Sheep breeding schemes for Iceland

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Summary

Altogether 540 alternatives for the Icelandic sheep breeding scheme were evaluated by stochastic simulation of a breeding population with about 120.000 ewes, considering the genetic gain for an aggregate genotype including eight traits as well as the rate of inbreeding. Selection was made according to three selection indexes, with different weights on investigated traits. Two breeding schemes were simulated: a scheme with test rams in natural mating in local flocks and elite rams (from one and a half years of age) in AI across all flocks in the country (NMAI2 scheme) and a scheme where, in addition to test rams, the youngest elite rams were used in natural mating in local flocks (from one and a half years of age), (NMAI1 scheme). One alternative within the NMAI1 scheme was used as a control representing the current breeding scheme for each selection index.

Both schemes included different proportions of ewes inseminated/mated to elite rams vs. test rams (EM%) and varying numbers of ewes inseminated per elite ram in AI (EAIn), and numbers of ewes mated per test ram in natural mating (TNMn). Within the NMAI1 scheme the number of ewes mated to each elite ram in natural mating (ENMn) also varied.

With a restriction on the rate of inbreeding ($\leq$ 0.8% per generation), the NMAI2 scheme resulted in more annual genetic gain than the NMAI1 scheme for all selection indexes. Improvement was found to be possible also under the NMAI1 scheme by changing the annual ram usage (EM%) from the current control breeding scheme.

For both scheme the lowest EM% should be chosen (30%), TNMn equals 50, combined with average EAIn (NMAI2: 900 ewes, NMAI1: 700 ewes), and 60 ENMn within NMAI1.

Keywords: Icelandic sheep, breeding scheme, selection index, genetic gain, rate of inbreeding, stochastic simulation.

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1 Introduction

Sheep production is the second most important sector in Icelandic agriculture contributing 22% to the total agricultural income in 2006. In 2007 lamb meat accounted for 28% of the meat consumption in Iceland, but had fallen from over 50% in 1990. (The Farmers Association of Iceland, 2010). Excluding state subsidies, around 87% of all income in sheep production is from lamb meat (Hagþjónusta landbúnaðarins, 2010).

The Icelandic sheep population counted for 460.000 winterfed sheep in December 2008 (The Farmers Association of Iceland, 2010), distributed in about 2.800 flocks with a trend towards fewer and larger sheep flocks in recent years (Johannesson, 2010). The Farmers Association of Iceland maintains the sheep recording system. Over 90% of winterfed sheep in Iceland were recorded in 2009 (Jónmundsson, 2010). A sharp increase was observed in the proportion of recorded sheep after recording was made a compulsory part of a quality controlled scheme in sheep production in 2003, which gives farmers access to increased subsidies. (Jónmundsson, 2010; The Farmers Association of Iceland and Government Offices of Iceland, 2007; The Farmers Association of Iceland, 2010). Only one breed of sheep is kept in Iceland, the North European short-tailed Icelandic sheep (Dyrmundsson and Niznikowski, 2010).

The first trial on artificial insemination (AI) of sheep in Iceland was made 1939 (Dyrmundsson et al., 2007) and has been used each year since 1963 (Ólafsson, 2004). Around 30.000 ewes are inseminated annually, mainly with fresh semen (Dyrmundsson et al., 2007). Two AI stations are in operation during the first three weeks in December with around forty elite rams. Sheep breeders inseminate their own ewes with the simple vaginal insemination technique, "shot in the dark", usually in the first days of mating before the onset of natural mating using their own rams. The annual usage of each AI ram has no other limitations than the ram´s daily production. (Jóhannesson, 2010).

In the thirties Iceland was divided into several isolation zones with livestock fences, due to the risk of spreading the lung disease "Maedi-visna". After this disease was eradicated, the isolation zones were used to prevent spreading of the scrapie disease. Movement of live sheep across these livestock fences is normally not allowed and in some cases exchange of animal across flocks within an isolation zone is prohibited (Matvælastofnun, 2011). A recent study has shown high genetic contributions of AI rams to the first generations on restocked farms after scrapie eradications in eastern Iceland (Árnadóttir et al., 2010). Large numbers of replacement ram (60%) and ewe (15%) lambs each year are sired by AI rams (Dyrmundsson et al., 2007). Considering these facts artificial insemination forms the basis for the distribution of genetic merit in the whole population.

