Irish Journal of Agricultural and Food Research **52:** 119–133, 2013

Meta-analysis to investigate relationships between somatic cell count and raw milk composition, Cheddar cheese processing characteristics and cheese composition

U. Geary[1†], N. Lopez-Villalobos[2], B. O'Brien[1], D.J. Garrick[2] and L. Shalloo[1]
[1]*Livestock Systems Research Department, Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland*
[2]*Institute of Veterinary, Animal and Biomedical Sciences, Massey University, Palmerston North, New Zealand*

The relationship between elevated somatic cell count (SCC) and raw milk composition, cheese processing and cheese composition, was investigated by meta-analysis using available literature representing 45 scientific articles. With respect to raw milk composition there was a significant positive relationship between SCC and the protein and fat contents and a significant negative relationship between SCC and the lactose content. In relation to cheese processing, there was a significant negative relationship between SCC and recoveries of protein and fat. As SCC increased cheese protein content declined and cheese moisture content increased.

Keywords: cheese; meta-analysis; milk; somatic cell count

Introduction

Mastitis is a costly disease within the dairy industry, which manifests itself at both farm and processor level and has been identified as one of the most economically relevant diseases of dairy cattle in Ireland (More *et al.* 2010). In Ireland, as per EU regulations, the somatic cell count (SCC) threshold for milk purchasers is 400,000 cells/mL and the current national average SCC is 252,000 cells/mL (Teagasc 2012). Geary *et al.* (2012a) found that Irish farms sustained large losses in profit when bulk milk SCC (BMSCC) increased above 100,000 cells/mL. While a large body of research has been completed

†Corresponding author: Una Geary, Tralee, Co. Kerry, Tel.: +353 86 3584629; Fax: +353 25 42340;
E-mail: una.geary@hotmail.com

estimating the costs of mastitis at farm level (Steeneveld, Swinkels and Hogeveen 2007; Huijps, Lam and Hogeveen 2008; Geary *et al.* 2012a), less focus has been paid to the impact that elevated SCC has on the processing characteristics of milk and therefore on the processing sector.

Mastitis is inflammation of the mammary gland which is a production disease caused by infection which occurs in a mammary quarter following entry of bacteria through the teat canal. In response to bacterial infection, SCC of milk will increase, with a SCC of 200,000 cells/mL generally accepted as an indicator of the presence of a mastitis infection (International Dairy Federation 1997). It has been suggested that SCC for a healthy lactating cow should not exceed 100,000 cells/mL (Doggweiler and Hess 1983; Kromker *et al.* 2001). Research has shown that elevated SCC is associated with changes in milk composition; however, there is not much consensus in the literature on the direction and scale of this effect (Auldist and Hubble 1998; Hortet and Seegers 1998; O'Brien *et al.* 1999a,b,c). There is literature consensus that as SCC increases, total nitrogen content of raw milk increases, casein as a percentage of true protein (CN/TP) decreases, whey protein increases and the lactose content of raw milk decreases (Table 1). The evidence of the effect of SCC on the

Table 1. Summary of existing literature on the effect of somatic cell count on raw milk composition, cheese production and cheese composition

Components[1]	Effect	Significance
Raw milk composition (%)		
CP	Not consistent	Variable
True protein	Not consistent	Variable
Total nitrogen	Increase	Not significant
NPN	Not consistent	Variable
NCN	Not consistent	Variable
CN	Not consistent	Variable
CN as a percentage of true protein	Decrease	Significant
Whey protein	Increase	Variable
Whey fat	Not consistent	Variable
Fat	Not consistent	Variable
Lactose	Decrease	Variable
TS	Not consistent	Variable
SNF	Not consistent	Variable
Cheese production and cheese composition (%)		
Fat in whey	Increase	Variable
Protein in whey	Not consistent	Variable
NCN in whey	Not consistent	Significant
CN in whey	Not consistent	Significant
Moisture	Increase	Variable
Protein in cheese	Decrease	Variable
Fat in cheese	Not consistent	Variable
Protein:Fat ratio[2]	Not consistent	Variable
Protein recovery	Not consistent	Variable
Fat recovery	Not consistent	Variable
TS	Not consistent	–

[1]CP = crude protein; NPN = Non-protein nitrogen; NCN = non-casein nitrogen; CN = casein; TS = total solids; SNF = solids non fat.
[2]This is not a %.

other components of milk is varied in terms of direction, scale and significance. Similarly, the production of dairy products from milk with elevated SCC has been characterised by reduced product yield, reduced yield efficiency, increased losses in the production of cheese (e.g. whey) and reduced product quality (Ali, Andrews and Cheesman 1980; Auldist *et al.* 1996; O'Brien *et al.* 2004, 1997; Mazal *et al.* 2007). Authors agree that as SCC increases fat in whey increases, moisture in cheese increases and protein in cheese decreases (Table 1). The literature is varied on the effect of SCC on other cheese production and cheese composition variables.

Meta-analysis is a useful tool to synthesise the available literature to estimate relationships between SCC and raw milk composition, cheese processing and cheese composition. The advantages of a meta-analysis are that it allows you to combine the results of many studies which can be generalised to a larger population, the precision and accuracy of estimates can be improved as more data is used which in turn may increase the statistical power to detect an effect has greater power than individual studies to detect small but significant effects of various components and gives more precise estimates of the size of the effects (St-Pierre 2001; Crombie and Davies 2009). However, there are some methodological challenges that need to be considered when conducting a meta-analysis; selection bias of the studies identified and included in the analysis and publication bias as studies which show negative or insignificant results are less likely to be published (Walker, Hernandez and Kattan 2008). While a number of systematic reviews have been conducted on the current subject matter, to the best of the authors knowledge a meta-analysis has not previously been published in this area.

The objective of this study was to determine relationships between SCC and raw milk composition, cheese processing characteristics and cheese composition by pooling available literature and applying meta-analysis across the studies.

