Published in Animal Journal

Heritability of phenotypic udder traits to improve resilience to mastitis in Texel ewes

R.E. Crump1, S. Cooper2, E.M. Smith2a, C. Grant2, L.E. Green1b

*1School of Life Sciences and Zeeman Institute for Systems Biology and Infectious Disease Epidemiology Research, University of Warwick, Coventry, CV4 7AL*

*2School of Life Sciences, University of Warwick, Coventry, CV4 7AL*

*aPresent address: The British Texel Sheep Society Ltd, Stoneleigh Park, Kenilworth, CV8 2LG.*

*bPresent address: College of Life and Environmental Sciences, University of Birmingham, Edgbaston B15 2TT*

Corresponding author: Laura Green. Email: l.e.green.1@bham.ac.uk

**Table S1** *Deviance information criteria (DIC) for individual animal models for ewe heritability of udder phenotypes with various combinations of fixed effects*

|  |  |  |
| --- | --- | --- |
| Phenotype |   | Fixed effects tested for inclusion in the model |
|   | FSD | FSD, EA | FSD, DIM | FSD, EA, DIM |
| Teat placement | 2022.61 | 2019.92 | 2022.49 | 2019.37 |
| Udder drop | 1718.41 | 1708.25 | 1719.69 | 1708.94 |
| Degree of separation | 2290.07 | 2291.51 | 2291.11 | 2292.41 |
| Udder width | 2907.05 | 2894.59 | 2899.37 | 2884.11 |
| Left teat length | 725.71 | 725.93 | 719.12 | 722.22 |
| Chronic mastitis | 902.48 | 904.66 | 904.3 | 906.46 |
| Left teat lesion | 531.3 | 533.24 | 531.97 | 533.87 |
| Right teat lesion | 572.57 | 573.2 | 574.07 | 574.71 |
| Any teat lesion | 699.28 | 702.33 | 701.04 | 704.08 |

FSD = Flock observation date, EA = ewe age, DIM = days in milk. The lowest value of DIC for each phenotype was included in the model.

**Table S2** *Marginal posterior distributions of variance components, heritabilities and repeatabilities of continuous traits for heritability of ewe udder phenotypic traits estimated with an individual animal model with repeated records*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Trait | Parameter | Mean | SD | Percentiles | MAP |
|   |   |   |   | 2.5% | 50% | 97.5% |   |
| Teat placement | $σ\_{e}^{2}$1 | 0.634 | 0.0634 | 0.518 | 0.632 | 0.76 | 0.628 |
|  | $σ\_{a}^{2}$2 | 0.422 | 0.0819 | 0.276 | 0.418 | 0.588 | 0.411 |
|  | $σ\_{pe}^{2}$3 | 0.0003 | 0.0015 | 0 | 0.0001 | 0.0017 | 0 |
|  | *h2* | 0.401 | 0.0369 | 0.33 | 0.401 | 0.474 | 0.401 |
|  | *r* | 0.401 | 0.0369 | 0.33 | 0.401 | 0.475 | 0.402 |
| Udder drop | $$σ\_{e}^{2}$$ | 0.307 | 0.0415 | 0.23 | 0.305 | 0.387 | 0.298 |
|  | $$σ\_{a}^{2}$$ | 0.156 | 0.0532 | 0.0664 | 0.153 | 0.267 | 0.15 |
|  | $$σ\_{pe}^{2}$$ | 0.166 | 0.0544 | 0.0798 | 0.162 | 0.275 | 0.151 |
|  | *h2* | 0.244 | 0.0439 | 0.162 | 0.243 | 0.597 | 0.517 |
|   | *r* | 0.517 | 0.0418 | 0.434 | 0.518 | 0.597 | 0.517 |
| Degree of separation | $$σ\_{e}^{2}$$ | 1.04 | 0.12 | 0.81 | 1.04 | 1.27 | 1.04 |
|  | $$σ\_{a}^{2}$$ | 0.526 | 0.15 | 0.251 | 0.519 | 0.828 | 0.503 |
|  | $$σ\_{pe}^{2}$$ | 0.201 | 0.141 | 0.0461 | 0.16 | 0.526 | 0.0447 |
|  | *h2* | 0.272 | 0.0443 | 0.189 | 0.27 | 0.362 | 0.268 |
|   | *r* | 0.42 | 0.0465 | 0.329 | 0.42 | 0.51 | 0.424 |
| Udder width | $$σ\_{e}^{2}$$ | 2.32 | 0.211 | 1.88 | 2.33 | 2.69 | 2.36 |
|  | $$σ\_{a}^{2}$$ | 0.422 | 0.179 | 0.144 | 0.397 | 0.823 | 0.278 |
|  | $$σ\_{pe}^{2}$$ | 0.187 | 0.194 | 0.0295 | 0.0968 | 0.698 | 0.0294 |
|  | *h2* | 0.129 | 0.0394 | 0.0621 | 0.126 | 0.214 | 0.115 |
|   | *r* | 0.234 | 0.0494 | 0.141 | 0.232 | 0.334 | 0.239 |
| Left teat length | $$σ\_{e}^{2}$$ | 0.0992 | 0.0111 | 0.0793 | 0.0988 | 0.121 | 0.098 |
|  | $$σ\_{a}^{2}$$ | 0.085 | 0.0153 | 0.0577 | 0.0843 | 0.116 | 0.0833 |
|  | $$σ\_{pe}^{2}$$ | 0.0002 | 0.0005 | 0 | 0.0001 | 0.0015 | 0 |
|  | *h2* | 0.462 | 0.036 | 0.391 | 0.462 | 0.533 | 0.472 |
|   | *r* | 0.463 | 0.036 | 0.392 | 0.533 | 0.472 | 0.463 |