To investigate possible improvements of the present breeding scheme for the Icelandic sheep, the population was analyzed with various alternative assumptions, using a stochastic simulation program developed and described by Eikje et al. (2010; 2011). The present breeding scheme is based on BLUP breeding values for four individual traits (carcass conformation grade, carcass fat grade, prolificacy and productivity of ewes) that are not weighted together into one index. Economic weights for traits under selection within the Icelandic sheep have never been calculated.

The objective of the present study was to make inferences about the optimum use of AI (proportion of ewes inseminated and number of ewes inseminated to each AI rams) and the annual use of elite and test rams by natural mating, considering both genetic gain and the rate of inbreeding. The simulations included eight traits and the selections were made on three selection indexes, with varying desirable gain for the investigated traits in percentage of gain in the aggregate genotype, given in Table 1.

2 Materials and methods

A breeding population totalling 120.000 ewes was stochastically simulated, generating individual genotypes for a total of 8 traits, as well as the inbreeding coefficient. An overview of traits is given in Appendix 1. The computer program used was described by Eikje et al. (2010; 2011). It was assumed that the simulation of 120.000 ewes would give satisfactory results as a model of the whole population of 460.000 sheep. The simulations were run on a linux cluster (operated by the University of Oslo), allowing for many alternatives to be run simultaneously, each run taking about 20 hours.

2.1 Schemes

Two breeding schemes were compared, based on both natural mating and artificial insemination.

NMAI1: Six months old test rams and 1 ½ year and older elite rams were ranked, selected and used for natural mating in local flocks. By means of AI, elite rams, 2 ½ years and older, were selected and used across all flocks, mated to 10% of the ewes in the flock.
NMAI2: Six months old test rams were ranked, selected and used for natural mating in local flocks. Elite rams 1 ½ year and older were selected and used by AI across all flocks.

In both schemes, and for the same parameters (genetic gain and inbreeding), the best combination of the proportion of ewes mated to elite rams vs. test rams (EM%), number of ewes mated to each test and elite ram in natural mating (TNMn/ENMn) and number of ewes inseminated by elite rams (EAIn) was investigated. An overview of schemes and alternatives are given in Table 2. In total 540 alternatives were simulated.

2.2 Stochastic simulation

A similar stochastic simulation was described by Eikje et al. (2010; 2011) but changes made on the computer program for this study are included in the following description.

2.2.1 Base population

All the assumptions for the base population were based on data from the sheep recording system maintained by the Farmers Association of Iceland. The dataset contained information about 130.000 ewes in 344 flocks with a minimum of 15 years, of continuous recording, in the years 2008 and 2009. This data was used to form the base rather than data representing the whole recording system due to irregular structure of data from flocks that recently joined the recording, especially evident in missing information on the age of ewes (Jón Viðar Jónmundsson, personal communication).

The structure of flock sizes was obtained from the size distribution of those 344 flocks with more weight on the larger flocks, considering the development in flock sizes during the last two decades (Johannesson, 2010). Flocks with less than 200 ewes were not included since small flocks are often located close to each other and function in fact as one large flock. In the simulation 252 flocks were included, for each flock the size was determined by drawing a random number utilising the flock sizes distribution given in Appendix 2.

Age distributions of ewes and rams in the base populations, was randomly assigned from the age distribution given in Appendix 3.

Adult ewes were culled at random each year, the cumulative probability of being culled in each age class, as a proportion of all ewe lambs selected as replacements, is given in Appendix 4. In addition, ewes were culled if they did not conceive after two oestrous cycles. Conception rates after natural mating and AI were 96% and 67%, respectively (Jónmundsson, 2010).

2.2.2 Selection indexes

Three selection indexes were investigated with varying desirable gain for the eight traits simulated, in percentage of gain in the aggregate genotype. For each selection index, adjusted index weight was used for selection. The weight was calculated as the product of genetic standard deviation (σ_A) of the respective trait and its desired gain weight within the selection index, resulting in an index point weight. Desired gain weights and the index point weights for each trait in the three selection indexes are given in Table 1.