Materials and Methods

Data compilation and descriptive statistics

Inclusion criteria. A systematic review of the literature was carried out using Google Scholar, the index of which includes most peer-reviewed online journals of Europe and America's largest scholarly publishers plus scholarly books and other non-peer reviewed journals. No timeline was included in the search; all relevant articles were eligible for inclusion regardless of publication date. The search terms included: SCC, mastitis, milk composition, cheese, processing, dairy products and milk quality. The references of every identified article were reviewed to identify any omitted articles. For a study to be included in the analysis it had to report on milk composition and/or cheese processing and/or cheese composition by SCC. Data must have been reported in a usable format, i.e. data presented in graphs were not inferred and so were not included in the analysis. Systematic reviews were excluded from the analysis, while they provided an overview of the literature they did not report numerical values which could be included in the meta-analysis, in this instance the original publications proved superior data sources. In total, 32 published articles were included in the meta-analysis of raw milk composition. Thirteen published articles were included in the meta-analysis of Cheddar cheese composition. There are no guidelines on the optimal number of publications to include in a meta-analysis, the only guidelines relate to the quality and selection of available data. The articles spanned from 1980–2009 and were representative of the international literature with data from New Zealand, USA, Australia, mainland Europe etc. Table 2 provides a summary of articles included in the analysis.

Databases. Two databases were constructed: D1 relating to SCC and raw milk composition and D2 relating to SCC and cheese processing and composition. The databases were constructed with rows representing treatments or groups and the columns represented treatment

Table 2. Summary of scientific papers included in the meta-analysis

<table>
<tr><th rowspan="2">Study</th><th rowspan="2">Number of treatment groups</th><th colspan="2">Somatic cell count categories (cells/mL)</th></tr>
<tr><th>Raw milk</th><th>Cheese</th></tr>
<tr><td>Santos, Ma and Barbano 2003</td><td>2</td><td>26,000–1,113,000</td><td></td></tr>
<tr><td>Ali et al. 1980</td><td>1</td><td></td><td>45,000–200,000</td></tr>
<tr><td>Auldist et al. 1996</td><td>1</td><td colspan="2">121,000–1,463,000[1]</td></tr>
<tr><td>Marino et al. 2005</td><td>2</td><td></td><td>300,000–600,000</td></tr>
<tr><td>Mitchell, Fedrick and Rogers 1986</td><td>1</td><td colspan="2">250,000–50,0000</td></tr>
<tr><td>Rogers et al. 1989a,b</td><td>2</td><td>125,000–1,000,000</td><td></td></tr>
<tr><td>Ma et al. 2000</td><td>1</td><td>45,000–849,000</td><td></td></tr>
<tr><td>Rogers and Mitchell 1994</td><td>2</td><td></td><td>125,000–500,000</td></tr>
<tr><td>Mazal et al. 2007</td><td>1</td><td>100,000–600,000</td><td></td></tr>
<tr><td>Klei et al. 1998</td><td>1</td><td>83,000–872,000</td><td></td></tr>
<tr><td>Barbano et al. 1991</td><td>1</td><td colspan="2">53,000–928,000</td></tr>
<tr><td>Coulon et al. 1998</td><td>1</td><td>100,000–400,000</td><td></td></tr>
<tr><td>Urech, Puhan and Schallibaum 1999</td><td>1</td><td>84,000–293,000</td><td></td></tr>
<tr><td>O’Brien et al. 1999b</td><td>1</td><td>380,000–284,000</td><td></td></tr>
<tr><td>O’Brien et al. 2004</td><td>1</td><td colspan="2">6,000–920,000</td></tr>
<tr><td>Coulon et al. 2002</td><td>1</td><td>110,000–596,000</td><td></td></tr>
<tr><td>O’Brien et al. 1999a</td><td>1</td><td>271,969–632,383</td><td></td></tr>
<tr><td>Ogola, Shitandi and Nanua 2007</td><td>1</td><td>125,000–750,000</td><td></td></tr>
<tr><td>Kelly et al. 1998</td><td>2</td><td>233,000–572,500</td><td></td></tr>
<tr><td>Somers et al. 2003</td><td>1</td><td>5,000–800,000</td><td></td></tr>
<tr><td>Hickey et al. 2006</td><td>3</td><td colspan="2">181,000–426,000</td></tr>
<tr><td>Cooney et al. 2000</td><td>1</td><td>113,000–528,000</td><td></td></tr>
<tr><td>Sapru et al. 1997</td><td>2</td><td colspan="2">47,000–90,000</td></tr>
<tr><td>Schutz, Hansen and Steuernagel 1990</td><td>3</td><td>104,900–244,400</td><td></td></tr>
<tr><td>Myllys and Rautala 1995</td><td>1</td><td>201,900–359,300</td><td></td></tr>
<tr><td>Ostersen, Foldager and Hermansen 1997</td><td>1</td><td>45,000–273,000</td><td></td></tr>
<tr><td>White et al. 2001</td><td>2</td><td>71,000–453,100</td><td></td></tr>
<tr><td>O’Brien et al. 1997</td><td>3</td><td>268,000–444,000</td><td></td></tr>
<tr><td>O’Brien et al. 1999c</td><td>3</td><td>128,000–315,000</td><td></td></tr>
<tr><td>Kefford et al. 1995</td><td>2</td><td colspan="2">82,000–430,000</td></tr>
<tr><td>Butler et al. 2010</td><td>2</td><td>218,000–360,000</td><td></td></tr>
<tr><td>Vianna et al. 2008</td><td>1</td><td>100,000–700,000</td><td></td></tr>
<tr><td>Andretta et al. 2007</td><td>1</td><td>100,000–800,000</td><td></td></tr>
<tr><td>Walsh et al. 1998</td><td>1</td><td>181,000–544,000</td><td></td></tr>
<tr><td>Auldist et al. 2004</td><td>1</td><td colspan="2">121,000–161,000</td></tr>
<tr><td>Grandison and Ford 1986</td><td>2</td><td></td><td>46,000–1,602,000</td></tr>
<tr><td>Popescu and Angel 2009</td><td>1</td><td></td><td>240,000–640,000</td></tr>
</table>

[1]Numbers between raw milk and cheese indicate that manuscripts reported values relating to raw milk composition and cheese processing and/or cheese composition.

characteristics and measured variables. Each experiment included in the database was assigned an individual study number. Where multiple years of data were reported each year of data was included in the database.

Database 1. The data captured in D1 were SCC, milk crude protein (CP), milk true protein (TP), milk total nitrogen (TN), milk non-protein nitrogen (NPN), milk non-casein nitrogen (NCN), milk casein (CN), milk casein as a percentage of true protein ratio (CN/TP), milk whey protein, milk whey fat, milk fat, milk lactose, milk total solids (TS) and milk solids non-fat (SNF).

Not all variables were reported in all studies, where possible these variables were calculated. As per industry standard, TP was calculated by multiplying CP by 94% (Barbano and Lynch 1999). Total nitrogen was calculated by dividing CP by 6.38 and NPN was calculated by subtracting TP from CP (Barbano and Lynch 1999).

