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Evaluation of New Fall Rye Cultivar 'Bono' in Single and Double Cropping Systems

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Abstract: A new fall rye (FR, *Secale cereale* L.) cv. Bono was investigated as a novel cropping option in Saskatchewan, Canada. In this study, the performance of Bono was compared to Hazlet FR, and both cultivars were compared to winter triticale (WT, *Triticosecale* Wittm.) cv. Pika in single cropping (SC) or in double cropping (DC) systems with spring barley (*Hordeum vulgare* L.) was evaluated in the Dark Brown soil zone, 2019–2021. Five replicated (n = 4) treatments were: (i) BonoFR; (ii) HazletFR; (iii) PikaWT; (iv) Barley–BonoFR; and (v) Barley–HazletFR. The first crop of barley was harvested at soft dough stage, followed by the second crop of FR seeded in the same year and harvested between flag leaf to heading emergence the following summer for greenfeed hay. Bono did not differ ($p > 0.05$) in DMY (1.2 Mg ha^{-1}) or nutritive value from Hazlet, however, both FRs differed ($p = 0.01$) from WT by higher nitrogen use efficiency (NUE, 41.0 vs. 33.7) and NDF (541.8 vs. 479.3 g kg^{-1}), but lower CP (155.3 vs. 187.1 g kg^{-1}). Double cropping barley with fall ryes increased total DMY, nutrients yield per ha, and minerals uptake by up to 83% and NUE by 35.3%. In conclusion, Bono fall rye could be an equal quality alternative to Hazlet, although the current higher seed price may delay its adoption.

Keywords: winter cereal; fall rye; double cropping; nutrient uptake

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1. Introduction

One possibility for intensification of agriculture is the practice of double cropping—sequentially harvesting two crops in one year from the same parcel of land [1]. Double cropping, which involves producing a second crop after the harvest of the first crop, offers an opportunity to utilize the late-season heat and moisture resources after cash crop harvest [2]. Early harvested crops, such as winter cereals or annual forages, can provide a window of opportunity for double cropping with cover crops in the Canadian prairies [3]. Hybrid rye (*Secale cereale* L.) is now being considered as a novel cropping option in western Canada due to its high yield potential, fast growing, and earlier maturing (matures rapidly at the flag-leaf, boot and early-heading stages) and harvest. In Iowa, USA, for example, when seeded in the fall, cereal rye will grow before going into winter dormancy and resume growth early the following spring and is harvested for grain in mid-to-late July [4]. Growing fall rye may also address forage demand during drought conditions due to its fibrous root system and efficient use of nitrogen (N) along with spring moisture [5]. In Alberta, Canada, Moyer et al. [6] revealed that a short-duration fall rye cover crop during the fallow phase of rotation suppressed weeds and offered soil protection, while maintaining subsequent crop yields. McCartney et al. [7] explored further that annual ryegrass and fall rye have desirable characteristics in terms of nutritive value for stockpile grazing, as quality remains higher into the fall when the nutritive value of perennial species begins to diminish. On the other hand, Kilcher [8] in Swift Current, Saskatchewan, Canada, found that fall grazing of fall rye reduced subsequent grain yields by 17%, whereas spring grazing reduced yields by only 10%, and grazing both in fall and spring reduced grain yields by 25% in this region of the semi-arid mixed grass prairie. Hazlet is the dominant commercial rye cultivar grown in western Canada [9] and is adapted to the soils and climate of the Canadian prairies, where it performs consistently well [10]. Since its introduction in 2016, a relatively new cultivar, KWS Bono hybrid fall rye, has been praised for consistently high yields and good quality grain production, and it is well suited to all regions in Canada [11]. Although, as McCartney et al. [12] noted, limited work has been conducted with winter cereals as dual-purpose crops in Canada, especially with newer cultivars of fall rye for adaptability and suitability as greenfeed for double cropping and grazing, which has yet to be evaluated for the western Canadian prairie regions.

The objectives of this study were to determine: (i) forage dry matter yield (DMY) and nutritive value of hybrid fall rye cv. Bono and cv. Hazlet compared to winter triticale cv. Pika in a single cropping system and both fall rye cultivars in a double cropping system; (ii) evaluate barley DMY and nutritive value for a double cropping system; (iii) suitability of each forage for double cropping systems; and (iv) costs and net returns for each single and double cropping system.

2. Materials and Methods

2.1. Study Site and Experimental Design

In spring 2019, a study site was selected at the Livestock and Forage Centre of Excellence (LFCE) located in Clavet, Saskatchewan, Canada. The soil type at the site is classified as Dark Brown [13]. The site was left fallow in the summer of 2018. The five treatments were composed of three single cropping treatments of winter cereals that included two cultivars of fall rye (cvs. Bono and Hazlet) (i) BonoFR; (ii) HazletFR; and one cultivar of winter triticale (cv. Pika) (iii) PikaWT; and two double cropping treatments of spring barley (cv. Maverick) harvested for greenfeed hay followed by the two fall rye cultivars, Bono and Hazlet, (iv) Barley-BonoFR; and (v) Barley-HazletFR. Replicated treatments ($n = 4$) were randomly allocated to a total of 20 plots (Figure 1). Each plot was 2.4×6 m in size with a 14.4 m^2 plot area. There was a 0.5-m gap between treatment plots and a 2-m gap between replicates (blocks). The experimental design was a Randomized Complete Block Design. A flowchart showing the sequence of the work both in single and double cropping systems is presented in Figure 2.