2.2.3 Selection

Selection of ewe and ram lambs for replacement by breeders in Iceland is carried out by conformation assessment and ultrasound measurements by trained assessors (Jónmundsson, 2001). The simulation program by Eikje et al. (2010) works with different selection methods so selection was based on the following criterion (score): $0.5(SI_S + SI_D) + (ww_i - \overline{ww_f})$, where SI are the selection indexes of the sire and dam of the selection candidate from the preceding year, ww_i is the weaning weight of the i-th selection candidate and $\overline{ww_f}$ is the average weaning weight in the f-th flock. The i-th animal's weaning weight was generated as: $ww_i = \mu + tbv_i + tbvm_d + e_i$, where μ is the population mean (given by Einarsson et al., 2011), tbv_i is the true breeding value for individual effect on weaning weight of animal i, $tbvm_d$ is the effect of the maternal true breeding value of the dam and e_i is the environmental effect. Environmental effects were generated by multiplying a vector of random standard normal deviates with the Cholesky decomposed environmental (co)variance matrix (Appendix 1).

All selections of ewe and ram lambs were within the flock and lambs not selected for breeding were slaughtered. The selection criterion for elite ewes (one and half years or older) and rams was the selection index of the animal, but in NMAI1, the AI-rams were selected on the selection index from the preceding year (assuming that a long time in quarantine at AI stations does not allow selection on the most updated index) and ewe lambs were always ranked behind adult ewes which is in accordance to regular practice in most breeding flocks.

2.2.4 Mating

In NMAI2 elite rams in AI were mated at random to the best elite ewes, and the remaining ewes were mated to test rams at random. In NMAI1 elite rams in AI were mated to the top 10% of elite ewes at random; elite rams in natural mating were similarly mated the second best elite ewes (20%; 40% or 60%). Finally, test rams were mated to the remaining ewes, at random. Ewes that did not conceive after insemination were subsequently mated naturally to an elite ram in NMAI1 and to a test ram in NMAI2.

If expected inbreeding coefficients of the progeny exceeded 3.1%, mating was not allowed. However, after five unsuccessful attempts to find a ram where the inbreeding coefficient of the progeny was below this limit, the mating was accepted.

2.2.5 Lambing

Phenotypes for the number of lambs born were needed for replacement purposes. For 1-, 2- and 3- year-old ewes, assignment of phenotypic values as a category, for the i-th animal in each of these first three age-classes, j-th class, was based on thresholds (t), that is, to category *h* when $t_{hj} < tbv_{ij} + e_{ij} \leq t_{hj+1}$, on the standard normal distribution obtained from a transformation of proportion of ewes in each lambing category (i.e. number of lambs born) in 2008 and 2009 (Appendix 5). For older ewes, phenotypes for the number of lambs born were simulated as follows; genotypes as for 3-year olds and the environmental effect from the environmental standard deviation of the number of lambs born at 3 years of age, that is, by assuming that the environmental correlations with the number of lambs born at lower ages (1-, 2- and 3- year-olds) was zero. A random half of all lambs born was assigned to each sex, for which the fractions given in Appendix 6 were assigned, randomly, to survival until weaning.

2.2.6 Replicates, true and predicted breeding values, aggregate genotype (ΔG) and rate of inbreeding (ΔF)

Owing to the considerable size of the populations simulated, each alternative investigated was replicated only 10 times and each replicate was run for 20 years. Results for genetic gains were calculated from the last 15 years of selection, while for rate of inbreeding per generation the last 8 years were used.

True breeding values and BLUP breeding values were approximated as in Eikje et al. (2010). Briefly described, the method samples multivariate breeding values sequentially, for each selection candidate, its sire and dam, as well as the multivariate distribution of true and predicted breeding values (of the same animals). This distribution relies on the prediction error (co)variance, derived from individual mixed model equations, utilising information on the animal itself with its progeny and its parents with progeny.

Estimates of the annual genetic gain for each trait were calculated as linear regression coefficients of the true breeding values, with Proc GLM model in the SAS 9.2 statistical software package.

The genetic gain in the aggregate genotype per year, for each alternative in each selection index, was the sum over all traits in the breeding goal. The genetic gain was calculated as the sum of the products between the estimates of genetic gain of each trait per year and the respective weight in index points. These values (ΔG) were used for comparative purposes. The sums forming the aggregate genotype are thus not comparable across selection indexes.

To calculate the proportion of each trait of the aggregate genotype within alternatives, the estimated genetic gain of the trait was multiplied with its respective weight in index points and divided by the sum of the aggregate genotype in current alternative.

