

Reducing the period of data collection for intake and gain to improve response to selection for feed efficiency in beef cattle

Richard Mark Thallman,^{*,1,2} Larry A. Kuehn,^{*,2} Warren M. Snelling,^{*} Kelli J. Retallick,[†]
Jennifer M. Bormann,[†] Harvey C. Freetly,^{*} Kristen E. Hales,^{*} Gary L. Bennett,^{*} Robert L. Weaver,[†]
Daniel W. Moser,[†] and Michael D. MacNeil^{†,‡,||}

^{*}USDA, ARS, USMARC, Genetics, Breeding, and Animal Health Research Unit, Clay Center, NE 68933;
[†]Department of Animal Science, Kansas State University, Manhattan, KS 66502; [‡]Delta G, Miles City, MT 5930;
^{||}University of the Free State, Bloemfontein 9300, South Africa

ABSTRACT: Shortening the period of recording individual feed intake may improve selection response for feed efficiency by increasing the number of cattle that can be recorded given facilities of fixed capacity. Individual DMI and ADG records of 3,462 steers and 2,869 heifers over the entire intake recording period (range 62 to 154 d; mean 83 d; DMI83 and ADG83, respectively), DMI and ADG for the first 42 d of the recording period (DMI42 and ADG42, respectively), and postweaning ADG based on the difference between weaning and yearling weights (PADG) were analyzed. Genetic correlations among DMI42 and DMI83, ADG42 and ADG83, ADG42 and PADG, and ADG83 and PADG were 0.995, 0.962, 0.852, and 0.822, respectively. Four objective functions [feed:gain ratio in steers (FGS) and heifers (FGH); residual gain (RG); and residual feed intake (RFI)] based on DMI83 and ADG83 were considered. Indices using DMI42 and ADG42 (I42); DMI42 and PADG (IPW); and DMI42, ADG42, and PADG (IALL) were developed. Accuracy of the 5 EBV, 4 objectives, and 12 objective × index combinations were computed for all 12,033 animals in the pedigree. Accuracies of indices (IA) were summarized for animals with accuracies for objectives (OA) of 0.25, 0.5, 0.75,

and 1. For the RG objective and animals with OA of 0.75, indices I42, IPW, and IALL had IA of 0.63, 0.55, and 0.67, respectively. Differences in IA increased with increased emphasis on ADG83 in the objective. Differences in IA between I42 and IPW usually increased with OA. Relative efficiency (RE) of selection on 42-d tests compared with 83 d was computed based on differences in IA and selection intensities of 5%, 25%, 50%, and 75% under the 83-d scenario, assuming 65% more animals could be tested for 42 d. For 25% selected for the RG objective, and animals with OA of 0.75, indices I42, IPW, and IALL had RE of 1.02, 0.90, and 1.10, respectively. As % selected, OA, and emphasis on DMI increased, RE increased. Relative efficiency varied considerably according to assumptions. One-half of the scenarios considered had RE > 1.15 with a maximum of 2.02 and 77% RE > 1.0. A shorter period of recording DMI can improve selection response for feed efficiency. Selection for the efficiency objectives would not affect PADG. It will be most effective if ADG over the period coinciding with intake recording and ADG over a much longer period of time are simultaneously included in a multiple-trait genetic evaluation with DMI and used in a selection index for efficiency.

Key words: beef cattle, feed efficiency, selection index

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¹Corresponding author: Mark.Thallman@ars.usda.gov

²These authors contributed equally to this work.

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INTRODUCTION

Feed efficiency has been a topic of great interest for more than a century ([Mumford et al.](#),

1917). Byerly (1941) found variation in DMI independent of BW and level of production and proposed the index now referred to as residual feed intake (RFI) and commonly attributed to Koch et al. (1963). However, Koch et al. (1963) recommended use of ADG adjusted for DMI as the preferred measure of biological efficiency because it was considered the most accurate mathematical description of cause and effect. Lin (1980) and Gunsett (1984) suggested a linear selection index to improve traits defined as ratios, such as DMI/ADG. For beef cattle, protocols suggesting the concurrent measurement of DMI and ADG over a period of 70 d following a 21-d adaptation period have been recommended for calculating feed efficiency (Beef Improvement Federation, 2016). However, the test period required to accurately measure DMI is of considerably shorter duration (Archer et al., 1997; Archer and Bergh, 2000; Wang et al., 2006). Calculation of postweaning ADG as the difference between weights taken at *circa* 205 d and 365 d is routine (Beef Improvement Federation, 2016). Multiple-trait genetic evaluation of DMI and ADG as separate traits is feasible (MacNeil et al., 2011) and lends itself to calculation of EBV for efficiency without loss of information (Kennedy et al., 1993). Manafiazar et al. (2017) found that shortening the feed intake period to 42 d could facilitate more powerful experiments that target DMI or efficiency phenotypes and/or reduce their cost. However, use of DMI recorded over a shortened test period remains relatively unexplored in the context of genetic evaluation of feed efficiency. The objective was to evaluate indices in the context of national genetic evaluation for their accuracy in predicting feed efficiency from short-duration DMI tests and to estimate differences in selection response due to short-duration tests. A secondary objective was to estimate genetic parameters for differing test period durations.

MATERIALS AND METHODS

Data used came from 3,462 steers and 2,869 heifers born between 2003 and 2014 at the U.S. Meat Animal Research Center (USMARC), Clay Center, NE. The USMARC Institutional Animal Care and Use Committee approved the procedures used and the data were collected in accordance with Federation of Animal Science Societies (FASS, 2010) guidelines. Portions of these data were used in previous studies (Rolfe et al., 2011; Retallick et al., 2017) with the methodology described providing further details. Data from these studies were

included in this analysis to improve estimation of (co)variance components.

Dry matter intake and BW data collection during DMI trials were described in Retallick et al. (2017). Briefly, DMI was recorded on animals born from 2003 to 2007 (and some from 2008) using Calan Broadbent Feeding Systems (American-Calan-Broadbent, Northwood, NH, USA) in pens with 4 to 8 animals. Feed refusals were collected once per week. The remainder of the animals' DMI records was collected using an Insentec System (Hokofarm B.V., Marknesse, The Netherlands). Intake recording periods ranged from 62 to 154 d (average 83 d). Steers were fed a high-concentrate finishing ration while heifers were fed a forage-based ration for development as breeding heifers. Animals were weighed once every 2 or 3 wk during the DMI trials, and on 2 consecutive days at the start and the end of the trials. Average daily gain was derived by fitting a quadratic regression to the weights of each animal and subtracting the predicted initial weight from the predicted final weight and dividing by the number of days. In addition to average daily DMI and ADG recorded from the trial, we also derived a shortened test period DMI and ADG for the first 42 d, which were computed from quadratic regression of weights on 2 consecutive days at the start of trial and the next 2 or 3 weights, depending on whether animals were weighed every 2 or 3 wk. Because the data were censored retrospectively, double BW were not available for the end of the artificial 42-d trial.

(Co)variance components were estimated using REML procedures of ASReml (version 4.0; VSN International, Ltd, Hemel Hempstead, UK). The multiple-trait model included DMI from the short test period (DMI42); DMI from the long test period (DMI83); ADG from the short and long test periods (ADG42 and ADG83), respectively; and postweaning ADG calculated from the difference between adjusted weaning and yearling weights (PADG). Fixed independent variables were sex, contemporary group classifications and linear effects of age on test (all traits except PADG), direct heterosis (fraction of expected breed heterozygosity to account for heterosis), and proportions of each breed. Details of expected breed heterozygosity and breed proportions were described in Ahlberg et al. (2016). Random effects for each trait were additive direct genetic effects of 12,033 animals in the pedigree and the residuals.

