Increasing hybrid rye level substituting wheat grain with or without enzyme on growth performance and carcass traits of growing-finishing barrows and gilts

Miranda N. Smit,[†] Xun Zhou,[‡] José L. Landero,[‡] Malachy G. Young,[‡] and Eduardo Beltranena[†,1]

[†]Alberta Agriculture and Forestry, Livestock and Crops Division, Edmonton T6H 5T6, Alberta, Canada; and [‡]Gowans Feed Consulting, Wainwright T9W 1L2, Alberta, Canada

ABSTRACT: New European, fall-planted hybrid rye grown in western Canada is more resistant to ergot and fusarium and has lower content of anti-nutritional factors than common rye. We evaluated the effect of feeding increasing hybrid rye level substituting wheat grain and non-starch polysaccharide (NSP) enzyme inclusion in diets fed to growing-finishing pigs raised under western Canadian commercial conditions. In total, 1,008 pigs (~44 kg body weight [BW]) housed in 48 pens by sex, 21 pigs per pen, were fed diets with one of three rye (var. KWS Bono; KWS LOCHOW GMBH) inclusion levels substituting wheat grain: low (L; one-third of wheat replaced), medium (M; two-thirds of wheat replaced), or high (H; most wheat replaced), either without (WO) or with (W) enzyme inclusion (280 units of β-glucanase and 900 units of xylanase per kilogram feed; Endofeed W DC; GNC Bioferm) over four growth phases (Grower 2: d 0 to 22, Grower 3: d 23 to 42, Finisher 1: d 43 to 63, Finisher 2: d 64 to slaughter). Pen BW, feed added, and orts were measured on d 0, 22, 42, 63, 76, 91, and at slaughter weight (130 kg). Warm carcasses were weighed and graded (Destron). BW was not affected by either increasing hybrid rye level substituting wheat grain or enzyme inclusion throughout the trial. For the entire trial (d 0 to 76), pigs fed increasing hybrid rye level substituting wheat grain had decreased ($P < 0.050$) average daily feed intake (ADFI; L 3.05, M 2.98, H 2.91 kg/d) and average daily weight gain (ADG; L 1.01, M 1.00, H 0.97 kg/d). Enzyme inclusion did not affect ADFI but tended ($P = 0.080$) to increase ADG (WO 0.98, W 1.00 kg/d). Enzyme inclusion improved ($P < 0.050$) gain-to-feed ratio only in pigs fed the H rye level. Most carcass traits were not affected by either increasing hybrid rye level substituting wheat grain or enzyme inclusion. Increasing dietary hybrid rye level substituting wheat grain increased ($P < 0.001$) cost per tonne of feed (L 240.28, M 241.28, H 242.20 Can$/kg), but did not affect feed cost per pig or per kilogram BW gain. Enzyme inclusion increased ($P < 0.001$) cost per tonne of feed (WO 240.36, W 242.15 Can$/kg), but feed cost per pig (WO 82.14, W 80.44 Can$ per pig) and per kilogram BW gain (WO 0.96, W 0.94 Can$/kg gain) were reduced ($P < 0.050$). In conclusion, fall-planted hybrid rye can completely replace wheat grain in grower-finisher pig diets without affecting feed efficiency, feed cost per pig or feed cost per kilogram BW gain. Inclusion of NSP enzyme would be recommended for diets including high rye levels to improve feed efficiency and ADG.

Key words: carcass traits, enzyme, growth performance, hybrid rye, pig

Transl. Anim. Sci. 2019.3:1561–1574
doi: 10.1093/tas/txz141

[1]Corresponding author: eduardo.beltranena@gov.ab.ca

Received May 14, 2019.
Accepted August 19, 2019.

INTRODUCTION

Wheat and barley are the most commonly fed grains to swine in western Canada. Small cereals such as rye can also be available at competitive prices to replace or complement wheat or barley. Traditionally, rye has not been fed widely to pigs mainly because of concerns over ergot alkaloids and anti-nutritional factors that could reduce feed intake and affect growth performance (Friend and MacIntyre, 1970).

A new European fall-planted hybrid rye grown in western Canada is more resistant to ergot (Miedaner and Geiger, 2015) and fusarium and produces greater yield per unit of land (Jürgens et al., 2012). Rye has greater content of non-starch polysaccharides (NSPs) such as arabinoxylans than wheat or barley grain (McGhee and Stein, 2018) and could, therefore, benefit from NSP enzyme inclusion in diets. Enzymes could hydrolyze NSP in rye grain to improve digestibility of most nutrients (Campbell and Bedford, 1992). Net energy (NE) value (NRC, 2012), standardized ileal digestible (SID) lysine content (Cervantes-Pahm et al., 2014), and price (King, 2017) of rye fall in between those of wheat and barley grain making rye a potential cereal feedstuff that can be cost effective in swine diets.

Few growth trials feeding rye to growing-finishing pigs have been documented and the few publications that exist mostly focused on feeding rye substituting barley grain (Thacker et al., 1999, 2002; Hooper et al., 2002; Schwarz et al., 2014, 2016). Therefore, our objective was to determine the effect of increasing hybrid rye level substituting wheat grain and NSP enzyme inclusion in diets fed to barrows and gilts raised under western Canadian commercial conditions by comparing the growth performance, dressing, carcass traits, and feed cost vs. benefit. The null hypothesis of this experiment was that growing-finishing barrows and gilts fed increasing hybrid rye level substituting wheat grain with or without NSP enzyme would perform, dress, and grade not different from each other.

MATERIALS AND METHODS

Study procedures were reviewed and animal use was approved by the University of Alberta Animal Care and Use Committee for Livestock and followed principles established by the Canadian Council on Animal Care (CCAC, 2009). The study was conducted at a commercial pig farm that had a grower-finisher barn set up as a test facility (Lougheed, AB, Canada).

Animals and Housing

In total, 1,008 pigs (504 barrows and 504 gilts; PIC 380 × Large White/Landrace [Camborough; PIC Canada, Winnipeg, MB, Canada]) were randomly placed into 48 pens by sex, 21 pigs per pen. At the start of the trial, pigs averaged 44 kg body weight (BW) and between-pen variation was 2.6 kg. Pens measured 6.1 × 2.4 m, allowing 0.7 m^2 per pig. Flooring of each pen was fully slatted concrete, sidings were concrete panels with open slotting, and the front gate was made of polyvinyl chloride planking hinged at both ends. Each pen was equipped with one wet-dry feeder (model F1-115, Crystal Spring Hog Equipment, St. Agathe, MB, Canada) with two opposing feeding places located halfway along a dividing wall between pens. An additional water bowl drinker was located on the opposite sidewall toward the back of the pen. The room was ventilated using negative pressure and temperature was maintained within the thermoneutral zone for pigs. Artificial light was provided for 14 h (0600 to 2000 hours) followed by 10 h of darkness in the windowless barn.

Experiment Design and Diets

Pens were blocked by area of the rectangular growout room. Within area block, pens of barrows or gilts were randomly allocated to be fed diets with one of three rye substitution levels: low (one-third of wheat replaced), medium (two-thirds of wheat replaced), or high (most wheat replaced; Table 1), either with or without enzyme inclusion (200 mg/kg replacing wheat grain) containing 1,400 units of β-glucanase and 4,500 units of xylanase per gram of product (Endofeed W DC; GNC Bioferm, Bradwell, SK, Canada). Hybrid rye fed in this trial was the variety "KWS Bono" developed by KWS LOCHOW GMBH (Bergen, Germany) grown at Kalco Farms, Gibbons (AB, Canada). The nutrient content of rye, wheat, field pea, and wheat distillers dried grains and solubles (DDGS) fed is presented in Table 2.