Database 2. The data captured in D2 were SCC, cheese protein content, cheese fat content, protein-to-fat-ratio in cheese, protein recovery, fat recovery, fat in whey, protein in whey, NCN in whey, CN in whey, cheese moisture content and TS. As before, each of the variables captured in the database were not consistently reported in all studies included in the D2 database but no variables were calculated in this instance.

Tables 3 and 4 provide some descriptive statistics of the variables included in the analysis for both databases. Some of the variables in both datasets had <10 observations which had an impact on determining a significant relationship between SCC and key variables.

In this analysis SCC was converted to somatic cell score (SCS) based on calculations following Wiggans and Shook (1987):

$$SCS = \log_2(SCC) \quad [1]$$

an SCC of 100,000 cells/mL equates to a SCS of 16.610, 200,000 cells/mL equates to a SCS of 17.610, 300,000 cells/mL equates to a SCS of 18.195, 400,000 cells/mL equates to a SCS of 18.609 and 500,000 cells/mL equates to a SCS of 18.932. The SCC was converted to SCS to normalise the data thus making it more suitable for further

Table 3. Descriptive statistics of the raw milk composition papers included in Database 1 for the meta-analysis

Components[1] (%)	n	Mean	SD	Maximum	Minimum
Somatic cell score[2]	142	17.811	1.345	20.480	12.551
CP	137	3.384	0.297	4.860	2.800
True protein	137	3.188	0.286	4.568	2.660
Total nitrogen	137	0.530	0.047	0.760	0.440
NPN	137	0.205	0.073	0.360	0.025
NCN	23	0.220	0.227	0.810	0.101
CN	93	2.703	0.518	4.440	1.130
CN as a percentage of true protein	106	76.207	13.444	83.600	56.500
Whey protein	44	0.636	0.137	1.080	0.481
Whey fat	3	0.313	0.021	0.330	0.290
Fat	115	4.024	0.562	5.820	2.920
Lactose	93	4.625	0.262	5.150	3.370
TS	29	12.365	0.602	13.960	11.520
SNF	12	8.751	0.310	9.460	8.380

[1,2]See footnotes to Table 1.

Table 4. Descriptive statistics of the cheese processing and composition papers included in Database 2 for the meta-analysis

Components[1] (%)	n	Mean	SD	Maximum	Minimum
Somatic cell score[2]	57	18.093	1.650	21.054	12.551
Fat in whey	21	0.494	0.275	1.010	0.230
Protein in whey	25	0.703	0.377	1.080	0.130
NCN[1] in whey	6	0.130	0.009	0.140	0.120
CN[1] in whey	6	0.073	0.035	0.140	0.040
Moisture	47	40.026	6.753	60.290	33.300
Protein in cheese	26	24.653	1.111	26.750	22.300
Fat in cheese	26	33.581	1.555	36.600	30.990
Protein:Fat ratio[2]	22	75.547	5.642	86.767	67.360
Protein recovery	19	75.547	2.721	79.600	72.660
Fat recovery	19	91.559	1.509	93.580	86.600
TS	4	48.250	1.893	51.000	47.000

[1,2]See footnotes to Table 1.

analysis in the regression models. The scatter plots in Figures 1–4 provide a graphical overview of the relationships of key variables with SCS.

Meta-analysis methodology

Two sets of analyses were carried out, the first to determine relationships between SCS and raw milk composition and the second to determine relationships between SCS and cheese processing characteristics and cheese composition.

Model. The change in (1) the milk composition variables and (2) the cheese processing and composition variables such as SCS changed were analysed with random regression models with linear, quadratic and cubic effects using Proc MIXED of SAS (SAS 2010).

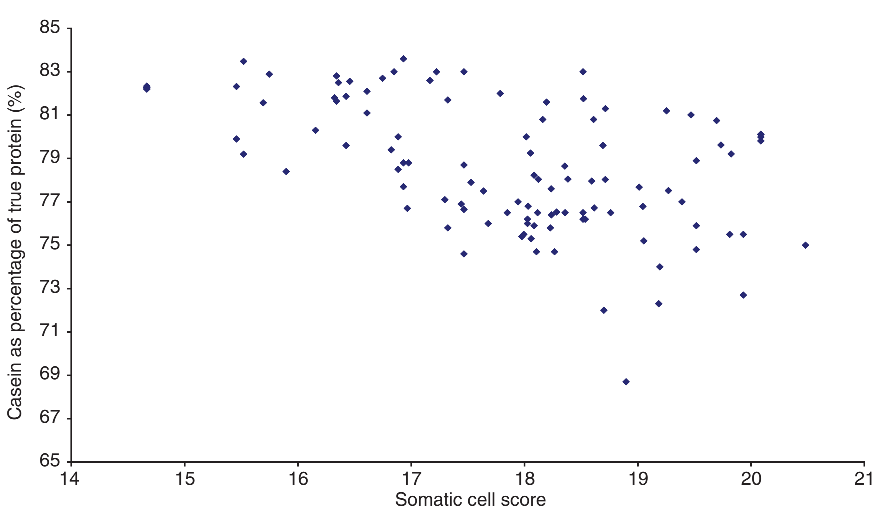

Figure 1. Relationship of raw milk casein as a percentage of true protein to somatic cell score.

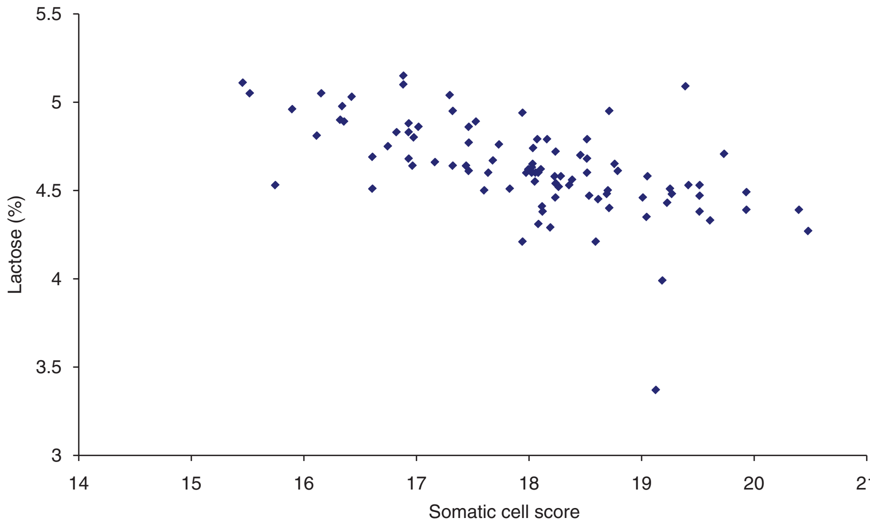

Figure 2. Relationship of raw milk lactose to somatic cell score.