Contemporary groups for DMI42, DMI83, ADG42, and ADG83 were defined as the group of animals of the same sex, tested in the same facility, during the same time period. This usually encompassed sex and year-season of birth, but heifers born from 2005 through 2007 were tested in 2 randomly

allocated, 84-d shifts. One-half were tested from late November to mid-February and one-half from early March to late May; while 1 shift was on trial, the other shift was fed a similar ration in typical feedlot pens. One-third of the steers born in spring 2013 were fed 154 d, while the remaining two-thirds were fed only 63 d to free the facility for a different project. Contemporary groups for PADG were more like those for weight traits in national cattle evaluation: they considered animal groupings at both weaning and yearling weights. Each birth year-season typically included several PADG contemporary groups, comprising calves weaned from various management units across the research center. There were 226 animals that did not have PADG records because they did not have adjusted yearling weights.

The breeding objective function used to compare strategies would ideally be based on concurrent measurement of DMI and ADG over an extended period. The traits in the available data that are closest to the ideal are DMI83 and ADG83, respectively; therefore, the objective function was based on them. An objective function of two traits must specify the economic value of one trait relative to the other, in this case, the value of a kilogram of feed consumed relative to the value of a kilogram of BW gained. Four objective functions, each with a different empirically determined relative economic value, were used to compare strategies. Following Lin (1980), the first 2 objective functions were based on feed efficiency expressed as feed:gain ratio in steers (FGS) and heifers (FGH). Thus, the economic weight assigned to ADG83 was 1.0 and the weight assigned to DMI83 was the negative of the ratio of the mean ADG83 to mean DMI83 in steers and heifers, respectively. For the third objective, residual gain (RG), the economic weights were predicated on improvement of ADG83 while holding DMI83 constant. Thus, the economic weight assigned to ADG83 was 1.0 and the weight assigned to DMI83 was the negative of the genetic regression of ADG83 on DMI83 (Eisen, 1977; Lin, 1980). Similarly, economic weights for the fourth objective, RFI, were predicated on improvement of DMI83 while holding ADG83 constant, such that the economic weights were 1.0 for ADG83 and the negative reciprocal of the genetic regression of DMI83 on ADG83 for DMI83 (Lin, 1980).

For each of the 4 breeding objectives, 3 selection indices were calculated from subsets of the 3 remaining traits to determine the most effective way to utilize feed intake recorded over a short period (DMI42). Each of those indices included DMI42 as the measure of intake and differed in the

subset of traits used to evaluate gain: 1) DMI42 and ADG42; 2) DMI42 and PADG; and 3) DMI42, ADG42, and PADG. Each objective function was also compared with the 3 indices derived from it to evaluate the relative efficiency (RE) of long- and short-duration tests.

Following Schneeberger et al. (1992), index weights (\mathbf{b}) were calculated as:

$$\mathbf{b} = \mathbf{G}_{11}^{-1} \mathbf{G}_{12} \mathbf{v}$$

where \mathbf{G}_{11} = the $m \times m$ genetic variance-covariance matrix for the selection criteria [where m is the number of traits (2 or 3) in the index]; \mathbf{G}_{12} = the $m \times 2$ genetic covariance matrix that relates selection criteria to the 2 traits in the breeding objective; and \mathbf{v} = the 2×1 vector of economic values for the 2 traits in the breeding objective.

Each of the 3 indices described above was computed in a separate multiple-trait BLUP analysis including only the traits represented in that particular index. Predicted index values and their SE of prediction were computed using the PREDICT statement of ASReML, which computes a linear function of the solution vector and its SE. For computation of selection indices, the form is $\mathbf{b}'\hat{\mathbf{u}}$. Four PREDICT statements, 1 using the index weights for each objective function, were included in the BLUP analysis for each index. These BLUP analyses were conditional on variance components estimated in the 5-trait REML analysis described above. Predictions of the objective functions and their SE of prediction were computed by 4 PREDICT statements (with $\mathbf{b}' = \mathbf{v}'$) in a BLUP analysis of all 5 traits.

The accuracy of the index for prediction of the breeding objective, following the notation and derivations in Schneeberger et al. (1992) is:

$$\begin{aligned} \text{Corr}(\mathbf{b}'\hat{\mathbf{u}}_i, \mathbf{v}'\mathbf{g}_i) &= \frac{\mathbf{b}'\text{Cov}(\hat{\mathbf{u}}_i, \mathbf{g}_i')\mathbf{v}}{\sqrt{\text{Var}(\mathbf{b}'\hat{\mathbf{u}}_i)\mathbf{v}'\text{Var}(\mathbf{g}_i)\mathbf{v}}} \\ &= \frac{\mathbf{b}'\text{Var}(\hat{\mathbf{u}}_i)\mathbf{G}_{11}^{-1}\mathbf{G}_{12}\mathbf{v}}{\sqrt{\text{Var}(\mathbf{b}'\hat{\mathbf{u}}_i)\mathbf{v}'\mathbf{a}_{ii}\mathbf{G}_{22}\mathbf{v}}} \\ &= \frac{\mathbf{b}'\text{Var}(\hat{\mathbf{u}}_i)\mathbf{b}}{\sqrt{\text{Var}(\mathbf{b}'\hat{\mathbf{u}}_i)\mathbf{v}'\mathbf{a}_{ii}\mathbf{G}_{22}\mathbf{v}}} \\ &= \sqrt{\frac{\text{Var}(\mathbf{b}'\hat{\mathbf{u}}_i)}{\mathbf{a}_{ii}\mathbf{v}'\mathbf{G}_{22}\mathbf{v}}} \\ &= \sqrt{\frac{\mathbf{a}_{ii}\mathbf{b}'\mathbf{G}_{11}\mathbf{b} - \text{SEP}(\mathbf{b}'\hat{\mathbf{u}}_i)^2}{\mathbf{a}_{ii}\mathbf{v}'\mathbf{G}_{22}\mathbf{v}}} \end{aligned}$$

where $\hat{\mathbf{u}}_i$ is the vector of EBV of traits in the index for an individual, \mathbf{g}_i is the vector of breeding values of traits in the objective function for the same individual, a_{ii} is the diagonal element of the numerator relationship matrix for that individual (1 + inbreeding), \mathbf{G}_{22} is the genetic variance–covariance matrix for the traits in the breeding objective, and $\text{SEP}(\mathbf{b}'\hat{\mathbf{u}}_i)$ is the SE of prediction of the index.

The accuracy of the index simplifies in special cases. If the EBV are assumed to have complete accuracy, it is:

$$\text{Corr}(\mathbf{b}'\hat{\mathbf{u}}_i, \mathbf{v}'\mathbf{g}_i) = \sqrt{\frac{\mathbf{b}'\mathbf{G}_{11}\mathbf{b}}{\mathbf{v}'\mathbf{G}_{22}\mathbf{v}}}$$

and the accuracy of prediction of the objective function is:

$$\begin{aligned} \text{Corr}(\mathbf{v}'\hat{\mathbf{u}}_i, \mathbf{v}'\mathbf{g}_i) &= \sqrt{\frac{a_{ii}\mathbf{v}'\mathbf{G}_{22}\mathbf{v} - \text{SEP}(\mathbf{v}'\hat{\mathbf{u}}_i)^2}{a_{ii}\mathbf{v}'\mathbf{G}_{22}\mathbf{v}}} \\ &= \sqrt{1 - \frac{\text{SEP}(\mathbf{v}'\hat{\mathbf{u}}_i)^2}{a_{ii}\mathbf{v}'\mathbf{G}_{22}\mathbf{v}}} \end{aligned}$$

(similar to the accuracy of an EBV).