Before the start of the trial, a common Grower 1 diet was fed to all pigs for 13 d. Test diets were fed to slaughter weight over four growth phases (Grower 2: d 0 to 22, Grower 3: d 23 to 42, Finisher 1: d 43 to 63, Finisher 2: d 64 to slaughter). Diets had similar inclusion of wheat DDGS and field pea per growth phase. Ingredient NE values were calculated using EvaPig based on chemical analysis of samples for that year's crop; SID AA coefficients were taken from AminoDat 5.0. An NE value of

Table 1. Ingredient composition and analyzed nutrients (%, standardized to 12% moisture) of grower and finisher diets[1] with increasing hybrid rye[2] level substituting wheat grain[3] with or without enzyme[4] inclusion

	Grower 2			Grower 3			Finisher 1			Finisher 2		
	Rye substituting wheat			Rye substituting wheat			Rye substituting wheat			Rye substituting wheat		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Ingredients, %												
Wheat, ground	31.32	15.58	1.99	41.20	20.51	1.99	44.08	21.93	2.00	45.64	22.68	1.99
Rye, ground	15.66	31.20	44.60	20.60	41.03	59.15	22.03	43.90	63.58	22.82	45.50	65.93
Wheat DDGS	28.72	28.72	28.72	21.72	21.72	21.72	23.45	23.45	23.45	24.01	24.01	24.01
Field pea, ground	20.48	20.48	20.48	13.91	13.91	13.91	8.10	8.10	8.10	5.22	5.22	5.22
Canola oil	1.32	1.54	1.73	0.40	0.69	1.00	0.40	0.71	0.99	0.40	0.72	1.02
Limestone	1.22	1.19	1.16	1.00	0.97	0.95	0.97	0.93	0.89	1.01	0.97	0.93
Mono/di-calcium phosphate	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
L-Lysine·HCl	0.47	0.47	0.47	0.40	0.40	0.39	0.35	0.35	0.34	0.32	0.32	0.31
Vitamin/mineral premix[5,6,7]	0.10	0.10	0.10	0.10	0.10	0.10	0.07	0.07	0.07	0.05	0.05	0.05
L-Threonine	0.11	0.11	0.12	0.08	0.08	0.09	0.04	0.05	0.05	0.02	0.02	0.03
DL-Methionine	0.05	0.05	0.06	0.03	0.03	0.04	0.00	0.00	0.01	0.00	0.00	0.00
$CuSO_4 \cdot 5 H_2O$	0.04	0.04	0.04	0.04	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Phytase[8]	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.01
L-Tryptophan	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Analyzed nutrient content, %												
Starch	41.16	35.55	35.51	40.05	32.87	39.60	42.13	34.79	28.51	36.12	41.89	37.37
CP	19.29	18.91	18.72	17.72	16.92	17.35	18.75	17.56	17.09	17.53	17.49	16.21
NDF	11.76	12.61	11.83	11.56	11.27	12.19	11.40	11.61	11.54	11.02	11.77	11.94
ADF	6.46	6.69	5.88	6.49	5.82	5.77	6.05	5.77	5.77	5.62	5.49	5.79
Crude fiber	3.20	3.31	2.98	3.23	3.24	3.02	2.82	3.05	2.79	3.17	2.85	2.60
Crude fat	3.57	3.82	4.00	2.99	3.07	3.19	2.90	2.82	3.47	3.24	3.34	3.51
Ash	4.04	4.14	4.38	3.94	3.82	3.70	3.77	3.73	4.05	4.03	4.58	4.29
Potassium	0.74	0.73	0.71	0.64	0.63	0.62	0.62	0.64	0.62	0.61	0.61	0.62
Calcium	0.56	0.58	0.71	0.55	0.57	0.48	0.53	0.48	0.59	0.54	0.62	0.61
Phosphorus	0.48	0.45	0.46	0.43	0.42	0.41	0.41	0.43	0.41	0.44	0.43	0.42
Chloride	0.46	0.54	0.53	0.48	0.52	0.46	0.50	0.47	0.56	0.59	0.71	0.68
Sodium	0.26	0.28	0.28	0.27	0.28	0.24	0.28	0.27	0.33	0.36	0.44	0.40
Magnesium	0.16	0.16	0.15	0.15	0.15	0.14	0.16	0.16	0.15	0.15	0.15	0.15
AAs, %												
Alanine	0.64	0.62	0.24	0.57	0.67	0.54	0.62	0.55	0.57	0.48	0.61	0.55
Arginine	0.81	0.90	1.01	1.45	0.87	0.60	0.77	1.00	0.60	1.17	0.89	0.71
Aspartic acid	1.22	1.21	1.29	1.04	1.06	0.99	1.09	0.95	0.96	0.81	0.91	0.97
Cysteine	0.77	0.55	7.85	3.44	0.63	0.24	0.45	0.95	1.31	1.66	0.40	0.49
Glutamic acid	4.19	4.30	4.60	4.52	3.84	3.13	4.65	5.19	3.43	4.45	1.06	3.43
Glycine	0.71	0.82	0.81	0.63	0.72	0.59	0.74	0.84	0.62	0.71	0.62	0.74
Histidine	0.33	0.38	0.77	0.28	0.39	0.27	0.34	0.48	0.28	0.60	0.36	0.32
Isoleucine	0.40	0.68	0.40	0.32	0.68	0.24	0.62	0.69	0.25	0.67	0.61	0.56
Leucine	1.01	1.17	0.68	1.29	1.11	0.72	0.98	1.15	0.75	0.93	1.10	0.75
Lysine	0.81	0.70	0.99	0.71	0.90	0.67	0.79	0.67	0.66	0.66	0.71	0.60
Methionine	0.45	0.32	0.69	0.65	0.33	0.30	0.30	0.38	0.40	0.45	0.27	0.26
Phenylalanine	0.69	0.63	0.71	0.59	0.74	0.50	0.64	0.75	0.52	0.62	0.79	0.62
Proline	1.41	1.36	1.49	1.28	1.42	1.08	1.46	1.66	1.21	1.40	1.58	1.41
Serine	0.84	0.65	0.61	0.73	0.35	0.65	0.88	0.74	0.69	0.31	0.72	0.67
Threonine	0.58	0.60	0.59	0.47	0.39	0.44	0.48	0.64	0.43	0.68	0.47	0.43
Tryptophan	0.20	0.18	0.21	0.18	0.15	0.18	0.18	0.22	0.19	0.18	0.14	0.17
Tyrosine	0.55	0.49	0.55	0.37	0.43	0.31	0.51	0.59	0.32	0.48	0.38	0.47

Table 1. Continued

	Grower 2			Grower 3			Finisher 1			Finisher 2		
	Rye substituting wheat			Rye substituting wheat			Rye substituting wheat			Rye substituting wheat		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Valine	0.55	0.85	0.48	0.47	0.84	0.36	0.51	0.65	0.40	0.48	0.77	0.46
NSPs, %												
Glucose	3.92	4.68	4.41	4.37	4.31	4.47	3.81	4.20	4.30	3.81	3.87	4.13
Xylose	3.19	3.58	3.56	3.44	3.50	3.60	3.30	3.37	3.65	3.33	3.52	3.62
Arabinose	2.26	2.52	2.51	2.54	2.56	2.71	2.36	2.48	2.64	2.38	2.47	2.58
Uronic acids	0.80	0.84	0.73	0.78	0.81	0.76	0.64	0.70	0.64	0.64	0.57	0.60
Galactose	0.59	0.57	0.59	0.50	0.42	0.44	0.38	0.37	0.38	0.37	0.37	0.37
Mannose	0.45	0.48	0.52	0.43	0.42	0.46	0.41	0.39	0.51	0.41	0.45	0.48
Total	11.20	12.67	12.32	12.07	12.01	12.44	10.91	11.50	12.12	10.95	11.25	11.77

[1]Grower 2 diets were fed from d 0 to 22, Grower 3 diets from d 23 to 42, Finisher 1 diets from d 43 to 63, and Finisher 2 diets from d 63 until the day of shipping for slaughter.

[2]KWS LOCHOW GMBH (Bergen, Germany).

[3]A small amount of ground wheat (1.97% to 2%) was used to flush the microscale after adding the small inclusion ingredients.

[4]Enzyme (Endofeed W DC; GNC Bioferm, Bradwell, SK, Canada) provided 280 units of β-glucanase and 900 units of xylanase per kilogram diet.

[5]Provided the following per kilogram of Grower 2 and 3 diets: Zn, 100 mg; Fe, 100 mg; Cu, 15 mg; Mn, 40 mg; I, 1 mg; Se, 0.3 mg; vitamin A, 8,000 IU; vitamin D, 1,500 IU; vitamin E, 30 IU; niacin, 20 mg; D-pantothenic acid, 12 mg; riboflavin, 4 mg; menadione, 2 mg; pyridoxine, 2 mg; folic acid, 0.5 mg; thiamine,1 mg; D-biotin, 0.1 mg; and vitamin B12, 0.02 mg.

[6]Provided the following per kilogram of Finisher 1 diet: Zn, 70 mg; Fe, 70 mg; Cu, 10.5 mg; Mn, 28 mg; I, 0.7 mg; Se, 0.21 mg; vitamin A, 5,600 IU; vitamin D, 1,050 IU; vitamin E, 21 IU; niacin, 14 mg; D-pantothenic acid, 8.4 mg; riboflavin, 2.8 mg; menadione, 1.4 mg; pyridoxine, 1.4 mg; folic acid, 0.35 mg; thiamine, 0.7 mg; D-biotin, 0.07 mg; and vitamin B12, 0.01 mg.