To calculate the rate of inbreeding per generation (ΔF), the following formula was used:

$$\Delta F = \left((\textstyle\sum_{t=13}^{20} (F_t - F_{t-1})/(1 - F_{t-1}))/8 \right) * \left((L_{SS} + L_{SD} + L_{DS} + L_{DD})/4 \right),$$

where, F_t is the average inbreeding coefficient in year *t* and L_{SS}, L_{SD}, L_{DS} and L_{DD} are generation intervals of sire to son, sire to daughter, dam to son and dam to daughter, respectively. Alternatives were sought that maximised the average genetic gain of the aggregate genotype, for a predicted rate of inbreeding of 0.8% or less per generation, corresponding with the recommendation of 0.5% to 1% per generation of Bijma (2000).

2.2.7 Control alternative within selection indexes

Alternatives based on the average usage of rams in the data from Iceland in years 2008 and 2009 were included in the NMAI1 scheme with 70 EM%, 20 TNMn, 30 ENMn and 700 EAIn. This alternative was used as a control representing the current breeding scheme in each selection index.

3 Results

The control alternative in the NMAI1 scheme resulted in 16.72 (ΔF=0.87%), 21.43 (ΔF=1.07%) and 12.78 (ΔF=0.54%) index points, respectively for SI1, SI2 and SI3. In Table 3 the largest annual genetic gains are listed, obtained within the NMAI1 scheme by combinations of ENMn/TNMn. All the results were within the 30% elite mating alternative with varying numbers of ewes mated to AI rams (results not shown). The highest gain was observed with ENMn equals 60 in all selection indexes, in some cases ENMn equals 90 resulted in higher gains in combination with small ewe groups mated to each test ram. The risk of increased inbreeding is however greater with ENMn equals 90, therefore ENMn equals 60 seems preferable for a sustainable breeding plan. The alternatives with maximum annual gain within the NMAI1 scheme resulted in 109.9%, 106.2% and 108.8%, of the control alternative representing the current breeding scheme, obtained within SI1, SI2 and SI3, respectively.

Annual genetic gain for all selection indexes in both schemes is shown in Figure 1, combining the number of ewes inseminated by elite rams in AI (EAIn) within the number of ewes mated to each test ram (TNMn). Also, illustrates the figure that increased numbers of ewes inseminated by AI rams as well as increased numbers of ewes mated to test rams, in combination with low elite mating percentages, give higher annual genetic gain. However, the 0.8% restriction of the rate of inbreeding per generation sets certain limits. The rate of inbreeding (ΔF) increases much slower in the NMAI2 scheme than in the NMAI1 scheme, under SI2 is ΔF high in most alternatives compared to SI3.

In the NMAI2 scheme the highest gains were obtained under alternatives with 900 ewes inseminated by each AI ram. In both SI1 and SI3 the highest gain was observed when 50 ewes were mated to each test ram in combinations with 30% elite mating. For SI2 the optimum results were found when 35 ewes were mated to each test ram together with 50% elite mating (Table 4), likely due to the restriction of 0.8% set by ΔF. The best alternatives resulted in 21.94 (ΔF=0.78%), 25.83 (ΔF=0.76%) and 16.62 (ΔF=0.62%), index points, respectively for SI1, SI2 and SI3. Those results are 131.2%, 120.5% and 130.0%, of the control alternative representing the current breeding scheme, obtained within SI1, SI2 and SI3, respectively.

In Table 4 are listed the best NMAI2 alternatives under each selection index and the annual genetic gain of each trait, estimated as linear regression coefficients of the true breeding values on year as well as the proportion of each trait in the aggregate genotype within alternative given. All the proportions of the traits shown in Table 4 were quite stable for the entire range of the 540 alternatives investigated (results not shown).

These results show several deviations from what was desired (Table 1), especially for the maternal part of weaning weight in SI2, where the actual weight on this trait is almost double compared to the predefined weight. In SI3 the carcass conformation grade and carcass fat grade show positive deviations from what was desired. The same was true for carcass weight under SI1, but lower in magnitude than the deviation of maternal part of weaning weight. Other deviations were low, mainly less than were expected.

The difference in gain of the true breeding value obtained for the direct part of weaning weight between SI3 (0.4862 kg/year) and SI1 (0.2216 kg/year) compared to the carcass weight is extreme (0.3661 kg/year under SI3; 0.3066 kg/year under SI1). Under SI3 the selection emphasis is on carcass traits and those results, indicate that heavier animals with lower carcass percentages are being selected for breeding.

4 Discussion

The results show that a breeding scheme with different usage of rams compared to the breeding scheme used today will have the potential of increasing annual genetic gain in Icelandic sheep breeding. The main influence on increased annual genetic gain is obtained by lower elite mating percentage, in combination with maximum use of test rams.