The model used was:

$$y_{km} = \sum_{i=0}^{3} b_i x_k^i + \sum_{i=0}^{3} \alpha_{im} x_{km}^i + e_{km} \qquad [2]$$

where y_{km} is observation k in study m for any of the dependent variables (i.e. fat content, protein content, etc.), b_i are fixed polynomial regression coefficients of SCS on variable y (b_0 = intercept, b_1 = linear effect, b_2 = quadratic effect and b_3 = cubic effect), α_{im} are random regression coefficients of SCS on variable y in study m (α_{0m} = intercept, α_{1m} = linear effect, α_{2m} = quadratic effect and α_{3m} = cubic effect), x_{km}^i is the kth observation of SCS in study m at the power 0, 1, 2 and 3, and e_{km} is the residual error associated with observation y_{km}.

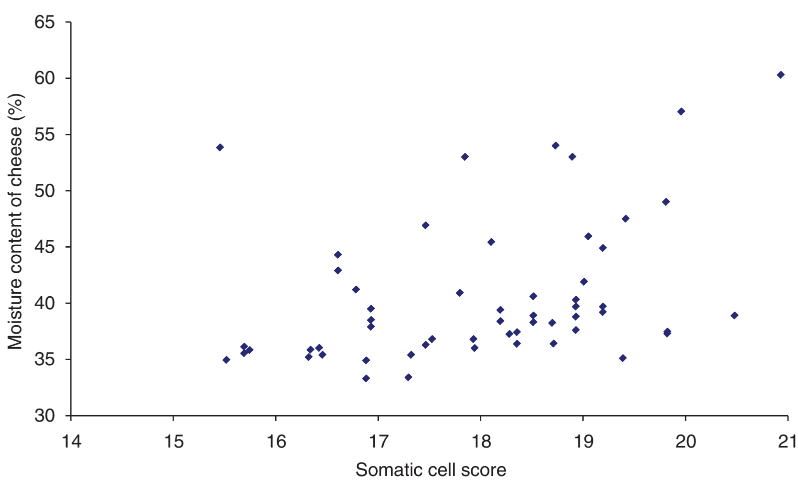

Figure 3. Relationship of cheese moisture to somatic cell score.

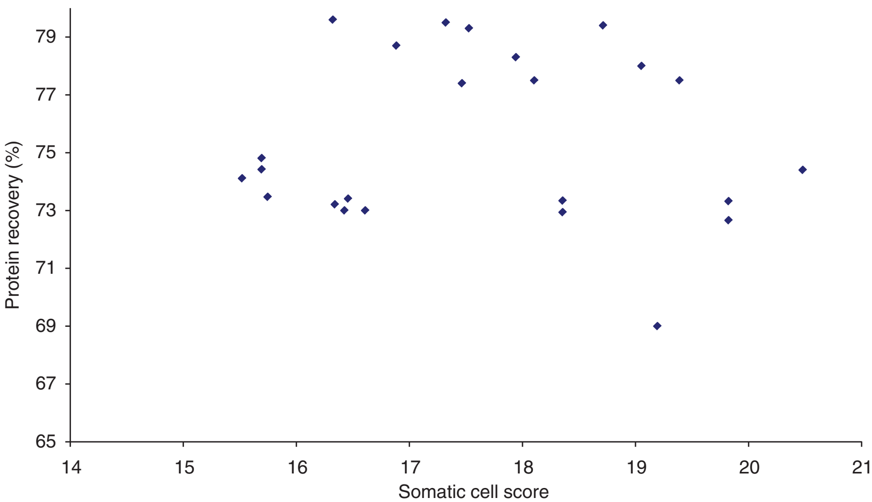

Figure 4. Relationship of protein recovery in cheese processing to somatic cell score.

In this analysis, the regression coefficients were not weighted by their standard errors (SE), as many of the scientific articles had not reported SE in their findings. Linear, quadratic and cubic effects were declared to be significant at a probability of <0.10.

Scenario analysis. Scenario analysis was carried out to determine the impact of high SCC levels on the overall analysis.

Somatic cell count range. Data for SCC categories as high as 2,000,000 cells/mL were captured in both databases. As the SCC cut-off for collecting milk in the EU is 400,000 cells/mL and in the US is 750,000 cells/mL, some of the data is not applicable to practical circumstances. Therefore as part of the scenario analysis the raw milk dataset was edited, with all observations relating to SCC >800,000 cells/mL removed. The analyses outlined above were carried out with the edited raw milk dataset.

Results

Relationship between SCS and raw milk composition

Linear. Somatic cell score had significant positive relationships with CP content (P<0.01), TP content (P<0.01), TN content (P<0.01), NPN content (P<0.05), whey protein content (P<0.01) and fat content (P<0.05) (Table 5), with the proportion of each component in raw milk increasing as SCS increased. A significant negative relationship between SCS and lactose content (P<0.01) and CN/TP (P<0.01) was identified by the model, with the lactose content and CN/TP in raw milk decreasing as SCS increased (Table 5). Figures 1 and 2 provide scatter plots of the CN/TP and lactose data for each study, respectively.

The relationship between SCS and the CN and TS content of raw milk was not found to be significant (Table 5). The effect of SCS on NCN, whey fat and SNF could not be determined by the model.

Table 5. Effect of somatic cell score on raw milk composition

Components[1] (%)	Intercept	SE	P-value	Slope	SE	P-value
CP	1.8923	0.4760	0.0004	0.0842	0.0277	0.0049
True protein	1.7348	0.4553	0.0007	0.0821	0.0265	0.0043
Total nitrogen	0.2971	0.0745	0.0004	0.0132	0.0043	0.0050
NPN	0.0899	0.0432	0.0462	0.0067	0.0026	0.0167
NCN			No estimates generated			
CN	1.7614	0.5321	0.0037	0.0479	0.0310	0.1379
Casein as a percentage of true protein	95.7043	6.1059	<0.0001	–0.9668	0.3288	0.0078
Whey protein	–0.0970	0.2093	0.6778	0.0419	0.0102	0.0045
Whey fat	0.1360	0.0208	–	0.0099	0.0020	–
Fat	1.7409	0.8357	0.0476	0.1175	0.0471	0.0196
Lactose	7.2808	0.7234	<0.0001	–0.1468	0.0409	0.0019
TS	8.0706	2.7912	0.0341	0.0060	0.0611	0.9261
SNF			No estimates generated			

[1]See footnotes to Table 1.