The efficiency of 42-d tests relative to 83-d tests was computed from the relative accuracies of indices computed from tests of the 2 putative lengths and from assumptions regarding the relative selection intensities of DMI tests of the respective lengths. Assuming a 21-d dietary adaptation period, $1.65 = (83 \text{ d} + 21 \text{ d}) / (42 \text{ d} + 21 \text{ d})$ as many animals could be tested annually in given infrastructure with 42-d test periods as with 83-d. Relative efficiency was computed for 4 alternative scenarios of proportion selected: 5%, 25%, 50%, or 75% selected from 83-d tests with corresponding selection intensities of 2.063, 1.271, 0.798, and 0.424, respectively. Selecting the same number of parents from 42-d tests results in proportions selected of 3.0%,

15.1%, 30.3%, or 45.4% with corresponding selection intensities of 2.264, 1.549, 1.224, and 0.873, respectively. Relative efficiency was computed as:

$$\text{Relative efficiency} = \frac{\text{accuracy of the 42-d index} \times \text{selection intensity with 42-d test}}{\text{accuracy of the 83-d index} \times \text{selection intensity with 83-d test}}$$

Indices were compared on accuracy and RE for samples of animals with objective accuracies adjusted to 0.25, 0.5, and 0.75. For each of the 4 objectives, the linear regression of index accuracy on objective accuracy was computed for between 929 and 1,231 animals with accuracies ranging from 0.2 to 0.3, between 893 and 3,092 animals with accuracies ranging from 0.45 to 0.55, and between 37 and 289 animals with accuracies ranging from 0.7 to 0.8. These regressions were used to adjust the index accuracies of these animals to objective accuracies of 0.25, 0.5, or 0.75, respectively.

RESULTS AND DISCUSSION

Phenotypic means and SD that characterize the animals used in this study are presented in [Table 1](#). As would be expected, animals fed over a longer test period consumed more feed each day and the associated SD were reduced. Likewise, extending the interval over which ADG was measured reduced the phenotypic variation among animals.

It is noteworthy that both genetic and residual variances decreased with increasing duration over which DMI and ADG were measured ([Table 2](#)), whereas the estimates of heritability for ADG increased ([Table 3](#)). On the other hand, estimates of heritabilities of DMI were similar over 42 or 83 d. Estimates of heritability reported herein were similar to those resulting from a subset of these data collected over a 140-d test period ([Rolfe et al., 2011](#)), but were substantially less than those reported by [Arthur et al. \(1997\)](#) for a 119-d test. [Archer et al. \(1997\)](#) observed only minor effects of

Table 1. Estimates of means (\bar{x}) and SD for measures of DMI (kg/d) and ADG (kg/d) in steers and heifers

	DMI42 ^a		DMI83		ADG42		ADG83		PADG	
	\bar{x}	SD	\bar{x}	SD	\bar{x}	SD	\bar{x}	SD	\bar{x}	SD
Heifers (n = 2,869)	7.71	1.11	8.10	1.03	1.03	0.23	0.93	0.18	1.00	0.13
Steers (n = 3,462)	9.12	1.25	9.62	1.17	1.79	0.32	1.60	0.24	1.65	0.16

^aADG83 and DMI83 were ADG and DMI, respectively, over the entire test period, which averaged 83 d; ADG42 and DMI42 were ADG and DMI, respectively, over the first 42 d of test period; PADG was postweaning ADG.

Table 2. Estimates and SE of genetic (on diagonal) and residual (bottom row) variances and genetic (above diagonal) and residual (below diagonal) covariances for measures of DMI (kg/d) and ADG (kg/d)

Traits ^a	DMI42	DMI83	ADG42	ADG83	PADG
DMI42	0.511 ± 0.047	0.487 ± 0.044	0.052 ± 0.008	0.042 ± 0.006	0.053 ± 0.005
DMI83	0.805 ± 0.036	0.470 ± 0.042	0.051 ± 0.008	0.042 ± 0.006	0.050 ± 0.005
ADG42	0.127 ± 0.007	0.129 ± 0.007	0.012 ± 0.002	0.010 ± 0.001	0.009 ± 0.001
ADG83	0.080 ± 0.006	0.103 ± 0.005	0.039 ± 0.001	0.010 ± 0.001	0.008 ± 0.001
PADG	0.071 ± 0.004	0.073 ± 0.004	0.017 ± 0.001	0.014 ± 0.001	0.009 ± 0.001
Residual variance	0.973 ± 0.040	0.824 ± 0.035	0.072 ± 0.002	0.038 ± 0.001	0.016 ± 0.001

^aADG83 and DMI83 were ADG and DMI, respectively, over the entire test period, which averaged 83 d; ADG42 and DMI42 were ADG and DMI, respectively, over the first 42 d of test period; PADG was postweaning ADG.

Table 3. Estimates and SE of heritabilities (on diagonal), genetic (above diagonal), and residual (below diagonal) correlations among measures of DMI and ADG

Traits ^a	DMI42	DMI83	ADG42	ADG83	PADG
DMI42	0.344 ± 0.029	0.995 ± 0.003	0.647 ± 0.059	0.600 ± 0.057	0.769 ± 0.032
DMI83	0.899 ± 0.005	0.363 ± 0.029	0.665 ± 0.055	0.625 ± 0.050	0.766 ± 0.030
ADG42	0.479 ± 0.019	0.529 ± 0.018	0.147 ± 0.023	0.962 ± 0.023	0.852 ± 0.046
ADG83	0.416 ± 0.021	0.582 ± 0.018	0.738 ± 0.009	0.200 ± 0.026	0.822 ± 0.038
PADG	0.563 ± 0.019	0.625 ± 0.018	0.505 ± 0.018	0.559 ± 0.018	0.361 ± 0.030

^aADG83 and DMI83 were ADG and DMI, respectively, over the entire test period, which averaged 83 d; ADG42 and DMI42 were ADG and DMI, respectively, over the first 42 d of test period; PADG was postweaning ADG.

the period over which data were collected beyond 42 d on estimates of either additive genetic variance or heritability of both DMI and ADG. The selection indices are described in [Table 4](#). Following [Lin \(1980\)](#), economic weights for DMI83 in the feed:gain ratio breeding objectives were -0.115 for heifers and -0.166 for steers. The economic weights for DMI83 in the RG and RFI objectives were -0.089 and -0.228 , respectively. The economic weight for ADG83 in all objectives was 1.0.

Accuracies of the selection indices are summarized in [Table 5](#). The average (SD) objective function accuracies for steers with DMI were 0.566 (0.035), 0.578 (0.033), 0.618 (0.029), and 0.651 (0.026) for RG, FGH, FGS, and RFI, respectively, and 0.570 (0.034), 0.583 (0.032), 0.623 (0.029), and 0.657 (0.026), respectively, for heifers with DMI.

The dams of many of the animals in this study also had been recorded for DMI as heifers; therefore, accuracies of evaluation reached higher levels than would be typical in seedstock operations that measure DMI only on the top fraction of bulls produced in the herd. Sires (not measured themselves) ranged from 1 to several hundred progeny measured for DMI.

The estimated genetic correlation of 0.995 between DMI42 with DMI83 ([Table 3](#)) suggests it may be possible to shorten the DMI recording period beyond 42 d without impacting the accuracy of the DMI evaluation.

Test periods shorter than 42 d may be beneficial, but in this retrospective analysis of data collected for other purposes, it was not feasible to pair ADG records with DMI collected over shorter periods, because some groups were weighed at 2-wk intervals and others at 3-wk intervals. A practical factor limiting the benefits of shortening the test period too far is the time (several weeks usually, 21 d recommended in [Beef Improvement Federation, 2016](#)) required to train new animals to effectively use and become accustomed to DMI recording equipment; thus, halving the test period does not double throughput.