The NMAI2 scheme will give more annual genetic gain compared to the control alternative today (NMAI1 scheme). Eikje et al. (2011) found similar results; 30% of the ewes should optimally be inseminated and each test ram mated to 50 ewes. In this study a higher optimum was found for EAIn within NMAI2 (900 ewes) than in Eikje et al. (2011). However, in practice mating 50 ewes to each test ram is probably too extreme biologically, especially in the NMAI2 scheme where, in addition, ewes that return to oestrus after insemination are also mated to these test rams.

The current breeding scheme in Iceland is similar to the NMAI1 scheme. One of the purposes of the present work was to investigate the optimum annual use of elite rams in natural mating, to find alternatives which will improve genetic gain from the control alternative used today. It should be mentioned that the main difference of the NMAI1 scheme in this study and that of Eikje et al. (2011) was the proportion of ewes mated to elite rams in natural mating. In the current study this parameter varied from 20% to 60% of the ewes (24.000 to 72.000 ewes), while it was fixed to 10% (12.000 ewes) in Eikje et al. (2011). The optimum was that 60 ewes should be mated to each elite ram in natural mating.

In the NMAI1 scheme the elite mating by AI was fixed to 10% (12.000 ewes), but varied from 30% to 70% (36.000 to 84.000 ewes) within the NMAI2 scheme. The main reason for more annual genetic gain obtained with the NMAI2 scheme is that selected elite rams, have higher genetic merit than within the NMAI1 scheme.

However, it will be unrealistic to increase the average proportion of ewes inseminated up to 30% in the whole sheep population in Iceland (≈138.000 ewes and 150 AI rams), mainly because that would increase cost of the breeding work considerably. However, it is possible to increase the use of inseminations because the AI stations could house up to 70 AI rams without investment in new buildings (Sveinn Sigurmundsson, personal communication). In the upcoming years it should be realistic to almost double the number of inseminated ewes, from 30.000 ewes today to 50.000.

Another important purpose of the present work was to investigate the effects of selection indexes with different weighting on traits included. It was decided to investigate indexes with relatively equally weight on the traits under selection (SI1) as well as indexes with extreme weight on maternal traits (SI2) and also on carcass traits (SI3).

The high genetic gain in true breeding value of direct weaning weight obtained under SI3 (Table 4) makes it unacceptable for selection as this would result in heavier animals with lower carcass percentages that are not biologically robust. This is an example of undesirable side effects of the selection that often occur under extreme selection on production traits, as reviewed in Rauw et al. (1998) for several farm animal species.

The huge change in weaning weight as a maternal trait in SI2 (Table 4) makes it also as a risky index to select for. This occurs mainly by the high desired gain weight (Table 1) as well as considerable low genetic correlation (-0.55; Appendix 1).

In SI1 the same optimum are found for EM%, TNMn and EAIn (Table 4) as for SI3, lower optimum found under SI2 is likely due to the 0.8% restriction on ΔF.

In the future, genetic analysis on health and welfare traits will definitely be given an increased attention. Such traits are often maternal and a selection index as SI2, with emphasis on maternal traits could be more common in 10-20 years time. Then, traits like lambing ease, mastitis and survival of lambs would help breeders to make the sheep production more efficient in way to reduce cost. Likely would such an index result in same optimum as obtained under SI1 and SI3 due to sophisticated genetic structure. However, important consequences for simulating such an index are larger breeding population to reduce the risk of increased ΔF. Also, is necessary to improve the recording on those traits to make genetic analysis possible as well as the calculations of economic weights needs to be carried out.

5 Conclusion

The results of the study show that scheme (NMAI2) where young test rams are used in natural mating in local flocks and all elite rams are used in AI across all flocks in the country is recommended for maximum genetic gain. There a low EM% should be chosen (30%), TNMn equals 50 ewes and EAIn 900 ewes.

Due to high costs of introducing the NMAI2 scheme as a breeding scheme for Iceland, utilising the results of the NMAI1 and NMAI2 schemes in combinations, is more realistic in the upcoming years.

The recommended option for a sheep breeding scheme for Iceland in 2020 could thus be as follows: Elite mating percentage should be between 30% and 50%, where up to 15% of adult ewes should inseminated by AI rams (700 EAIn). Each test ram should be mated to at least 35 ewes and elite rams in natural mating used for the remaining ewes (up to 60 ewes each). These optimums are likely insensitive to the selection indexes.

