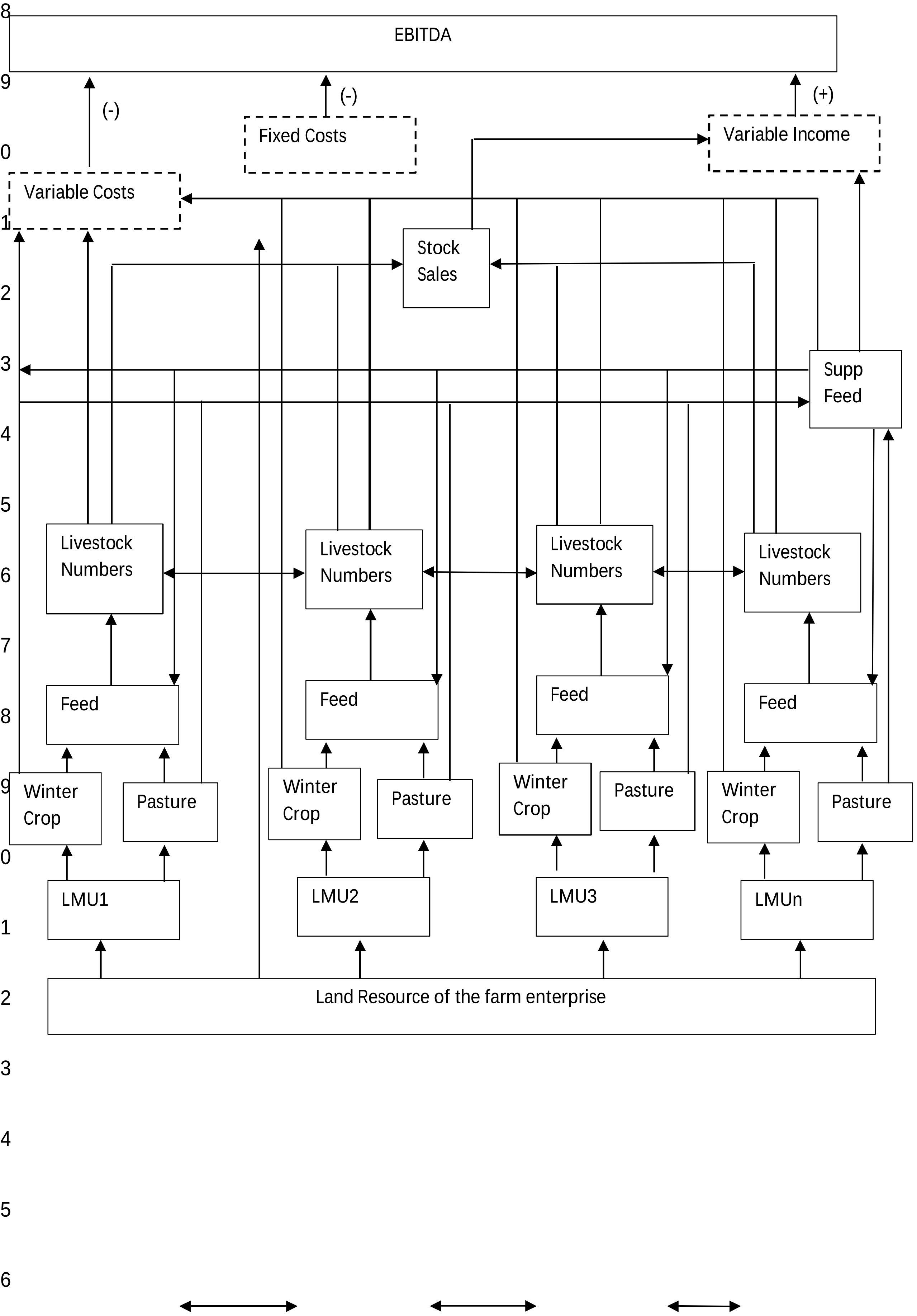
EBITDA
(-)
(-)
(+)
Fixed Costs
Variable Income
Variable Costs
Stock Sales
Supp Feed
Livestock Numbers
Livestock Numbers
Livestock Numbers
Livestock Numbers
Feed
Feed
Feed
Feed
Winter Crop
Pasture
Winter Crop
Pasture
Winter Crop
Pasture
Winter Crop
Pasture
LMU1
LMU2
LMU3
LMUn
Land Resource of the farm enterprise

Figure 1 Conceptualisation diagram of INFORM

The INFORM is a combination of an annual financial budget (the objective function, which is maximised), feed budget and livestock reconciliation, each of which were divided into 26 fortnightly periods. The feed budget within each LMU must balance, with the pasture covers at the end of the year equalling those at the start of the year. The livestock reconciliation must also balance. The sheep system within INFORM is breeding and finishing, with both meat and wool produced. The cattle system within INFORM is a beef cow system that can sell weaners store at weaning, or finishes them. A dairy heifer grazing component is also included. The deer system is a venison production system, with velvet being a by-product.

The model allows for the definition of a range of constraints applied to livestock operations to occur in specific LMUs. For example, logical restrictions can be applied to LMUs including periods when cattle are not allowed on a LMU and supplementary feed cannot be made on a LMU. Deer are restricted to deer LMUs with the required infrastructure. Sheep and cattle can be allocated to any LMU, accepting other constraints or designed periods of restriction. Further, INFORM can select the optimal size of LMUs for an investment to change the pattern of forage supply. For example this feature includes the ability to investigate the addition of new pasture species (or cultivars) into the farm system.

Linear programming (Nuthall 2011a; Nuthall 2011b; Pannell 1997) was chosen as the optimisation methodology as it allows an objective to be maximised (e.g. measure of profit) within a number of constraints that define the farm system, including the physical limits on area in pasture use, upper and lower pasture covers, livestock numbers and sales. Further, it creates the basis for the use of both stochastic and non-linear optimisation routines. The formulation is an allocation model (Baker 2011; Taha 1982) where you want the best allocation of the finite pasture, crops and supplementary feed resources available on each LMU to specific economic livestock activities. INFORM is an annual-steady-state model of a pastoral farming system designed to assist with strategic-decision-making. The linear programming equations formed by INFORM can be divided into a single objective and a number of constraints. This structure will allow the model to be extended from a single year steady state model to a multi-year model. Then farm systems which include year to year variation in prices and pasture production in response to normal climatic variation can be analysed and designed.

3.1 Objective

The objective (Z) is the financial budget that is being maximised subject to meeting all the constraints. It contains the costs and income for the farm system.

$$\begin{aligned} Z = Maximise(&Animal\ Income - Animal\ Costs - Animal\ Transfer\ Costs \\ &+ Supplementary\ Feed\ Income - Supplementary\ Feed\ Costs \\ &- Crop\ Costs - Land\ Costs - Enterprise\ Costs) \end{aligned} \qquad (1)$$

3.1.1.1 Animal income

There are a number of sources of animal income – store (non-prime) animals sold at weaning, prime animals sold at and post weaning, cull ewes, cows and hinds, as well as grazing rising 1 year (R1yr) and rising 2 year (R2yr) dairy replacements for dairy farmers. These are described in equation (2). Weaner lambs, beef calves and deer are split into sex groups at weaning. Each of these is split into quintiles, the average weight of which is calculated from the weaning weight and coefficient of variation of each age-sex class.