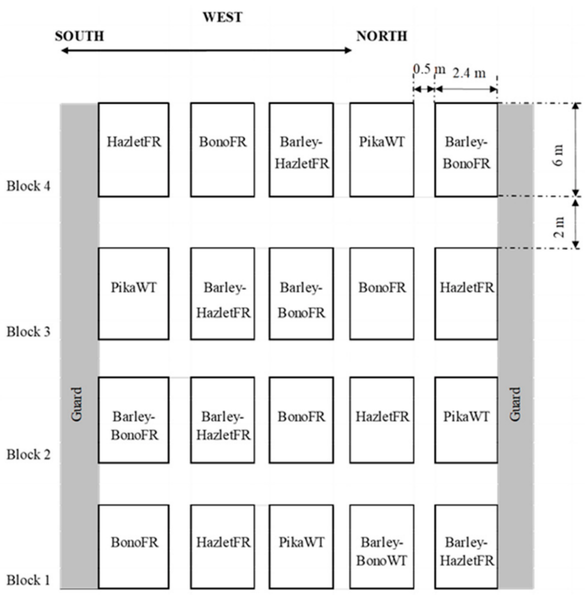

Figure 1. Experimental field layout of trial. *Note:* BonoFR, fall rye cv. Bono; HazletFR, fall rye cv. Hazlet; PikaWT, winter triticale cv. Pika; Barley-BonoFR, double cropping treatment of spring barley (cv. Maverick) followed by BonoFR; Barley-HazletFR, double cropping treatment of spring barley followed by HazletFR.

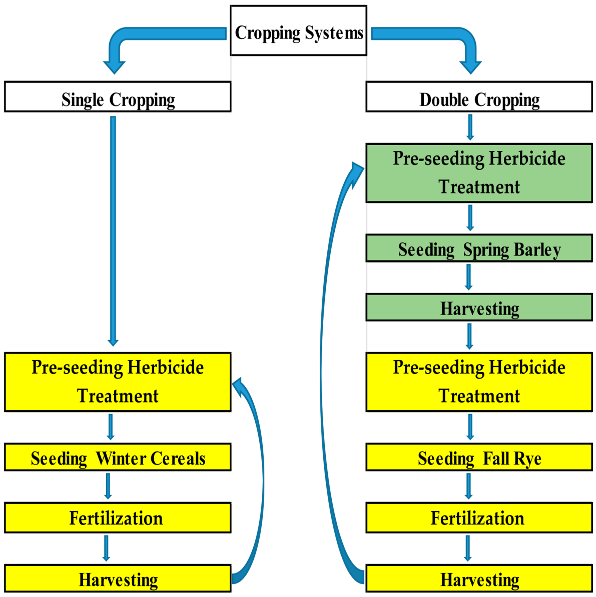

Figure 2. A flowchart showing the sequence of the work both in single and double cropping systems. Green box represents barley and yellow box represents winter cereals agronomics.

2.2. Weed Management

All the agronomic information for the trial is presented in Table 1. Weed management was similar across all plots. Before seeding (14 May and 11 September for the first and second crops, respectively), all plots were sprayed with glyphosate at 0.9 L ha^{-1} (Roundup; Monsanto, Creve Coeur, Greater St. Louis, Missouri, USA) using a 3-point hitch 2019 Rogers 90 cm (30 ft) sprayer (Cleveland Alliances Ltd. Duns, Berwickshire, UK). It was speculated that soil moisture may decrease after forage harvest, therefore, prior to seeding of the second crop, plots were tilled and sprayed (11 September) with glyphosate to minimize shading and moisture competition.

Table 1. Agronomic information of winter cereal in single cropping system and barley in double cropping system with fall rye over 3 years (2019 to 2021).

	Forage		
Item	**Barley † (cv. Maverick)**	**Fall Rye (cvs. Bono and Hazlet)**	**Winter Triticale (cv. Pika)**
Pre-seeding herbicide	0.9 L ha^{-1}	0.9 L glyphosate ha^{-1}	0.9 L glyphosate ha^{-1}
Pre-seeding herbicide date	14 May 2019	11 September 2019	11 September 2019
Soil sampling	15 May 2019	15 May 2019	15 May 2019
Seeding date	16 May 2019 18 June 2020	17 September 2019 18 September 2020	17 September 2019 18 September 2020
Seeding rate (PLS m^{-2})	244	250	360
Row spacing	30 cm	30 cm	30 cm
Harvest date	6 August 2019 1 September 2020	15 June 2020 22 June 2021	15 June 2020 22 June 2021
Fertilization rate	–	23 kg actual N ha^{-1} (in double cropping plots)	–
Fertilization date	–	21 October 2020 and 2021	–

Note. † Barley was early spring barley (cv. Maverick). PLS, pure live seeds.

2.3. Crop Establishment

The first barley crop was seeded in mid-May 2019 and 2020 (Table 1). Fall rye cultivars (both as single and double cropping systems) and winter triticale (as a single cropping system) were seeded in mid-September 2019 and 2020. Barley, fall rye cultivars, and winter triticale were sown at 244, 250, and 360 pure live seeds (PLS) m^{-2} (136.6, 85, and 151.2 kg ha^{-1}), respectively. Seeding was done using a pull type Wintersteiger (Wintersteiger AG, Ried, Austria) at row spacing of 30 cm. Seeding depth for fall rye cultivars and winter triticale was 3.75 cm and for barley it was 2.5 cm.

2.4. Harvesting

Winter cereals were harvested for greenfeed between the flag leaf and heading emergence, and spring barley in a double cropping system was harvested at the soft dough stage (Table 1), using a plot harvester, Haldrup F-55 (Haldrup GmbH, Ilshofen, Germany), followed by second crop planting.