Double weights at the end of the 42-d trial were not available in these data; thus, ADG42 had an additional source of residual variation relative to ADG83 that is not due to length of the test. In designing a testing scheme based on short DMI trials, weighing on 2 successive days at the beginning and end of test, foregoing midpoint tests, and fitting a linear regression might result in lower residual variance and higher heritability of ADG42 with the same or fewer trips across the BW scale.

For the purpose of genetic evaluation, previous studies ([Archer et al., 1997](#); [Archer and Bergh, 2000](#); [Wang et al., 2006](#); [Culbertson et al., 2015](#)) and this work clearly support the contention that a test of 42-d duration is sufficient for measuring DMI in growing beef cattle. The substantial magnitude of

Table 4. Description of selection indices to improve breeding objectives for feed efficiency

Breeding objective ^a	Emphasis on DMI ^b	Gain traits in index ^{a,c}	Index weights		
			DMI42	ADG42	PADG
FGS ^d (ADG83 – 0.166 DMI83)	1.166	ADG42	-0.160	0.829	
		PADG	-0.170		0.898
		ADG42, PADG	-0.167	0.756	0.319
FGH (ADG83 – 0.115 DMI83)	0.805	ADG42	-0.112	0.840	
		PADG	-0.121		0.898
		ADG42, PADG	-0.118	0.780	0.115
RG (ADG83 – 0.089 DMI83)	0.625	ADG42	-0.088	0.846	
		PADG	-0.096		0.898
		ADG42, PADG	-0.094	0.792	0.102
RFI (ADG83 – 0.228 DMI83)	1.601	ADG42	-0.218	0.815	
		PADG	-0.229		0.898
		ADG42, PADG	-0.227	0.726	0.169

^aADG83 and DMI83 were ADG (kg/d) and DMI (kg/d), respectively, over the entire test period, which averaged 83 d; ADG42 and DMI42 were ADG (kg/d) and DMI (kg/d), respectively, over the first 42 d of test period; PADG was postweaning ADG (kg/d).

^bEmphasis on DMI was computed as (|relative economic value of DMI83| × genetic SD of DMI83)/(relative economic value of ADG83| × genetic SD of ADG83).

^cAll indices included DMI42 as the measure of DMI.

^dThe objective functions were FGS and FGH; RG; and RFI. The relative economic values of the objective functions are indicated in parentheses on the lines following the abbreviated names of the objectives.

Table 5. Accuracy of selection indices to improve breeding objectives for feed efficiency

Breeding objective ^a	Gain traits in index ^{a,b}	Objective accuracy ^c			
		0.25	0.5	0.75	1.00
FGS ^d (ADG83 – 0.166 DMI83)	ADG42	0.209 (0.003) ^e	0.430 (0.010)	0.667 (0.009)	0.96
	PADG	0.190 (0.005)	0.393 (0.011)	0.608 (0.005)	0.84
	ADG42, PADG	0.216 (0.003)	0.445 (0.008)	0.687 (0.005)	0.96
FGH (ADG83 – 0.115 DMI83)	ADG42	0.181 (0.005)	0.383 (0.015)	0.635 (0.015)	0.95
	PADG	0.175 (0.013)	0.357 (0.025)	0.557 (0.008)	0.75
	ADG42, PADG	0.210 (0.004)	0.429 (0.009)	0.673 (0.007)	0.95
RG (ADG83 – 0.089 DMI83)	ADG42	0.171 (0.006)	0.365 (0.016)	0.629 (0.017)	0.94
	PADG	0.181 (0.018)	0.362 (0.027)	0.552 (0.005)	0.72
	ADG42, PADG	0.212 (0.005)	0.431 (0.008)	0.674 (0.008)	0.94
RFI (ADG83 – 0.228 DMI83)	ADG42	0.224 (0.002)	0.457 (0.006)	0.697 (0.004)	0.98
	PADG	0.208 (0.003)	0.428 (0.007)	0.656 (0.004)	0.91
	ADG42, PADG	0.226 (0.002)	0.461 (0.006)	0.703 (0.003)	0.98

^aADG83 and DMI83 were ADG (kg/d) and DMI (kg/d), respectively, over the entire test period, which averaged 83 d; ADG42 and DMI42 were ADG (kg/d) and DMI (kg/d), respectively, over the first 42 d of test period; PADG was postweaning ADG (kg/d).

^bAll indices included DMI42 as the measure of DMI.

^cIndex accuracies were summarized from data points within ± 0.05 of the stated objective accuracy after adjusting for the slope of the trend line relative to objective accuracy within that interval.

^dThe objective functions were FGS and FGH; RG; and RFI.

^eMean (SD) index accuracy after adjusting for variation in objective accuracy of the animals summarized.

the genetic correlations among measures of ADG across the various periods of time observed in the present study was not anticipated based on the previous studies as well as results from [Retallick et al. \(2017\)](#) in which a substantial portion of the data used herein was analyzed, although the analyses also differed slightly, especially in regard to the sets of traits included and that sexes were combined for this analysis. These genetic correlations led to the

accuracies of selection indices to improve feed efficiency based on data from a 42-d evaluation of DMI and ADG having accuracy ≥ 0.94 ([Table 5](#)) when the objective function has complete accuracy.

Relative efficiency of selection for 42-d tests compared with 83-d tests is reported in [Table 6](#) for 4 scenarios in which the proportion of animals selected to be parents relative to the number tested for DMI under the status quo of longer tests ranged

Table 6. Efficiency of selection indices from 42-d test relative to indices from 83-d test for feed efficiency^a

Breeding objective ^b	Gain traits in index ^{b,c}	Objective accuracy ^d											
		0.5				0.75				1.00			
		% Selected (83-d test) ^e				% Selected (83-d test)				% Selected (83-d test)			
		5	25	50	75	5	25	50	75	5	25	50	75
FGS ^f (ADG83 – 0.166 DMI83)	ADG42	0.94	1.05	1.32	1.77	0.98	1.08	1.36	1.83	1.05	1.17	1.47	1.98
	PADG	0.86	0.96	1.21	1.62	0.89	0.99	1.24	1.67	0.92	1.02	1.29	1.73
	ADG42, PADG	0.98	1.08	1.37	1.83	1.01	1.12	1.40	1.89	1.05	1.17	1.47	1.98
FGH (ADG83 – 0.115 DMI83)	ADG42	0.84	0.93	1.17	1.58	0.93	1.03	1.30	1.74	1.04	1.16	1.46	1.96
	PADG	0.78	0.87	1.10	1.47	0.82	0.91	1.14	1.53	0.82	0.91	1.15	1.54
	ADG42, PADG	0.94	1.05	1.32	1.77	0.98	1.09	1.38	1.85	1.04	1.16	1.46	1.96
RG (ADG83 – 0.089 DMI83)	ADG42	0.80	0.89	1.12	1.50	0.92	1.02	1.29	1.73	1.03	1.15	1.44	1.94
	PADG	0.79	0.88	1.11	1.49	0.81	0.90	1.13	1.52	0.79	0.88	1.10	1.48
	ADG42, PADG	0.95	1.05	1.32	1.77	0.99	1.10	1.38	1.85	1.03	1.15	1.44	1.94
RFI (ADG83 – 0.228 DMI83)	ADG42	1.00	1.11	1.40	1.88	1.02	1.13	1.43	1.91	1.08	1.19	1.50	2.02
	PADG	0.94	1.04	1.31	1.76	0.96	1.07	1.34	1.80	1.00	1.11	1.40	1.87
	ADG42, PADG	1.01	1.12	1.41	1.90	1.03	1.14	1.44	1.93	1.08	1.19	1.50	2.02

^aRelative efficiency was computed as (accuracy of the 42-d index × selection intensity with 42-d test)/(accuracy of the 83-d index × selection intensity with 83-d test).