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Table 1. *Desired gain weights and index point weights for each trait in the simulation by different selection indexes.*

	Selection index 1 (SI1)		Selection index 2 (SI2)		Selection index 3 (SI3)	
Trait	Desired gain weight*	Index point weight	Desired gain weight*	Index point weigh	Desired gain weight*	Index point weigh
Weaning weight, individual (kg)	0.00 %	0.00	0.00 %	0.00	0.00 %	0.00
Weaning weight, maternal (kg)	20.00 %	18.11	40.00 %	36.21	10.00 %	9.05
Carcass weight (kg)	20.00 %	22.94	6.67 %	7.65	26.67 %	30.59
Carcass conformation grade	20.00 %	24.34	6.67 %	8.11	26.67 %	32.46
Carcass fat grade	20.00 %	27.21	6.67 %	9.07	26.67 %	36.28
Nu. of lambs born, 1 year	6.67 %	39.22	12.50 %	73.53	3.33 %	19.61
Nu. of lambs born, 2 years	6.67 %	33.33	15.00 %	75.00	3.33 %	16.67
Nu. of lambs born, 3 years	6.67 %	40.40	12.50 %	75.76	3.33 %	20.20

*The sum of the desired gain weights equals 100%.

Table 2. *Schemes based on natural mating and artificial insemination (NMAI), with alternatives simulated for the percentage of ewes mated to elite rams (EM%), number of ewes mated naturally to each test ram/elite ram (TNMn/ENMn) and number of ewes inseminated by each elite ram (EAIn).*

	EM%	TNMn[1)]	ENMn[1)]	EAIn[2)]
NMAI1[3)]	30, 50, 70	20, 35, 50	30, 60, 90	500, 700, 900, 1100, 1300
NMAI2[4)]	30, 50, 70	20, 35, 50	-	500, 700, 900, 1100, 1300

Details for use of rams when ewes do not conceive at first oestrus are given in the text.

1) Used within birth flock.

2) Used at the national level.

3) Elite rams in natural mating, 1 ½ - 7 year of age, elite rams in AI 2 ½ - 7 years of age. AI rams mated 10% of the ewes in the flock

4) Elite rams in AI, 1 ½ - 7 years of age.

Table 3. *The largest annual genetic gain for the combinations of ENMn/TNMn that did not exceed the 0.8% rate of inbreeding per generation in all selection indexes for the NMAI1 scheme. Values are given as genetic gain in index points (ΔG) and as rate of inbreeding per generation (ΔF) in brackets.*

Index	TNMn	ENMn 30	ENMn 60	ENMn 90
Selection index 1	20	16.61 (0.54)	16.88 (0.47)	16.67 (0.30)
	35	17.46 (0.51)	17.50 (0.46)	17.90 (0.55)
	50	18.08 (0.75)	**18.38** (0.76)	18.37 (0.80)
Selection index 2	20	21.12 (0.63)	21.63 (0.65)	21.77 (0.60)
	35	22.15 (0.78)	22.13 (0.65)	X
	50	22.41 (0.78)	**22.75** (0.76)	X
Selection index 3	20	12.78 (0.54)	12.85 (0.64)	12.92 (0.71)
	35	13.45 (0.73)	13.34 (0.57)	13.40 (0.50)
	50	13.35 (0.46)	**13.90** (0.75)	13.66 (0.52)

X = no alternative was below 0.8% rate of inbreeding per generation in this combination of TNMn/ENMn.
The alternatives with maximum annual gain (marked in bold) resulted in 109.9%, 106.2% and 108.8%, of the control alternative representing the current breeding scheme, obtained within SI1, SI2 and SI3, respectively.

Table 4. *Annual genetic gain of each trait, in the best NMAI2 alternative, estimated as linear regression coefficients of true breeding values (b) on year and proportion of the trait in the aggregate genotype (%).*

	Selection index 1		Selection index 2		Selection index 3	
EM% - TNMn - EAIn	30-50-900		50-35-900		30-50-900	
Trait	b	%	b	%	b	%
Weaning weight, direct (kg)	0.2216	0.0	-0.3286	0.0	0.4862	0.0
Weaning weight, maternal (kg)	0.3132	25.8	0.4955	69.5	0.1172	6.4
Carcass weight (kg)	0.3066	32.0	0.0661	2.0	0.3661	17.9
Carcass conformation grade	0.1478	16.4	0.0354	1.1	0.1850	36.1
Carcass fat grade	0.1255	15.6	0.0284	1.0	0.1646	36.0
Nu. of lambs born, 1 year	0.0225	4.0	0.0328	9.3	0.0116	1.4
Nu. of lambs born, 2 years	0.0209	3.2	0.0321	9.3	0.0162	1.1
Nu. of lambs born, 3 years	0.0159	3.0	0.0264	7.8	0.0093	1.1

ΔG = 21.94 (ΔF=0.78%), 25.83 (ΔF=0.76%) and 16.62 (ΔF=0.62%), index points, respectively, for selection index 1, 2 and 3.