2.5. Nutritive Value Analysis

Forage samples were dried in a forced-air oven at 55 °C for 48 h, ground to pass through a 1-mm screen using a Wiley mill (Thomas-Wiley, Philadelphia, PA), and stored for further analysis. The nutritive value analysis included crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), calcium (Ca), total phosphorus (P), and potassium (K). Sequential NDF and ADF were determined using an $ANKOM^{200}$ fiber analyzer (Model 200; ANKOM; Fairport, NY, USA). Total N was determined using the micro-Kjeldahl method [14] and was multiplied by 6.25 to determine CP content, soluble protein (SP) by the borate-phosphate procedure [14], and rumen degradable protein (RDP) by the procedure outlined by Krishnamoorthy et al. [15]. Calcium and potassium concentrations were determined using an atomic absorption spectrophotometer [14] (Method 978.02; PerkinElmer, Model 2380, CN, Waltham, MA, USA), while total P was analyzed using a spectrophotometer [14] (Method 946.06, Pharmacia, LKB-Ultraspec® III, Stockholm, Sweden). The ash content was determined by heating at 600 °C for 4 h [14] (Method 923.03). Total digestible nutrients (TDN), net energy for gain (NE_g), and net energy maintenance (NE_m) were calculated using the grass–legume Penn State equation according to Adams [16]. Relative feed value was calculated as RFV = (DDM × DMI)/1.29; where DDM = digestible DM calculated as 88.9 − (0.779 × %ADF) and potential DMI = dry matter intake calculated as 120/%NDF [17]. Relative forage quality (RFQ) was calculated as RFQ = 1.9449 × RFV − 67.038 [18].

2.6. Calculation of Nutrient Yield

The nutrient yield of crude protein and total digestible nutrients per hectare were calculated by multiplying crop forage yield (kg ha^{-1}) by nutrient content (% DM) to allow a comparison of nutrient yield potential for animal feed production among treatment forages. Since N taken up by fall rye was mainly partitioned to the shoot material, measurement of rye cover crop aboveground biomass provides the main N amount available for recycling from the fall rye cover crop and main amount for estimation of fall rye cover crop N uptake [1]. The plant yield response to total N in the plant as forage N use efficiency was calculated as harvested plant DMY (kg ha^{-1}) divided by total N (kg N ha^{-1}) in the plant.

2.7. Weather

Monthly mean air temperature (°C) and total precipitation (mm) data from 2019 to 2021 and long-term averages (LTA; 30-year, from 1981 to 2010) were obtained from Saskatoon Research Farm, Saskatoon, SK according to Environmental Canada's climate data online (www.climate.weatheroffice.ec.gc.ca (accessed on 28 January 2022)), which is based on the LFCE weather station located 1 km from the study site.

2.8. Soil Nutrient Evaluation and Fertilizer Application

Prior to the trial start (15 May 2019), soil composite samples were collected to a depth of 30 cm from the individual plots using a hand Dutch auger and analyzed for available nitrate–nitrogen (NO_3–N), phosphate–phosphorus (HPO_4/H_2PO_4–P), K, and sulfate–sulfur (SO_4–S) (ALS Laboratory, Saskatoon, SK, Canada). Based on soil test recommendations, N fertilizer broadcast was applied 30 d after seeding fall ryes for the double cropping plots (Table 1) at 35 and 60 kg N ha^{-1} as 46-0-0 for 2019 and 2020, respectively.

2.9. Economic Evaluation

Cost estimates for cropping inputs and field equipment used to grow and harvest the forage in each treatment were based on actual invoices received, suggested retail prices, and published values. All dollar ($) values are in Canadian dollars (Can$1.25 = US$1). Costs included were seed, herbicide, nitrogen, seeding, spraying, cultivating (double cropping only), cutting, baling, hauling, and cash rental rate for the land. Barley seed was purchased for \$0.39 kg^{-1} (\$8.50 bu^{-1}), Hazlet fall rye was purchased for \$0.31 kg^{-1} (\$8.00 bu^{-1}), and Pika winter triticale was valued at \$0.55 kg^{-1} (\$13.00 bu^{-1}). Suggested retail pricing for Bono fall rye was \$76 per unit (seeded at 1.98 units ha^{-1}) (C. Geisam, pers. comm. 10 Feb, 2022). Herbicide was valued at \$6.00 L^{-1} and applied at 0.9 L ha^{-1}. Nitrogen fertilizer was valued at \$555 $tonne^{-1}$ (\$1.21 kg^{-1} N) based on the 5-year average pricing for urea (46-0-0) published by Alberta Agriculture and Forestry's Alberta Farm Input Survey [19]. Published custom rates were used for spraying (\$12.35 ha^{-1}), seeding (\$56.81 ha^{-1}), cutting (\$49.40 ha^{-1}), and baling (\$11 $bale^{-1}$) [20]. Bales were assumed to weigh 660 kg, bales and hauling was estimated at \$5 $bale^{-1}$ [21]. A cash rental rate of \$123.50 ha^{-1} was also included, based on the published median rate for cash rental agreements in Saskatchewan [22]. Total forage cost (\$ ha^{-1}) was calculated by summing total cropping and haying costs.

The crop RFQ-adjusted market value ($Price_{adj}$) for each treatment was calculated using the following formula:

$$Price_{adj,}\ \$\ Mg^{-1} = 109.07 + [(RFQ - 130) \times 0.9925] \quad (1)$$

where, 109.07 is two-year (2019–2020) average fall market value for greenfeed (\$ Mg^{-1}) as published in the Saskatchewan Forage Council's Fall Forage Market Price Discovery report [21]; RFQ is relative forage quality; 130 is typical barley greenfeed RFQ value [23]; 0.9925 is multiplier which indicates every unit change in RFQ has been shown to change forage sold at auction by \$0.9925 Mg^{-1} [24]. Returns (\$ ha^{-1}) or market value of forage were calculated by multiplying DMY by an RFQ-adjusted price for greenfeed hay. The net return for each treatment was found by subtracting greenfeed production costs (growing plus haying and hauling bales) from market value of the forage.