^bADG83 and DMI83 were ADG (kg/d) and DMI (kg/d), respectively, over the entire test period, which averaged 83 d; ADG42 and DMI42 were ADG (kg/d) and DMI (kg/d), respectively, over the first 42 d of test period; PADG was postweaning ADG (kg/d).

^cAll indices included DMI42 as the measure of DMI.

^dRelative efficiency was summarized from data points within ± 0.05 of the stated objective accuracy after adjusting for the slope of the trend line relative to objective accuracy within that interval.

^eRelative efficiency was evaluated at 5%, 25%, 50%, or 75% of animals tested for 83 d selected to become parents. The same number of parents could be selected from (83 + 21)/(42 + 21) = 1.65 times as many animals tested for 42 d, corresponding to % selected of 3.0%, 15.1%, 30.2%, or 45.4%, respectively. The ratios of corresponding selection intensities possible from 42-d test relative to 83 d are 1.10, 1.22, 1.53, and 2.06, respectively.

^fThe objective functions were FGS and FGH; RG; and RFI.

from 5% to 75%. The scenario of 5% selected corresponds to an elite seedstock producer testing all bulls in the herd to be marketed and selecting only the top 5% of those bulls to sire the next generation in the herd. The scenarios of 25% and 50% selected correspond to seedstock producers sending the top (based on criteria other than DMI) bulls from their herds to a central testing facility and selecting bulls from that reduced set to sire their next generation. The scenarios of 50% and 75% correspond to testing the heifers produced in a seedstock herd and retaining the best based on a feed efficiency index. None of these scenarios are completely realistic because beef cattle breeders select for many economically relevant traits besides feed efficiency. Nonetheless, the amount of improvement in selection response that could be expected across the industry from increasing throughput of existing facilities by shortening the testing period probably falls within the range specified by these scenarios. Relative efficiency was much greater under the

assumption of 75% of tested animals selected than under the scenario of 5%, because the ratios of selection intensities were 2.06 and 1.10, respectively. When selection intensity is high, decreasing proportion selected has little impact on response and can be overwhelmed by a modest increase in accuracy.

Nonetheless, there are several benefits to collecting more DMI records that were not accounted for by the measure of RE. The increase in selection response was modeled only on the increase in selection intensity compared with the direct reduction in accuracy of individuals due to shorter duration of individual DMI recording. In addition to not having high amounts of PADG records, the model does not take into account the indirect increase in accuracy of genetic evaluation of DMI due to the opportunity to measure DMI on greater numbers of relatives and contemporaries of the animals being evaluated.

Under most scenarios considered in Table 6, selection indices calculated from the estimates of

genetic (co)variance would accelerate response to selection for feed efficiency measured over the previously recommended longer duration of test period (Beef Improvement Federation, 2016) due to greater selection intensity, provided that the testing facility would operate at full capacity. This conclusion differs from that of Archer et al. (1997) who found the efficiency of selection to improve RFI based on DMI measured for 35 d coupled with ADG measured over 70 d to be on average 90% as efficient as using both measurements collected over a 70-d test period. However, the opportunity to evaluate a greater number of candidates for selection and, thus, increase selection intensity was not considered.

The accuracies of the 3 selection indices were compared for each of the 4 breeding objectives in Table 5. These comparisons were made for animals having accuracies of the objective function of 0.25, 0.5, and 0.75, as well as the theoretical scenario of all animals having complete accuracy for all EBV. The 3-trait index had greater accuracy than either of the 2-trait indices under all scenarios. The differences between the accuracy of the 3-trait index and the index of ADG42 and DMI42 were very small in the theoretical scenario, but much greater in animals with less accurate EBV. The index of ADG42 and DMI42 was generally more accurate than the index of PADG and DMI42. Accuracy of the selection indices decreased as the relative emphasis on DMI83 in the breeding objective decreased. It might have been anticipated that the greater heritability of PADG would have made it a more valuable contribution to an index than ADG42, but the greater genetic correlation with ADG83 made ADG42 the more valuable index component.

The relationships among accuracies of indices and breeding objectives are illustrated in Fig. 1. The 3 indices all include DMI42 to represent the DMI component of the objective, but differ in whether ADG42, PADG, or both are included to represent the ADG component. Consequently, the indices perform similarly with the objective that places the least emphasis on ADG (Fig. 1D), but quite differently with the objective that places the greatest emphasis on ADG (Fig. 1C).

Animals in the analysis had complete records for DMI42, ADG42, DMI83, and ADG83, but there were 226 of those animals that did not have records for PADG. They follow a different trajectory and are indicated separately in Fig. 2. For the index of DMI42 and PADG and the 3-trait index, the animals without PADG records form curvilinear trails below the main linear cluster of

animals. For the index of DMI42 and ADG42, the animals without PADG records fall on a line with slightly greater slope than the remainder.

This analysis did not take advantage of the far greater number of PADG records that were available on relatives of the animals with DMI recorded. The opportunity to leverage PADG records of vast numbers of relatives is even greater in national genetic evaluation. The 2 measures of ADG being considered contribute different types of information to the indices based on them. The huge number of PADG records potentially available for animals that cannot be measured for DMI supports its inclusion in the index. However, ADG42 is more highly correlated with the measure of ADG in the objective function and would be affected similarly to DMI42 by any sickness or other event that occurred during the test period. There are good reasons to include both in the index.

Genetic correlations of PADG with the objective function were 0.44, 0.26, -0.07 , and -0.32 for breeding objectives corresponding to RG, FGH, FGS, and RFI, respectively (Table 7). Thus, PADG is not generally a useful indicator trait in genetic evaluation of feed efficiency unless accompanied by DMI records. Nonetheless, the relatively vast quantity of recorded data for PADG used in national cattle evaluation schemes provides an opportunity for extending the genetic evaluation of feed efficiency by allowing shorter tests and, consequently, DMI records on increased numbers of animals. Use of the resulting EBV in calculating indices for feed efficiency is a recommended strategy for genetic improvement of feed efficiency (MacNeil et al., 2011; Nielsen et al., 2013).

Determining the optimum value of intake relative to gain is not a trivial problem and the optimum solution varies not only with respect to relative market prices, but also with production practices, feedstuff availabilities, and environments. Furthermore, values of intake and gain involve more than their respective market prices; differences in maintenance energy influence time on feed, and thus, allocation of overhead costs. Traits that reflect fatness and muscling should be included along with feed efficiency in most indices; therefore, relative economic values of intake and gain should be estimated jointly with relative economic values of fatness and muscling. Because of all these factors, a wide range of relative economic values of intake were considered.

The range of relative economic values of DMI relative to ADG spanned by the 4 objective functions considered includes plausible values