Quadratic and Cubic. None of the quadratic or cubic effects were found to be significant.

Relationship between SCS and cheese processing and composition

Linear. Somatic cell score had a significant positive relationship with the moisture content of cheese (P<0.05), with moisture content increasing by 0.546% as SCS increased by one unit (Table 6). Figure 3 provides a graphical overview of the cheese moisture data for each study. Somatic cell score had a significant negative relationship with the protein content of cheese (P<0.10), protein recovery (P<0.10) and fat recovery (P<0.10) (Table 6). Figure 4 provides a graphical overview of the protein recovery data for each study.

The relationship between SCS and protein in whey and protein:fat ratio was not found to be significant. The relationship between SCS and fat in whey and the fat content of cheese could not be estimated by the model (Table 6).

Quadratic and Cubic. None of the quadratic or cubic models were found to be significant, with the exception of moisture where SCS had a significant positive

Table 6. Effect of somatic cell score on cheese processing and cheese composition

Components[1] (%)	Intercept	SE	P-value	Slope	SE	P-value
Cheese processing						
Fat in whey			No estimates generated			
Protein in whey	0.9354	0.4849	0.1493	–0.0123	0.0299	0.7088
NCN in whey	–0.0158	0.0528	–	0.0080	0.0025	–
CN in whey	–0.2055	0.3565	–	0.0154	0.0169	–
Protein recovery	86.0994	4.5510	0.0003	–0.5737	0.2398	0.0965
Fat recovery	103.9300	4.5683	0.0002	–0.7083	0.2742	0.0815
Cheese composition						
Moisture	30.0559	4.2257	<0.0001	0.5457	0.1973	0.0199
Protein in cheese	29.5445	2.2800	<0.0001	–0.2680	0.1272	0.0890
Fat in cheese			No estimates generated			
Protein:Fat ratio[2]	53.5545	19.2225	0.0495	1.2796	1.1510	0.3289
TS	45.3012	6.9736	–	0.1707	1.1441	–

[1,2]See footnotes to Table 1.

quadratic relationship with moisture in cheese (P<0.01) as well as a significant linear relationship (P<0.01).

Scenario analysis

Somatic cell count range. Capping the raw milk database at 800,000 cells/mL had very little impact on findings. The same components of raw milk that had a significant relationship with SCS maintained those relationships. The scenario analysis did have an additional finding, while the original analysis did not find SCS to have a significant relationship with the CN content of milk, the scenario analysis found that as SCS increased the CN content of milk increased significantly by 0.063% (P<0.10). The scenario analysis suggests that the results from this study are robust at different cell count levels.

Discussion

Based on the analyses presented here elevated SCS had a significant relationship with CP, TP, TN, NPN, whey protein, fat, lactose and CN/TP of raw milk. In addition, as SCS increased protein recovery, fat recovery, cheese protein and cheese moisture were significantly affected.

Milk composition

Fat. The analysis presented found that as SCS increased, the fat content in milk increased. This echoes findings of Cooney *et al.* (2000) and Ma *et al.* (2000), which were included in the analysis, who found fat content to be significantly correlated with SCC. However, these findings conflict with many other manuscripts also included in the analysis which did not find a significant relationship between SCC and the fat content of milk (Rogers, Mitchell and Bartley 1989b; Rogers and Mitchell 1989; Walsh *et al.* 1998; Andreatta *et al.* 2007). An explanation of why the evidence is conflicting was provided by Auldist (2000), stating that a decline in milk fat concentrations during mammary infection is logical given the reduced synthetic and secretory ability of the mammary gland during the infection. He goes on to state; however, the concentrating effect of a reduction in milk yield can offset any reduction in the synthesis and secretion of milk fat, thus producing a negligible change in overall fat concentration or even an increase. Grazing conditions can affect somatic cell count in milk in extreme conditions. These conditions are generally associated with poor climatic conditions (e.g. related to cow hygiene). However, under standard grazing conditions, an association between grass intake and milk somatic cell count would not be expected. Within the objective of achieving synchrony of feed supply and feed demand, the calving and thus drying off practices of all cows occur simultaneously. This creates an involution and low milk volume (dilution) effect which can manifest itself in a high cell count at industry level.

Protein. In this analysis CP, TP, TN and NPN were found to increase significantly as SCS increased. As included in the dataset, this is similar to findings of Klei *et al.* (1998) (skim milk) and Ma *et al.* (2000). Mazal *et al.* (2007) agreed that high SCC milk (800,000 cells/mL) had significantly higher CP and NPN content but found that it had significantly lower TP content than low SCC milk. Contradictory to these findings however, Somers *et al.* (2003), Walsh *et al.* (1998), Vianna *et al.* (2008) and others found no significant relationship between SCC and protein or its components as included in the dataset. Auldist's (2000) understanding of why the evidence is conflicting; when a cow has an elevated SCC there is a decrease in casein coupled with an increase in whey protein, which produces negligible change in total milk protein. The decrease in casein is partly due to reduced synthesis and secretion of casein as a result of physical damage to the mammary epithelial cells, whereas increases in the concentrations of whey protein are due in part to the influx of serum proteins from the blood, decreasing casein yield expressed as a percentage of total protein (Auldist 2000).

Casein. There was not a significant relationship between SCS and the CN content of milk, similar to the findings of Rogers and Mitchell (1989) and Mazal *et al.* (2007) which were included in the meta-analysis. Scenario analysis presented in the current paper, which capped SCC at 800,000 cells/mL, found the CN content of milk increased significantly as SCC increased. The reason the effect of SCS on casein content of milk was not detected when the whole dataset was included could be explained by a dilution effect of higher SCS milks. Therefore when milk with SCS of >800,000 cells/mL were excluded in the scenario analysis the relationship between SCS and casein was concentrated and so, could be detected. The available literature agrees on the negative relationship between SCC milk and the CN/TP ratio of raw milk. Coulon *et al.* (1998) found this decrease in the CN/TP ratio became significant when SCC >200,000 cells/mL.

