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Bayesian evaluation of budgets for endemic disease control: An example using management changes to reduce milk somatic cell count early in the first lactation of Irish dairy cows☆

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ABSTRACT

The aim of this research was to determine budgets for specific management interventions to control heifer mastitis in Irish dairy herds as an example of evidence synthesis and 1-step Bayesian micro-simulation in a veterinary context. Budgets were determined for different decision makers based on their willingness to pay. Reducing the prevalence of heifers with a high milk somatic cell count (SCC) early in the first lactation could be achieved through herd level management interventions for pre- and peri-partum heifers, however the cost effectiveness of these interventions is unknown. A synthesis of multiple sources of evidence, accounting for variability and uncertainty in the available data is invaluable to inform decision makers around likely economic outcomes of investing in disease control measures. One analytical approach to this is Bayesian micro-simulation, where the trajectory of different individuals undergoing specific interventions is simulated. The classic micro-simulation framework was extended to encompass synthesis of evidence from 2 separate statistical models and previous research, with the outcome for an individual cow or herd assessed in terms of changes in lifetime milk yield, disposal risk, and likely financial returns conditional on the interventions being simultaneously applied. The 3 interventions tested were storage of bedding inside, decreasing transition yard stocking density, and spreading of bedding evenly in the calving area. Budgets for the interventions were determined based on the minimum expected return on investment, and the probability of the desired outcome. Budgets for interventions to control heifer mastitis were highly dependent on the decision maker's willingness to pay, and hence minimum expected return on investment. Understanding the requirements of decision makers and their rational spending limits would be useful for the development of specific interventions for particular farms to control heifer mastitis, and other endemic diseases.

1. Introduction

For 50% of Irish dairy herds, reducing the prevalence of heifers with high milk somatic cell count (SCC) between 5 and 30 days in milk (DIM) would be associated with savings through increased longevity, and lifetime milk yield (Archer et al., 2013a, b). A reduction in the prevalence of heifers with high SCC early in lactation could be achieved through herd level management interventions targeted at

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pre- and *peri-partum* (ppp) heifers (Green et al., 2008). Previous studies have identified risk factors for mastitis in heifers (De Vliegher et al., 2012), however the cost and efficacy of particular management changes have yet to be evaluated in the field. Data on the likely cost effectiveness of management interventions is therefore unavailable. However, potentially effective interventions may not be deemed to be 'cost effective' if they are too expensive to implement, or the desirable outcome is too uncertain for particular decision makers (Spiegelhalter et al., 2004). It is therefore unrealistic for economic analyses to assume an unlimited 'willingness to pay' for each Euro saved through reduced disease costs, however rational budgets for management interventions are unknown. This information would facilitate the development of practical advice to control heifer mastitis on Irish dairy farms.

Uncertainty and variability in parameters can be handled with a Bayesian analyses, in which prior knowledge is combined with data obtained from a particular study to generate posterior probability distributions for outcomes that represent the updated state of knowledge, and are inherently useful for decision makers (Spiegelhalter et al., 2004; Bolstad, 2007). As a further aid to decision making, the Bayesian approach can be extended by using micro-simulation to generate posterior predictions for particular scenarios that require clear interpretation (Parmigiani, 2002). The trajectory of individuals is modelled as if a carefully controlled trial were conducted, varying only the exposure of interest. This approach is useful when such a trial would be impossible or very expensive (Archer et al., 2013a, b). Making distributional assumptions can be avoided, and all uncertainty and relationships between variables can be propagated through to the final outcome by using a 1-step procedure (Chessa et al., 1999; Spiegelhalter et al., 2004). A 2-step micro-simulation procedure, where distributions for parameters are obtained from other research and expert opinion is more common, and has been used to estimate the cost of high SCC shortly after calving in heifers (Huijps et al., 2009a). The integrated 1-step procedure has been applied to investigate the impact of management interventions in dairy herds, with iterations propagated from a single model (Green et al., 2010). However, the approach can be extended to synthesise evidence from multiple sources, as used in cost effectiveness analyses for human medical treatments (O'Hagan and Stevens, 2001; Spiegelhalter and Best, 2003). To our knowledge this method has not been applied in a veterinary context. As an example of its application, the aim of this research was to use 1-step Bayesian micro-simulation to synthesise evidence and determine budgets for specific management interventions to control heifer mastitis in Irish dairy herds under different circumstances.