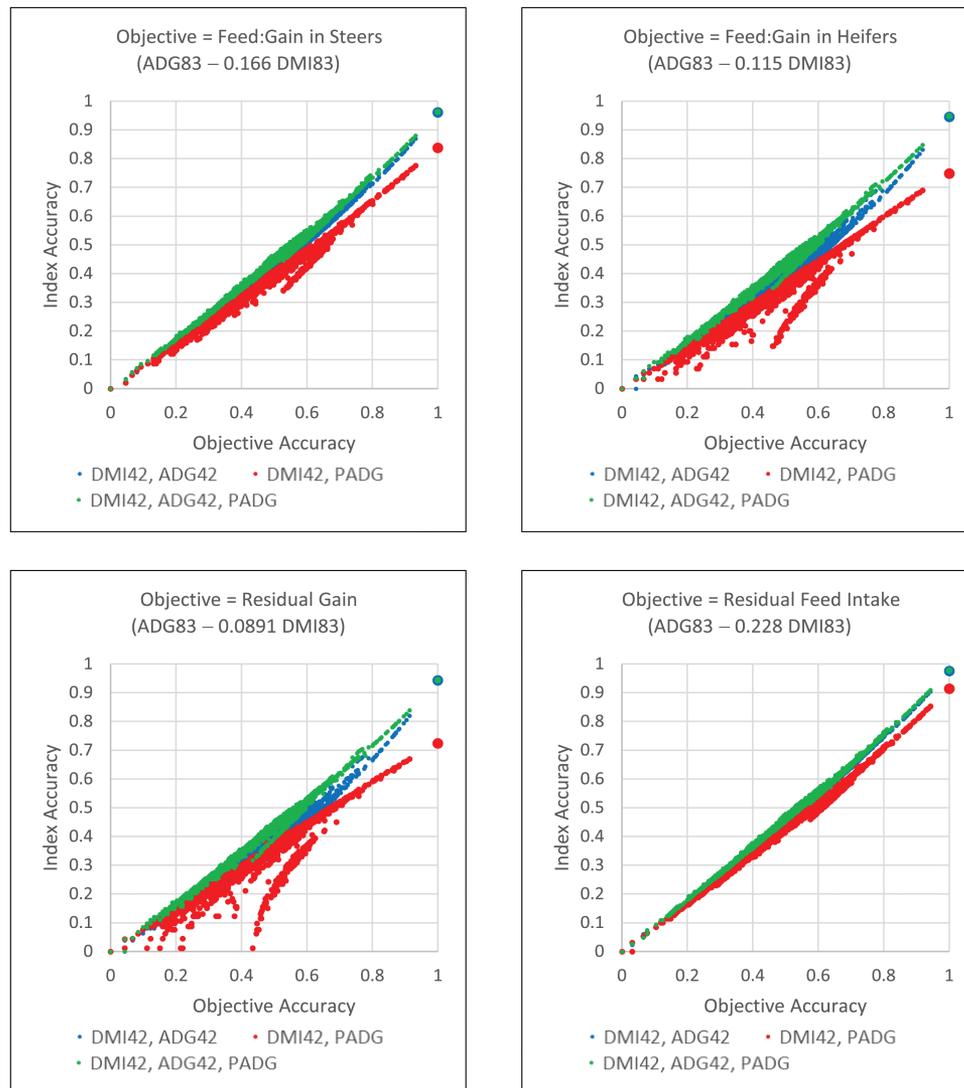


Figure 1. Accuracies of indices relative to accuracy of objective function. Each panel represents a different objective with the relative economic value of DMI relative to ADG indicated in parentheses. Within each panel, 3 indices (over different sets of indicator traits) were compared. The traits were DMI (kg/d) and ADG (kg/d) measured for either the first 42 d on test (DMI42 and ADG42, respectively) or the full test period (DMI83 and ADG83, respectively), and ADG (kg/d) derived from the difference between weaning and yearling weights (PADG).

conditional on historical relative costs of feed and values of gain for beef cattle in the United States by accounting for zero change in DMI or zero change in ADG as well as intermediate levels of selection for both traits. Over this range of relative economic values of DMI, the 3-trait index of DMI42, ADG42, and PADG was uniformly better than either of the 2-trait indices that each included only 1 measure of ADG.

Part of the advantage of the 3-trait index was directly due to the inclusion of all 3 traits in the index, but part of it was due to the inclusion of all 3 sources of information in the genetic evaluation from which the index was derived. As a practical matter, partitioning the advantage between the reasons is unimportant; the only reason to limit the

index to 2 traits would be the cost of adding the third trait to the genetic evaluation.

In practice, national cattle evaluation systems will need to use data from tests of varying lengths. Treating intake and gain as daily values instead of totals over the test period has the advantage of accommodating this variation without the necessity of changing the genetic evaluation software and procedures. Evaluations could be made a bit better and could reward longer tests by reducing the residual variances proportional to the inverse square root of the test period length. Greater improvements could be made by utilizing all available weights in a random regression analysis or by providing for an additional gain period that is intermediate to the intake recording period and postweaning gain.

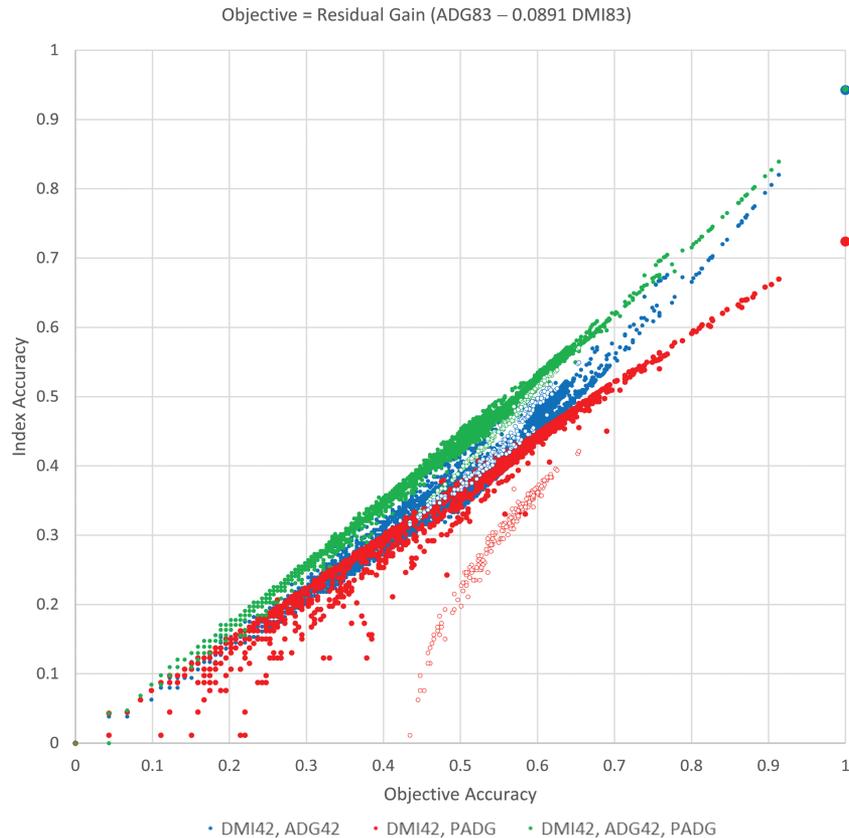


Figure 2. Accuracies of indices relative to accuracy of objective function vary for individuals with different combinations of traits recorded. The open circles represent 226 individuals without PADG records. Accuracies of the indices that included PADG were considerably lower for those animals. The traits were DMI (kg/d) and ADG (kg/d) measured for either the first 42 d on test (DMI42 and ADG42, respectively) or the full test period (DMI83 and ADG83, respectively), and ADG (kg/d) derived from the difference between weaning and yearling weights (PADG).

Table 7. Estimates of genetic correlations between indices and measures of DMI and ADG

Objective ^a	Index ^b	DMI42	DMI83	ADG42	ADG83	PADG
FGS	Objective	-0.59	-0.57	0.20	0.29	-0.07
FGS	DMI42, ADG42	-0.61	-0.59	0.20	0.23	-0.11
FGS	DMI42, PADG	-0.70	-0.70	-0.06	-0.02	-0.09
FGS	DMI42, ADG42, PADG	-0.61	-0.59	0.20	0.23	-0.08
FGH	Objective	-0.25	-0.22	0.53	0.62	0.26
FGH	DMI42, ADG42	-0.27	-0.24	0.56	0.57	0.24
FGH	DMI42, PADG	-0.34	-0.33	0.31	0.33	0.34
FGH	DMI42, ADG42, PADG	-0.26	-0.24	0.56	0.57	0.27
RG	Objective	-0.03	0.00	0.70	0.78	0.44
RG	DMI42, ADG42	-0.03	0.00	0.74	0.73	0.44
RG	DMI42, PADG	-0.04	-0.04	0.53	0.54	0.61
RG	DMI42, ADG42, PADG	-0.03	0.00	0.74	0.73	0.47
RFI	Objective	-0.79	-0.78	-0.08	0.00	-0.32
RFI	DMI42, ADG42	-0.81	-0.79	-0.08	-0.05	-0.36
RFI	DMI42, PADG	-0.87	-0.87	-0.29	-0.24	-0.35
RFI	DMI42, ADG42, PADG	-0.81	-0.79	-0.08	-0.05	-0.33

^aThe objective functions were FGS and FGH; RG; and RFI.