Lactose. The analysis showed as SCS increased, lactose percentage decreased by 0.15% per unit increase in SCS. This is consistent across the international literature included in the meta-analysis (Klei *et al.* 1998; Cooney *et al.* 2000; Vianna *et al.* 2008) with the exception of Somers *et al.* (2003) who found that although lactose content generally decreased as SCC increased it was not significant. Research suggests that the reduction of lactose in milk as SCC increased can be explained by lactose leaking out of milk via paracellular pathways, demonstrated by elevated concentrations of lactose in the blood and urine of cows with mastitis (Auldist 2000).

Cheese processing

Fat and protein recovery. Protein and fat recovery were found to significantly decrease as milk SCS increased. Lucey and Kelly (1994) suggested that recoveries of fat and protein in cheese are a more reliable method of assessing the effects of SCC on cheese yield than comparing actual and adjusted cheese yields. They stated that the reduction in the recoveries of fat and protein in cheese with increased SCC may be due to impaired rennet coagulation and cheese making properties or increased proteolysis and lipolysis in high SCC milk.

Cheese composition

Moisture. The moisture content of cheese was found to significantly increase as milk SCS increased, similar to findings of Barbano, Rasmussen and Lynch (1991), Auldist *et al.* (1996), Vianna *et al.* (2008) and others that were included in the dataset. However, this conclusion is not unanimous across the literature with Cooney *et al.* (2000) and O'Brien *et al.* (2004) finding no significant relationship between SCC and cheese moisture content which were also included in the meta-analysis. Increases in cheese moisture with elevated SCC may be caused by a slow, weak coagulation due largely to altered milk protein composition, mineral imbalance and an increased milk pH (Auldist 2000).

Protein. As milk SCS increased the protein content of cheese significantly decreased ($P<0.10$) similar to the findings of Cooney *et al.* (2000) and Andreatta *et al.* (2007) which were included in the pooled dataset. Vianna *et al.* (2008) found no significant difference in the protein content of Prato cheese produced with high (>700,000 cells/mL) and low (<200,000 cells/mL) SCC milk. The reduction in cheese protein with elevated SCC may be explained by the reduction in protein recovery. Auldist (2000) attributes this as being largely due to a decrease in casein as a percentage of total protein, since it is mostly casein that is incorporated into the curd, while the whey is expelled during syneresis. In addition it could be argued that the increased moisture content of cheese as SCC increased could negatively impact the milk solids content of the cheese.

Fat. In this analysis the relationship between SCS and the fat content of cheese could not be determined. Cooney *et al.* (2000) found that as SCC increased the fat content in cheese increased ($P<0.05$). However, Rogers and Mitchell (1994) found that as milk SCC increased cheese fat decreased, explained by increased fat losses to the whey. Very few studies found a significant relationship between milk SCC and the fat content of cheese.

Cheese quality. Authors generally agree that as the levels of SCC increase there is a detrimental effect on the organoleptic properties of cheese (Barbano *et al.* 1991; Rogers and Mitchell 1994; Popescu and Angel 2009). Auldist and Hubble (1998) found that negative effects on the organoleptic properties of cheese were reported for milk with SCC as low as 100,000 cells/mL. Grandison and Ford (1986) concluded that even a small increase in SCC can negatively impact cheese processing and Seynk *et al.* (1985) recommended cheese manufacturers to keep SCC <200,000 cells/mL. The available literature highlights the importance of maintaining low BMSCC for high quality cheese production.

Applications

Phelan *et al.* (1982) and O'Keeffe (1984) highlighted the impact of seasonality on milk composition in the Irish dairy industry and the impact this has on product mix, composition and volume of product. The current seasonal milk production system in Ireland presents its own challenges for processors (Geary *et al.* 2013) with higher processing costs and lower market returns. The additive effect of mastitis on the natural constraints of a seasonal milk production system could have considerable economic implications thus compromising profitability. The findings presented in this analysis will be incorporated into the MPSM (Geary *et al.* 2010, 2012b) to determine the impact of milk with elevated levels of SCC on processing costs, product yields (i.e. cheese yield), milk returns, milk price paid to farmers and values per kg of fat and protein.

Conclusion

The meta-analysis presented here has highlighted that elevated SCC has significant relationships with CP, TP, TN, NPN, CN/TP, whey protein, fat and TS content of raw milk. Elevated SCC is significantly related to fat and protein recovery in cheese processing and the protein and moisture content of cheese. The impact of these compositional and production changes as a result of elevated SCC need to be quantified at processor level to determine the impact on product sales, processing costs and milk returns across the dairy industry.

References

Ali, A.E., Andrews, A.T. and Cheesman, G.C. 1980. Influence of elevated somatic cell count on casein distribution and cheese-making. *Journal of Dairy Research* **47**: 393–400.

Andreatta, E., Fernandes, A.M., Santos, M.V., Goncalves de Lima, C., Mussarelli, C., Marques, M.C. and Auguste Fernandes de Oliveira, C. 2007. Effects of milk somatic cell count on physical and chemical characteristics of mozzarella cheese. *Australian Journal of Dairy Technology* **62**: 166–170.

Auldist, M.J. 2000. Effects of mastitis on raw milk and dairy products. *Proceedings of: Pacific Congress on Milk Quality and Mastitis Control, Nagano, Japan*, pages 191–204.

Auldist, M.J. and Hubble, I.B. 1998. Effects of mastitis on raw milk and dairy products. *Australian Journal of Dairy Technology* **53**: 28–36.

Auldist, M.J., Coast, S., Sutherland, B.J., Mayes, J.J., McDowell, G.H. and Rogers, G.L. 1996. Effect of somatic cell count and stage of lactation on raw milk composition and the yield and quality of Cheddar cheese. *Journal of Dairy Research* **63**: 269–280.

Auldist, M.J., Johnston, K.A., White, N.J., Fitzsimons, W.P. and Boland, M.J. 2004. A comparison of the composition, coagulation characteristics and cheesemaking capacity of milk from Friesian and Jersey dairy cows. *Journal of Dairy Research* **71**: 51–57.

Barbano, D. and Lynch, J. 1999. "Fact Sheet – Milk Protein Testing – FAQ's". Changing from Crude Protein to True Protein. Available online: http://future.aae.wisc.edu/publications/milk_protein_testing.pdf [accessed 12 November 2013].

Barbano, D.M., Rasmussen, R.R. and Lynch, J.M. 1991. Influence of milk somatic cell count and milk age on cheese yield. *Journal of Dairy Science* **74**: 369–388.

Butler, S.T., de Feu, M.A., O'Brien, B., Guinee, T.P. and Murphy, J.J. 2010. Short communication: The effect of dry period duration and dietary energy density in early lactation on the rennet gelation properties of milk. *Journal of Dairy Science* **93**: 524–528.