2.10. Statistical Analysis

Statistical analysis was performed using the Proc MIXED procedure of SAS software [25]. Replicate (plot) was considered a random effect; cultivar and mixture were designated as fixed effects.

Therefore, the model used for the analysis was:

$$Y_{j(i)} = \mu + Fi + V_{j(a)} + V_{j(t)} + eij$$

where, $Y_{j(i)}$ is an observation of the dependent variable for the forage (entry) j in the forage i; μ is the population mean for the variable; F_i is the forage type i, i = a, t; a is for single crop, and t is for double cropping with barley; $V_{j(a)}$ is the effect of fall rye cultivar (Hazlet and Bono) nested within single crop; $V_{j(t)}$ is the effect of double cropping (Barley-HazletFR and Barley-BonoFR) nested within double cropping; and e_{ij} is the random error associated with the observation $j(i)$. Treatment contrasts [25] (single cropping vs. double cropping; BonoFR vs. HazletFR; Fall ryes vs. PikaWT; Barley–BonoFR vs. Barley–HazletFR) were used to determine treatment differences. Treatment means were determined using Tukey's multiple range test and were considered significant when $p < 0.05$. The one-way ANOVA analysis was performed using ANOVA procedures of SAS [25] and the output of the ANOVA analysis is available as a supplementary material (Supplementary Tables S1–S3). Due to the nature of the data, statistical analysis of economic evaluation was not performed. The correlations between relevant traits were calculated using the CORR procedure of SAS [25] and correlation coefficients were classified as strong ($r > 0.6$), moderate ($0.6 > r > 0.4$), or weak ($r < 0.4$), respectively.

3. Results

3.1. Environmental Condition

Monthly mean temperature and precipitation data for the study site over the study years are shown in Table 2. Total precipitation at the study site during the growing seasons (April to October) was similar in 2019 and 2020 (82% and 92% of LTA); however, total precipitation was only 54% of LTA in 2021, averaging 76% of LTA over the 3-year period.

Average monthly temperatures followed mostly similar patterns as LTAs recorded over the study years. Although temperatures varied in some years, with lower temperatures for April observed in 2020 (11.5% lower than LTA), for October in 2019 and 2020 (18% and 28% lower than LTA, respectively), with October temperatures averaged over the 3 years being at 57% of LTA, with higher temperatures experienced in 2021 for June, July, and September (averaged at 113% of LTA) and for October (125% of LTA).

Overall, the 3-year average of precipitation and temperature data reflected dryer growing seasons with cooler October for forage production with drought conditions in 2021 at the study site.

Table 2. Monthly mean air temperature and precipitation at Clavet, (Dark Brown soil zone) Saskatchewan, Canada over 3 years (2019 to 2021).

	Monthly Mean Temperature (°C)					Monthly Mean Precipitation (mm)				
Month	**2019**	**2020**	**2021**	**3-Year avg.**	**LTA †**	**2019**	**2020**	**2021**	**3-Year avg.**	**LTA**
January	−14.1	−14.4	−11.2	−13.3	−13.9	7.2	8.3	9.0	8.2	14.6
February	−24.2	−12.4	−19.4	−18.7	−11.4	11.1	1.5	1.2	4.6	9.1
March	−6.1	−7.9	−2.0	−5.4	−4.9	2.7	10.1	1.3	4.7	14.5
April	4.8	−0.6	4.5	2.9	5.2	0.4	10.9	3.5	4.9	21.8
May	9.7	11.1	10.1	10.3	11.8	4.4	42.1	35.5	27.3	36.5
June	16.0	15.3	18.0	16.4	16.1	84.8	106.9	41.7	77.8	63.6
July	17.8	19.0	21.4	19.4	19	67.6	52.1	17.7	45.8	53.8
August	15.4	18.04	17.8	17.9	18.2	20.3	16.2	38.4	25.0	44.4
September	12.3	11.70	13.7	12.6	12	39.5	23.6	5.6	22.9	38.1
October	0.8	1.24	5.5	2.5	4.4	11.2	3.5	6.7	7.1	18.8
November	−5.5	−6.71	−2.4	−4.9	−5.2	13.1	20.5	10.2	14.6	12.4
December	−12.0	−10.5	–	−11.2	−12.4	4.1	1.7	–	2.9	12.8

Note. † LTA, Long-term average from 1981 to 2010. Data were obtained from Environment Canada (www.climate.weatheroffice.ec.gc.ca (accessed on 28 January 2022) for Saskatoon (Climate ID 4057165; 52°17′ N, 106°72′ W).

3.2. Soil Nutrients

Soil available nutrients in the form of nitrate–nitrogen (NO_3–N), phosphate– phosphorus (HPO_4/H_2PO_4–P), potassium (K), and sulfate–sulfur (SO_4–S) averaged at 8.1, 41.9, 701, and 23.6 kg ha^{-1}, respectively (data not shown).

3.3. Crop Yield in Single and Double Cropping Systems

Dry matter yield of winter cereals (fall ryes and winter triticale) in single cropping systems and barley first crop and fall rye second crop in double cropping systems are presented in Table 3. Forage productions of winter cereals ($p > 0.05$) in single cropping and fall ryes in single and double cropping systems were virtually analogous ($p > 0.05$) with each system averaging at 1.2 Mg ha^{-1}.