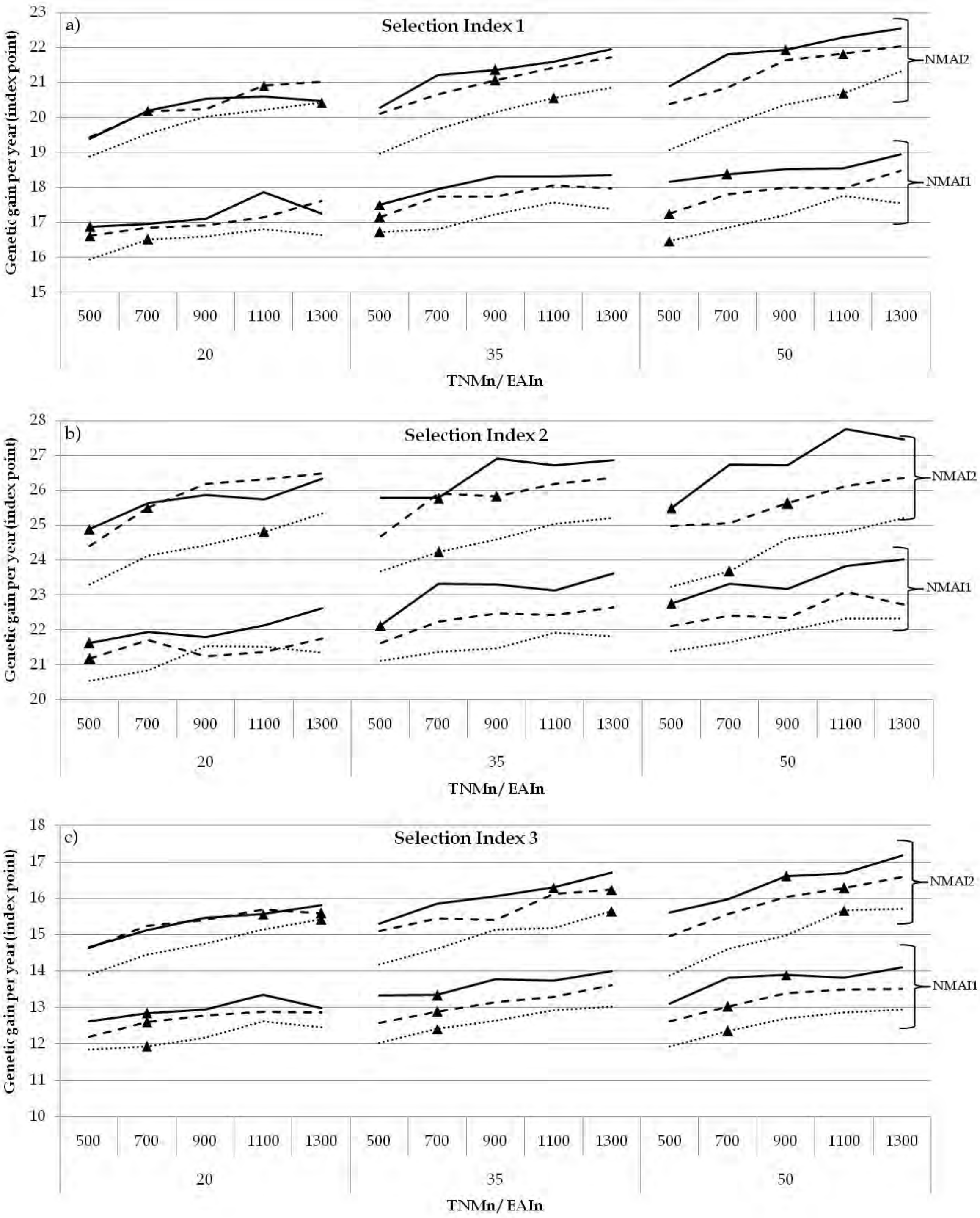

Figure 1 Annual genetic gain in index points in schemes NMAI1 and NMAI2 for varying EM% (── 30% elite mating, - - - 50% elite mating, ········· 70% elite mating) and increasing number of ewes inseminated by each elite ram (EAIn) within number of ewes mated to test rams (TNMn), in different selection indexes (a) Selection index 1, (b) Selection index 2, (c) Selection index 3. In NMAI1, 60 ewes were mated to each elite ram in natural mating. Triangles indicate the largest EAIn resulting in $\Delta F \leq 0.8\%$ per generation. No triangles on lines indicate that $\Delta F \geq 0.8\%$.

7 Appendices

7.1 Appendix 1 – Genetic parameters

Genetic parameters used for simulations of the different traits of Icelandic Sheep.

	wwd[a]	wwm[b]	cw[c]	cg[d]	cf[e]	nl1[f]	nl2[g]	nl3[h]
wwd	**0.22**	-0.55	0.84	0.00	0.00	0.00	0.00	0.00
wwm	0.00	**0.09**	0.00	0.00	0.00	0.00	0.00	0.00
cw	0.00	0.00	**0.18**	0.00	0.00	0.00	0.00	0.00
cg	0.00	0.00	0.00	**0.35**	0.40	0.00	0.00	0.00
cf	0.00	0.00	0.00	0.00	**0.31**	0.00	0.00	0.00
nl1	0.00	0.00	0.00	0.00	0.00	**0.17**	0.68	0.64
nl2	0.00	0.00	0.00	0.00	0.00	0.00	**0.14**	0.87
nl3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.11**
(σ_A)	1.70	1.10	0.87	0.82	0.74	0.17	0.20	0.20
(σ_E)	2.65	2.65	1.52	1.11	1.10	0.38	0.50	0.48

Heritability in bold on the diagonal, genetic correlations above the diagonal, genetic s.d. (σ_A) and environmental s.d. (σ_E) on the bottom lines. Environmental correlations not known.

[a] Weaning weight, individual[1]

[b] Weaning weight, maternal[1]

[c] Carcass weight[1]

[d] Carcass conformation grade[1]

[e] Carcass fat grade[1]