$$
\begin{aligned}
AnimalIncome = {} & \sum_{k=1}^{5}\sum_{s=1}^{2}\left(PriceStoreLambs_{k,s} \times \sum_{i=1}^{LMU} SellStoreLambs_{i,j,k,s}\right) \\
& + \sum_{j=1}^{26}\sum_{k=1}^{5}\sum_{n=1}^{2}\sum_{s=1}^{2}\left(PricePrimeLambs_{j,k,s,n} \times \sum_{i=1}^{LMU} SellPrimeLambs_{i,j,k,s,n}\right) \\
& + \sum_{k=1}^{5}\sum_{s=1}^{3}\left(PriceStoreBCalves_{k,s} \times \sum_{i=1}^{LMU} SellStoreBCalves_{i,j,k,s}\right) \\
& + \sum_{j=1}^{26}\sum_{k=1}^{5}\sum_{n=1}^{3}\sum_{s=1}^{3}\left(PricePrimeCattle_{j,k,s,n} \times \sum_{i=1}^{LMU} SellPrimeCattle_{i,j,k,s,n}\right) \\
& + \sum_{k=1}^{5}\sum_{s=1}^{2}\left(PriceStoreDCalves_{k,s} \times \sum_{i=d_1}^{LMU} SellStoreDCalves_{i,j,k,s}\right) \\
& + \sum_{j=1}^{26}\sum_{k=1}^{5}\sum_{n=1}^{2}\sum_{s=1}^{2}\left(PricePrimeDeer_{j,k,s,n} \times \sum_{i=d_1}^{LMU} SellPrimeDeer_{i,j,k,s,n}\right) \\
& + \sum_{j=ce_1,ce_2}\left(PriceCullEwe_{j} \times \sum_{i=1}^{LMU} SellCullEwe_{i,j}\right) \\
& + \sum_{j=cc_1,cc_2}\left(PriceCullCow_{j} \times \sum_{i=1}^{LMU} SellCullCow_{i,j}\right) \\
& + \sum_{j=cd_1,cd_2}\left(PriceCullHind_{j} \times \sum_{i=d_1}^{LMU} SellCullHind_{i,j}\right) \\
& + \sum_{j=1}^{26}\sum_{n=1}^{2}\left(Price\ DairyGrazer_{n} \times \sum_{i=1}^{LMU} DairyGrazer_{i,j,n}\right)
\end{aligned}
\tag{2}
$$

Where

$PriceStoreLambs_{j,k,s}$ is the net price (of cartage, yardage and commission) of a lamb sold store in the period of weaning ($j = w_l$), weight band k ($k = 1, \ldots, 5$) and sex s (ewes, wethers);

$SellStoreLambs_{i,j,k,s}$ is the number of store lambs sold from LMU i, period j, weight band k ($k = 1, \ldots, 5$) and sex s (ewes, wethers);

$PricePrimeLambs_{j,k,s,n}$ is the net price of lambs sold prime in period j, weight band k, of sex s and age n (up to 1 year old, over 1 year of age);

$SellPrimeLambs_{i,j,k,s,n}$ is the number of lambs from LMU i sold prime in period j, weight band k, of sex s and age n ;

$PriceStoreBCalves_{j,k,s}$ is the net price of weaner beef cattle sold store in the period of weaning ($j = w_c$), weight band k and sex s (heifers, bulls, steers);

$SellStoreBCalves_{i,j,k,s}$ is the number of store cattle beasts sold from LMU i, period j, weight band k and sex s;

$PricePrimeCattle_{j,k,s,n}$ is the net price of cattle sold prime in period j, weight band k, of sex s (heifer, steer, bull) and age n (up to 1 year old, 1 to 2 year old, over 2 years of age);

$SellPrimeCattle_{i,j,k,s,n}$ is the number of cattle from LMU i sold prime in period j, weight band k, of sex s and age n ;

$PriceStoreDCalves_{j,k,s}$ is the net price of weaner deer sold store in the period of weaning ($j = w_d$), weight band k and sex s (females, males);

$SellStoreDCalves_{i,j,k,s}$ is the number of store deer sold from LMU i, period j, weight band k and sex s;

$PricePrimeDeer_{j,k,s,n}$ is the net price of deer sold prime in period j, weight band k, of sex s and age n (up to 1 year old, over 1 year of age);

$SellPrimeDeer_{i,j,k,s,n}$ is the number of deer from LMU i sold prime in period j, weight band k, of sex s and age n ;

$PriceCullEwe_j$ is the net price of cull ewes sold in period j;

$SellCullEwe_{i,j}$ is the number of cull ewes sold from LMU i in period j;

$PriceCullCow_j$ is the net price of cull cows sold in period *j*;

$SellCullCow_{i,j}$ is the number of cull cows sold from LMU i in period j;

$PriceCullHind_j$ is the net price of cull Hinds sold in period *j*;

$SellCullHind_{i,j}$ is the number of cull hinds sold from LMU i in period j;

$Price\ DairyGrazer_n$ is the net price received per fortnight for a dairy grazers of age *n* (up to 1 year old, over 1 year of age);

$DairyGrazer_{i,j,n}$ is the number of dairy grazers of age *n* in period *j* and on LMU *i*.

Store prices are an input ($/kg live-weight) for all livestock species as are cull prices ($/kg carcass weight). The carcass weight for cull animals is estimated using the dress out percentage (DO%) and live-weight, both of which are inputs.

The carcass weight of prime animals is also calculated from the live-weight at sale day and DO%. For prime deer there is no grading based on fatdepth. The meat schedule has weight classes and sex classes. In both sheep and beef the meat schedule includes grading based on the fat depth over the 12th rib, 11cm from the carcass midline (GR fat depth). The GR in cattle is estimated from the carcass weight, sex and breed of the animal, with the equations developed using output from BeefSpecs (http://beefspecs.agriculture.nsw.gov.au/) which produced rump (P8) fat depth. These were then converted to GR fat depth using equations of Hopkins *et al.* (1993). The GR for sheep carcasses was derived from data from years 1982 to 1983 of the Wiremu trial (Waldron *et al.* 1992) and are based on carcass weight and sex (ewe and wether). The equations are summarised in Appendix 9.1.

3.1.1.2 Animal costs

The costs associated with animals can be represented as:

$$
\begin{aligned}
AnimalCosts = {} & EweCost \times \sum_{i=1}^{LMU}\sum_{j=1}^{26} Ewes_{i,j} \\
& + ReplEweCost \times \sum_{i=1}^{LMU}\sum_{j=1}^{26}\sum_{n=1}^{2} ReplEwes_{i,j,n} \\
& + FinLambCost \times \sum_{i=1}^{LMU}\sum_{j=1}^{26}\sum_{k=1}^{5}\sum_{s=1}^{2}\sum_{n=1}^{2} FinLambs_{i,j,k,s,n} \\
& + CowCost \times \sum_{i=1}^{LMU}\sum_{j=1}^{26} Cows_{i,j} \\
& + ReplCowCost \times \sum_{i=1}^{LMU}\sum_{j=1}^{26}\sum_{n=1}^{2} ReplCows_{i,j,n} \\
& + FinCattleCost \times \sum_{i=1}^{LMU}\sum_{j=1}^{26}\sum_{k=1}^{5}\sum_{s=1}^{3}\sum_{n=1}^{3} FinCattle_{i,j,k,s,n} \\
& + HindCost \times \sum_{i=d_1}^{LMU}\sum_{j=1}^{26} Hinds_{i,j} \\
& + ReplHindCost \times \sum_{i=d_1}^{LMU}\sum_{j=1}^{26}\sum_{n=1}^{2} ReplHind_{i,j,n} \\
& + FinDeerCost \times \sum_{i=d_1}^{LMU}\sum_{j=1}^{26}\sum_{k=1}^{5}\sum_{n=1}^{2}\sum_{n=1}^{2} FinDeer_{i,j,k,s,n}
\end{aligned}
\tag{3}
$$

Where:

$EweCost$ is the cost of running a ewe for a fortnight (animal heath, labour, etc). Wool income is subtracted from the costs,

$Ewes_{i,j}$ is the number of ewes on LMU *i* in period *j*,

$ReplEweCost$ is the cost of running a replacement ewe for a fortnight,

$ReplEwes_{i,j,n}$ is the number of replacement ewes of age *n* (up to 1 year old, over 1 year old) on LMU *i* in period *j*,

$FinLambCost$ is the cost of running a finishing lamb for a fortnight,

$FinLambs_{i,j,k,s,n}$ is the number of finishing lambs of age *n* (up to 1 year old, over 1 year old), sex *s* (ewe, wether), weight band *k*, on LMU *i* in period *j*,

$CowCost$ is the cost of running a cow for a fortnight,

$Cows_{i,j}$ is the number of cows on LMU *i* in period *j*,

$ReplCowCost$ is the cost of running a replacement cow for a fortnight,

$ReplCows_{i,j,n}$ is the number of replacement cows of age *n* (up to 1 year old, over 1 year old) on LMU *i* in period *j*,

$FinCattleCost$ is the cost of running a finishing cattle beast for a fortnight,

$FinCattle_{i,j,k,s,n}$ is the number of finishing cattle beasts of age *n* (up to 1 year old, over 1 year old), sex *s* (heifer, steer, bull), weight band *k*, on LMU *i* in period *j*,

$HindCost$ is the cost of running a hind for a fortnight (velvet income from spikers and stags is subtracted from the costs),

$Hinds_{i,j}$ is the number of hinds on LMU *i* in period *j*,

$ReplHindCost$ is the cost of running a replacement hind for a fortnight,

$ReplHind_{i,j,n}$ is the number of replacement hinds of age *n* (up to 1 year old, over 1 year old) on LMU *i* in period *j*,

$FinDeerCost$ is the cost of running a finishing deer for a fortnight,

$FinDeer_{i,j,k,s,n}$ is the number of finishing deer of age *n* (up to 1 year old, over 1 year old), sex *s* (female, male), weight band *k*, on LMU *i* in period *j*.