Cooney, S., Tiernan, D., Joyce, P. and Kelly, A.L. 2000. Effect of somatic cell count and polymorphonuclear leucocyte content of milk on composition and proteolysis during ripening of Swiss-type cheese. *Journal of Dairy Research* **67**: 301–307.

Coulon, J.B., Hurtaud, C., Remond, B. and Verite, R. 1998. Factors contributing to variation in the proportion of casein in cows' milk true protein: a review of recent INRA experiments. *Journal of Dairy Research* **65**: 375–387.

Coulon, J.B., Gasqui, P., Barnouin, J., Ollier, A., Pradel, P. and Pomies, D. 2002. Effect of mastitis and related-germ on milk yield and composition during naturally-occurring udder infections in dairy cows. *Animal Research* **51**: 383–394.

Crombie, I. and Davies, H.T. 2009. What is meta-analysis? In: "What is…?" Series, Second Edition, Evidence Based Medicine. NPR09/1112 Available online: http://www.medicine.ox.ac.uk/bandolier/painres/download/whatis/meta-an.pdf [accessed 12 November 2013].

Doggweiler, R. and Hess, E. 1983. Zellgehalt in der Mich ungeschädigter Euter. *Milchwissenschaft* **38**: 167–188.

Geary, U., Lopez-Villalobos, N., Garrick, D.J. and Shalloo, L. 2010. Development and application of a processing model for the Irish dairy industry. *Journal of Dairy Science* **93**: 5091–5100.

Geary, U., Lopez-Villalobos, N., Begley, N., McCoy, F., O'Brien, B., O'Grady, L. and Shalloo, L. 2012a. Estimating the effect of mastitis on the profitability of Irish dairy farms. *Journal of Dairy Science* **95**: 3662–3673.

Geary, U., Lopez-Villalobos, N., Garrick, D.J. and Shalloo, L. 2012b. An analysis of the implications of a change to the seasonal milk supply profile in the Irish dairy industry utilizing a seasonal processing sector model. *Journal of Agricultural Science* **150**: 389–407.

Geary, U., Lopez-Villalobos, N., Garrick, D. and Shalloo, L. 2013. Spring calving versus split calving: Effects on farm, processor and industry profitability for the Irish dairy industry. *Journal of Agricultural Science*. DOI: http://dx.doi.org/10.1017/S0021859613000397.

Grandison, A.S. and Ford, G.D. 1986. Effects of variations in somatic cell count on the rennet coagulation properties of milk and on the yield, composition and quality of Cheddar cheese. *Journal of Dairy Research* **53**: 645–655.

Hickey, D.K., Kilcawley, K.N., Beresford, T.P., Sheehan, E.M. and Wilkinson, M.G. 2006. The influence of a seasonal milk supply on the biochemical and sensory properties of Cheddar cheese. *International Dairy Journal* **16**: 679–690.

Hortet, P. and Seegers, H. 1998. Calculated milk production losses associated with elevated somatic cell counts in dairy cows: review and critical discussion. *Veterinary Research* **29**: 497–510.

Huijps, K., Lam, T.J.G.M. and Hogeveen, H. 2008. Costs of mastitis: Facts and perception. *Journal of Dairy Research* **75**: 113–120.

International Dairy Federation. 1997. "Recommendations for Presentation of Mastitis-Related Data. Bulletin No. 321/1997". International Dairy Federation, Brussels, Belgium, 36 pages.

Kefford, B., Christian, M.P., Sutherland, B.J. and Mayes, J.J. 1995. Seasonal influences on Cheddar cheese manufacture: influence of diet quality and stage of lactation. *Journal of Dairy Research* **62**: 529–529.

Kelly, A., Reid, S., Joyce, P., Meaney, W. and Foley, J. 1998. Effect of decreased milking frequency of cows in late lactation on milk somatic cell count, polymorphonuclear leucocyte numbers, composition and proteolytic activity. *Journal of Dairy Research* **65**: 365–373.

Klei, L., Yun, J., Sapru, A., Lynch, J., Barbano, D., Sears, D. and Galton, D. 1998. Effects of milk somatic cell count on cottage cheese yield and quality. *Journal of Dairy Science* **81**: 1205–1213.

Krömker, V., Grabowski, N.T., Redetzky, R. and Hamann, J. 2001. Detection of mastitis using selected quarter milk parameters. *2nd International Symposium on Bovine Mastitis and Milk Quality, Vancouver, Canada*, pages 486–487.

Lucey, J. and Kelly, J. 1994. Cheese yield. *International Journal of Dairy Technology* **47**: 1–14.

Ma, Y., Ryan, C., Barbano, D.M., Galton, D.M., Rudan, M.A. and Boor, K.J. 2000. Effects of somatic cell count on quality and shelf-life of pasteurized fluid milk. *Journal of Dairy Science* **83**: 264–274.

Marino, R., Considine, T., Sevi, A., McSweeney, P.L.H. and Kelly, A.L. 2005. Contribution of proteolytic activity associated with somatic cells in milk to cheese ripening. *International Dairy Journal* **15**: 1026–1033.

Mazal, G., Vianna, P.C.B., Santos, M.V. and Gigante, M.L. 2007. Effect of somatic cell count on Prato cheese composition. *Journal of Dairy Science* **90**: 630–636.

Mitchell, G.E., Fedrick, I.A. and Rogers, S.A. 1986. The relationship between somatic cell count, composition and manufacturing properties of bulk milk 2. Cheddar cheese from farm bulk milk. *Australian Journal of Dairy Technology* **41**: 12–14.

More, S.J., McKenzie, K., O'Flaherty, J., Doherty, M.L., Cromie, A.R. and Magan, M.J. 2010. Setting priorities for non-regulatory animal health in Ireland: Results from an expert Policy Delphi study and a farmer priority identification survey. *Preventative Veterinary Medicine* **95**: 198–207.

Myllys, V. and Rautala, H. 1995. Characterization of clinical mastitis in primiparous heifers. *Journal of Dairy Science* **78**: 538–545.

O'Brien, B., Murphy, J.J., Connolly, J.F., Mehra, R., Guinee, T.P. and Stakelum, G. 1997. Effect of altering the daily herbage allowance in mid lactation on the composition and processing characteristics of bovine milk. *Journal of Dairy Research* **64**: 621–626.