2. Materials and methods

2.1. Overview

A micro-simulation was used for a partial budget analysis to estimate the likely economic impact of specific interventions to reduce SCC in Irish dairy heifers between 5 and 30 DIM (SCC1) in terms of change in lifetime milk yield and cow disposal risk (Fig. 1). Lifetime milk yield is determined by survival time and milk yield while alive. Cow disposal risk was used to determine replacement costs where culling occurred. The impact of management interventions reported to reduce SCC1 was modelled using the simulation. Potential financial savings associated with applying the interventions were estimated from the mean difference in lifetime milk yield, and disposal risk at herd level with and without the interventions being applied. The probability of cost effectiveness, and maximum rational spend for implementing these management interventions was estimated for different decision makers based on their willingness to pay.

2.2. Lifetime milk yield model (Model 1)

This model evaluated the association between the SCC1, and lifetime milk yield over 5 to 8 years for heifers in Irish dairy herds (Archer et al., 2013a). The dataset included records from 53,652 heifers in 5922 Irish herds. This was split into 2 samples of 2328, and 3594 herds at random. A linear model with lifetime milk yield as the outcome, and a random effect to account for variation between herds, was fitted to the data for the first sample of herds; data for the second sample was used for cross validation. The model was developed in a Bayesian framework using WinBUGS 1.4.3 (Lunn et al., 2000) and took the form;

$$y_{ij} = \alpha + \mathbf{X_{ij}}\boldsymbol{\beta_1} + \mathbf{X_j}\boldsymbol{\beta_2} + u_j + e_{ij},$$

$$u_j \sim \mathrm{Normal}(0, \sigma_u^2),$$

$$e_{ij} \sim \mathrm{Normal}(0, \sigma_e^2),$$

where y_{ij} = lifetime milk yield for the ith cow in the jth herd, α = intercept value, $\mathbf{X_{ij}}$ = matrix of exposure variables for each cow, $\boldsymbol{\beta_1}$ = vector of coefficients for $\mathbf{X_{ij}}$, $\mathbf{X_j}$ = matrix of exposure variables for each herd, $\boldsymbol{\beta_2}$ = vector of coefficients for $\mathbf{X_j}$, u_j = a random effect to account for residual variation between herds, and e_{ij} = residual level 1 error. Parameters were estimated from 10,000 Markov chain Monte Carlo (MCMC) iterations, following a burn in of 1000 simulations during which time chain convergence occurred. Vague prior distributions were used for; $\sigma_u^{-2} \sim \mathrm{Gamma}(0.001,\ 0.001)$, $\sigma_e^{-2} \sim \mathrm{Gamma}(0.001,\ 0.001)$, and $\boldsymbol{\beta} \sim \mathrm{Normal}\ (0, 10^6)$, to give the major influence to the data in the estimation of parameters (Green et al., 2004). To focus attention on the ppp period for the control of heifer mastitis, only confounding variables deemed to be operating by 30 DIM, such as month of first calving and DIM at the first recording were investigated for inclusion. The model was a good fit to the data, and performed well in cross validation. The coefficients from this model directly fed into the micro-simulation are summarised in Table 1. Overall, one unit increase in the natural logarithm of (ln) SCC1 was associated with a median decrease in lifetime milk yield of 865 (95% Bayesian credibility interval (CI) 702 to 1025) kg.