Barley as the first crop in a double cropping system produced 6.0 ± 4.17 Mg ha^{-1} (means ± SD) over the 2 years. Expectedly, greater total DMY (barley DMY + fall rye DMY) (7.1 vs. 1.2 Mg ha^{-1}; $p < 0.01$) was accumulated in double cropping barley with fall rye compared to fall ryes as single crops.

Table 3. Dry matter yield (means ± SD) of whole-crop winter cereals in single and double cropping systems.

	DMY (Mg ha^{-1})		
Item	**Barley**	**Winter Cereal**	**Total**
Single Cropping (SC)			
BonoFR †	–	1.2 ± 1.11	1.2 ± 1.11
HazletFR	–	1.3 ± 1.29	1.3 ± 1.29
PikaWT	–	1.0 ± 0.75	1.0 ± 0.75
SEM	–	0.22	0.22
Double Cropping (DC)			
Barley-BonoFR	6.2 ± 4.38	1.1 ± 1.05	7.3 ± 4.25
Barley-HazletFR	5.7 ± 4.25	1.2 ± 1.06	6.9 ± 5.65
SEM	1.04	0.27	1.44
p-value			
BonoFR in SC vs. HazletFR in SC	–	0.84	0.84
Fall Ryes in SC vs. PikaWT	–	0.57	0.57
BonoFR in DC vs. HazletFR in DC	0.84	0.94	–
Fall Ryes in SC vs. in DC	–	0.79	–
Total DMY in SC vs. in DC	–	–	<0.01

Note. † BonoFR, fall rye cv. Bono; HazletFR, fall rye cv. Hazlet; PikaWT, winter triticale cv. Pika; Barley-BonoFR, double cropping treatment spring barley (cv. Maverick) followed by BonoFR; Barley-HazletFR, double cropping treatment of spring barley (cv. Maverick) followed by HazletFR; Total, barley DMY + fall rye DMY; SEM, standard error of mean; SD, standard deviation.

3.4. Crop Nutritive Value and Digestible Nutrients in Single and Double Cropping Systems

The nutritive value and digestibility of whole-crop barley in a double cropping system with fall rye cultivars are presented in Table 4. Spring barley was not different ($p > 0.05$) in nutritive value over the 2 years (avg. 91.1 ± 16.53 g kg^{-1} CP, 474.3 ± 43.43 g kg^{-1} NDF, 672.0 ± 23.40 g kg^{-1} TDN, and 193.6 ± 24.27 RFQ; means ± SD), whether grown with Bono or Hazlet fall rye. The mineral composition of barley, however, differed between the double cropping treatments in that double cropping barley with Bono fall rye had lower K ($p < 0.01$), Mg ($p = 0.05$), and Mn ($p = 0.03$) concentrations than with Hazlet fall rye (Table 4).

Nutrient composition and digestibility of whole-crop winter cereals in single and double cropping systems are presented in Table 5. The new fall rye cv. Bono did not differ ($p > 0.05$) in nutrient profile or energy values from the conventional cv. Hazlet in either of the cropping systems. When fall ryes were compared to Pika winter triticale, however, there were differences in basic nutrient contents and relative feed and net energy values, as both cultivars contained less ash (74.6 ± 11.9 vs. 90.9 ± 11.8 g kg^{-1}, $p = 0.01$), CP (155.3 ± 22.4 vs. 187.1 ± 20.2 g kg^{-1}; $p = 0.01$), SP (75.3 ± 12.0 vs. 85.3 ± 7.3 g kg^{-1}; $p = 0.01$), RDP (115.4 ± 14.4 vs. 136.3 ± 12.1 g kg^{-1}; $p < 0.01$), relative feed value (RFV, 109.9 ± 16.3 vs. 128.9 ± 11.1 ; $p = 0.01$), relative forage quality (RFQ, 146.8 ± 14.9 vs. 183.6 ± 19.3; $p = 0.01$), and NE_g (0.84 ± 0.07 vs. 0.90 ± 0.05 Mcal kg^{-1}; $p = 0.05$), but had higher NDF (541.8 ± 52.2 vs. 479.3 ± 26.1 g kg^{-1}; $p = 0.01$) and tended to have higher ADF (329.9 ± 43.8 vs. 294.1 ± 25.7 g kg^{-1}; $p = 0.06$). In addition, there was a trend for higher SP (84.4 ± 18.2 vs. 78.6 ± 8.9 g kg^{-1} DM; $p = 0.10$) in forages from double cropping than from single cropping system.

Mineral composition and digestibility of whole-crop fall rye in single and double cropping systems are presented in Table 6. The lowest K (21.8 ± 2.75 g kg^{-1}; $p = 0.05$) concentration was detected in Bono, intermediate in Hazlet (24.8 ± 4.23 g kg^{-1}) fall rye, and highest (28.4 ± 5.24 g kg^{-1}; $p = 0.01$) in Pika winter triticale.

Forage protein and total digestible nutrient yields obtainable from whole-crop winter cereals in single and double cropping systems are presented in Table 7. As it would be anticipated, total forage CP (658.4 vs. 177.6 kg ha^{-1}; $p < 0.01$) and TDN (4519.8 vs. 788.3 kg ha^{-1}; $p < 0.01$) yields from a hectare of double cropping system were greater than from single cropping system. Expectedly as well, both CP and TDN yields per hectare were strongly and positively correlated ($r > 0.97$; $p < 0.001$) with total DMY (data not shown). However, for the winter cereals, correlations between forage CP concentration with CPY and TDN concentration with TDNY were $r = -0.54$ and $r = -0.88$, respectively.