3.1.1.3 Animal transfer costs

Sheep, beef and dairy grazers can move between any two LMU on a fortnightly basis. Deer can only move between the deer LMUs, defined by the fencing infrastructure. There is a cost of moving animals between LMUs[1].

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[1] Currently the same cost applies to the movement of animals between LMUs. A future upgrade should allow for the cost to vary. This would account for the situation where transportation is required to shift animals between LMUs, or where there is a large labour costs and or distances for animals to walk between LMUs.

$$\begin{aligned}
&AnimalTransCost \\
&\quad = TransCostEwe \times \sum_{\substack{i=1\\ i\neq i'}}^{LMU} \sum_{i'=1}^{LMU} \sum_{j=1}^{26} Ewes_{i,i',j} + TransCostLamb \\
&\quad \times \sum_{\substack{i=1\\ i\neq i'}}^{LMU} \sum_{i'=1}^{LMU} \sum_{j=1}^{26} \sum_{n=1}^{2} \left(\sum_{k=1}^{5} \sum_{s=1}^{2} FinLambs_{i,i',j,k,\mathrm{n},s} + ReplEwes_{i,i',j,n} \right) \\
&\quad + TransCostCow \times \sum_{\substack{i=1\\ i\neq i'}}^{LMU} \sum_{i'=1}^{LMU} \sum_{j=1}^{26} Cows_{i,i',j} \\
&\quad + \sum_{n=1}^{3} \Bigg(TransCostCattle_{n} \\
&\quad \times \sum_{\substack{i=1\\ i\neq i'}}^{LMU} \sum_{i'=1}^{LMU} \sum_{j=1}^{26} \left(\sum_{k=1}^{5} \sum_{s=1}^{3} FinCattle_{i,i',j,k,n,s} + ReplCows_{i,i',j,n} \right) \Bigg) \\
&\quad + TransCostHinds \times \sum_{\substack{i=d_1\\ i\neq i'}}^{LMU} \sum_{i'=d_1}^{LMU} \sum_{j=1}^{26} Hinds_{i,i',j} \\
&\quad + TransCostDeer \\
&\quad \times \sum_{\substack{i=d_1\\ i\neq i'}}^{LMU} \sum_{i'=d_1}^{LMU} \sum_{j=1}^{26} \sum_{n=1}^{2} \left(\sum_{k=1}^{5} \sum_{s=1}^{2} FinDeer_{i,i',j,k,\mathrm{n},s} + ReplHinds_{i,i',j,n} \right) \\
&\quad + \sum_{n=1}^{2} \left(TransCostDGrazer_{n} \times \sum_{\substack{i=1\\ i\neq i'}}^{LMU} \sum_{i'=1}^{LMU} \sum_{j=1}^{26} DairyGrazer_{i,i',j,n} \right)
\end{aligned} \tag{4}$$

Where

$TransCostEwe$ is the cost of moving a ewe from one LMU to another

$Ewes_{i,i',j}$ Number of ewes moved at the end of period *j* from LMU i to i' where $i \neq i'$

$TransCostLamb$ is the cost of moving a ewe from one LMU to another

$FinLambs_{i,i',j,k,\mathrm{n},s}$ Number of finishing lambs of sex *s* age *n* weight band *k* moved at the end of period *j* from LMU i to i', where $i \neq i'$

$ReplEwes_{i,i',j,n}$ Number of replacement ewes of age *n* moved at the end of period *j* from LMU i to $i'$where $i \neq i'$

$TransCostCow$ is the cost of moving a cow from one LMU to another

$Cows_{i,i',j}$ Number of cows moved at the end of period *j* from LMU i to $i'$where $i \neq i'$

$TransCostCattle_n$ is the cost of moving a finishing cattle beast of age *n* from one LMU to another

$FinCattle_{i,i',j,k,n,s}$ Number of finishing cattle of sex *s* age *n* weight band *k* moved at the end of period *j* from LMU i to i', where $i \neq i'$

$ReplCows_{i,i',j,n}$ Number of replacement cows of age *n* moved at the end of period *j* from LMU i to $i'$where $i \neq i'$

$TransCostHinds$ is the cost of moving a hind from one LMU to another

$Hinds_{i,i',j}$ Number of hinds moved at the end of period *j* from LMU i to $i'$where $i \neq i'$

$TransCostDeer$ is the cost of moving a finishing deer from one LMU to another

$FinDeer_{i,i',j,k,n,s}$ Number of finishing deer of sex *s* age *n* weight band *k* moved at the end of period *j* from LMU i to i', where $i \neq i'$

$ReplHinds_{i,i',j,n}$ Number of replacement hinds of age *n* moved at the end of period *j* from LMU i to $i'$where $i \neq i'$

$TransCostDGrazer_n$ is the cost of moving a dairy grazer of age *n* from one LMU to another

$DairyGrazer_{i,i',j,n}$ Number of dairy grazers of age *n* moved at the end of period *j* from LMU i to i', where $i \neq i'$

3.1.1.4 Supplementary feed income

This is the income received from selling supplementary feed. It can be summarised as:

$$SuppFeedIncome = SuppFeedPrice \times \sum_{i=1}^{LMU} SuppFeedSold_i \quad (5)$$

Where

$SuppFeedPrice$ is the price ($) received for supplementary feed sold per kg DM (an input into the model)

$SuppFeedSold_i$ is the amount of supplementary feed sold from LMU *i*

3.1.1.5 Supplementary feed costs

These are the costs associated with making and feeding out supplementary feed, as well as transferring supplementary feed between LMUs (an option to purchase supplementary feed will be added in a future version).

$$\begin{aligned} SuppFeedCost = {} & SuppFeedMakeCost \times \sum_{i=1}^{LMU} \sum_{j=1}^{26} SuppFeedMade_{ij} \\ & + SuppFeedCost \times \sum_{i=1}^{LMU} \sum_{j=1}^{26} SuppFed_{i,j} \\ & + SuppFeedTransCost \times \sum_{\substack{i=1 \\ i \neq i'}}^{LMU} \sum_{i'=1}^{LMU} SuppFeedTrans_{i,i'} \end{aligned} \quad (6)$$

Where

$SuppFeedMakeCost$ is the cost ($/kg DM) to make supplementary feed

$SuppFeedMade_{ij}$ is the amount of supplementary feed (kg DM) made in LMU *i* and period *j*;

$SuppFeedCost$ is the cost ($/kg DM) of feeding out supplementary feed;

$SuppFed_{i,j}$ is the amount (kg DM) of supplementary feed fed out in LMU *i* and period *j*;

$SuppFeedTransCost$ is the cost of transferring supplementary feed between LMUs[2]

$SuppFeedTrans_{i,i'}$ is the amount of supplementary feed transferred between LMU i and i' where $i \neq i'$

3.1.1.6 Crop costs

The costs associated with planting a crop can vary with LMU. These costs can be represented as:

$$CropCosts = \sum_{i=1}^{LMU} CropCost_i \times Crop_i \qquad (7)$$

Where

$CropCost_i$ is the cost ($/ha) of establishing the crop and replanting the area back into grass in LMU *i*,

$Crop_i$ is the area (ha) of crop planted in LMU *i*.

3.1.1.7 Land costs

The costs associated with maintaining the land which includes fertiliser, weed and pest and fence repairs and maintenance can vary significantly between LMUs. These costs can be represented as:

---

[2] Currently this is a single cost regardless of which LMUs the transfer occurs between. In the future this will be altered to reflect better handle specific actions on a LMU that might include lease blocks, run-offs, or large farms.

$$LandCosts = \sum_{i=1}^{LMU} \sum_{j=1}^{26} LandCost_{ij} \times Land_{ij} \tag{8}$$

Where

$LandCost_{ij}$ is the cost (\$/ha) of maintaining LMU *i* for period *j*,

$Land_{ij}$ is the area (ha) of LMU *i* in period *j.*

3.1.1.8 Enterprise costs

These costs are ones primarily associated with running the business and not linked directly to a specific livestock type or class or land unit or are not included elsewhere. Costs such as legal, accountancy and communication are included in this category.