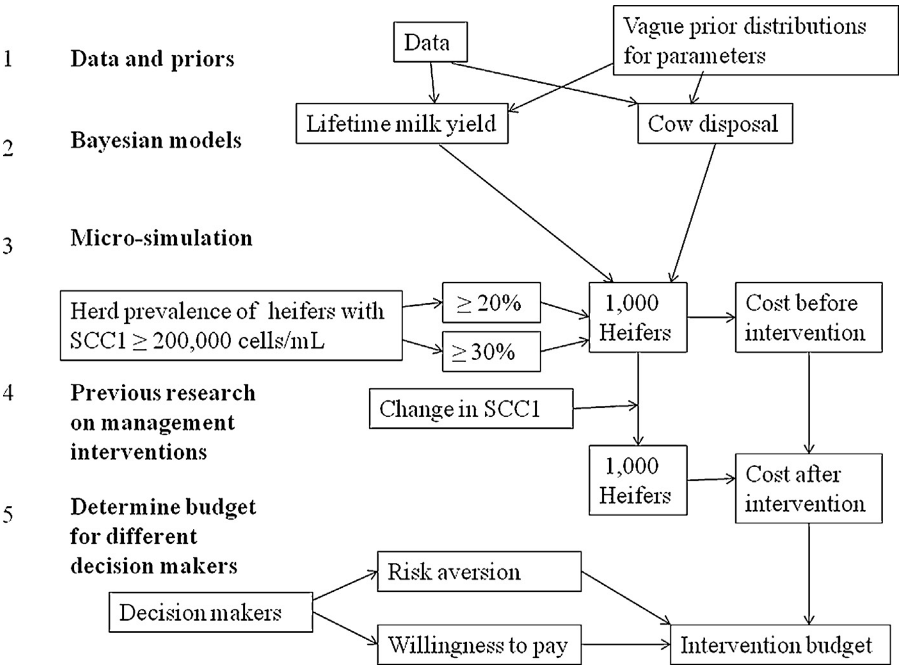

Fig. 1. Overview of the 1-step micro-simulation procedure. Iterations from Bayesian models for lifetime milk yield and disposal risk from separate analyses were run in parallel, and applied to 1000 theoretical cows in herds with ≥20%, and ≥30% of heifers with high somatic cell count (≥200,000 cells/mL) between 5 and 30 days in milk (SCC1). Savings associated with keeping bedding materials inside rather than outside (change in the natural logarithm of SCC1 (ln SCC1) ~ Normal(−0.15, 0.02)), increasing transition yard area from <1.25 m^2 to >1.25 m^2/1000 kg of milk production (change in ln SCC1 ~ Normal(−0.12, 0.01)), and ensuring that bedding in the calving area was spread evenly instead of unevenly (change in ln SCC1 ~ Normal(−0.19, 0.05); based on subjective assessments in previous research (Green et al., 2007, 2008)) were simulated. The assumed distribution of revenue from milk margin was ~Normal (mean = 0.17, standard deviation = 0.03) €/L, replacement cost was €1451/cow disposal, and decision maker willingness to pay for interventions (k) was between €0 and €1/€1 of potential saving. Savings were accrued through increased lifetime milk yield, and decreased disposal risk of cows. Interventions were deemed cost effective for a particular decision maker when incremental net benefit (INB) ≥ 0, where INB = (k × savings) − costs. The budget for the interventions was therefore the savings when INB = 0, and this was determined at different levels of certainty for each value of k.

Table 1
Lifetime milk yield model (Archer et al., 2013a)[a]; parameters used in the micro-simulation procedure.

Exposure (baseline)	95% Bayesian credibility interval		
	Lower 2.5%	Median	Upper 97.5%
Intercept	−4819	10,950	26,260
ln[b] SCC1[c] (4.65)	−1025	−865	−702
First calving February 2007	2979	4418	5832
ln AFC[d] (6.71)	−8302	−6906	−5484

[a] Only relevant parameters shown.
[b] Natural logarithm.
[c] First test day somatic cell count record at 5 to 30 days in milk during parity 1.
[d] Age at first calving (days).

2.3. Cow disposal model (Model 2)

This model evaluated the association between SCC1, and survival over a 5 year period from 2005 to 2009, for heifers in Irish dairy herds (Archer et al., 2013b). The dataset used for model development was based on 147,458 test day records from 7537 heifers in 812 herds. A separate dataset containing 144,113 records from 7353 heifers in 808 herds was used for cross validation. Cows were censored at their last recording, if identified at a later date in other herds, or if recorded at the last available test date for their herd. Otherwise, date of disposal was taken to be at the last test date for each cow. Survival time was calculated as the number of days between the dates of first calving and the last recording, and this was split into 50 day intervals. Data were analysed in a Bayesian framework using WinBUGS 1.4.3 (Lunn et al., 2000). A discrete time logistic survival model was used which took the form;

$$\text{disposed}_{ijk} \sim \text{Bernoulli}(\text{probability} = \pi_{ijk}),$$

$$\text{logit}(\pi_{ijk}) = \alpha + \text{int}_{ijk} + \text{int}_{ijk}^2 + \text{int}_{ijk}^3 + \mathbf{X_{ijk}}\boldsymbol{\beta}_1 + \mathbf{X_{jk}}\boldsymbol{\beta}_2 + \mathbf{X_k}\boldsymbol{\beta}_3 + v_k + u_{jk},$$

$$v_k \sim \text{Normal}(0,\ \sigma_v^2),$$

$$u_{jk} \sim \text{Normal}(0,\ \sigma_u^2),$$

where disposed$_{ijk}$ is the binary occurrence of culling in the ith 50 day interval (int) from first calving for the jth cow in the kth herd, α = intercept value, $\mathbf{X_{ijk}}$ = matrix of exposure variables for each interval, $\boldsymbol{\beta}_1$ = vector of coefficients for $\mathbf{X_{ijk}}$, $\mathbf{X_{jk}}$ = matrix of exposure variables for each cow, $\boldsymbol{\beta}_2$ = vector of coefficients for $\mathbf{X_{jk}}$, $\mathbf{X_k}$ = matrix of exposure variables for each herd, $\boldsymbol{\beta}_3$ = vector of coefficients for $\mathbf{X_k}$, v_k = random effect to account for residual variation between herds, u_{jk} = random effect to account for residual variation between cows. Parameters were estimated

Table 2
Cow disposal model (Archer et al., 2013b)[a]; parameters used in the micro-simulation procedure.