[f] Number of lambs born, 1 year[2]

[g] Number of lambs born, 2 years[2]

[h] Number of lambs born, 3 years[2]

Genetics parameters for traits marked with (1) reported by Einarsson et al. (2011) and for traits marked with (2) by Arnason and Jonmundsson (2008).

7.2 Appendix 2 – Flock sizes

Distribution of flock sizes in the simulations.

Flock sizes	Number of flocks
201 to 300 ewes	41
301 to 400 ewes	56
401 to 450 ewes	28
451 to 500 ewes	26
501 to 550 ewes	26
551 to 600 ewes	19
601 to 700 ewes	27
701 to 800 ewes	16
801 to 950 ewes	13

7.3 Appendix 3 – Age distributions

Age distributions of ewes and elite rams based on data from 344 flocks in the years 2008 and 2009.

	Years								
	1	2	3	4	5	6	7	8	≥ 9
Ewes	0.17	0.17	0.15	0.13	0.11	0.10	0.079	0.055	0.037
Elite rams	-	0.46	0.29	0.15	0.063	0.022	0.009	0.003	0.001

7.4 Appendix 4 – Proportions of ewes culled

Cumulative proportions of ewes culled in each age class (of those recruited at ½ year of age) based on data from 344 flocks in the years 2008 and 2009.

Years									
1 ½	2 ½	3 ½	4 ½	5 ½	6 ½	7 ½	8 ½	9 ½	10 ½
0.06	0.14	0.22	0.31	0.41	0.53	0.70	0.87	0.96	1.0

7.5 Appendix 5 – Proportion of ewes giving birth to 1, 2, 3 or 4 lambs

Proportions of ewes giving birth to 1, 2, 3 or 4 lambs by age class based on data from 344 flocks in the years 2008 and 2009.

Ewe age (years)	1	2	3	4
1	0.765	0.234	0.001	0.000
2	0.224	0.752	0.023	0.001
≥ 3	0.144	0.763	0.089	0.004

7.6 Appendix 6 – Proportions of lambs surviving

Proportions of lambs surviving until weaning based on data from 344 flocks in the years 2008 and 2009.

1 year old dams	≥ 2 year old dams
0.820	0.910