3.1.2 Constraints

3.1.2.1 Land area

When the option to have variable sized LMU areas is invoked a series of constraints are required to ensure LMUs are allocated correctly over the year.

$$Land_{i,j} + C_{ij} Crop_i \ = Area_i \tag{9}$$

Where

C_{ij} = 1 if $Area_i$ has crop in period *j*, 0 otherwise.

When the option to have variable sized LMU areas is invoked constraints in equation 8 are modified to ensure LMUs are allocated correctly over the year. For each group of variable LMUs

$$\sum_{i=i_a}^{i_n} \left(Land_{i,j} + C_{ij} Crop_i \right) = \sum_{i=i_a}^{i_n} Area_i \tag{10}$$

Where

i_a to i_n represent LMUs *a* to *n* that vary in size for that group.

And to ensure LMUs remain the same size over the 26 periods, for all variable sized LMUs

$$Land_{i,j} + P_{i,j}Crop_i \quad = Land_{i,j+1} + G_{i,j+1}Crop_i \tag{11}$$

Where

$P_{i,j}$ is 1 when period *j* is the plant date of the crop in LMU *i*, 0 otherwise

$G_{i,j}$ is 1 when period *j* is the plant date of the new grass in LMU *i*, 0 otherwise

3.1.2.2 Feed

These constraints ensure feed is apportioned correctly. Firstly, for each LMU crop production is balanced with fortnightly feeding.

$$\sum_{j=s_i}^{e_i} CropFeed_{i,j} \; = Yldc_i \times \; Crop_i \tag{12}$$

Where

$CropFeed_{i,j}$ is the amount (kg DM) of crop fed in LMU i in period

s_i is the period crop can first be fed in LMU i

e_i is the last period crop can be fed in LMU i

$Yldc_i$ is the yield (kg DM/ha) of the crop in LMU i.

For each period (*j*) within each LMU (*i*) the feed removed and closing pasture cover must balance that grown and opening pasture cover.

$$
\begin{aligned}
PCover_{i,j} + Effy_m^{-1} \times SuppMade_{i,j} + AnimalRQs_{i,j} \\
= PGrown_{i,j} \times Land_{i,j} + PCover_{i,j-1} + Effy_f \times SuppFeed_{i,j} \\
+ FeedCrop_{i,j}
\end{aligned}
\qquad (13)
$$

Where

$Effy_m$ is the efficiency of making supplementary feed (the proportion of dry matter present at harvest that is available to be fed out)

$AnimalRQs_{ij}$ is the DM requirements of animals on LMU *i* in period *j* (the feed requirements of sheep and cattle are estimated using GrazPlan equations (Freer *et al.* 2012) and for deer (Dryden 2011; NRC 2007; Oftedal 1984). The feed requirements allow for the utilisation of the feed (i.e. the proportion of DM that disappears that actually gets consumed by the animal)

$PGrown_{ij}$ is the kg of DM grown on LMU *i* in period *j*

$Land_{ij}$ is area of land in pasture on LMU *i* in period *j*

$SuppFeed_{i,j}$ is the kg of DM of supplementary feed fed out on LMU *i* in period *j*

$Effy_f$ is the efficiency of feeding out supplementary feed (the proportion of DM fed out that gets consumed by the animals)

$FeedCrop_{i,j}$ is the kg DM of crop fed on LMU *i* in period *j.*

There is a limit on the amount of supplementary feed that can be fed in any period, with the user specifying the maximum proportion of the intake. Further, no finishing animals are included in this estimation.

$$\begin{aligned} SuppFeed_{i,j} \leq\; & x_s\left(EweRQs_{i,j} + \sum_{n=1}^{2} ReplEweRQs_{i,j,n}\right) \\ & + x_c\left(CowRQs_{i,j} + \sum_{n=1}^{2} ReplCowRQs_{i,j,n}\right) \\ & + x_d\left(HindRQs_{i,j} + \sum_{n=1}^{2} ReplHindRQs_{i,j,n}\right) + x_{dg}\sum_{n=1}^{2} DGrazerRQs_{i,j,n} \end{aligned} \tag{14}$$

Where

x_s, x_c, x_d, x_{dg} is the specified maximum proportion of the diet coming from supplementary feed for sheep, beef cattle, deer and dairy grazers, respectively,

$EweRQs_{i,j}$ is the ewe DM requirements on LMU_i for period *j*,

$ReplEweRQs_{i,j,n}$ is the DM requirements of ewe replacements of age *n*, on LMU_i for period *j*,

$CowRQs_{i,j}$ is the cow DM requirements on LMU_i for period *j*,

$ReplCowRQs_{i,j,n}$ is the DM requirements of beef cow replacements of age *n*, on LMU_i for period *j*,

$HindRQs_{i,j}$ is the hind DM requirements on LMU_i for period *j*,

$ReplHindRQs_{i,j,n}$ is the DM requirements of hind replacements of age *n*, on LMU_i for period *j*,

$DGrazerRQs_{i,j,n}$ is the DM requirements of dairy grazer of age *n*, on LMU_i for period *j.*

Pasture covers at the end of each period *j* on each LMU *i* are constrained to fall between minimum ($mincover_{i,j}$) and maximum values ($maxcover_{i,j}$).

$$PCover_{i,j} \geq mincover_{i,j} \times Land_{i,j} \qquad (15)$$

$$PCover_{i,j} \leq maxcover_{i,j} \times Land_{i,j} \qquad (16)$$

3.1.2.3 Animals

For each LMU there are a number of constraints to control livestock numbers. The number of ewe replacements is given by

$$ReplEwes_{i,c,2} = RepRate_{ewes} \times Ewes_{i,m} \qquad (17)$$

Where

$ReplEwes_{i,c,2}$ is the number of replacement ewes of age group two on LMU *i* period *c* (*c* is the period that the post weaning ewe cull occurs)

$RepRate_{ewes}$ is the replacement rate of the ewes,

$Ewes_{i,m}$ is the number of ewes on LMU *i* period *m* where *m* is the period mating begins.

The number of post weaning cull ewes is given by

$$CullEwes_{i,c} \leq ReplEwes_{i,c,2} \qquad (18)$$

and cull dry ewes post pregnancy scanning (these are culled 2 weeks after scanning)

$$CullEwes_{i,ps+1} = Dry_{ewes} \times Ewes_{i,ps} \qquad (19)$$

where

$Ewes_{i,ps}$ is the number of ewes on LMU *i* in period *ps* (period of pregnancy scanning)

Dry_{ewes} is the proportion ewes that are dry at pregnancy scanning

$CullEwes_{i,ps+1}$ is the number of dry ewes culled from LMU *i* in the period after scanning.

At weaning lambs are split into two sexes (ewes and wethers), then each sex is split into five (*k*) equal sized groups based on live-weight. The replacement ewe lambs are assumed to come equally from the five ewe lamb weight bands (hence the 0.2 in equation (20). $Ewes_{i,p}$ is the number of ewes in LMU *i* present at the start of lambing and NLW is the number of lambs weaned per ewe present at the start of lambing (assuming a 50% sex ratio and 20% of animals of each sex are in each weight band gives the 0.1 weighting to NLW in equation (20).

$$FinEweLambsWnd_{i,k} + 0.20 \times ReplEwesWnd_i = 0.1 \times NLW \times Ewes_{i,p} \qquad (20)$$

Similarly for the wether lambs weaned, for each LMU *i*,

$$FinWetherLambsWnd_{i,k} = 0.1 \times NLW \times Ewes_{i,p} \qquad (21)$$

The lambs at weaning then need to be tied to the number at the end of the period (*j*), allowing for sales, transfers to and from other LMUs, where $TransFinEweLambsWnd_{ii',k}$ is the number of ewe lambs of weight band *k* that are transferred from LMU i to LMU i'. For ach LMU *i* and weight class *k*,

$$
\begin{aligned}
&SellStoreEweLambsWnd_{i,k} + SellPrimeEweLambsWnd_{i,k} + FinEweLambs_{i,j,k} \\
&\qquad + \sum_{\substack{i'=1\\ i'\neq i}}^{LMU} TransFinEweLambsWnd_{i,i',k} \\
&\qquad = FinEweLambsWnd_{i,k} + \sum_{\substack{i'=1\\ i'\neq i}}^{LMU} TransFinEweLambsWnd_{i',i,k}
\end{aligned} \tag{22}
$$

The store wether lambs have the same constraints.