[7]Provided the following per kilogram of Finisher 2 diet: Zn, 50 mg; Fe, 50 mg; Cu, 7.5 mg; Mn, 20 mg; I, 0.5 mg; Se, 0.15 mg; vitamin A, 400 IU; vitamin D, 750 IU; vitamin E, 15 IU; niacin, 10 mg; D-pantothenic acid, 6 mg; riboflavin, 2 mg; menadione, 1 mg; pyridoxine, 1 mg; folic acid, 0.25 mg; thiamine, 0.5 mg; D-biotin, 0.05 mg; and vitamin B12, 0.01 mg.

[8]Ronozyme P-(M) 200; DSM Nutritional Products Canada Inc., Ayr, ON, Canada.

2.47 and 2.39 Mcal/kg and a SID Lys content of 0.26% and 0.28% was used for wheat and rye, respectively. Diets were formulated to provide 3.9, 3.3, 2.9, and 2.7 g SID Lys/Mcal NE per growth phase. Other amino acid (AA) ratios to Lys were set as per the ideal protein concept (NRC, 2012). Premixes were added to exceed vitamins and trace mineral requirements (NRC, 2012) per growth phase. Pigs had free access to water and the assigned phase test diet in mash form.

Measurements and Calculations

A robotic feeding system (Feed Logic; Feed Logic Co., Willmar, MN) delivered and electronically tracked the amount of assigned test diet fed to each pen. Pigs were group weighed at the initiation of feeding the experimental diets (d 0) and on d 22, 42, 63, 76, 91, and at target slaughter weight. Feed remaining in the pen feeder on weigh days was estimated by leveling the feed, measuring to the top of the feeder hopper, and calculating the leftover orts using an equation that accounted for measured diet bulk density (maximum weight error 0.1%; Seneviratne et al., 2010). Collected data were used to calculate pen average daily feed intake (ADFI), average daily weight gain (ADG), and feed efficiency expressed as ADG/ADFI (gain-to-feed ratio [G:F]).

Pigs were fed the assigned test regimen until the attainment of target slaughter weight (130 kg). As pigs grew near target market weight, several pigs from each pen were individually weighed and used as reference size pigs to select other pigs to be sent for slaughter that week. Pigs were shipped for slaughter on d 73, 75, 80, 82, 87, 89, 96, 102, and 109. Pigs were fasted for 16 to 20 h prior to slaughter. Pigs were slaughtered at a commercial abattoir (Maple Leaf, Brandon, MB, Canada) following typical commercial procedures. Warm carcasses were weighed including head, kidneys, omental fat and feet, and were graded for backfat and loin depth using a light-reflectance probe (Destron PG-100, Destron Technologies, Markham, ON, Canada) inserted between the third and fourth last ribs, 7 cm off the midline (Pomar and Marcoux, 2003). Lean yield was estimated using an established equation (lean, % = 68.1863 − 0.7833 × backfat + 0.0689 × loin + 0.0008 × backfat × backfat − 0.0002 × loin × loin + 0.0006 × backfat × loin, [backfat and loin

Table 2. Analyzed nutrient content (%, as fed basis), ergot and mycotoxin content (ppb, as fed basis) of ingredients fed in the trial

	Wheat			Rye (KWS Bono)			
	Batch 1 (Grower 2 and 3)	Batch 2 (Finisher 1)	Batch 3 (Finisher 2)	Batch 1 (Grower 2 and 3)	Batch 2 (Finisher 1 and 2)	Wheat DDGS	Field pea
Nutrient, %							
Dry matter	86.62	86.87	87.14	87.29	87.41	91.28	86.34
Starch	60.92	52.67	49.77	46.06	55.04	na[1]	na
CP	11.65	11.74	12.59	10.03	10.07	35.16	19.75
NDF	8.84	11.26	9.04	11.56	10.18	23.21	8.06
ADF	2.70	2.55	2.67	2.65	2.46	16.98	6.68
Crude fiber	2.03	2.03	2.11	1.76	1.87	6.37	4.64
Crude fat	1.78	1.85	1.85	1.12	2.35	6.24	1.19
Ash	1.44	1.41	1.51	1.40	1.34	4.97	2.37
Potassium	0.39	0.40	0.41	0.49	0.44	1.22	0.95
Phosphorus	0.30	0.30	0.34	0.25	0.27	0.87	0.33
Magnesium	0.11	0.11	0.12	0.10	0.10	0.32	0.11
Chloride	0.05	0.05	0.05	0.08	0.06	0.15	0.08
Calcium	0.04	0.04	0.04	0.05	0.05	0.11	0.09
Sodium	0.00	0.00	0.00	0.00	0.00	0.23	0.01
AAs, %							
Alanine	0.38	0.38	0.44	0.40	0.35	na	na
Arginine	0.44	0.43	0.60	0.48	0.40	na	na
Aspartic acid	0.61	0.61	0.71	0.67	0.50	na	na
Cysteine	10.21	11.83	1.13	17.26	0.51	na	na
Glutamic acid	2.97	2.91	3.65	2.24	2.05	na	na
Glycine	0.44	0.44	0.57	0.65	0.38	na	na
Histidine	0.25	0.22	0.32	0.24	0.22	na	na
Isoleucine	0.21	0.20	0.37	0.34	0.26	na	na
Leucine	0.59	0.57	0.80	0.57	0.46	na	na
Lysine	0.25	0.25	0.34	0.33	0.26	na	na
Methionine	0.64	0.66	0.28	0.66	0.20	na	na
Phenylalanine	0.41	0.39	0.55	0.41	0.32	na	na
Proline	1.01	0.98	1.21	0.87	0.74	na	na
Serine	0.71	0.70	0.09	0.60	0.40	na	na
Threonine	0.27	0.26	0.36	0.24	0.12	na	na
Tryptophan	0.14	0.14	0.15	0.10	0.10	na	na
Tyrosine	0.26	0.25	0.34	0.22	0.17	na	na
Valine	0.31	0.31	0.49	0.48	0.43	na	na
NSPs, %							
Glucose	3.46	3.45	3.49	5.25	4.32	na	na
Xylose	3.46	3.50	3.46	4.80	4.42	na	na
Arabinose	2.11	2.01	2.17	2.87	2.66	na	na
Uronic acids	0.32	0.33	0.35	0.25	0.34	na	na
Galactose	0.25	0.25	0.28	0.30	0.29	na	na
Mannose	0.18	0.19	0.21	0.36	0.39	na	na
Total	9.78	9.73	9.95	13.82	12.41	na	na
Ergot alkaloids							
Ergometrine	ND[2]	ND	ND	ND	ND	na	na
Ergosine	ND	low[3]	ND	ND	ND	na	na
Ergocornine	ND	mid[4]	ND	ND	ND	na	na
Ergocryptine	ND	mid	ND	ND	ND	na	na
Ergotamine	ND	ND	mid	low	low	na	na
Ergocristine	ND	ND	ND	mid	mid	na	na
Mycotoxin content							
Vomitoxin (ppm)	0.3	<0.2	0.3	<0.2	<0.2	na	na
Fumonisin (ppb)	<222	<222	<222	<222	<222	na	na
T-2 toxin (ppb)	<20	<20	<20	<20	<20	na	na
Ochratoxin A (ppb)	<5	<5	<5	<5	<5	na	na
Zearalenone (ppb)	<5	<5	<5	<5	<5	na	na
Aflatoxin (ppb)	<2	<2	<2	<2	<2	na	na

[1]Not analyzed.
[2]Not detected. Detection limit was ≤20 ng/g.
[3]A result labeled as "low" is close to, but above, the limit of detection, 20 to 40 ng/g.
[4]A result labeled as "mid" is at least an order of magnitude higher than "low," 200 to 400 ng/g.

depth measurements in mm]; AAFC et al., 1994). Carcass index was determined using the packer's grid that interpolated warm carcass weight and estimated lean yield. Carcass dressing was calculated as carcass weight divided by farm live weight at the time of shipping.

Feed cost was calculated as the sum of products of ingredient cost by inclusion level. Feed cost per pig was calculated as the sum of products of phase diet ADFI by diet cost. Feed cost per kilogram BW gain was calculated as the sum of products of phase diet ADFI by diet cost divided by overall ADG. Gross income subtracting feed cost (ISFC) was calculated multiplying carcass weight by index by pork price on the day of slaughter minus the sum of products of phase diet ADFI by diet cost. Index 110 indicates that the producer was paid a 10% premium over the 100-index base pork price on the day of slaughter.