Exposure (baseline)	95% Bayesian credibility interval (odds ratio)		
	Lower 2.5%	Median	Upper 97.5%
Intercept	0.002	0.002	0.003
ln[b] SCC1[c] (4.64)	1.020	1.052	1.085
TDY1[d] (23 kg)	0.968	0.976	0.983
TDF1[e] (0.04)	0.000	0.001	0.090
ln AFC[f] (6.70)	1.770	2.263	2.930
[ln interval[g]]$\hat{1}$ (2.28)	1.260	1.361	1.473
[ln interval]$\hat{2}$ (2.28)	1.847	1.970	2.100
[ln interval]$\hat{3}$ (2.28)	1.198	1.247	1.298
DIM[h] (<100)			
100 to 199	2.642	2.939	3.264
200 to 304	5.280	5.883	6.554

[a] Only relevant parameters shown.
[b] Natural logarithm.
[c] First test day somatic cell count record between 5 and 30 days in milk (DIM) during parity 1.
[d] First test day milk yield record (kg) between 5 and 30 DIM in parity 1.
[e] First test day fat record (proportion) between 5 and 30 DIM in parity 1.
[f] Age at first calving (days).
[g] 50 day intervals from first calving. Included as polynomials.
[h] DIM category in the penultimate interval for each cow. Missing category not shown.

from 10,000 MCMC iterations for parameter estimation, following a burn in of 1000 MCMC simulations during which time chain convergence occurred. Vague prior distributions were used for σ_v^{-2}~Gamma(0.001, 0.001), σ_u^{-2}~Gamma(0.001, 0.001), and $\boldsymbol{\beta} \sim$ Normal (0, 10^6). Confounding variables investigated included DIM at the first recording. The model was a good fit to the data, and performed well in cross validation. The coefficients from this model directly fed into the micro-simulation are shown in Table 2. Disposal odds increased by 5% (CI 2% to 9%) per unit increase in ln SCC1.

2.4. One-step micro-simulation model

2.4.1. Implementation

Coefficients from Models 1 and 2 were combined with data from theoretical cows to generate predictions of lifetime milk yield and the occurrence of disposal within 1750 days from first calving for the ith cow in the jth herd ($y{\cdot}\mathrm{pred}_{ij}$);

$$y \cdot \mathrm{pred}_{ij} \sim p(y \cdot \mathrm{pred}_{ij} | \boldsymbol{\beta}, \mathbf{X}^{\mathbf{sim}}),$$

where $\boldsymbol{\beta}$ is a vector of coefficient distributions (Tables 1 and 2), and $\mathbf{X}^{\mathbf{sim}}$ is a matrix of data for simulated heifers. This included an indicator variable to denote a first calving in February 2007 (aged 24 months), and data from a first milk recording (including ln SCC1) at 5 to 30 DIM simulated from observed normal distributions based on ≥20%, and ≥30% initial herd level prevalence of heifers with SCC1 ≥200,000 cells/mL (Table 3). Interval specific indicator variables were used for month of last recording and DIM category in the penultimate interval. To account for variability in parameters this procedure was carried out at each of 10,000 MCMC iterations using WinBUGS 1.4.3 (Lunn et al., 2000).

2.4.2. Economic simulation

At every iteration, the difference in lifetime milk yield for each cow in these scenarios, before and after applying the management interventions, was multiplied by the estimated gross margin (Milk price – variable costs of production) ~ Normal (mean = 0.17, standard deviation = 0.03) €/L (Hennessy et al., 2011), to give the predicted difference in milk revenue. In addition at every iteration, the difference in the number of cows disposed within 1750 days from first calving for each scenario was multiplied by €1451 (Kennedy et al., 2011), to estimate replacement costs. Following the assumed management interventions, the cost differences associated with increased lifetime milk yield and decreased cow disposal risk were expressed as a mean financial value per heifer in the herd (Fig. 1). Posterior distributions of total savings per heifer in the herd were plotted as a cumulative frequency distribution to show the probability of different levels of return in an intuitive form.

2.4.3. Simulation of management interventions

Three interventions applicable to mastitis control for housed ppp heifers to improve environmental hygiene, and therefore reduce the risk of new intramammary infections were selected from previous research (Table 4, Green et al., 2008). The interventions were storage of bedding inside, decreasing transition yard stocking density (from <1.25 m^2 to >1.25 m^2/1000 kg of annual mean milk production for

Table 3
Observed herd frequency[a], and heifer level[b] means (variances) categorised by high SCC1[c] prevalence.