Constraints are needed to tie finishing lambs between periods, allowing lambs to be sold prime at the beginning of the period ($SellPrimeLambs_{ijk}$) and for transfers between LMUs. Also $LambSurv$ allows for deaths between periods. Note that no lambs are sold in the period subsequent to the weaning period. For each LMU *i,* period *j* and weight class *k*,

$$
\begin{aligned}
&SellPrimeEweLambs_{i,j,k} + FinEweLambs_{i+1,j,k} + \sum_{\substack{i'=1\\ i'\neq i}}^{LMU} TransFinEweLambs_{i,i',k} \\
&= LambSurv \times FinEweLambs_{i,j,k} + \sum_{\substack{i'=1\\ i'\neq i}}^{LMU} TransFinEweLambs_{i',i,k}
\end{aligned} \tag{23}
$$

These tie constraints are repeated, allowing for aging of lambs to become yearlings, if input data allows.

The wether lambs ties between periods have the same structure.

For ach LMU *i* and period *j*, the constraints used to transition ewes from one period to the next, allowing for deaths and transfers in and out to other LMUs is

$$\begin{aligned} & Ewes_{i,j} + \sum_{\substack{i'=1 \\ i' \neq i}}^{LMU} TransEwes_{i,i',j} \\ & = EweSurv \times Ewes_{i,j-1} + \sum_{\substack{i'=1 \\ i' \neq i}}^{LMU} TransEwes_{i',i,j} \end{aligned} \tag{24}$$

where $EweSurv$ is the probability of a ewe surviving from one period to the next.

Ewe transfers are not permitted from two weeks prior to lambing until weaning.

At ewe culling after lamb weaning, ewes are culled and replacement 2-tooths become ewes, and the constraint becomes

$$\begin{aligned} & Ewes_{i,j} + \sum_{\substack{i'=1 \\ i' \neq i}}^{LMU} TransEwes_{i,i',j} + EwesCull_{i,j} \\ & = EweSurv \times Ewes_{i,j-1} + \sum_{\substack{i'=1 \\ i' \neq i}}^{LMU} TransEwes_{i',i,j} + Repl2Ths_{i,j} \end{aligned} \tag{25}$$

At ewe culling after pregnancy scanning (the dries are culled), the ewe transition constraint becomes

$$\begin{aligned} & Ewes_{i,j} + \sum_{\substack{i'=1 \\ i' \neq i}}^{LMU} TransEwes_{i,i',j} + EwesCull_{i,j} \\ & = EweSurv \times Ewes_{i,j-1} + \sum_{\substack{i'=1 \\ i' \neq i}}^{LMU} TransEwes_{i',i,j} \end{aligned} \tag{26}$$

There are a similar set of constraints for deer, however they are restricted being on LMUs designated for deer (sheep and cattle can move onto the deer LMUs, but not vice versa).

Dairy grazers have transition constraints between periods and LMUs similar to the sheep, except without the culls. The starting period for weaners is the period specified from the input and the exit date is specified. The same process occurs with yearling dairy grazers.

The beef cattle have a similar structure to the sheep. The major difference is INFORM decides whether to leave the bulls entire or castrate them to produce steers. Hence there is an additional sex ratio constraint (see equation (20) for the derivation of 0.1 multiplier):

$$FinBullsWnd_{i,j,k} + FinSteersWnd_{i,j,k} = 0.1 \times NCW \times Cows_{i,p}$$
$$where \;\; i = 1, \dots , LMU \;\; j = 1, \dots ,26 \; k = 1, \dots ,5 \qquad (27)$$

$Cows_{i,p}$ is the number of cows in LMU i at start of calving and *NCW* is the number of calves weaned per cow pregnant.

As with hinds and ewes, cows (and calves) can’t be transferred between LMUs during late pregnancy until part way through lactation. For beef cows this is from 2 periods prior to calving until 4 periods after calving.

Also cattle can be excluded from LMUs for any number of periods (e.g., minimise damage over winter on a sensitive landscape). For a restriction applying to LMU i and period j the constraint is:

$$Cows_{i,j} + \sum_{n=1}^{2} CowRepl_{i,j,n} + \sum_{n=1}^{3}\sum_{k=1}^{5} FinHfrs_{i,j,n,k} + \sum_{n=1}^{3}\sum_{k=1}^{5} FinSteers_{i,j,n,k} + \sum_{n=1}^{3}\sum_{k=1}^{5} FinBulls_{i,j,n,k} + \sum_{n=1}^{2} DairyGrazer_{i,j,n} = 0 \tag{28}$$

Where *n* is age group (R1yr, R2yr and R3yr) and *k* ranges over the 5 weight groups.

3.2 Inputs

The data inputs required by INFORM are not dissimilar from most farm systems models, but differ in requiring independently obtained biological data for each of the LMUs that make up the farm (Table 1). The type of data ranges from physical (e.g., effective land area of each LMU, pasture production for each LMU) livestock (e.g., animal weights, growth rates, key dates) to financial data (e.g. meat schedules and farm costs, including those associated with each LMU).

Table 1 Inputs required for INFORM

Farm	Area of farm and each LMU Number of Deer LMUs Latitude of farm
Pasture (For each fortnight within each LMU)	Pasture growth rate Pasture energy content Minimum and maximum allowable pasture covers Pasture utilisation by the animals Periods cattle excluded
Crop (For each LMU where a crop	Planting date Crop yield and energy content

can be planted)	Crop utilisation by the animals First possible grazing date Last possible First grazing date of new grass
Supplementary feed	LMUs on which supplementary feed can be made Cost of making and feeding out Price received for sale Maximum percentage of an animal’s fortnightly intake that can come from supplementary feed
Livestock (For each species and sex-age class)	Fortnightly weights and growth rates Scanning and weaning percentages Animal deaths Parturition and weaning dates Cull dates Replacement rate
Financial	Annual per animal costs Annual per ha costs (for each LMU) Annual cost associated with the enterprise Meat schedules Wool schedules Store stock prices Cost of transferring animals between LMUs Dairy Grazer agistment price

3.3 Outputs

The outputs from the INFORM are the steady-state livestock policies (i.e., Livestock types, classes and numbers) that would maximise profit (EBITDA) for the resources, inputs and specified livestock performance levels (Table 2). Fortnightly animal numbers allocated to each LMU, animal sale dates and weights are reported along with pasture and crop information, including pasture covers for each LMU, crop and supplementary feed consumption.

Table 2 Outputs from INFORM

Pasture (For each LMU)	Pasture cover at the end of the fortnight for each LMU
Crop (For each LMU where a crop can be planted)	Area planted Amount fed each fortnight
Supplementary feed (For each LMU)	Amount of supplementary feed made, and either transferred to other LMUs, fed or sold
Livestock (For each species and sex-age class)	Number of each livestock class present at the end of each period on each LMU Number of sales, price and live-weight at the end of each fortnight Number of transfers to other LMUs at the end of each period The period and number of culls Daily feed requirements
Financial	EBITDA

4 Preliminary validation

A validation test of INFORM was conducted using a sheep and beef farm consisting of five distinct LMUs, each with different pasture growth rates, running a mixed sheep and beef livestock operation to establish if (i) there was sufficient flexibility in the model framework to be able to integrate the independently entered biological data from each LMU and with specified livestock performance to derive a feasible livestock policy and (ii) a sensibility test against expert knowledge and the credibility of the model against it ability to mimic reality. A key feature of sensibility testing is a sensitivity analysis of important components, which allows a test of the robustness of the model.