O'Brien, B., Mehra, R., Connolly, J.F. and Harrington, P. 1999a. Seasonal variation in the composition of Irish manufacturing and retail milks: 1. Chemical composition and renneting properties. *Irish Journal of Agricultural and Food Research* **38**: 53–64.

O'Brien, B., Murphy, J.J., Guinee, T., Ryan, G. and Mehra, R. 1999b. "Chemical Composition and Processability of Milks from Herds with Different Calving Patterns". *End of Project Report 4349, Dairy Production Research Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland*, 24 pages.

O'Brien, B., Dillon, P., Murphy, J.J., Mehra, R., Guinee, T.P., Connolly, J.F., Kelly, A. and Joyce, P. 1999c. Effects of stocking density and concentrate supplementation of grazing dairy cows on milk production, composition and processing characteristics. *Journal of Dairy Research* **66**: 165–176.

O'Brien, B., Gallagher, B., Joyce, P., Meaney, W.J. and Kelly, A. 2004. Milk SCC and PMN as indicators of milk processability and subsequent cheese quality. *Proceedings of the 54th European Association of Animal Production Annual Meeting, Bled, Slovenia, Session code: C6*. 12 Abstract No. 365.

O'Keeffe, A.M. 1984. Seasonal and lactational influences on moisture content of Cheddar cheese. *Irish Journal of Food Science and Technology* **8**: 27–37.

Ogola, H., Shitandi, A. and Nanua, J. 2007. Effect of mastitis on raw milk compositional quality. *Journal of Veterinary Science* **8**: 237–242.

Ostersen, S., Foldager, J. and Hermansen, J.E. 1997. Effects of stage of lactation, milk protein genotype and body condition at calving on protein composition and renneting properties of bovine milk. *Journal of Dairy Research* **64**: 207–219.

Phelan, J.A., O'Keeffe, A.M., Keogh, M.K. and Kelly, P.M. 1982. Studies of milk composition and its relationship to some processing criteria: 1. Seasonal changes in the composition of Irish milk. *Irish Journal of Food Science and Technology* **6**: 1–11.

Popescu, A. and Angel, E. 2009. Analysis of milk quality and its importance for milk processors. *Zootehnie si Biotehnologic* **42**: 501–506. Available online: http://www.usab-tm.ro/fileadmin/fzb/simpozion%202009/Volumul1/management/Popescu%201.pdf [accessed 12 November 2013].

Rogers, S.A., Slattery, S.L., Mitchell, G.E., Hirst, P.A. and Grieve, P.A. 1989a. The relationship between somatic cell count, composition and manufacturing properties of bulk milk. III: Individual proteins. *Australian Journal of Dairy Technology* **44**: 49–52.

Rogers, S.A., Mitchell, G.E. and Bartley, J.P. 1989b. The relationship between somatic cell count, composition and manufacturing properties of bulk mild. IV: Non-protein constituents. *Australian Journal of Dairy Technology* **44**: 53–56.

Rogers, S.A. and Mitchell, G.E. 1989. The relationship between somatic cell count, composition and manufacturing properties of bulk milk. V: Pasteurized milk and skim milk powder. *Australian Journal of Dairy Technology* **44**: 57–60.

Rogers, S.A. and Mitchell, G.E. 1994. The relationship between somatic cell count, composition and manufacturing properties of bulk milk. VI: Cheddar cheese and skim milk yoghurt. *Australian Journal of Dairy Technology* **49**: 70–74.

SAS. 2010. Version 9.3. SAS Institute Inc., Cary, NC, USA.

Santos, M.V., Ma, Y. and Barbano, D.M. 2003. Effect of somatic cell count on proteolysis and lipolysis in pasteurized fluid milk during shelf-life storage. *Journal of Dairy Science* **86**: 2491–2503.

Sapru, A., Barbano, D.M., Yun, J., Klei, L.R., Oltenacu, P.A. and Bandler, K.A. 1997. Cheddar cheese: influence of milking frequency and stage of lactation on composition and yield. *Journal of Dairy Science* **80**: 437–446.

Schutz, M.M., Hansen, L.B. and Steuernagel, G.R. 1990. Variation of milk, fat, protein, and somatic cells for dairy cattle. *Journal of Dairy Science* **73**: 484–493.

Somers, J.M., O'Brien, B., Meaney, W.J. and Kelly, A.L. 2003. Heterogeneity of proteolytic enzyme activities in milk samples of different somatic cell count. *Journal of Dairy Research* **70**: 45–50.

St-Pierre, N.R. 2001. Invited review: integrating quantitative findings from multiple studies using mixed model methodology. *Journal of Dairy Science* **84**: 741–755.

Steeneveld, W., Swinkels, J. and Hogeveen, H. 2007. Stochastic modelling to assess economic effects of treatment of chronic subclinical mastitis caused by *Streptococcus uberis*. *Journal of Dairy Research* **74**: 459–467.

Teagasc. 2012. National Farm Survey Results. 2011 Dairy Enterprise. Available online: http://www.teagasc.ie/publications/2012/1398/DairyFactsheet2011-TeagascNFS.pdf [accessed 12 November 2013], 3 pages.

Urech, E., Puhan, Z. and Schallibaum, M. 1999. Changes in milk protein fraction as affected by subclinical mastitis. *Journal of Dairy Science* **82**: 2402–2411.

Vianna, P.C.B., Mazal, G., Santos, M.V., Bolini, H.M.A. and Gigante, M.C. 2008. Microbial and sensory changes throughout the ripening of Prato cheese made from milk with different levels of somatic cells. *Journal of Dairy Science* **91**: 1743–1750.

Walker, E., Hernandez, A.V. and Kattan, M.W. 2008. Meta-analysis: Its strengths and limitations. *Cleveland Clinic Journal of Medicine* **75**: 431–439.

Walsh, C.D., Guinee, T.P., Harrington, D., Mehra, R.A.J., Murphy, J. and Fitzgerald, R.J. 1998. Cheesemaking, compositional and functional characteristics of low-moisture part-skim Mozzarella cheese from bovine milks containing κ-casein AA, AB or BB genetic variants. *Journal of Dairy Research* **65**: 307–315.

White, S.L., Bertrand, J.A., Wade, M.R., Washburn, S.P., Green, J.T. and Jenkins, T.C. 2001. Comparison of fatty acid content of milk from Jersey and Holstein cows consuming pasture or a total mixed ration. *Journal of Dairy Science* **84**: 2295–2301.

Wiggans, G.R. and Shook, G.E. 1987. A lactation measure of somatic cell count. *Journal of Dairy Science* **70**: 2666–2672.

Received 23 September 2013