Chemical Analyses

Diets and main ingredients were ground through a 0.5-mm screen in a centrifugal mill (Retsch GmbH, Haan, Germany). Diets and ingredients were analyzed using the AOAC International (AOAC, 2016), American Oil Chemists' Society (AOCS, 2017), or Ankom Technology (2017) methods for moisture (AOAC 930.15), crude protein (CP; AOAC 990.03[M]), crude fat (AOCS Am 5-04), ash (AOAC 923.03), crude fiber (AOCS BA 6a-05), acid detergent fiber (ADF; Ankom method 12[M]), neutral detergent fiber (NDF; Ankom method 13[M]), starch (enzymatic UV method, Cat. No. 10207748035; R-Biopharm, Darmstadt, Germany), and AA (AOAC 994.12) content at the Central Testing Laboratories (CTL), Winnipeg, MB, Canada. Wheat and rye samples were also analyzed for mycotoxins using ELISA tests at CTL, for NSP content using gas–liquid chromatography (as described by Meng et al., 2005) at the University of Manitoba, and for ergot alkaloid semiquantitatively using liquid chromatography–tandem mass spectrometry (as described by Krska et al., 2008) at the Organic Residue Laboratory of Alberta Agriculture and Forestry (Edmonton, AB, Canada).

Statistical Analyses

Trial data were analyzed as 3 × 2 × 2 factorial resulting in four pens per rye level substituting wheat grain × enzyme inclusion × sex. Growth performance, dressing, carcass, and feed cost vs. benefit data were analyzed using the MIXED procedure of SAS. Pen was the experimental unit for all variables. Models included the fixed effects of rye level substituting wheat grain (low, medium, high), enzyme inclusion (with or without), sex (barrows, gilts), and interactions. Block was the random term in the model. Initial BW was tested as covariate for ADFI, ADG, and G:F, and was included if it improved the fit of the model. Overall ADFI, ADG, and G:F were analyzed using closeout data. BW, ADFI, ADG, and G:F were analyzed as repeated measures including growth phase as repeated term; growth phase was added as a fixed effect and the interactions of growth phase with the other fixed effects were analyzed. An appropriate covariance structure was selected by comparing the goodness-of-fit measures of different structures. The Kenward–Roger correction was used for the denominator degrees of freedom. The proportion of pigs shipped for slaughter was analyzed with a generalized linear model (GLIMMIX procedure in SAS) using a binomial distribution and logit link function. Growth performance data are reported until d 76 on test. To test the hypotheses, $P < 0.05$ was considered significant and $P < 0.10$ a trend.

RESULTS

Dietary Nutrients

Increasing dietary hybrid rye inclusion in substitution for wheat grain generally decreased dietary starch, CP, ADF, and crude fiber content whereas it generally increased dietary NDF and crude fat content (Table 1). Numerically, hybrid rye batches fed in this trial had lower CP and crude fiber, and slightly greater NDF content than the three batches of wheat grain (Table 2). Starch, ADF, ash, and mineral content were within a similar range for the hybrid rye and wheat grain batches. Crude fat content was variable between the two hybrid rye batches (Table 2). Each measured NSP component, except for uronic acid, was greater in hybrid rye than wheat, resulting in greater total NSP content. Of the measured ergot alkaloids, ergosine, ergocornine, ergocryptine, and ergotamine were greater in one of the three wheat samples compared with the two hybrid rye grain samples, whereas ergocristine was greater in hybrid rye than wheat grain (Table 2). Mycotoxin levels were low for all wheat and hybrid rye grain samples (Table 2).

Growth Performance

As the number of pigs remaining in pens after start of shipment for slaughter was not different among treatments on d 76, but was different on d 91 (data not shown), we decided to use d 76 as the end of the study for growth performance variables, so as to not confound treatment effects with stocking density effects. There were no three-way interactions among hybrid rye level substituting wheat grain, enzyme inclusion, and sex for growth performance parameters. Effects of sex were as expected and are not described. There were no two-way interactions between hybrid rye substitution level and enzyme inclusion, hybrid rye substitution level and sex, or enzyme inclusion and sex unless described later.

BW was not affected by either increasing hybrid rye level substituting wheat grain or enzyme inclusion throughout the trial (Table 3). For the entire trial (d 0 to 76), pigs fed increasing hybrid rye substitutions had decreased ADFI and ADG. Enzyme inclusion did not affect ADFI but tended (P = 0.080) to increase ADG by 20 g/d. There was an interaction (P < 0.050) between hybrid rye substitution level and enzyme inclusion for feed efficiency; enzyme inclusion improved G:F only in pigs fed the high rye substitution level whereas enzyme inclusion did not affect G:F in pigs fed low or medium rye inclusion levels (Table 4). There was also an interaction (P < 0.050) between enzyme inclusion and sex for G:F; enzyme inclusion improved G:F in gilts but not in barrows (Table 5).

Increasing dietary hybrid rye level substituting wheat grain and enzyme inclusion did not affect ADFI in grower phases (Table 3). There was an interaction (P < 0.050) between hybrid rye

Table 3. Growth performance per growth phase and overall (d 0 to 76) of growing-finishing barrows and gilts fed diets with increasing hybrid rye[1] level substituting wheat grain with or without enzyme[2] inclusion[3]

	Rye substituting wheat			Enzyme inclusion		Sex			P value		
	Low	Medium	High	Without	With	Barrows	Gilts	SEM	Rye	Enzyme	Sex
BW, kg											
Overall (d 0 to 76)									0.695	0.9899	<0.0001
d 0	43.7	43.7	43.8	43.7	43.7	43.7	43.7	1.2	na[4]	na	0.8447
d 22	64.7	66.0	66.0	66.1	65.0	66.4	64.7	1.2	na	na	0.0006
d 42	84.6	86.0	85.9	85.7	85.3	87.0	84.0	1.2	na	na	<0.0001
d 63	106.5	109.6	108.1	107.5	108.7	108.8	107.4	1.6	na	na	0.3829
d 76	116.0	115.7	115.2	115.6	115.7	118.0	113.2	1.3	na	na	<0.0001
ADFI, kg/d											
Overall (d 0 to 76)[5]	3.049^{z}	2.975^{z,y}	2.911^{y}	2.966	2.990	3.183	2.773	0.024	0.0067	0.4664	<0.0001
Grower 2	2.243	2.264	2.257	2.294	2.215	2.363	2.146	0.020	0.8289	na	<0.0001
Grower 3	2.732	2.703	2.747	2.727	2.728	2.872	2.583	0.020	0.4420	na	<0.0001
Finisher 1[6]	3.126^{z}	3.035^{z}	2.886^{y}	2.991	3.041	3.259	2.773	0.039	0.0039	na	<0.0001
Finisher 2[6]	3.431^{z}	3.314^{y}	3.213^{y}	3.311	3.328	3.561	3.078	0.032	0.0017	na	<0.0001
ADG, kg/d											
Overall (d 0 to 76)	1.013^{z}	0.998^{z,y}	0.971^{y}	0.984	1.004	1.037	0.950	0.012	0.0114	0.0798	<0.0001
Grower 2[7]	0.954^{y}	1.014^{z}	1.008^{z}	1.015	0.969	1.027	0.957	0.017	0.0217	0.0168	na
Grower 3[7]	0.994	0.996	0.995	0.977	1.014	1.029	0.962	0.017	0.9964	0.0543	na
Finisher 1[7]	1.006^{z}	0.981^{z,y}	0.947^{y}	0.970	0.986	1.024	0.932	0.015	0.0067	0.2577	na
Finisher 2[7]	1.056^{z}	1.003^{y}	0.970^{y}	1.002	1.016	1.056	0.962	0.017	0.0014	0.4333	na
G:F, kg/kg											
Overall (d 0 to 76)[5,6]	0.333	0.336	0.334	0.332	0.337	0.326	0.343	0.003	0.7211	0.1148	<0.0001
Grower 2	0.426	0.442	0.447	0.438	0.438	0.435	0.442	0.006	na	na	na
Grower 3	0.364	0.369	0.363	0.358	0.372	0.358	0.372	0.005	na	na	na
Finisher 1	0.324	0.325	0.329	0.325	0.327	0.316	0.337	0.005	na	na	na
Finisher 2	0.308	0.303	0.303	0.303	0.306	0.296	0.313	0.005	na	na	na

[x,y,z]Means within a row without a common superscript differ (P < 0.050).

[1]KWS LOCHOW GMBH (Bergen, Germany).

[2]200 mg/kg inclusion rate containing 1,400 units of β-glucanase and 4,500 units of xylanase per gram of product (Endofeed W DC; GNC Bioferm, Bradwell, SK, Canada).

[3]LSmeans based on four pens of 21 pigs each per hybrid rye level substituting wheat grain × enzyme inclusion × sex.

[4]Not applicable. There was no interaction between the fixed effect and growth phase; therefore, P values are not given for each growth phase.