MAP =maximum a posteriori probability

1$σ\_{e}^{2}$= variance of e = vector of random residual effects

2$σ\_{a}^{2}$ = variance of a = vector of random animal effects

3$σ\_{pe}^{2}$= variance of u = vector of random permanent environmental effects associated with ewes

*h2 = heritability*

**Table S3** *Marginal posterior distributions of variance components, heritabilities and repeatabilities of binary traits for udder phenotypes in ewes estimated with an individual animal model with repeated records*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Trait | Parameter | Mean | SD | Percentiles | MAP |
|   |   |   |   | 2.50% | 50% | 97.50% |   |
| Chronic mastitis | $σ\_{a}^{2}$1 | 0.36278 | 0.23669 | 0.04078 | 0.31901 | 0.92031 | 0.21607 |
| $σ\_{pe}^{2}$2 | 0.0005 | 0.00242 | 0.00001 | 0.00007 | 0.00174 | 0.00002 |
|  | *h23* | 0.09666 | 0.05219 | 0.02226 | 0.0884 | 0.21917 | 0.05832 |
|   | *r* | 0.09671 | 0.05219 | 0.0223 | 0.08844 | 0.21919 | 0.05925 |
| Left teat Lesion | $$σ\_{a}^{2}$$ | 0.48234 | 0.35379 | 0.04008 | 0.40653 | 1.39118 | 0.19756 |
| $$σ\_{pe}^{2}$$ | 0.00038 | 0.00165 | 0.00001 | 0.00007 | 0.00166 | 0.00002 |
|  | *h2* | 0.12342 | 0.07273 | 0.023 | 0.11073 | 0.29431 | 0.06695 |
|   | *r* | 0.12346 | 0.07273 | 0.02306 | 0.11076 | 0.29435 | 0.06692 |
| Right teat Lesion | $$σ\_{a}^{2}$$ | 0.56167 | 0.3806 | 0.0598 | 0.4863 | 1.48308 | 0.33203 |
| $$σ\_{pe}^{2}$$ | 0.00035 | 0.00152 | 0.00001 | 0.00007 | 0.00162 | 0.00002 |
|  | *h2* | 0.14128 | 0.07426 | 0.03278 | 0.1304 | 0.31263 | 0.10039 |
|   | *r* | 0.14132 | 0.07425 | 0.03283 | 0.13045 | 0.31267 | 0.10042 |
| Any teat lesion | $$σ\_{a}^{2}$$ | 0.37653 | 0.26795 | 0.03245 | 0.32027 | 1.06284 | 0.16672 |
| $$σ\_{pe}^{2}$$ | 0.00044 | 0.00203 | 0.00001 | 0.00007 | 0.00167 | 0.00002 |
|  | *h2* | 0.09919 | 0.05885 | 0.01841 | 0.08897 | 0.23909 | 0.05199 |
|   | *r* | 0.09923 | 0.05884 | 0.01846 | 0.089 | 0.23918 | 0.06561 |

MAP =maximum a posteriori probability

1$σ\_{a}^{2}$ = variance of a = vector of random animal effects

2$σ\_{pe}^{2}$= variance of u = vector of random permanent environmental effects associated with ewes