^bADG83 and DMI83 were ADG and DMI, respectively, over the entire test period, which averaged 83 d; ADG42 and DMI42 were ADG and DMI, respectively, over the first 42 d of test period; PADG was postweaning ADG.

Including postweaning gain of the entire population in the multiple-trait evaluation of intake and gain over the test period will leverage gain data of relatives that were not measured for intake.

If individual feed intake could be measured for all animals at no cost, tests of longer duration would provide more response to selection than shorter tests. Shorter tests are a practical solution

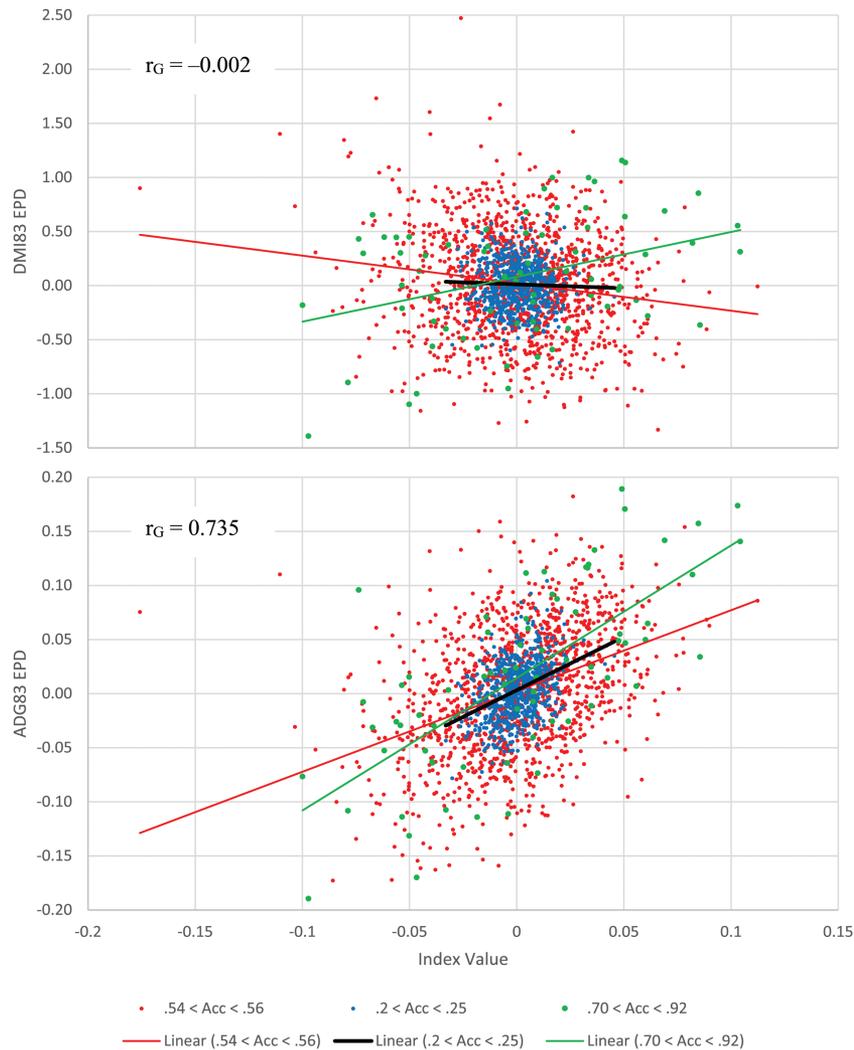


Figure 3. The relationship between EBV included in the objective function ($RG = \text{ADG83} - 0.089 \text{DMI83}$) relative to the index of DMI42 and ADG42 is plotted for animals in 3 different ranges of accuracy of the objective (0.2–0.25, 0.54–0.56, and 0.75–0.92). The traits were DMI (kg/d) and ADG (kg/d) measured for either the first 42 d on test (DMI42 and ADG42, respectively) or the full test period (DMI83 and ADG83, respectively). The trend lines represent linear regressions of the EBV on the index for the 3 sets of observations. The genetic correlation (r_G) between the index and each of the objective traits is shown.

to the economic reality that measuring individual feed intake is expensive, but important. To whatever extent shortening tests does not facilitate testing a greater number of animals, longer tests will generally provide more accurate evaluations. Utilizing a facility year-round will generally require splitting groups (that would otherwise have been considered contemporaries) into early and late testing periods in the facility, especially for breeders with one breeding season per year. Strategies for doing so without introducing selection bias need to be developed. If both bulls and heifers are to be tested, they can be tested at different times of year. To the extent that groups must be tested at different ages, it is an open question whether early and late measures have sufficient genetic correlations to be considered the same trait.

The trend lines in Fig. 3 illustrate that the responses in the individual traits that comprise the objective may differ depending on the amount and sources of information contributing to the index. Most of the other combinations of objectives and indices showed more similarity in slope of the trend lines. The trend lines in Fig. 4 illustrate that selecting for an index specifically designed for the objective function to be uncorrelated with ADG can result in a negative correlated response in ADG. Genetic correlations among the 5 traits in the analysis with the 12 indices and 4 objectives are reported in Table 7.

Genetic evaluations of feed efficiency should include DMI, ADG over the same period as DMI, and PADG in the same multiple-trait analysis. A test period of 42 d of DMI recording is