[5]There was an interaction (P < 0.050) between enzyme inclusion and sex.

[6]There was an interaction (P < 0.050) between hybrid rye level substituting wheat grain and enzyme inclusion.

[7]There was an interaction (P < 0.010) between hybrid rye level substituting wheat grain and sex.

Table 4. Interactions between hybrid rye level substituting wheat grain and enzyme inclusion on growth performance[1]

	Low rye substitution level		Medium rye substitution level		High rye substitution level			
Enzyme inclusion	Without	With	Without	With	Without	With	SEM	*P* value
G:F, overall (d 0 to 76), kg/kg	0.329^{y}	$0.337^{y,z}$	0.339^{z}	$0.333^{y,z}$	0.328^{y}	0.341^{z}	0.004	0.0212
ADFI, Finisher 1, kg/d	$3.088^{z,y}$	3.165^{z}	$2.953^{y,x}$	$3.118^{z,y}$	$2.933^{y,x}$	2.839^{x}	0.067	0.0107
ADFI, Finisher 2, kg/d	3.445^{z}	$3.418^{z,y}$	$3.337^{z,y,x}$	$3.291^{z,y,x,w}$	3.152^{w}	$3.274^{y,x,w}$	0.056	0.0090

[w,x,y,z]Means within a row without a common superscript differ ($P < 0.050$).

[1]LSmeans based on four pens of 21 pigs each per hybrid rye level substituting wheat grain × enzyme inclusion × sex.

Table 5. Interactions between enzyme inclusion and sex on growth performance[1]

	Barrows		Gilts			
Enzyme inclusion	Without	With	Without	With	SEM	*P* value
ADFI, overall (d 0 to 76), kg/d	3.136^{z}	3.230^{z}	2.796^{y}	2.751^{y}	0.033	0.0456
G:F, overall (d 0 to 76), kg/kg	0.327^{x}	0.325^{x}	0.338^{y}	0.348^{z}	0.004	0.0435

[x,y,z]Means within a row without a common superscript differ ($P < 0.050$).

[1]LSmeans based on four pens of 21 pigs each per hybrid rye level substituting wheat grain × enzyme inclusion × sex.

substitution level and enzyme inclusion for ADFI in finisher phases; in Finisher 1 phase, high hybrid rye substitution resulted in lower ADFI than low rye inclusion when no enzyme was added, whereas in Finisher 2 phase, high hybrid rye substitution resulted in lower ADFI than low hybrid rye inclusion when an enzyme was included (Table 4). Inclusion of enzyme reduced ($P < 0.050$) ADG in Grower 2 phase, increased ($P = 0.054$) ADG in Grower 3 phase, but did not affect ADG in Finisher phases (Table 3). There was an interaction ($P < 0.050$) among dietary hybrid rye substitution level, sex, and growth phase for ADG; for barrows, increasing hybrid rye substitution increased ADG in Grower 2 phase, did not affect ADG in Grower 3 phase, and decreased ADG in Finisher phases whereas for gilts, increasing hybrid rye substitution did not affect ADG in Grower 2 and 3 and Finisher 2 phases, and decreased ADG in Finisher 1 phase (Table 6). Feed efficiency (G:F) was not affected by increasing hybrid rye inclusion or enzyme inclusion for any of the growth phases (Table 3).

Shipping for Slaughter and Carcass Characteristics

The total proportion of pigs shipped to slaughter was not affected by either increasing hybrid rye level substituting wheat grain or enzyme inclusion (Table 7). Although the aim was to ship pigs at a fixed live BW as required by the packer, shipping weight (Table 8) was greater ($P < 0.050$) for pigs fed the low hybrid rye substitution level than those fed the medium level. Therefore, number of days to slaughter was confounded with shipping weight and the estimated number of days to a fixed live BW of 130 kg was calculated. Estimated days to 130 kg live BW was not affected by either increasing hybrid rye level substituting wheat grain or enzyme inclusion. Because of the difference in live shipping weight, carcass weight also tended ($P = 0.074$) to be greater in pigs fed low vs. medium hybrid rye substitution levels. However, dressing percentage was not different among hybrid rye substitution levels. Backfat, loin depth, lean yield, and calculated carcass revenue were not affected by increasing dietary hybrid rye substitution level (Table 8). Enzyme inclusion did not affect most carcass traits. There was a three-way interaction ($P < 0.050$) for index among dietary hybrid rye substitution level, enzyme inclusion, and sex; enzyme inclusion did not affect index in gilts, nor in barrows fed low or medium hybrid rye substitution levels, but decreased index in barrows fed high hybrid rye substitution level (data not shown).

Feed Cost vs. Benefit

Enzyme inclusion increased ($P < 0.001$) feed cost per tonne by Can$ 1.79 (Table 9). However, feed cost per pig and per kilogram BW gain were reduced ($P < 0.050$) by Can$ 1.70 and Can$ 0.02, respectively, when enzyme was included in the diets, whereas ISFC was not affected by enzyme inclusion (Table 9). There was an interaction ($P < 0.050$) between increasing dietary hybrid rye level substituting wheat grain and sex for feed cost per tonne, feed cost per pig, feed cost per kilogram BW gain, and ISFC. Feed cost per tonne increased with

Table 6. Interactions between hybrid rye level substituting wheat grain and sex on growth performance[1]

	Barrows			Gilts				
Rye substitution level	Low	Medium	High	Low	Medium	High	SEM	*P* value
ADG, kg/d								
Grower 2	0.979^{y,x}	1.036^{z,y}	1.067^{z}	0.930^{x}	0.992^{y,x}	0.948^{x}	0.025	0.0009
Grower 3	1.014^{z,y}	1.035^{z}	1.036^{z}	0.974^{z,y}	0.958^{y}	0.954^{y}	0.025	0.0338
Finisher 1	1.046^{z}	1.033^{z,y}	0.994^{y,x}	0.965^{x,w}	0.930^{w,v}	0.901^{v}	0.021	<0.0001
Finisher 2	1.128^{z}	1.065^{y}	0.975^{x}	0.983^{x}	0.940^{x}	0.964^{x}	0.024	<0.0001

[v,w,x,y,z]Means within a row without a common superscript differ ($P < 0.050$).

[1]LSmeans based on four pens of 21 pigs each per hybrid rye level substituting wheat grain × enzyme inclusion × sex.

Table 7. Effects of feeding diets with increasing hybrid rye[1] level substituting wheat grain with or without enzyme[2] inclusion on the proportion of growing-finishing barrows and gilts shipped to slaughter per period (d 73 to 105) and in total[3]

	Rye substituting wheat			Enzyme inclusion		Sex			*P* value		
	Low	Medium	High	Without	With	Barrows	Gilts	SEM	Rye	Enzyme	Sex
Shipped by d 76, %[4]	22.4	24.8	22.4	22.9	23.4	30.7	17.0	1.9	0.7159	0.8422	<0.0001
Shipped by d 91, %[4]	52.8	58.3	52.3	52.1	56.9	64.0	44.6	2.2	0.2463	0.1425	<0.0001
Pigs shipped total, %[5]	96.3	94.6	97.8	95.9	96.9	95.7	97.1	0.9	0.1582	0.4187	0.2804

[1]KWS LOCHOW GMBH (Bergen, Germany).

[2]200 mg/kg inclusion rate containing 1,400 units of β-glucanase and 4,500 units of xylanase per gram of product (Endofeed W DC; GNC Bioferm, Bradwell, SK, Canada).

[3]LSmeans based on four pens of 21 pigs each per hybrid rye level substituting wheat grain × enzyme inclusion × sex.

[4]Calculated as no. of pigs shipped/ no. of pigs on d 0 × 100.

[5]Calculated as (no. of pigs on d 0 − no. of pig removed from trial due to mortality or morbidity)/no. of pigs on d 0 × 100.