		Herd level prevalence of cows with SCC1 ≥ 200,000 cells/mL	
		≥20%	≥30%
Observed data	Percentage of herds	59%	26%
	ln[d] SCC1	4.82 (1.47)	5.06 (1.56)
	Milk1[e]	23 (30.0)	22 (33.3)
	Fat1[f]	0.04 (0.00007)	0.04 (0.00007)

[a] Based on 7423 Irish dairy herds.
[b] Based on 233,176 heifers in 7423 Irish dairy herds.
[c] First test day somatic cell count record (cells/mL) between 5 and 30 days in milk (DIM) during parity 1.
[d] Natural logarithm.
[e] First test day milk yield record (kg) between 5 and 30 DIM during parity 1.
[f] First test day fat record (proportion) between 5 and 30 DIM during parity 1.

Table 4

Change in (natural logarithm of) SCC1[a] associated with management interventions (Green et al., 2008).

Normal distribution parameters	Storage of bedding material inside	Decreased transition yard[b] stocking density	Even spreading of bedding in calving area
Mean	−0.15	−0.12	−0.19
Variance	0.02	0.01	0.02

[a] Somatic cell count at 5 to 30 days in milk during parity 1.

[b] From <1.25 m^2 to >1.25 m^2 per 1000 kg of herd annual mean milk production/cow.

the herd), and spreading of bedding evenly in the calving area. Storage of bedding material inside implies it is more likely to be dry when used, and therefore less able to support microbial growth. Increase in transition yard area/cow implies the yard has less contamination. Spreading of bedding material evenly in the calving area was determined by the subjective opinion of farm assessors (Green et al., 2008), and it is assumed this provides a more hygienic environment compared to if the bedding material is clumped. The reported normal distributions for change in ln SCC1 associated with these interventions were used (Table 4); the mean was available, and the variance was estimated given that the CIs reported were equivalent to 2 standard deviations (Green et al., 2008). Draws from these distributions were added to the simulated ln SCC1 for each cow (Fig. 1), to determine the impact of the 3 interventions when applied together for herds with ≥20%, or ≥30% initial prevalence of heifers with SCC1 ≥200,000 cells/mL.

2.5. Willingness to pay

Willingness to pay (k) is defined as the maximum amount a particular decision maker will pay for every €1 of potential saving, and hence the return on investment that would be acceptable (Spiegelhalter et al., 2004). Cost effectiveness is determined by the attitude of the decision maker. The value chosen for k reflects the minimum return on investment the decision maker expects over and above the intervention cost in order that they would consider the intervention to be cost effective. Decision makers typically do not divulge their willingness to pay; therefore a sensitivity analysis is required to evaluate how the incremental net benefit (INB) varies with k where;

$$\mathrm{INB}[k] = k \times \text{difference in savings} - \text{difference in costs, and}$$
$$k = (0:10) \times €0.1.$$

Appropriate levels of spending for the control of mastitis in heifers during the ppp period are unknown. Therefore, posterior distributions for the maximum intervention cost (when INB[k] = 0) were determined. The maximum intervention cost determines the budget available for implementing the interventions in order that they are considered ‘cost effective’ by a particular decision maker.

3. Results

On average the interventions led to a 13% reduction in the prevalence of heifers with SCC1 ≥200,000 cells/mL. For herds with ≥20%, or ≥30% of heifers with SCC1 ≥200,000 cells/mL that applied all three interventions, there was 75% certainty of total savings of at least €24 or €61/heifer calved into the herd respectively; the full range of possibilities is shown in Fig. 2. It follows that for an example herd of 80 cows, that incorporates 20 new heifers/year, ≥6 of which with SCC1 ≥200,000 cells/mL, there would be a 75% probability of saving at least €1220 through these interventions; further scenarios for the example herd, and an identical herd with ≥4 new heifers with SCC1 ≥200,000 cells/mL/year are shown in Table 5. These savings represent the intervention budget for a decision maker who is content to at least break even on investment. Most savings are through increased revenue from the higher lifetime milk yield of cows following the interventions (Table 5). There was 62% probability that there would be a decrease in replacement costs. However, it is not possible to be 75% certain of a saving through decreased replacement costs,