3*h2 = heritability*

**Table S4** *Marginal distributions of variance components and heritabilities from an individual animal model INLA analyses of continuous udder traits in ewes with a fixed effect of litter size either included or excluded from the model*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Trait | Litter size in model  | Parameter | Mean | SD |   | Percentiles | MAP |
|   |   |   |   | 2.50% | 50% | 97.50% |   |
| Teat placement | Yes | $σ\_{e}^{2}$1 | 0.714 | 0.078 | 0.571 | 0.712 | 0.868 | 0.71 |
|  |  | $σ\_{a}^{2}$2 | 0.302 | 0.089 | 0.15 | 0.296 | 0.487 | 0.284 |
|  |  | *h2* | 0.303 | 0.042 | 0.223 | 0.302 | 0.387 | 0.303 |
|  | No | $$σ\_{e}^{2}$$ | 0.713 | 0.078 | 0.571 | 0.711 | 0.867 | 0.71 |
|  |  | $$σ\_{a}^{2}$$ | 0.302 | 0.089 | 0.15 | 0.296 | 0.486 | 0.284 |
|   |   | *h2* | 0.303 | 0.042 | 0.224 | 0.303 | 0.387 | 0.299 |
| Udder drop | Yes | $$σ\_{e}^{2}$$ | 0.494 | 0.048 | 0.403 | 0.494 | 0.586 | 0.497 |
|  |  | $$σ\_{a}^{2}$$ | 0.108 | 0.051 | 0.029 | 0.102 | 0.218 | 0.084 |
|  |   | *h2* | 0.187 | 0.044 | 0.108 | 0.185 | 0.278 | 0.189 |
|  | No | $$σ\_{e}^{2}$$ | 0.496 | 0.05 | 0.403 | 0.496 | 0.591 | 0.499 |
|  |  | $$σ\_{a}^{2}$$ | 0.122 | 0.053 | 0.039 | 0.117 | 0.237 | 0.1 |
|   |   | *h2* | 0.206 | 0.044 | 0.126 | 0.204 | 0.297 | 0.199 |
| Degree of separation | Yes | $$σ\_{e}^{2}$$ | 1.292 | 0.15 | 1.02 | 1.29 | 1.583 | 1.295 |
|  |  | $$σ\_{a}^{2}$$ | 0.504 | 0.171 | 0.228 | 0.49 | 0.862 | 0.454 |
|  |   | *h2* | 0.288 | 0.044 | 0.205 | 0.288 | 0.377 | 0.284 |
|  | No | $$σ\_{e}^{2}$$ | 1.285 | 0.15 | 1.014 | 1.283 | 1.575 | 1.286 |
|  |  | $$σ\_{a}^{2}$$ | 0.513 | 0.171 | 0.235 | 0.499 | 0.87 | 0.465 |
|   |   | *h2* | 0.293 | 0.044 | 0.209 | 0.292 | 0.381 | 0.294 |
| Udder width | Yes | $$σ\_{e}^{2}$$ | 2.533 | 0.193 | 2.152 | 2.535 | 2.91 | 2.544 |
|  |  | $$σ\_{a}^{2}$$ | 0.323 | 0.172 | 0.085 | 0.292 | 0.732 | 0.213 |
|  |   | *h2* | 0.106 | 0.038 | 0.043 | 0.103 | 0.191 | 0.097 |
|  | No | $$σ\_{e}^{2}$$ | 2.583 | 0.204 | 2.187 | 2.584 | 2.982 | 2.594 |
|  |  | $$σ\_{a}^{2}$$ | 0.368 | 0.189 | 0.094 | 0.336 | 0.81 | 0.26 |
|   |   | *h2* | 0.116 | 0.039 | 0.051 | 0.113 | 0.203 | 0.106 |
| Left teat length | Yes | $$σ\_{e}^{2}$$ | 0.111 | 0.014 | 0.085 | 0.111 | 0.139 | 0.111 |
|  |  | $$σ\_{a}^{2}$$ | 0.076 | 0.018 | 0.046 | 0.075 | 0.113 | 0.072 |
|  |   | *h2* | 0.405 | 0.04 | 0.328 | 0.405 | 0.484 | 0.405 |
|  | No | $$σ\_{e}^{2}$$ | 0.11 | 0.014 | 0.084 | 0.11 | 0.138 | 0.11 |
|  |  | $$σ\_{a}^{2}$$ | 0.08 | 0.018 | 0.049 | 0.079 | 0.117 | 0.077 |
|   |   | *h2* | 0.421 | 0.039 | 0.344 | 0.421 | 0.498 | 0.423 |