Table 8. Carcass characteristics and calculated carcass revenue of barrows and gilts fed diets with increasing hybrid rye[1] level substituting wheat grain with or without enzyme[2] inclusion[3]

	Rye substituting wheat			Enzyme inclusion		Sex			*P* value		
	Low	Medium	High	Without	With	Barrows	Gilts	SEM	Rye	Enzyme	Sex
Ship weight, kg	133.4^{z}	132.0^{y}	132.5^{zy}	132.7	132.6	132.9	132.4	0.4	0.0361	0.9098	0.3056
Estimated days to 130 kg live BW from d 63	24.9	24.6	26.1	25.4	25.0	21.5	28.9	1.0	0.2934	0.6414	<0.0001
Carcass weight, kg	104.7	103.5	103.6	103.9	103.9	103.8	104.1	0.3	0.0742	0.9792	0.4402
Dressing, %[4]	78.2	78.2	78.2	78.1	78.3	78.0	78.4	0.2	0.9809	0.4476	0.0808
Backfat, mm[4]	18.0	17.6	17.6	17.7	17.7	18.9	16.5	0.3	0.4336	0.8275	<0.0001
Loin depth, mm[4]	62.7	63.6	64.1	63.2	63.7	62.2	64.7	0.4	0.1226	0.3942	<0.0001
Lean yield, g/kg	61.0	61.3	61.3	61.1	61.2	60.6	61.7	0.1	0.1197	0.6271	<0.0001
Index[4,5,6]	110.5^{y}	112.0^{z}	110.2^{y}	111.4	110.4	111.6	110.2	0.3	0.0125	0.0501	0.0066
Carcass revenue, Can$	174.28	173.39	170.95	173.65	172.10	173.52	172.23	0.98	0.1409	0.2732	0.3598

[y,z]Means within a row without a common superscript differ ($P < 0.050$).

[1]KWS LOCHOW GMBH (Bergen, Germany).

[2]200 mg/kg inclusion rate containing 1,400 units of β-glucanase and 4,500 units of xylanase per gram of product (Endofeed W DC; GNC Bioferm, Bradwell, SK, Canada).

[3]LSmeans based on four pens of 21 pigs each per hybrid rye level substituting wheat grain × enzyme inclusion × sex.

[4]Carcass weight used as covariate.

[5]Index 110 indicates that the producer was paid a 10% premium over the 100-index base pork price on the day of slaughter.

[6]There was a three-way interaction ($P < 0.010$) between hybrid rye substitution level for wheat grain, enzyme inclusion, and sex.

increasing hybrid rye substitution level in both barrows and gilts; sex did not affect feed cost per tonne in low and medium hybrid rye diets, but feed cost per tonne was greater in barrows than gilts for the high hybrid rye diet (Table 10). For barrows, both feed cost per pig and per kilogram BW gain were lower in the medium than the high hybrid rye diet with the low hybrid rye diet being intermediate, whereas for gilts, the low hybrid rye diet had lower feed cost per pig and per kilogram BW gain than the medium

Table 9. Feed cost and gross ISFC in Can$ of growing-finishing barrows and gilts fed diets with increasing hybrid rye[1] level substituting wheat grain with or without enzyme[2] inclusion[3]

	Rye substituting wheat			Enzyme inclusion		Sex			*P* value		
	Low	Medium	High	Without	With	Barrows	Gilts	SEM	Rye	Enzyme	Sex
Feed cost/tonne[4,5]	240.28^{x}	241.28^{y}	242.20^{z}	240.36	242.15	241.51	241.00	0.11	<0.0001	<0.0001	<0.0001
Feed cost/pig[4]	80.57	81.55	81.75	82.14	80.44	83.53	79.05	1.00	0.3049	0.0142	<0.0001
Feed cost/kg BW gain[4]	0.94	0.95	0.95	0.96	0.94	0.97	0.92	0.01	0.3401	0.0129	<0.0001
ISFC[4]	30.66	28.20	28.31	28.53	29.59	26.66	31.45	1.38	0.1328	0.3382	0.0001

^{x,y,z}Means within a row without a common superscript differ ($P < 0.050$).

[1]KWS LOCHOW GMBH (Bergen, Germany).

[2]200 mg/kg inclusion rate containing 1,400 units of β-glucanase and 4,500 units of xylanase per gram of product (Endofeed W DC; GNC Bioferm, Bradwell, SK, Canada).

[3]LSmeans based on four pens of 21 pigs each per hybrid rye level substituting wheat grain × enzyme inclusion × sex.

[4]There was an interaction ($P < 0.050$) between hybrid rye level substituting wheat grain and sex.

[5]Ingredient cost in Canadian dollars per tonne used in this analysis were: wheat grain Can$190, hybrid rye grain Can$180, wheat DDGS Can$200, field pea Can$250, canola oil Can$950, limestone Can$108, mono-/di-calcium phosphate Can$928, salt Can$84, L-Lysine-HCl Can$2,000, L-Threonine Can$3,150, DL-Methionine Can$3,800, L-Tryptophan Can$19,000, vitamin/mineral premix Can$6,100, $CuSO_4 \cdot 5\ H_2O$ Can$2,920, phytase Can$2,910, Endofeed W DC enzyme Can$10,000.

Table 10. Interactions between hybrid rye level substituting wheat grain and sex on feed cost and gross ISFC in Can$[1]

	Barrows			Gilts				
Rye substitution level	Low	Medium	High	Low	Medium	High	SEM	*P* value
Feed cost/tonne[2]	240.45^{w}	241.38^{y,x}	242.69^{z}	240.11^{w}	241.18^{x}	241.71^{y}	0.16	0.0150
Feed cost/pig	83.27^{z,y}	82.42^{y,x}	84.90^{z}	77.88^{v}	80.68^{x,w}	78.60^{w,v}	1.20	0.0184
Feed cost/kg BW gain	0.97^{z,y}	0.96^{y,x}	0.99^{z}	0.91^{v}	0.94^{x,w}	0.91^{w,v}	0.01	0.0195
ISFC	26.89^{x}	28.12^{y,x}	24.98^{x}	34.44^{z}	28.28^{y,x}	31.64^{z,y}	1.76	0.0184

^{v,w,x,y,z}Means within a row without a common superscript differ ($P < 0.050$).

[1]LSmeans based on 4 pens of 21 pigs each per hybrid rye level substituting wheat grain × enzyme inclusion × sex.

[2]Ingredient cost in Canadian dollars per tonne used in this analysis were: wheat grain Can$190, hybrid rye grain Can$180, wheat DDGS Can$200, field pea Can$250, canola oil Can$950, limestone Can$108, mono-/di-calcium phosphate Can$928, salt Can$84, L-Lysine-HCl Can$2,000, L-Threonine Can$3,150, DL-Methionine Can$3,800, L-Tryptophan Can$19,000, vitamin/mineral premix Can$6,100, CuSO4 • 5 H2O Can$2,920, phytase Can$2,910, Endofeed W DC enzyme Can$10,000.

hybrid rye diet with the high hybrid rye diet being intermediate (Table 10). For barrows, ISFC was not affected by increasing hybrid rye level substituting wheat grain, whereas for gilts, ISFC was lower for the low vs. the medium hybrid rye diet, with the high hybrid rye diet being intermediate (Table 10).

DISCUSSION

Rye is a cereal crop similar to wheat. It is popular in northern and eastern European countries for the production of dark bread and food products (Jürgens et al., 2012), grain stock for ethanol production, as forage/silage crop for ruminants, and cereal grain for pigs (http://www.ryebelt.com). In Canada, rye grain is best known for the production of whiskey and spirits. Its winter hardiness allows efficient use of spring melting snow runoff and extends the "work season" vs. spring-planted cereals for grain producers. Of ~175,000 hectares planted to rye in Canada, about 80% grows in the Prairie provinces (AAFC, 2019).

Novel European hybrid rye cultivars have recently been introduced to Canada. These hybrid rye cultivars yield 25% to 40% more over conventional rye, 15% to 20% over barley, and ~15% over winter wheat (King, 2017). Modern rye hybrids produce vast amounts of pollen because of PollenPlus technology (https://www.kws.com/corp/en/products/oilseed-rape/ryevolution/). The pollen overwhelm the stigma giving mold spores a lower chance of infecting the ear before the stigma closes. Fall-planted rye flowers earlier than spring-planted cereals so ergot and fusarium contamination risk is lower. Rye grain is not popular as an ingredient in pig feed in Canada compared with corn, wheat and barley, even triticale. However, greater hybrid rye grain yield compared with wheat (5,000 to 7,500 vs. 2,700 to 5,400 kg/ha) was an attractive incentive for us to evaluate feeding hybrid fall rye grain to pigs even if that might result in somewhat lower pig performance.

Early research showed decreased growth performance when pigs were fed high inclusions of rye grain (Friend and MacIntyre, 1969; Thacker et al., 1991; Thacker and Baas, 1996). However, these trials looked at rye replacing barley grain. Instead, we decided to evaluate feeding increasing hybrid rye inclusions replacing wheat grain. To the best of our knowledge, our trial is the first one comparing hybrid rye with wheat rather than barley (Schwarz et al., 2014, 2016) or a combination of barley, wheat, and triticale grain (Meyer et al., 2003; Bussières, 2018).