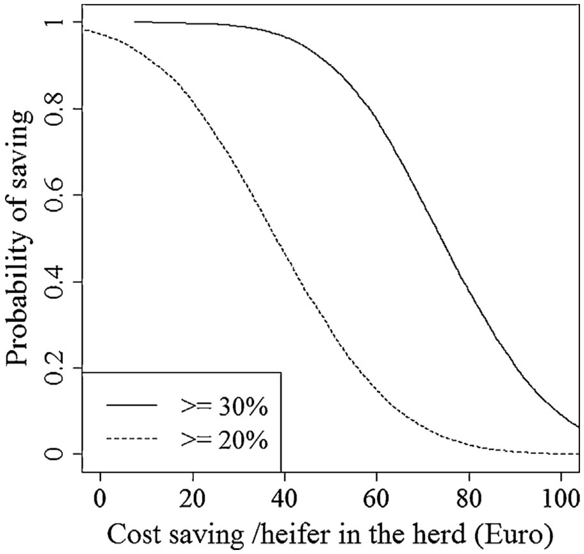

Fig. 2. Posterior predictions of cost saving at herd level. Bayesian models for lifetime milk yield, and the binomial occurrence of disposal of cows in any 50 day interval from first calving were run in parallel. Vague prior distributions were used for all parameters, and the models were both run for 10,000 Markov chain Monte Carlo iterations following a burn-in of 1000 iterations to allow chain convergence to occur. Model coefficients were applied to data from 1000 theoretical heifers in herds with ≥20%, and ≥30% of heifers with high somatic cell count (≥200,000 cells/mL) between 5 and 30 days (SCC1). Possible savings associated with keeping bedding materials inside rather than outside (change in the natural logarithm of SCC1 (ln SCC1) ~ Normal (−0.15, 0.02)), increasing transition yard area from <1.25 m^2 to >1.25 m^2/1000 kg of milk production (change in ln SCC1 ~ Normal (−0.12, 0.01)), and ensuring that bedding in the calving area was spread evenly, instead of unevenly (change in ln SCC1 ~ Normal(−0.19, 0.05); based on subjective assessments in previous research (Green et al., 2007, 2008)) were simulated, assuming milk margin ~ Normal (mean 17, standard deviation = 0.03) €/L, and €1451/cow disposal.

therefore at this level of certainty a worst case scenario would be of a maximum expected loss $\leq$€40 (Table 5). Fig. 3 shows that for a given probability of cost effectiveness, the potential budget for all 3 management interventions for the control of heifer mastitis increases with willingness to pay. Budgets appear more sensitive to the willingness of decision makers to pay, than to the probability of cost effectiveness. Even with considerable variation between decision makers, there would still be potential to invest €5 per heifer in the herd for the control of heifer mastitis in a worst case scenario where the decision maker must be 90% certain of $\geq$150% return (k = €0.4), in lower prevalence herds (Fig. 3). Potential budgets were higher in herds with higher prevalence of heifers with SCC1 $\geq$200,000 cells/mL, and in the best scenario investigated where the decision maker was content to be 60% certain of at least breaking even there would be a budget for the interventions of €69 per heifer in the herd (Fig. 3).

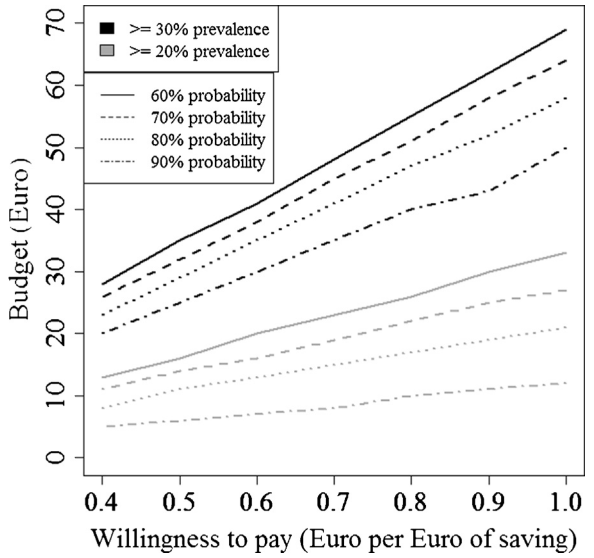

Fig. 3. Impact of willingness to pay and probability of cost effectiveness on budgets to control heifer mastitis. Budgets were determined from the potential change in the lifetime milk yield and disposal risk of heifers, resulting from the impact of 3 specific interventions on somatic cell count between 5 and 30 days in milk (SCC1). This was repeated for herds with $\geq$20%, and $\geq$30% of heifers with high SCC1 ($\geq$200,000 cells/mL). For housed *pre-* and *peri-partum* heifers the following 3 interventions to improve environmental hygiene were assumed to be implemented simultaneously; bedding material storage was inside instead of outside (change in the natural logarithm of SCC1 (ln SCC1) ~ Normal(−0.15, 0.02)), transition yard area increased from <1.25 m^2 to >1.25 m^2/1000 kg of herd mean annual milk production (change in ln SCC1 ~ Normal(−0.12, 0.01)), and bedding in the calving area was spread evenly, instead of unevenly (change in ln SCC1 ~ Normal(−0.19, 0.05); based on subjective assessments in previous research (Green et al., 2007, 2008)). The assumed distribution of revenue from milk margin was ~Normal (mean = 0.17, standard deviation = 0.03) €/L, replacement cost was €1451/cow disposal. Interventions were deemed cost effective for a particular decision maker when incremental net benefit (INB) $\geq$ 0, where INB = ($k \times$ savings) – costs. The budget for the interventions was therefore the savings when INB = 0, and this was determined at different levels of certainty for each value of k.