The evaluation consisted of comparing the outputs of INFORM with the real performance of the live-case farm. The 558 ha case study farm, which covered landscapes that vary from flat and easy rolling to easy hill and a small amount of steep land, was broken into five land management units (LMU). Data on the pasture production for each LMU is listed in Appendix 9.2.1 and key dates, animal performance and costs for the live-case farm listed in Appendix 9.2.2. Farm costs came from the 2012 MPI Farm Monitoring report for Central North Island Hill Country Sheep and Beef (http://www.mpi. govt.nz/newsresources/publications?title=Farm%20Monitoring%20 Report). These were split into animal (included animal health, labour, breeding, labour, etc.), land (rates, fertiliser, lime, etc.) and enterprise costs (accountancy, legal, etc.). The animal costs were allocated to sheep and cattle. For sheep the wool revenues were deducted from the sheep animal costs. Sheep were assumed to require 10% more labour per head than cattle, and cattle had a 50% higher animal health cost than sheep on a per head basis. Supplementary feed and cropping costs were not included in these calculations as they are options considered by the model. There was little difference in the farm system and EBITDA were found when INFORM was run for each of the following (i) the five individual LMUs, (ii) as a single area weighted LMU or (ii) when constrained to carry at least the number of cows and ewes currently farmed on the live farm, but more livestock (both physical and as stock units) were carried in each case than on the live-case farm (Figure 2). The difference in livestock numbers between model and actual which equated to 29% more stock units wintered (where a ewe is 1.22 SU and a ewe hogget is 1.0) could be due to a number of possibilities. The pasture input data provided to the model could have over-estimated pasture growth rates and or pasture utilisation by the animals or the range between the minimum and maximum average pasture covers was too wide. Each or all of would have resulted in an over-estimation of carrying capacity. Another possible reason for the difference in livestock numbers between the INFORM, which is a steady-state single year model that is populated with average pasture production data and the live-case farm livestock numbers, is the challenge of comparing farm systems derived from average data to a real on-farm situation, where the decision on the livestock policy invariably includes consideration of such issues as climatic variation and the uncertainties of the market. INFORM currently does not include this uncertainty.

Despite small differences in overall livestock numbers the ability of the model to mimic the live-case farm system gives confidence the model provides captures the dynamics of the farm systems and calculates plausible solutions. To this initial sensibility test can be added a sensitivity analysis, by varying key assumptions and constraints (Robertson et al. 2012). This allows further testing of the robustness of INFORM. Normally a sensitivity analysis involves varying pasture production, animal growth or financial information. The approach taken here, made possible by the new model framework, was to force ewe numbers above optimum to see what happened to EBITDA (Figure 2). Then beef cows were forced into the model in increasing numbers while allowing the model to calculate the optimum number of ewes. The response in EBITDA was not symmetric - increasing ewe numbers above the optimum resulted in a rapid decrease in EBITDA, with increasing ewe numbers by 242 and 742 from the optimal base of 5,258, resulted in a 2.2% and 8.4% decrease in EBITDA, respectively (Figure 2). However increasing cow numbers resulted in only a gradual decrease in

EBITDA, with the introduction of 350 beef cows, reducing ewe numbers by 1,758 to 3,500 only resulting in a decrease in EBITDA of 4.7%. This asymmetry may indicate why New Zealand sheep and beef farmers have a higher proportion of cattle than one would expect based on economic analyses. Perhaps this is a risk mitigation strategy for both seasonal grass production and price fluctuations.

The architecture of INFORM allows the operator to explore the contribution of each LMU to business performance, without the confounding influence of other system changes. An added benefit in separating the farm into five LMUs is that the livestock locations can be shown (Figure 3). A major advantage of having this picture of livestock numbers is that it becomes possible to visualise the effect of a single change (or indeed multiple changes) to farm resources on the configuration of the farm system. Similarly a picture of the pasture covers on each LMU throughout the year to achieve the required animal performance levels is another advantage the approach offers the user. This is important intelligence to operationalize any change to the system. Being able to visualise the effect of a restriction on the farm system, for example, excluding cattle from some areas of the farm during winter months to protect fragile soils, is another attribute of the approach. We can see where cattle would have to be carried instead and the impact this has on the farm system and on EBITDA.

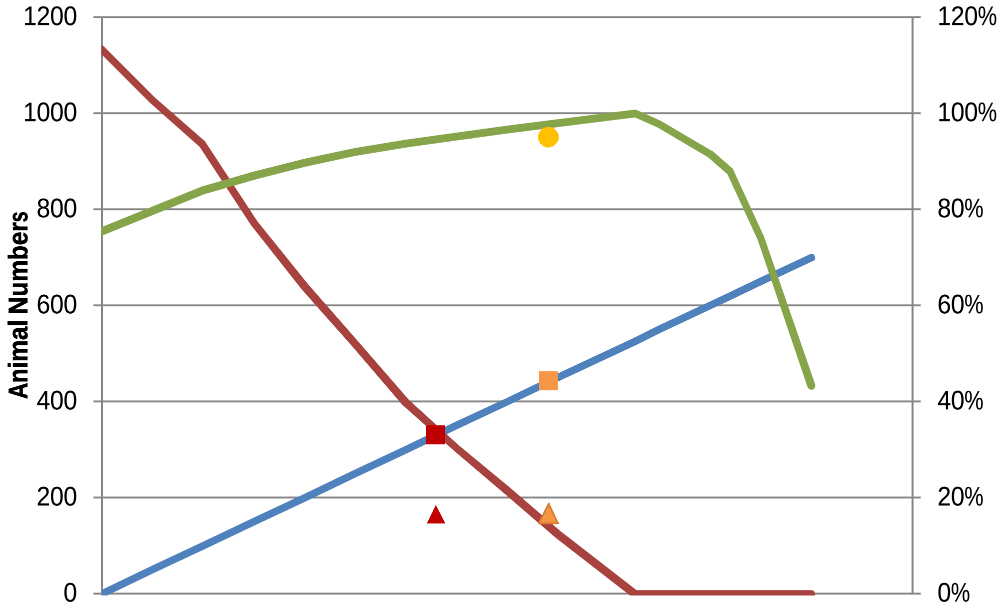

Figure 2 The actual number of animals (30th June) on-farm (ewes [x10] ■ and beef cows ▲, left hand sside), the number when the current system is optimised (ewes [x10] ■ and beef cows ▲) and EBITDA (% of optimum ●, right hand side) and EBITDA (% of optimum, ,rhs) with varying numbers of ewes (x10,) and beef cows ( ).

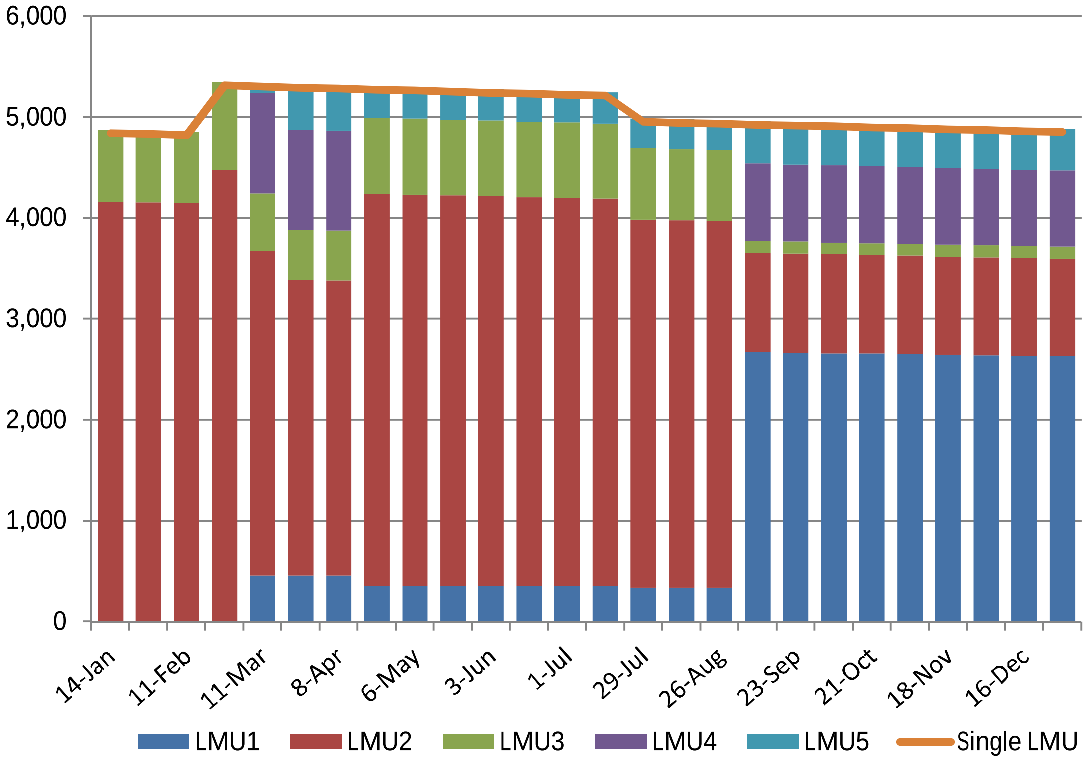

Figure 3 The number of ewes INFORM predicts to be on each of the 5 LMUs and if the farm was treated as a single LMU.