Feed intake was reduced feeding increasing hybrid rye level substituting wheat grain in finisher diets but not in grower diets, possibly due to finisher diets containing a greater proportion of cereal grain, and thus hybrid rye, than grower diets. The decrease in feed intake with increasing hybrid rye level substituting wheat grain was initially suspected to be because of greater mycotoxin or ergot alkaloid levels in the hybrid rye than wheat grain. However, laboratory tests on both hybrid rye and wheat grain samples confirmed that neither mycotoxins nor ergot alkaloids were a factor in reducing feed intake. We, therefore, believe that the decreased feed intake observed with increasing hybrid rye level substituting wheat grain was possibly caused by greater NSP content in rye vs. wheat grain fed in this trial. Increased NSP content makes digesta more viscous, slowing down passage rate through the gut (Bach Knudsen, 2011). Arabinoxylans are known to form highly viscous solutions in water associated with reduced feed intake (Jürgens et al., 2012). Hybrid rye fed in this trial had indeed greater amounts of arabinose and xylose than wheat grain. Therefore, pigs fed these less digestible complex sugars in high rye diets likely felt more full and were satisfied with slightly less feed. Thacker et al. (1999) showed that young pigs fed a low viscosity rye diet consumed 9% more feed than pigs fed a high viscosity rye diet. However, this difference did not reach statistical significance, making it hard to conclude whether viscosity was indeed a determining factor in feed consumption.

Because both feed intake and weight gain were reduced in parallel, feed efficiency was not affected by increasing hybrid rye inclusion level. Previous reports feeding rye substituting barley grain showed similar feed efficiency between high rye and barley control diets (Meyer et al., 2003; Schwarz et al., 2014; Bussières, 2018) whereas others showed better feed efficiency feeding high rye compared with barley control diets (Thacker et al., 1991, Thacker and Baas, 1996; Schwarz et al., 2016 [only numerically]). The improved feed efficiency feeding rye vs. barley was likely because rye had lower NDF and ADF content than barley grain (Thacker et al., 1991; NRC, 2012). Hybrid rye fed in our study had NDF and ADF content close to those of our wheat grain as well as similar starch and CP content. Moreover, our diets were formulated based on NE level and SID AA ratios, ensuring that our rye diets had similar feeding value. Similar feed efficiency showed that we estimated the NE level and SID AA content of the hybrid rye adequately.

Some of the complex soluble sugars that make up the NSP fraction could potentially be made more digestible by inclusion of pentosanases, enzymes that break down pentosans (Campbell and Bedford, 1992). Feed enzymes have greater effect in poultry than pigs likely due to a more hostile environment for feed enzymes in the pig stomach given the lower pH. Nevertheless, Thacker and Baas (1996) found pentosanase activity in the small intestine, suggesting an opportunity for pentosanases to affect digestibility and growth performance. Indeed, in earlier research, Thacker's laboratory showed improved F:G in one of their experiments with enzyme-supplemented meal-based rye diets (Thacker et al., 1991) but not with pelleted rye diets (Thacker et al., 1991, 1992; Thacker and Baas, 1996). More recent research has also found limited benefits of feeding NSP enzymes to growing pigs. Lærke et al. (2015) found that the ability of a combination of two xylanases to reduce viscosity, solubilize arabinoxylans, and release arabinoxylan degradation products was lower in rye than in wheat grain, and that these enzymes did not improve the digestibility of rye. Nørgaard et al. (2016) fed 4,000 units xylanase per kilogram and found no improvement in nutrient digestibility in rye diets compared to diets without xylanase. On the other hand, Villca et al. (2016) found that an enzyme complex including several glucanases and xylanase supplemented to a pelleted rye diet fed in a liquid feeding system improved digestibility of nutrients but did not result in significant effects on growth performance. Our trial fed non-pelleted/mash diets supplemented with an enzyme complex containing both xylanase and β-glucanase. This enzyme complex tended to increase ADG. Enzyme inclusion also resulted in better G:F but that was only evident at the high rye level substituting wheat grain. The mostly rye grain diet likely transited slower along the gut, staying longer and held the most water giving feed enzymes more time to break down rye pentosans.

Often, feeding alternative ingredients with greater fiber content results in reduced carcass dressing because of increased total empty weight of the gastrointestinal tract and(or) increased volume of digesta in the gut at slaughter (Kerr and Shurson, 2013). In our trial, carcass dressing was not reduced by increasing hybrid rye inclusion substituting wheat grain because rye NSPs were mostly soluble instead of bulky, insoluble cereal hulls. Indeed, NDF content was rather similar between the wheat and hybrid rye grain fed in this trial. Jha et al. (2013) showed that decreased carcass dressing was related to increased NDF content in diets. Differences in carcass traits such as backfat, loin depth, and lean yield are generally related to erroneous NE or SID AA values at feed formulation. In our trial, backfat did not increase or decrease with increasing hybrid rye level substituting wheat grain because we accounted for the greater rye NSP content as a lower NE value for rye compared with wheat grain. Loin depth was also not affected because we correctly accounted for differences in AA digestibility between rye and wheat grain when formulating diets. Most other studies that measured carcass characteristics also found no effect of feeding rye on backfat, loin depth, or lean yield (Hooper et al., 2002; Meyer et al., 2003; Schwarz et al, 2014, 2016; Villca et al., 2016). In one publication, enzyme inclusion in rye diets resulted in greater backfat and smaller loin depth and lean yield (Schwarz et al., 2016) whereas another publication showed a tendency for improved lean yield with enzyme inclusion in rye diets (Alert and Fröhlich, 2006). In our trial, enzyme inclusion did not have an effect on carcass traits, except for reduced index in barrows fed high hybrid rye inclusion levels. It is not clear what caused the reduced index because index was a packer's grid extrapolation of carcass weight and lean yield, and both were similar between pigs fed diets with or without enzyme inclusion.

Hybrid fall rye was sourced at Can$180 vs. Can$190 per metric tonne for wheat grain. However, diets with increasing rye level were costlier than wheat grain diets because canola oil was added to compensate for the lower NE value of rye. Nonetheless, the feed cost per pig or per kilogram BW gain was not different when increasing hybrid rye levels substituting wheat grain were fed. Schwarz et al. (2016) also mentioned greater feed cost for diets with rye substituting barley grain, and lower feed cost per pig or per kilogram BW gain. In our trial, gross income after subtracting feed cost was Can$2 lower for the high vs. the low rye diets although this difference did not reach significance. Previous results did show a significant improvement of the simplified direct surplus (similar to income subtracting feed cost) for diets with high rye inclusions compared to barley diets (Schwarz et al., 2014, 2016). Assuming hybrid fall rye yields 2,700 kg/ha more than wheat grain, using our trial results that would imply 691 kg more lean pork per hectare feeding 60% rye inclusion substituting wheat grain from 43.7 to 132.7 kg slaughter weight. Our study is unique in that it ties up pork to grain yield per unit of land, which is of paramount importance to pork producers growing their own crops and aiming to reduce the carbon footprint of pork production.

In conclusion, although increasing hybrid rye level substituting wheat grain decreased overall ADFI and ADG, hybrid rye can completely substitute wheat grain in grower-finisher pig diets without affecting carcass traits, feed cost per pig or per kilogram BW gain, and ISFC. Enzyme inclusion tended to improve overall ADG and improved feed efficiency in pigs fed the high rye substitution level for wheat grain. Inclusion of NSP enzyme would, therefore, be recommended for diets containing high rye levels to improve feed efficiency and ADG.

ACKNOWLEDGMENTS

We would like to thank KWS LOCHOW GMBH (Bergen, Germany) and GNC Bioferm (Bradwell, SK) for financial support. Appreciation is expressed to the Drumloche team for animal care and their expertise running the trial. Thanks also to Lewisville Pork Farm for the use of the animals and Sunhaven Farms Milling for supplying the feed. To Dr B. Slominski, our thanks for conducting the non-starch polysaccharides analysis in your laboratory at University of Manitoba.

Conflict of interest statement. None declared.

LITERATURE CITED

AAFC. 2019. Canada: Outlook for principal field crops. Agriculture and Agri-Food Canada Market Analysis Group, Canada. Available online: http://www.agr.gc.ca/resources/prod/doc/misb/mag-gam/fco-ppc/fco-ppc_2019-07-19-eng.pdf [accessed August 14, 2019].

AAFC; CVC; & CCP. 1994. Enquête nationale sur le rendement boucher du porc (1992): une initiative de recherche commune d'Agriculture et Agro-alimentaire Canada, le Conseil des viandes du Canada et le Conseil canadien du porc. Agriculture and Agri-Food, Canada. p. 107.

Alert, H-J., and B. Fröhlich. 2006. Roggeneinsatz in der Schweinemast. Schriftenreihe der Sächsischen Landesanstalt für Landwirtschaft, Heft 5/2006. Available online: https://publikationen.sachsen.de/bdb/artikel/14092. [accessed August 14, 2019] [In German].