Mineral uptake and N use efficiency of whole-crop winter cereals in single and double cropping systems are presented in Table 8. There was a strong correlation ($r > 0.95$; $p < 0.001$; data not shown) between barley DMY and total N, P, or K uptake. Fall ryes in double cropping systems with barley have greater uptake of minerals (avg. 105.3 vs. 28.7, 15.6 vs. 2.6, and 67.9 vs. 29.4 kg ha^{-1} of N, P, and K, respectively, $p \leq 0.01$) compared with single crops. In addition, the correlation analysis, in the current study, demonstrated strong ($r = 0.70$) and moderate ($r = 0.59$) relations of N use efficiency with total DMY and CPY, respectively.

Table 4. Nutrient composition (means ± SD) of whole-crop barley in double cropping system with fall rye.

Item	**Barley**			
	Barley-BonoFR †	**Barley-HazletFR**	**SEM**	***p*-Value**
Basic chemical profile (g kg^{-1} DM)				
ash	55.1 ± 0.66	57.7 ± 0.25	1.77	0.31
acid detergent fibre	275.8 ± 25.60	271.8 ± 31.84	10.22	0.79
neutral detergent fibre	481.5 ± 50.39	467.0 ± 31.75	15.66	0.52
crude protein	86.0 ± 13.11	96.3 ± 18.81	5.73	0.23
Total digestible nutrients	67.8 ± 2.68	67.3 ± 2.11	8.55	0.84
Relative feed value (RFV)	132.3 ± 19.79	135.8 ± 13.64	60.08	0.69
Relative forage quality (RFQ)	190.2 ± 28.74	197.0 ± 19.80	11.68	0.69
Energy values (Mcal kg^{-1} DM)				
net energy for gain	1.03 ± 0.10	1.04 ± 0.07	0.031	0.81
net energy maintenance	1.64 ± 0.11	1.65 ± 0.09	0.035	0.74
Macro minerals (g kg^{-1} DM)				
calcium	2.1 ± 0.03	2.2 ± 0.15	0.08	0.21
phosphorus	2.1 ± 0.03	2.2 ± 0.29	0.10	0.60
potassium	7.3 ± 0.32	8.0 ± 0.26	0.10	<0.01
magnesium	2.2 ± 0.23	2.5 ± 0.35	0.11	0.05
sodium	2.2 ± 0.16	3.2 ± 0.18	0.60	0.24
Micro minerals (mg kg^{-1} DM)				
copper	4.3 ± 0.46	4.3 ± 0.88	0.25	1.00
zinc	11.3 ± 3.81	11.3 ± 3.05	1.22	1.00
iron	222.0 ± 23.16	242.8 ± 57.65	15.53	0.36
manganese	20.8 ± 2.87	25.0 ± 4.21	1.27	0.03

Note. † BonoFR, fall rye cv. Bono; HazletFR, fall rye cv. Hazlet; Barley-BonoFR, double cropping treatment barley followed by BonoFR; Barley-HazletFR, double cropping treatment of early spring barley (cv. Maverick) followed by HazletFR. RFV = (DDM × DMI)/1.29 [18], where DDM = digestible DM calculated as 88.9 − (0.779 × %ADF) and potential DMI = dry matter intake calculated as 120/%NDF. RFQ = 1.9449 × RFV − 67.038 [23]. SEM, standard error of mean; SD, standard deviation.

Table 5. Nutrient composition (means ± SD) of whole-crop winter cereals in single and double cropping systems.

	Single Cropping (SC)				Double Cropping (DC)			*p*-Value			
Item	**BonoFR †**	**HazletFR**	**PikaWT**	**SEM**	**Barley-BonoFR**	**Barley-HazletFR**	**SEM**	**BonoFR in SC vs. HazletFR in SC**	**Fall Ryes in SC vs. PikaWT**	**BonoFR in DC vs. HazletFR in DC**	**Fall Ryes in SC vs. in DC**
Basic chemical profile (g kg^{-1} DM)											
ash	70.2 ± 13.9	79.0 ± 8.6	90.9 ± 74.7	3.13	79.3 ± 21.6	77.1 ± 19.2	5.36	0.18	0.01	0.84	0.56
acid detergent fibre (ADF)	321.4 ± 37.4	338.3 ± 50.9	294.1 ± 25.7	9.12	324.1 ± 61.5	332.4 ± 62.4	16.07	0.49	0.06	0.81	0.94
neutral detergent fibre (NDF)	534.7 ± 50.4	548.9 ± 56.9	479.3 ± 26.1	11.70	524.3 ± 101.4	539.6 ± 90.2	24.76	0.63	0.01	0.77	0.73
Crude protein profile (g kg^{-1} DM)											
crude protein (CP)	154.9 ± 24.3	155.7 ± 22.4	187.1 ± 20.1	5.71	174.1 ± 57.7	164.9 ± 54.8	14.95	0.95	0.01	0.76	0.37
soluble protein (SP)	73.0 ± 8.2	77.6 ± 7.2	85.3 ± 7.3	1.94	85.3 ± 16.4	83.4 ± 21.2	4.94	0.29	0.01	0.86	0.10
soluble protein (%CP)	47.7 ± 4.9	50.2 ± 3.4	45.9 ± 4.8	1.00	50.5 ± 5.3	51.4 ± 3.7	1.70	0.28	0.15	0.71	0.24
rumen degradable CP (RDP)	114.0 ± 15.2	116.7 ± 14.5	136.3 ± 12.2	3.73	129.6 ± 36.6	124.1 ± 38.0	11.93	0.74	<0.01	0.79	0.28
rumen degradable CP (%CP)	73.9 ± 2.5	75.1 ± 1.7	73.0 ± 2.4	5.07	75.3 ± 2.7	75.7 ± 1.9	9.64	0.29	0.15	0.72	0.24
Total digestible nutrients (TDN)	656.8 ± 37.6	643.3 ± 50.3	668.7 ± 33.8	8.85	650.6 ± 53.1	647.2 ± 52.9	13.69	0.58	0.33	0.91	0.95
Relative feed value (RFV)	112.3 ± 15.2	107.6 ± 18.2	128.9 ± 11.1	37.36	119.3 ± 38.7	113.4 ± 33.4	93.25	0.61	0.01	0.77	0.54
Relative forage quality (RFQ)	151.4 ± 20.5	142.2 ± 24.0	183.6 ± 15.4	12.31	165.0 ± 53.6	153.6 ± 45.1	26.59	0.61	0.01	0.77	0.54
Energy values (Mcal kg^{-1} DM)											
net energy for gain (NE_g)	0.87 ± 0.1	0.82 ± 0.1	0.90 ± 0.1	0.15	0.84 ± 0.1	0.83 ± 0.1	0.19	0.17	0.05	0.88	0.71
net energy for maintenance (NE_m)	1.52 ± 0.1	1.47 ± 0.14	1.56 ± 0.1	0.23	1.48 ± 0.1	1.48 ± 0.1	0.36	0.40	0.23	0.94	0.79