5 Discussion

The live-case study clear demonstrates that INFORM has the ability to describe the farm system from its component LMUs, with no difference in the optimal farm system found between treating a farm as a single LMU (using weighted average pasture details) or as its component LMUs. The ability of the model to integrate information from individual LMU’s creates the opportunity to assess with confidence the value of adding resources (e.g. fertiliser, pasture species) to different LMUs and explore how the farm system may change to capture that value. An added benefit in separating the farm into five LMUs is that the livestock locations can be shown and a picture of the pasture covers required on each LMU throughout the year to achieve the required animal performance levels painted.

A significant issue in farm system design and analysis is that often we are limited by our own imagination in identifying solutions. This might not be a limitation when experienced users are conducting simple analyses, but as we look at increasing the level of complicatedness, for example by considering LMUs as well as variability and by imposing environmentally driven constraints to the production system, the solution space quickly outgrows the ability of any individual to optimize or consider all possible solutions in any depth. Thus there is the need to develop models which can point the user towards solutions which might be quite unique and without precedent. The role of models should therefore be to improve decision making, acknowledging that judgement calls are made based on a combination of experience and evidence. One technique is to use approaches such as linear programming to find solutions rather than rely on user input. The novel land management unit based model framework with the appropriate constraints built in described in this paper can suggest solutions which are beyond the imagination of the user, and might be quite counter-intuitive. Thus developing models to better deal with complicated situations is likely to suggest some quite novel approaches to farm system design. It will also allow users to begin to include a wider range of farm system design issues and constraints into analyses.

Taken further, the land management unit based model approach incorporating variability and an optimisation routine also provide significant benefit in understanding the economic and practical implications of imposing constraints on utilization of resources within a farm system. For example McCall & Sheath (1993) demonstrate the potential advantages from considering variability when constructing farm systems to improve the financial outcome, compared with analysis limited to averages only. Korte and Rhodes (1992, 1993) demonstrated the merits of considering variability due to climate, rather than average climatic conditions when designing a resilient farm system to minimizing the impact of drought. In both these cases, variability was considered by conducting sensitivity analysis via repeated runs using either Stockpol (now commercialized as FARMAX http://www.farmax.co.nz/) and RANGEPACK HerdEcon models, respectively, a procedure which is laborious when done manually and is not likely to be repeated when analysing plausible options for individual farm systems.

Models which consider variability in farm system planning in a more automated manner have potential to provide additional insights to research outcomes and challenge current farm system design thinking possible with available analytical tools. In addition the model provides a useful framework for understanding trade-offs between resource economics, environmental considerations and farmer partialities. The modelling approach described in the paper allows optimization in the absence of constraints and the likely distribution of economic outcomes estimated. Constraints can then be added to the model for example excluding cattle from grazing on a sensitive land management unit over winter, or limits on greenhouse gas emissions to exceed a certain level and the model re-optimized. Comparison of outcomes with and without the constraint provides an insight into the economic implications of the constraint and the changes to the farm system required to absorb the constraint. The model framework allows for integration of independently obtained biological data from multiple land management units, so that responses to inputs or constraints can be isolated to a part of the farm or livestock class, but is sufficiently flexible to be able to impose a range of constraints with relative ease, and contains an optimization routine to search the solution space for alternative farm system designs. Constraints come in many forms. For example future agricultural supply chains in New Zealand, and maybe elsewhere, will require producers of livestock to provide animals for processing at set specifications and increasingly also at a pre-determined time. The capacity to calculate the cost and hence price and value of producing to a set of what is effectively a market constraint, in addition to resource, environment and operators variables, can be accommodated by the approach described in by having the animal performance set to be achieved.

The next step in the development of INFORM is to enhance it so we can better understand the impact of year to year variation on farm systems. This will allow a better understanding of the impact of variation on pastoral farm decision making and the value of investments that could be undertaken to minimise the variability (e.g., irrigation). This may lead to more appropriately directed research, compared with using a single year-steady-state-model. The linking together of multiple farms is also being explored. This could then be used at a strategic level to better understand the impact of variability on supply chains. It may lead to a better understanding of what the value of a contract to supply animals on a set date of a set specification should be and enable questions such as how many animals should be contracted at what time and how many are sold on the spot market can be answered.

6 Conclusion

A new generation integrated whole farm planning model has been developed that allows the farm to be split into its component LMUs. INFORM is an optimisation model which uses linear programming to define the optimal sheep, beef and deer pastoral farm system for the farm resources. It is a single year, steady-state-model.

INFORM allows the evaluation of investments that can be undertaken strategically on areas of the farm. This could include capital fertiliser application, different pasture species or winter crops. INFORM also shows what the new farm system might look like by reporting fortnightly where livestock numbers and classes are located. It also reports on animal sale dates, winter crop areas and supplementary feed details.

INFORM could also be expanded to investigate the effect of additional constraints on the farm system. This would give insight into what the farm system may morph into in order to maximise profit with the new constraint. The current approach to these types of questions is off limited by the imagination and experience of the person doing the modelling.

7 Acknowledgements

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9 Appendices

9.1 Fat depth equations

GR is fat depth (mm) for sheep and GR (mm) is the fat depth for cattle, CarcWt is carcass weight (kg).

9.1.1 Sheep

Ewe Lambs: $\mathrm{GR} = -5.2385 + 0.8417 * \mathrm{CarcWt}$

Wether Lambs: $\mathrm{GR} = -5.9765 + 0.8417 * \mathrm{CarcWt}$

9.1.2 Cattle

9.1.2.1 Angus

Heifer: $\mathrm{GR} = 8.1593 - 0.1486 * \mathrm{CarcWt} + 0.0007 * \mathrm{CarcWt}^2$

Steer: $\mathrm{GR} = 26.821 - 0.2964 * \mathrm{CarcWt} + 0.0009 * \mathrm{CarcWt}^2$

`Bull:` $\mathrm{GR} = \max(0.5, 29.187 - 0.2982 * \mathrm{CarcWt} + 0.0008 * \mathrm{CarcWt}^2)$

9.1.2.2 Hereford

Heifer: $\mathrm{GR} = 16.407 - 0.2176 * \mathrm{CarcWt} + 0.0008 * \mathrm{CarcWt}^2$

Steer: $\mathrm{GR} = 28.951 - 0.3026 * \mathrm{CarcWt} + 0.0008 * \mathrm{CarcWt}^2$

`Bull:` $\mathrm{GR} = \max(0.5, 27.932 - 0.2816 * \mathrm{CarcWt} + 0.0007 * \mathrm{CarcWt}^2)$

9.1.2.3 Continental

Heifer: $\mathrm{GR} = 21.877 - 0.2557 * \mathrm{CarcWt} + 0.0008 * \mathrm{CarcWt}^2$

Steer: $\mathrm{GR} = \max(0.5, 28.028 - 0.2788 * \mathrm{CarcWt} + 0.0007 * \mathrm{CarcWt}^2)$

`Bull:` $GR = \max(0.5, 27.654 - 0.269 * CarcWt + 0.0006 * CarcWt^2)$

9.1.2.4 Dairy or dairy cross

Heifer: $GR = 16.357 - 0.2171 * CarcWt + 0.0008 * CarcWt^2$

Steer: $GR = 28.108 - 0.284 * CarcWt + 0.0007 * CarcWt^2)$

`Bull:` $GR = \max(0.5, 26.212 - 0.2562 * CarcWt + 0.0006 * CarcWt^2)$

9.2 Case Farm data

9.2.1 Pasture growth, energy, utilisation and minimum and maximum covers

LMU	Period	Growth Rate	Energy	Utilisation	Pasture Cover	
					Minimum	Maximum
		(kgDM/ha/d)	(MJME/kgDM)		(kg DM/ha)	(kg DM/ha)
1	14-Jan	55	10.8	80%	1200	2500
1	28-Jan	55	10.8	80%	1200	2500
1	11-Feb	47	10.5	80%	1200	2500
1	25-Feb	45	10.5	80%	1200	2500
1	11-Mar	37	10.8	80%	1200	2500
1	25-Mar	35	10.8	80%	1200	2500
1	8-Apr	29	10.8	80%	1200	2500
1	22-Apr	25	10.8	80%	1200	2500
1	6-May	23	10.8	80%	1200	2500
1	20-May	20	10.8	82%	1200	2500
1	3-Jun	18	10.8	82%	1200	2500