4. Discussion

Budgets for interventions to control mastitis in heifers appear highly dependent on decision makers' willingness to pay, and hence expected minimum return on investment. In this study, a risk averse farmer with a low willingness to pay, and a herd with a low prevalence of heifers with high SCC1 may rationally invest up to €5 per heifer calved, which could cover the cost of basic protection to keep bedding material dry. At the other extreme, a farmer with higher prevalence herd, who is comfortable with less certainty in the interventions being cost effective and is more willing to pay, would be prepared to invest up to €69 per heifer calved, which would make investment in new buildings and facilities feasible (Fig. 3). Importantly, the large range of potential budgets to implement specific interventions influences what is practically achievable on particular farms. Therefore understanding the circumstances and characteristics of farmers is critical in order to facilitate changes to improve animal health and welfare.

Table 5
Components of savings associated with interventions[a] for an example herd that calves 20 heifers/year.

Probability of saving	Component of saving	Initial number of parity 1 cows with SCC1 $\geq$ 200,000 cells/mL (/20)	
		$\geq$6 ($\geq$30%)	$\geq$4 ($\geq$20%)
0.75	Lifetime milk[b]	$\geq$€1260	$\geq$€520
	Disposal[c]	$\geq$€–40	$\geq$€–40
	Total	$\geq$€1220	$\geq$€480
0.5	Lifetime milk	$\geq$€1360	$\geq$€640
	Disposal	$\geq$€120	$\geq$€120
	Total	$\geq$€1480	$\geq$€760
0.25	Lifetime milk	$\geq$€1440	$\geq$€760
	Disposal	$\geq$€300	$\geq$€280
	Total	$\geq$€1740	$\geq$€1040

[a] For housed *pre-partum* heifers the following interventions to improve environmental hygiene were implemented; bedding material storage was inside instead of outside (change in the natural logarithm of SCC1 (ln SCC1) ~ Normal(−0.15, 0.02)), transition yard area increased from <1.25 m^2 to >1.25 m^2/1000 kg of herd mean annual milk production (change in ln SCC1 ~ Normal(−0.12, 0.01)), and bedding in the calving area was spread evenly, instead of unevenly (change in ln SCC1 ~ Normal(−0.19, 0.05)).

[b] Minimum increase in revenue attributable to lifetime milk yield assuming a margin ~Normal(0.17, 0.03^2) €/L.

[c] Minimum increase in revenue attributable to cow disposal assuming a cost of €1451/cow disposed. Negative values indicate that increased cow disposal risk is possible following the interventions.

Farmers are known to have cost preferences for mastitis interventions which effectively weight costs based on factors such as the practicality of implementing the changes (Huijps et al., 2009b). Decision making is therefore complicated by variation in what is deemed ‘cost effective’ by different individuals. Attitude to risk varies between individuals, and decisions about implementing interventions to control disease must be made based on a level of risk regarding the economic outcome that is deemed acceptable. The expectations of farmers when making decisions around mastitis control are not well understood, and could be affected by their psychological, physiological, and emotional state (Hastie and Dawes, 2001). For instance, pride in keeping cows healthy was an important motivator for mastitis control in Dutch dairy herds (Valeeva et al., 2007). It is hard to put an economic value on emotions such as ‘pride’ attributable to controlling mastitis, and this could mean ‘willingness to pay’ exceeds what seems rational based on changes in lifetime milk yield and disposal risk alone. As a result of variation in mastitis risk through time, the efficacy of a management change is initially uncertain, depending on when it is applied relative to the background risk. Background variation in mastitis risk is likely to be related to factors that influence pathogen survival and multiplication in the environment, such as the ambient temperature, humidity, and hygiene of housing. Alternatively, cow factors such as metabolic stress or intercurrent disease may influence susceptibility to mastitis. Therefore, the interventions tested may not always be ‘cost effective’ on particular farms (Green et al., 2010). Furthermore, effectiveness of the interventions may be influenced by the manner in which changes are applied; if carried out poorly a small or no effect may be observed.