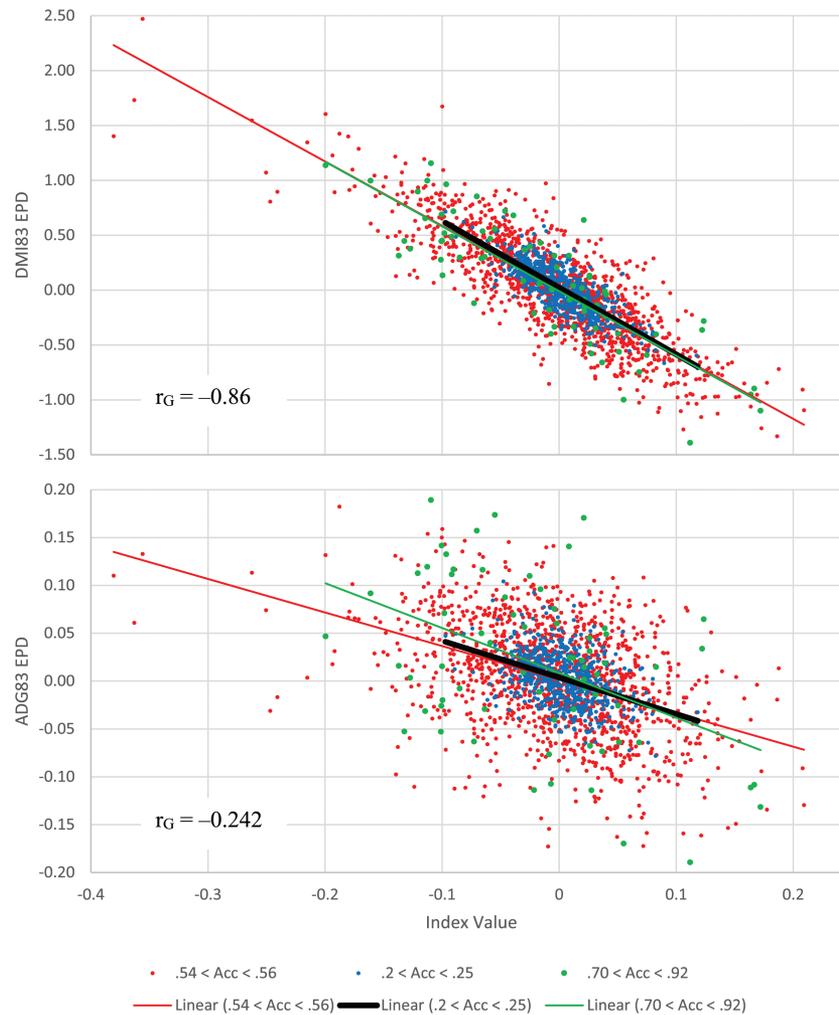


Figure 4. The relationship between EBV included in the objective function ($RFI = ADG83 - 0.228 DMI83$) relative to the index of DMI42 and PADG is plotted for animals in 3 different ranges of accuracy of the objective (0.2–0.25, 0.54–0.56, and 0.75–0.92). The traits were DMI (kg/d) and ADG (kg/d) measured for either the first 42 d on test (DMI42 and ADG42, respectively) or the full test period (DMI83 and ADG83, respectively), and ADG (kg/d) derived from the difference between weaning and yearling weights (PADG). The trend lines represent linear regressions of the EBV on the index for the 3 sets of observations. The genetic correlation (r_G) between the index and each of the objective traits is shown.

adequate and should improve selection response compared with longer test periods, provided that the shorter test period facilitates testing more animals each year in the facility. The genetic correlation between DMI42 and DMI83 suggests that even shorter test periods may be beneficial, but this hypothesis was not directly tested in this study.

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LITERATURE CITED

- Ahlberg, C. M., L. A. Kuehn, R. M. Thallman, S. D. Kachman, W. M. Snelling, and M. L. Spangler. 2016. Breed effects and genetic parameter estimates for calving difficulty and birth weight in a multibreed population. *J. Anim. Sci.* 94:1857–1864. doi:10.2527/jas.2015-0161
- Archer, J. A., P. F. Arthur, R. M. Herd, P. F. Parnell, and W. S. Pitchford. 1997. Optimum postweaning test for measurement of growth rate, feed intake, and feed efficiency in British breed cattle. *J. Anim. Sci.* 75:2024–2032. doi:10.2527/1997.7582024x
- Archer, J. A., and L. Bergh. 2000. Duration of performance tests for growth rate, feed intake and feed efficiency in four biological types of beef cattle. *Livest. Prod. Sci.* 65:47–55. doi:10.1016/S0301-6226(99)00181-5
- Arthur, P. F., J. A. Archer, R. M. Herd, E. C. Richardson, S. Exton, J. H. Wright, K. C. P. Dibley, and D. A. Burton. 1997. Genetic and phenotypic variation in feed intake, feed efficiency and growth in beef cattle. *Proc. Assoc. Adv. Anim. Breed. Genet.* 12:234–237.

- Beef Improvement Federation. 2016. Guidelines for uniform beef improvement programs. 9th rev. ed. Beef Improvement Federation, Prairie, MS.
- Byerly, T. C. 1941. Feed and other costs of producing market eggs. *Agric. Exp., Tech. Bull. No. A1*. Univ. Maryland, College Park.
- Culbertson, M. M., S. E. Speidel, R. K. Peel, R. R. Cockrum, M. G. Thomas, and R. M. Enns. 2015. Optimum measurement period for evaluating feed intake traits in beef cattle. *J. Anim. Sci.* 93:2482–2487. doi:10.2527/jas2014-8364
- Eisen, E. J. 1977. Restricted selection index: an approach to selecting for feed efficiency. *J. Anim. Sci.* 44:958–972. doi:10.2527/jas1977.446958x
- Federation of Animal Science Societies (FASS). 2010. Guide for the care and use of agricultural animals in research and teaching. Available from https://www.aaalac.org/about/Ag_Guide_3rd_ed.pdf
- Gunsett, F. C. 1984. Linear index selection to improve traits defined as ratios. *J. Anim. Sci.* 59:1185–1193. doi:10.2527/jas1984.5951185x
- Kennedy, B. W., J. H. J. van der Werf, and T. H. E. Meuwissen. 1993. Genetic and statistical properties of residual feed intake. *J. Anim. Sci.* 71:3239–3250. doi:10.2527/1993.71123239x
- Koch, R. M., L. A. Swiger, D. Chambers, and K. E. Gregory. 1963. Efficiency of feed use in beef cattle. *J. Anim. Sci.* 22:486–494. doi:10.2527/jas1963.222486x
- Lin, C. Y. 1980. Relative efficiency of selection methods for improvement of feed efficiency. *J. Dairy Sci.* 63:491–494. doi:10.3168/jds.S0022-0302(80)82960-2
- MacNeil, M. D., N. Lopez-Villalobos, and S. L. Northcutt. 2011. A prototype national cattle evaluation for feed intake and efficiency of Angus cattle. *J. Anim. Sci.* 89:3917–3923. doi:10.2527/jas.2011-4124
- Manafiazar, G., J. Basarab, L. McKeown, J. Stewart-Smith, V. S. Baron, M. D. MacNeil, and G. Plastow. 2017. Optimizing feed intake recording and feed efficiency estimation to increase the rate of genetic gain for feed efficiency in beef cattle. *Can. J. Anim. Sci.* 97:456–465. doi:10.1139/CJAS-2016-0118
- Mumford, H. W., H. S. Grindley, A. D. Emmett, and S. Bull. 1917. A study of the rate and economy of gains of fattening steers: with special reference to the influence of the amount and the character of feed consumed. *Agric. Exp. Sta., Bull. No. 197*. Univ. Illinois, Champaign.
- Nielsen, M. K., M. D. MacNeil, J. C. M. Dekkers, D. H. Crews Jr., T. A. Rathje, R. M. Enns, and R. L. Weaber. 2013. REVIEW: life-cycle, total industry genetic improvement of feed efficiency in beef cattle: blueprint for the Beef Improvement Federation. *Prof. Anim. Sci.* 29:559–565. doi:10.15232/S1080-7446(15)30285-0
- Retallick, K. J., J. M. Bormann, R. L. Weaber, M. D. MacNeil, H. L. Bradford, H. C. Freetly, K. E. Hales, D. W. Moser, W. M. Snelling, R. M. Thallman, et al. 2017. Genetic variance and covariance and breed differences for feed intake and average daily gain to improve feed efficiency in growing cattle. *J. Anim. Sci.* 95:1444–1450. doi:10.2527/jas2016.1260
- Rolfe, K. M., W. M. Snelling, M. K. Nielsen, H. C. Freetly, C. L. Ferrell, and T. G. Jenkins. 2011. Genetic and phenotypic parameter estimates for feed intake and other traits in growing beef cattle, and opportunities for selection. *J. Anim. Sci.* 89:3452–3459. doi:10.2527/jas.2011-3961
- Schneeberger, M., S. A. Barwick, G. H. Crow, and K. Hammond. 1992. Economic indices using breeding values predicted by BLUP. *J. Anim. Breed. Genet.* 109:180–187. doi:10.1111/j.1439-0388.1992.tb00395.x
- Wang, Z., J. D. Nkrumah, C. Li, J. A. Basarab, L. A. Goonewardene, E. K. Okine, D. H. Crews, and S. S. Moore. 2006. Test duration for growth, feed intake, and feed efficiency in beef cattle using the GrowSafe® system. *J. Anim. Sci.* 84:2289–2298. doi:10.2527/jas.2005-715