1	17-Jun	10	10.8	85%	1200	2500
1	1-Jul	10	10.8	85%	1200	2500
1	15-Jul	10	10.8	85%	1200	2500
1	29-Jul	10	10.8	85%	1200	2500
1	12-Aug	14	11.0	85%	1200	2500
1	26-Aug	15	11.0	82%	1200	2500
1	9-Sep	21	11.2	82%	1200	2500
1	23-Sep	25	11.2	80%	1200	2500
1	7-Oct	33	11.3	80%	1200	2500
1	21-Oct	40	11.3	80%	1200	2500
1	4-Nov	44	11.2	80%	1400	2500
1	18-Nov	55	11.1	80%	1400	2500
1	2-Dec	56	11.0	80%	1400	2500
1	16-Dec	65	11.0	80%	1400	2500
1	31-Dec	65	11.0	80%	1200	2500
2	14-Jan	50	10.5	80%	1200	2500
2	28-Jan	50	10.5	80%	1200	2500
2	11-Feb	38	10.3	80%	1200	2500
2	25-Feb	35	10.3	80%	1200	2500
2	11-Mar	27	10.5	80%	1200	2500
2	25-Mar	25	10.5	80%	1200	2500
2	8-Apr	22	10.5	80%	1200	2500
2	22-Apr	20	10.5	80%	1200	2500
2	6-May	19	10.5	80%	1200	2500
2	20-May	18	10.5	82%	1200	2500
2	3-Jun	16	10.5	82%	1200	2500
2	17-Jun	8	10.5	85%	1200	2500
2	1-Jul	8	10.5	85%	1200	2500

2	15-Jul	8	10.5	85%	1200	2500
2	29-Jul	8	10.5	85%	1200	2500
2	12-Aug	9	10.6	85%	1200	2500
2	26-Aug	10	10.7	82%	1200	2500
2	9-Sep	13	10.8	82%	1200	2500
2	23-Sep	15	10.9	80%	1200	2500
2	7-Oct	23	10.9	80%	1200	2500
2	21-Oct	30	10.8	80%	1200	2500
2	4-Nov	33	10.7	80%	1400	2500
2	18-Nov	40	10.7	80%	1400	2500
2	2-Dec	42	10.6	80%	1400	2500
2	16-Dec	40	10.6	80%	1400	2500
2	31-Dec	55	10.6	80%	1200	2500
3	14-Jan	30	10.5	80%	1200	2500
3	28-Jan	30	10.5	80%	1200	2500
3	11-Feb	26	10.3	80%	1200	2500
3	25-Feb	25	10.3	80%	1200	2500
3	11-Mar	17	10.5	80%	1200	2500
3	25-Mar	15	10.5	80%	1200	2500
3	8-Apr	13	10.5	80%	1200	2500
3	22-Apr	12	10.5	80%	1200	2500
3	6-May	11	10.5	80%	1200	2500
3	20-May	9	10.5	82%	1200	2500
3	3-Jun	8	10.5	82%	1200	2500
3	17-Jun	2	10.5	85%	1200	2500
3	1-Jul	2	10.5	85%	1200	2500
3	15-Jul	2	10.5	85%	1200	2500
3	29-Jul	2	10.5	85%	1200	2500

3	12-Aug	4	10.6	85%	1200	2500
3	26-Aug	5	10.7	82%	1200	2500
3	9-Sep	7	10.8	82%	1200	2500
3	23-Sep	8	10.9	80%	1200	2500
3	7-Oct	13	10.9	80%	1200	2500
3	21-Oct	18	10.8	80%	1200	2500
3	4-Nov	21	10.7	80%	1400	2500
3	18-Nov	28	10.7	80%	1400	2500
3	2-Dec	29	10.6	80%	1400	2500
3	16-Dec	35	10.6	80%	1400	2500
3	31-Dec	35	10.6	80%	1200	2500
4	14-Jan	40	10.8	80%	1200	2500
4	28-Jan	40	10.8	80%	1200	2500
4	11-Feb	32	10.5	80%	1200	2500
4	25-Feb	30	10.5	80%	1200	2500
4	11-Mar	22	10.8	80%	1200	2500
4	25-Mar	20	10.8	80%	1200	2500
4	8-Apr	17	10.8	80%	1200	2500
4	22-Apr	15	10.8	80%	1200	2500
4	6-May	13	10.8	80%	1200	2500
4	20-May	10	10.8	82%	1200	2500
4	3-Jun	9	10.8	82%	1200	2500
4	17-Jun	5	10.8	85%	1200	2500
4	1-Jul	5	10.8	85%	1200	2500
4	15-Jul	5	10.8	85%	1200	2500
4	29-Jul	5	10.8	85%	1200	2500
4	12-Aug	6	11.0	85%	1200	2500
4	26-Aug	7	11.0	82%	1200	2500

4	9-Sep	8	11.2	82%	1200	2500
4	23-Sep	8	11.2	80%	1200	2500
4	7-Oct	17	11.3	80%	1200	2500
4	21-Oct	25	11.3	80%	1200	2500
4	4-Nov	27	11.2	80%	1400	2500
4	18-Nov	32	11.1	80%	1400	2500
4	2-Dec	34	11.0	80%	1400	2500
4	16-Dec	45	11.0	80%	1400	2500
4	31-Dec	45	11.0	80%	1200	2500
5	14-Jan	55	10.8	80%	1200	2500
5	28-Jan	55	10.8	80%	1200	2500
5	11-Feb	47	10.5	80%	1200	2500
5	25-Feb	45	10.5	80%	1200	2500
5	11-Mar	37	10.8	80%	1200	2500
5	25-Mar	35	10.8	80%	1200	2500
5	8-Apr	29	10.8	80%	1200	2500
5	22-Apr	25	10.8	80%	1200	2500
5	6-May	23	10.8	80%	1200	2500
5	20-May	20	10.8	82%	1200	2500
5	3-Jun	18	10.8	82%	1200	2500
5	17-Jun	10	10.8	85%	1200	2500
5	1-Jul	10	10.8	85%	1200	2500
5	15-Jul	10	10.8	85%	1200	2500
5	29-Jul	10	10.8	85%	1200	2500
5	12-Aug	14	11.0	85%	1200	2500
5	26-Aug	15	11.0	82%	1200	2500
5	9-Sep	21	11.2	82%	1200	2500
5	23-Sep	25	11.2	80%	1200	2500

5	7-Oct	33	11.3	80%	1200	2500
5	21-Oct	40	11.3	80%	1200	2500
5	4-Nov	44	11.2	80%	1400	2500
5	18-Nov	55	11.1	80%	1400	2500
5	2-Dec	56	11.0	80%	1400	2500
5	16-Dec	65	11.0	80%	1400	2500
5	31-Dec	65	11.0	80%	1200	2500

9.2.2 Animal Performance, key dates and costs

	Beef Cattle	*Sheep*
Scan date	20 May	12 Jul
Scan Dry %	5%	5%
Scan % (foetuses / female pregnant)	100%	168%
Dry cull date	4 June	26 Jul
Parturition Date	30 Sep	16 Sep
Wean Date	12 Apr	16 Dec
Wean % (per female at parturition)	90%	140%
Wean Weight (kg)	240 (Bull), 230(Steer), 220(Heifer)	26 (average)
Cull Date	30 May	19 Feb
Mature female weight at parturition	515kg	57kg
Replacement Rate %	22%	22%
Mature female annual cost	$25	$25

Replacement female annual cost		$17	$7
Finishing animal annual cost		$17	$7
Death Rate	mature female	5% pa	5% pa
	replacements	5% pa	5% pa
	finishing animals	5% pa	5% pa
Current Stock numbers		165 cows	3,300 ewes