Note. † BonoFR, fall rye cv. Bono; HazletFR, fall rye cv. Hazlet; PikaWT, winter triticale cv. Pika; Barley-BonoFR, double cropping treatment of spring barley (cv. Maverick) followed by BonoFR; Barley-HazletFR, double cropping treatment of spring barley (cv. Maverick) followed by HazletFR. RFV = (DDM × DMI)/1.29 [18], where DDM = digestible DM calculated as 88.9 − (0.779 × %ADF) and DMI = dry matter intake calculated as 120/%NDF; RFQ = 1.9449 × RFV − 67.038 [23]. SEM, standard error of mean; SD, standard deviation.

Table 6. Mineral composition (means ± SD) of winter cereals in single and double cropping systems.

	Single Cropping (SC)				Double Cropping (DC)			*p*-Value			
Item	**BonoFR †**	**HazletFR**	**PikaWT**	**SEM**	**Barley-BonoFR**	**Barley-HazletFR**	**SEM**	**BonoFR in SC vs. HazletFR in SC**	**Fall Ryes in SC vs. PikaWT**	**BonoFR in DC vs. HazletFR in DC**	**Fall Ryes in SC vs. in DC**
Macro minerals (g kg^{-1}DM)											
calcium	2.9 ± 0.95	3.0 ± 0.61	2.8 ± 0.50	0.15	3.1 ± 0.90	3.0 ± 0.82	0.22	0.92	0.71	0.78	0.78
phosphorus	2.5 ± 0.64	2.5 ± 0.42	2.7 ± 0.38	0.11	2.7 ± 0.33	2.6 ± 0.23	0.07	0.92	0.35	0.20	0.20
potassium	21.8 ± 2.75	24.8 ± 4.23	28.4 ± 5.24	0.97	2.3 ± 0.45	2.4 ± 0.39	1.10	0.05	0.01	0.95	0.95
magnesium	2.2 ± 0.51	2.1 ± 3.58	2.4 ± 0.34	0.09	2.4 ± 0.89	2.3 ± 0.83	0.24	0.77	0.19	0.41	0.41
sodium	0.3 ± 0.23	0.3 ± 0.20	0.3 ± 0.06	0.04	0.9 ± 0.17	0.9 ± 0.16	0.41	0.90	0.93	0.17	0.17

Table 6. *Cont.*

Item	Single Cropping (SC)				Double Cropping (DC)			p-Value			
	BonoFR †	HazletFR	PikaWT	SEM	Barley-BonoFR	Barley-HazletFR	SEM	BonoFR in SC vs. HazletFR in SC	Fall Ryes in SC vs. PikaWT	BonoFR in DC vs. HazletFR in DC	Fall Ryes in SC vs. in DC
Micro minerals (mg kg^{-1}DM)											
copper	9.1 ± 4.10	7.7 ± 1.80	8.0 ± 1.29	0.58	7.7 ± 1.49	7.4 ± 2.15	0.90	0.42	0.73	0.85	0.40
zinc	27.6 ± 12.93	25.7 ± 8.82	35.1 ± 18.61	3.05	30.1 ± 12.22	27.7 ± 10.22	2.9	0.76	0.20	0.69	0.58
iron	237.3 ± 99.40	199.9 ± 54.86	188.3 ± 48.73	15.68	254.9 ± 119.54	228.3 ± 105.90	29.2	0.41	0.38	0.67	0.53
manganese	41.6 ± 18.92	46.6 ± 19.88	59.0 ± 23.61	4.63	51.7 ± 35.07	51.6 ± 31.00	8.5	0.64	0.13	0.99	0.45

Note. † BonoFR, fall rye cv. Bono; HazletFR, fall rye cv. Hazlet; PikaWT, winter triticale cv. Pika; Barley-BonoFR; double cropping treatment barley (cv. Maverick) followed by BonoFR; Barley-HazletFR, double cropping treatment of spring barley followed by HazletFR, SEM, standard error of mean; SD, standard deviation.

Table 7. Estimated crude protein and total digestible nutrient yield (means ± SD) from whole-crop winter cereals in single and double cropping systems.