Ankom Technology. 2017. Analytical methods for Fiber Analyzer A2000. Available online: https://www.ankom.com/analytical-methods-support/fiber-analyzer-a2000. [accessed August 14, 2019].

AOAC. 2016. Official methods of analysis of AOAC International. 20th ed. AOAC International, Rockville, MD.

AOCS. 2017. Official methods and recommended practices of the The American Oil Chemists' Society (AOCS). 7th ed. American Oil Chemists' Society, Urbana, IL.

Bach Knudsen, K. E. 2011. Triennial Growth Symposium: effects of polymeric carbohydrates on growth and development in pigs. J. Anim. Sci. 89:1965–1980. doi:10.2527/jas.2010-3602

Bussières, D. 2018. Impact of hybrid rye (Brasetto) on finisher pig performance, carcass and meat quality. J. Anim. Sci. 96(Suppl. S2):140. (Abstr.). doi:10.1093/jas/sky073.259

Campbell, G. L., and M. R. Bedford. 1992. Enzyme applications for monogastric feeds: a review. Can. J. Anim. Sci. 72:449–466. doi:10.4141/cjas92-058

Canadian Council on Animal Care in Science (CCAC). 2009. The care and use of farm animals in research, teaching and testing. Canadian Council on Animal Care in Science, Ottawa, ON, Canada.

Cervantes-Pahm, S. K., Y. Liu, and H. H. Stein. 2014. Digestible indispensable amino acid score and digestible amino acids in eight cereal grains. Br. J. Nutr. 111:1663–1672. doi:10.1017/S0007114513004273

Friend, D. W., and T. M. MacIntyre. 1969. Digestibility of rye and its value in pelleted rations for pigs. Can. J. Anim. Sci. 49:375–381. doi:10.4141/cjas69-049

Friend, D. W., and T. M. Macintyre. 1970. Effect of rye ergot on growth and N-retention in growing pigs. Can. J. Comp. Med. 34:198–202.

Hooper, W., P. Horne, A. McKellop, M. Perry, A. Roloson, I. Mutch, A. Ling, D. Mol, T. Rogers, R. Milton, et al. 2002. Optimal whole soybean inclusion rate for commercial swine diets and the use of rye as a feed ingredient for swine rations on Prince Edward Island. Final Report for PEI Pork, Industry Chair for Swine Research, Atlantic Veterinary College, University of Prince Edward Island, Canada, March 15, 2002. Not available online anymore.

Jha, R., J. K. Htoo, M. G. Young, E. Beltranena, and R. T. Zijlstra. 2013. Effects of increasing co-product inclusion and reducing dietary protein on growth performance, carcass characteristics, and jowl fatty acid profile of growing-finishing pigs. J. Anim. Sci. 91:2178–2191. doi:10.2527/jas.2011-5065

Jürgens, H. U., G. Jansen, and C. B. Wegener. 2012. Characterisation of several rye cultivars with respect to arabinoxylans and extract viscosity. J. Agric. Sci. 4:1–12. doi:10.5539/jas.v4n5p1

Kerr, B. J., and G. C. Shurson. 2013. Strategies to improve fiber utilization in swine. J. Anim. Sci. Biotechnol. 4:11. doi:10.1186/2049-1891-4-11

King, C. 2017. Why you should grow hybrid rye: yield advantages, pricing and market opportunities. Top Crop Manager, June 19, 2017. Available online https://www.topcropmanager.com/hybrid-rye-gaining-ground-20191. [accessed August 14, 2019].

Krska, R., G. Stubbings, R. Macarthur, and C. Crews. 2008. Simultaneous determination of six major ergot alkaloids and their epimers in cereals and foodstuffs by LC-MS-MS. Anal. Bioanal. Chem. 391:563–576. doi:10.1007/s00216-008-2036-6

Lærke, H. N., S. Arent, S. Dalsgaard, and K. E. Bach Knudsen. 2015. Effect of xylanases on ileal viscosity, intestinal fiber modification, and apparent ileal fiber and nutrient digestibility of rye and wheat in growing pigs. J. Anim. Sci. 93:4323–4335. doi:10.2527/jas.2015-9096

McGhee, M. L., and H. H. Stein. 2018. Apparent and standardized ileal digestibility of AA and starch in hybrid rye, barley, wheat, and corn fed to growing pigs. J. Anim. Sci. 96:3319–3329. doi:10.1093/jas/sky206

Meng, X., B. A. Slominski, C. M. Nyachoti, L. D. Campbell, and W. Guenter. 2005. Degradation of cell wall polysaccharides by combinations of carbohydrase enzymes and their effect on nutrient utilization and broiler chicken performance. Poult. Sci. 84:37–47. doi:10.1093/ps/84.1.37

Meyer, A., A. Schön, A. Brade, and P. Köhler. 2003. Wie wirkt sich ein Mischfutter mit Roggen als alleiniger Getreidekomponente auf die Leistung und Fettqualität von Mastschweinen aus? Forum angewandte Forschung in der Rinder- und Schweinefütterung, Fulda, Tagungsunterlage. p. 104–105. Bundesforschungsanstalt für Landwirtschaft, Germany [In German].

Miedaner, T., and H. H. Geiger. 2015. Biology, genetics, and management of ergot (Claviceps spp.) in rye, sorghum, and pearl millet. Toxins (Basel). 7:659–678. doi:10.3390/toxins7030659

Nørgaard, J. V., T. F. Pedersen, K. Blaabjerg, K. E. Bach Knudsen, and H. N. Laerke. 2016. Xylanase supplementation to rye diets for growing pigs. J. Anim. Sci. 94:91–94. doi:10.2527/jas2015-9775

NRC. 2012. Nutrient requirements of swine. 11th rev. ed. National Academy Press, Washington, DC.

Pomar, C., and M. Marcoux. 2003. Comparing the Canadian pork lean yields and grading indexes predicted from grading methods based on Destron and Hennessy probe measurements. Can. J. Anim. Sci. 83:451–458. doi:10.4141/A02-107

Schwarz, T., W. Kuleta, A. Turek, R. Tuz, J. Nowicki, B. Rudzki, and P. M. Bartlewski. 2014. Assessing the efficiency of using a modern hybrid rye cultivar for pig fattening, with emphasis on production costs and carcass quality. Anim. Prod. Sci. 55:467–473. doi:10.1071/AN13386

Schwarz, T., A. Turek, J. Nowicki., R. Tuz, B. Rudzki, and P. M. Bartlewski. 2016. Production value and cost-effectiveness of pig fattening using liquid feeding or enzyme-supplemented dry mixes containing rye grain. Czech J. Anim. Sci. 61:341–350. doi:10.17221/73/2015-CJAS

Seneviratne, R. W., M. G. Young, E. Beltranena, L. A. Goonewardene, R. W. Newkirk, and R. T. Zijlstra. 2010. The nutritional value of expeller-pressed canola meal for grower-finisher pigs. J. Anim. Sci. 88:2073–2083. doi:10.2527/jas.2009-2437

Thacker, P. A., and T. C. Baas. 1996. Effects of gastric pH on the activity of exogenous pentosanase and the effect of pentosanase supplementation of the diet on the performance of growing-finishing pigs. Anim. Feed Sci. Technol. 63:187–200. doi:10.1016/S0377-8401(96)01028-0

Thacker, P. A., G. L. Campbell, and J. GrootWassink. 1991. The effect of enzyme supplementation on the nutritive value of rye-based diets for swine. Can. J. Anim. Sci. 71:489–496. doi:10.4141/cjas91-058

Thacker, P. A., G. L. Campbell, and J. W. D. GrootWassink. 1992. Effect of salinomycin and enzyme supplementation on nutrient digestibility and the performance of pigs fed barley- or rye-based diets. Can. J. Anim. Sci. 72:117–125. doi:10.4141/cjas92-013

Thacker, P. A., G. L. Campbell, and G. J. Scoles. 1999. Performance of young growing pigs (17–34 kg) fed rye-based diets selected for reduced viscosity. J. Anim. Feed Sci. 8:549–556. doi:10.22358/jafs/69179/1999

Thacker, P. A., J. G. McLeod, and G. L. Campbell. 2002. Performance of growing-finishing pigs fed diets based on normal or low viscosity rye fed with and without enzyme supplementation. Arch. Tierernahr. 56:361–370. doi:10.1080/00039420215631

Villca, B., R. Lizardo, J. Broz, J. Brufau, and D. Torrallardona. 2016. Effect of a carbohydrase enzyme complex on the nutrient apparent total tract digestibility of rye-based diets fed to growing-finishing pigs under liquid feeding. J. Anim. Sci. 94:230–233. doi:10.2527/jas2015-9747