INLA = Integrated Nested Laplace Approximation

MAP =maximum a posteriori probability

1$σ\_{e}^{2}$= variance of e = vector of random residual effects

2$σ\_{a}^{2}$ = variance of a = vector of random animal effects

*h2 = heritability*

**Table S5** *Marginal distributions of sire and additive genetic variances and heritabilities from the sire model INLA analyses of binomial udder traits in ewes with a fixed effect of litter size either included or excluded from the model*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Trait | Litter size included  | Parameter | Mean | SD |   | Percentiles | MAP |
|   |   |   |   | 2.50% | 50% | 97.50% |   |
| Chronic mastitis | Yes | $σ\_{s}^{2}$1 | 0.158 | 0.109 | 0.015 | 0.136 | 0.428 | 0.09 |
|  | $σ\_{a}^{2}$2 | 0.632 | 0.435 | 0.061 | 0.544 | 1.712 | 0.359 |
|  |   | *h2* | 0.18 | 0.117 | 0.019 | 0.159 | 0.46 | 0.113 |
|  | No | $$σ\_{s}^{2}$$ | 0.148 | 0.105 | 0.013 | 0.126 | 0.416 | 0.079 |
|  |  | $$σ\_{a}^{2}$$ | 0.593 | 0.42 | 0.054 | 0.504 | 1.664 | 0.315 |
|   |   | *h2* | 0.169 | 0.113 | 0.016 | 0.148 | 0.449 | 0.1 |
| Left teat lesion | Yes | $$σ\_{s}^{2}$$ | 0.114 | 0.075 | 0.007 | 0.102 | 0.267 | 0.03 |
|  |  | $$σ\_{a}^{2}$$ | 0.454 | 0.3 | 0.03 | 0.407 | 1.067 | 0.121 |
|  |   | *h2* | 0.132 | 0.084 | 0.009 | 0.12 | 0.3 | 0.038 |
|  | No | $$σ\_{s}^{2}$$ | 0.114 | 0.075 | 0.008 | 0.105 | 0.265 | 0.031 |
|  |  | $$σ\_{a}^{2}$$ | 0.458 | 0.298 | 0.03 | 0.418 | 1.059 | 0.123 |
|   |   | *h2* | 0.133 | 0.084 | 0.009 | 0.123 | 0.298 | 0.04 |
| Right teat lesion | Yes | $$σ\_{s}^{2}$$ | 0.221 | 0.165 | 0.016 | 0.182 | 0.636 | 0.098 |
|  |  | $$σ\_{a}^{2}$$ | 0.882 | 0.66 | 0.065 | 0.728 | 2.543 | 0.392 |
|  |   | *h2* | 0.243 | 0.168 | 0.02 | 0.21 | 0.648 | 0.127 |
|  | No | $$σ\_{s}^{2}$$ | 0.229 | 0.17 | 0.018 | 0.191 | 0.661 | 0.108 |
|  |  | $$σ\_{a}^{2}$$ | 0.918 | 0.679 | 0.071 | 0.764 | 2.645 | 0.432 |
|   |   | *h2* | 0.253 | 0.171 | 0.022 | 0.22 | 0.669 | 0.139 |
| Any teat lesion | Yes | $$σ\_{s}^{2}$$ | 0.113 | 0.075 | 0.007 | 0.1 | 0.266 | 0.03 |
|  |  | $$σ\_{a}^{2}$$ | 0.452 | 0.3 | 0.03 | 0.401 | 1.065 | 0.12 |
|  |   | *h2* | 0.131 | 0.084 | 0.009 | 0.118 | 0.299 | 0.038 |
|  | No | $$σ\_{s}^{2}$$ | 0.13 | 0.086 | 0.008 | 0.114 | 0.304 | 0.034 |
|  |  | $$σ\_{a}^{2}$$ | 0.514 | 0.345 | 0.034 | 0.455 | 1.216 | 0.138 |
|   |   | *h2* | 0.149 | 0.096 | 0.01 | 0.134 | 0.338 | 0.044 |

INLA = Integrated Nested Laplace Approximation

MAP =maximum a posteriori probability

1$σ\_{s}^{2}$= variance of s = vector of random sire effects

2$σ\_{a}^{2}$ = variance of a = vector of random animal effects

*h2 = heritability*

**Table S6** *Correlations between maximum a posteriori estimated breeding value udder traits of sires with more than 5 ewe offspring*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 2. Udder drop | 0.24 |  |  |  |  |  |  |  |
| 3. Degree of separation | -0.29 | -0.13 |  |  |  |  |  |  |
| 4. Udder width | -0.21 | -0.57 | 0.31 |  |  |  |  |  |
| 5. Left teat length | 0.09 | -0.26 | 0.00 | 0.20 |  |  |  |  |
| 6. Udder coded | -0.18 | -0.08 | -0.25 | -0.06 | 0.22 |  |  |  |
| 7. Left teat coded | -0.09 | -0.12 | -0.12 | -0.16 | 0.01 | -0.04 |  |  |
| 8. Right teat coded | -0.17 | -0.16 | -0.05 | 0.07 | -0.10 | 0.17 | 0.44 |  |
| 9. Teats coded | -0.13 | -0.13 | -0.10 | -0.01 | -0.18 | -0.04 | 0.69 | 0.86 |

1 = Teat placement

**Supplementary Figure S1** *Mode and 95% confidence interval of posterior marginal distribution of heritability of continuous traits of udder morphology in Texel sheep as the mode and informativeness of the prior distribution of heritability varies*



**Supplementary Figure S2** *Mode and 95% confidence interval of posterior marginal distribution of heritability of binary phenotypic udder traits in Texel ewes as the mode and informativeness of the prior distribution of heritability varies*