For interventions to be perceived as ‘cost effective’, farmers should aim to implement changes for the least possible cost but within budget. However in practice, the findings from this study only inform rational levels of expenditure for mastitis control in heifers through the specific management changes tested, and other interventions may be more appropriate in different circumstances. Since the majority of Irish dairy heifers calve in early spring (Archer et al., 2013c), they are typically housed during the ppp period. Expansion in the Irish dairy industry with the imminent removal of European Union (EU) milk quotas in 2015 means that overstocking of housing may occur. The predominant causal pathogens associated with high SCC1 in Irish dairy heifers are currently unknown. However in Irish cows, major pathogens of environmental origin were frequently identified in cases of clinical mastitis throughout lactation (Keane et al., 2013a, b). It is therefore plausible that poor environmental hygiene during the ppp period is an increasingly important risk factor for mastitis in Irish heifers (De Vliegher et al., 2012). Interventions to improve the environmental hygiene of housed heifers were therefore selected as a relevant example, from the limited available literature on the effect of management changes on SCC in early lactation (Green et al., 2007, 2008). Since a multi-factorial approach to mastitis control is advised (Green et al., 2007; Anon, 2013), it was assumed that 3 management changes to improve environmental hygiene were applied simultaneously for ppp heifers. In addition to the importance of environmental hygiene for heifers housed during the ppp period, factors affecting host defences have also been identified as risks for mastitis, including udder oedema, nutrition, and factors relating to social integration into the herd following calving (De Vliegher et al., 2012). Furthermore, contagious transmission of pathogens between heifers can occur by cross suckling and via flies (McDougall et al., 2009). For a holistic approach to the control of heifer mastitis, further research should consider the efficacy, and hence likely budgets for different decision makers to implement management changes based on all risk factors.

Longevity has an influence on lifetime milk yield, but although SCC1 was positively associated with risk of disposal from the herd, replacement costs were relatively unimportant (Table 5). A possible reason for this is that in practice other considerations have an overriding influence on cow disposal decisions. For instance in seasonally calving herds, those cows not pregnant at the end of the breeding season may be a priority for disposal (Pinedo et al., 2010), which may limit the number of cows removed for other reasons. Availability of replacement heifers, space on the farm, and EU milk quota availability may also have an influence on disposal decisions. The budgets presented assume that ppp heifers are housed separately from dry/transition cows, as savings through applying the interventions to older cows were not evaluated. In this respect we have underestimated potential budgets if heifers and cows are housed together prior to calving. Other costs should also be considered, for instance the impact of reducing the prevalence of heifers with high SCC in early lactation on lifetime clinical mastitis costs, and milk quality. Clinical mastitis costs may be partially included in the current analysis through the impact on longevity and hence lifetime milk yield (Heikkilä et al., 2012). In the absence of a record of SCC1, data for heifers with clinical mastitis in early lactation were not available, which also suggests the budgets are an underestimate. Impact on clinical mastitis risk, in addition to labour, veterinary, and treatment cost was included in the estimate made by Huijps et al. (2009a) using a 2-step micro-simulation procedure. However, the economic impact was only assessed over the first lactation, hence their estimate of the average cost of high SCC shortly after calving in heifers over the first lactation of €31 (range 0 to 220)/heifer in the herd is not directly comparable to this study in which budgets were determined over a longer period.

The impact of management interventions in this study was based on research in English and Welsh dairy herds (Green et al., 2007, 2008) and assumed to be applicable under Irish conditions. The magnitude of losses through high SCC1 in English and Welsh herds were similar to those in Irish herds (Archer et al., 2013), and it is plausible the results are generalisable to these countries. Although the underlying models have been shown to be useful and generalisable to other Irish dairy herds (Archer et al., 2013a, b), further work is needed to validate the cost effectiveness analysis and budgets presented here. Ultimately, this requires observed data on the impact of management interventions on SCC1 in Irish dairy heifers to compare with model predictions. For the cost effectiveness analysis to be useful for decision support in practice, it should be extended to consider other endemic diseases so the relative benefits of control can be compared. A quantitative approach to determining priorities for investment would avoid reliance on subjective opinion (More et al., 2010), and this would be useful for Irish farmers to inform decisions on disease control investments in conjunction with national control plans for several endemic diseases (Anon, 2013). There may be overlapping benefits of certain management changes on multiple endemic diseases which would make them even more economically favourable. A survey of Irish farmers would be useful to further evaluate their 'risk aversion' and 'willingness to pay' for disease control. This information would help refine budgets, and therefore identify achievable farm management changes for validation of efficacy in future studies.

5. Conclusion

Potential budgets for specific management interventions to reduce the herd level prevalence of heifers with high SCC between 5 and 30 DIM increase with initial prevalence. Budgets appear more dependent on the willingness of decision makers to pay, than the probability of achieving the desired outcome, and hence perceived 'cost effectiveness'. Factors affecting the willingness of decision makers to pay for control measures require further investigation, as knowledge of rational spending limits is useful for the development of specific interventions for particular farms to control heifer mastitis and other endemic diseases.

Conflict of interest statement

The authors have no conflicts of interest.

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