Item	CPY †, kg ha^{-1}			TDNY, kg ha^{-1}		
	Barley	Winter Cereal	Total	Barley	Winter Cereal	Total
Single Cropping (SC)						
BonoFR	–	166.6 ± 147.74	166.6 ± 147.74	–	762.9 ± 694.84	762.9 ± 694.84
HazletFR	–	188.5 ± 168.63	188.5 ± 168.63	–	813.7 ± 747.90	813.7 ± 747.9
PikaWT†	–	182.5 ± 139.83	182.5 ± 139.83	–	642.2 ± 462.58	642.1 ± 462.58
SEM	–	31.65	31.65	–	134.92	134.92
Double Cropping (DC)						
Barley-BonoFR	526.8 ± 373.03	162.9 ± 141.38	651.5 ± 522.75	4144.8 ± 2959.04	695.9 ± 616.44	4657.2 ± 3750.33
Barley-HazletFR	549.4 ± 416.17	159.9 ± 126.94	665.3 ± 547.51	3862.3 ± 2871.03	720.0 ± 621.22	4382.3 ± 3634.88
SEM	95.49	34.50	137.46	949.05	158.94	949.05
p-value						
BonoFR in SC vs. HazletFR in SC	–	0.80	0.80	–	0.90	0.90
Fall Ryes in SC vs. PikaWT	–	0.94	0.94	–	0.62	0.62
BonoFR in DC vs. HazletFR in DC	0.91	0.97	0.96	0.85	0.94	0.89
Fall Ryes in SC vs. in DC	–	0.76	<0.01	–	0.74	<0.01

Note. † CPY, crude protein yield; TDNY, total digestible nutrients yield; BonoFR, fall rye cv. Bono; HazletFR, fall rye cv. Hazlet; PikaWT, winter triticale cv. Pika; Barley-BonoFR, double cropping treatment barley (cv. Maverick) followed by BonoFR; Barley-HazletFR, double cropping treatment of spring barley followed by HazletFR; Total, barley CPY/TDNY + fall rye CPY/TDNY; SEM, standard error of mean; SD, standard deviation.

Table 8. Mineral uptake and nitrogen use efficiency (means ± SD) of whole-crop winter cereals in single and double cropping systems.

	Nitrogen, kg ha^{-1}			Phosphorus, kg ha^{-1}			Potassium, kg ha^{-1}			N Use Efficiency (NUE)		
Item	**Barley**	**Winter Cereal**	**Total**	**Barley**	**Winter Cereal**	**Total**	**Barley**	**Winter Cereal**	**Total**	**Barley**	**Winter Cereal**	**Total**
Single Cropping (SC)												
BonoFR †	–	26.7 ± 23.6	26.7 ± 23.6	–	2.5 ± 2.0	2.5 ± 2.0	–	25.2 ± 22.7	25.1 ± 22.7	–	41.2 ± 6.2	41.2 ± 6.2
HazletFR	–	30.2 ± 27.0	30.2 ± 27.0	–	2.9 ± 2.4	2.9 ± 2.4	–	33.6 ± 32.5	33.6 ± 32.5	–	40.8 ± 5.6	40.8 ± 5.6
PikaWT	–	29.2 ± 22.4	29.2 ± 22.4	–	2.5 ± 1.7	2.5 ± 1.7	–	29.5 ± 25.6	29.5 ± 25.6	–	33.7 ± 3.6	33.7 ± 3.6
SEM		5.06	5.06		0.43	0.43		5.69	5.69		1.33	1.33
Double Cropping (DC)												
Barley-BonoFR	84.3 ± 59.7	26.1 ± 22.6	104.2 ± 83.7	13.1 ± 9.8	2.9 ± 2.5	15.8 ± 13.1	45.2 ± 32	24.0 ± 22.0	66.4 ± 54.9	74.5 ± 13.5	38.7 ± 10.3	66.3 ± 54.8
Barley-HazletFR	87.9 ± 66.6	25.6 ± 20.36	106.4 ± 87.6	12.6 ± 9.9	2.9 ± 2.5	15.4 ± 13.1	45.7 ± 33.5	26.7 ± 23.3	69.4 ± 57.5	67.7 ± 16.1	40.6 ± 9.9	60.6 ± 10.1
SEM	22.36	5.52	22.00	2.39	0.64	3.36	7.90	5.83	14.43	5.25	5.52	2.66
p-value												
BonoFR in SC vs. HazletFR in SC	–	0.80	0.80	–	0.75	0.73	–	0.58	0.58	–	0.91	0.91
Fall Ryes in SC vs. PikaWT	–	0.94	0.94	–	0.83	0.81	–	0.99	0.99	–	0.01	0.01
BonoFR in DC vs. HazletFR in DC	0.91	0.97	0.96	0.92	0.98	0.96	0.98	0.83	0.92	0.38	0.72	0.30
Fall Ryes in SC vs. in DC	–	0.71	<0.01	–	0.70	<0.01	–	0.63	0.01	–	0.69	<0.01

Note. † BonoFR, fall rye cv. Bono; HazletFR, fall rye cv. Hazlet; PikaWT, winter triticale cv. Pika; Barley-BonoFR, double cropping treatment barley (cv. Maverick) followed by BonoFR; Barley-HazletFR, double cropping treatment of spring barley followed by HazletFR, Total, barley nitrogen + fall rye nitrogen; SEM, standard error of mean; SD, standard deviation.

3.5. Economic Evaluation of Single and Double Cropping Systems

As Table 9 indicates, the costs to grow the forages ranged from \$246 ha^{-1} for Hazlet to \$370 ha^{-1} for Bono fall rye in single cropping systems.

Table 9. Forage production costs of winter cereals in single and double cropping systems over 2 years.

	Single Cropping (SC)			Double Cropping (DC)	
Item	**BonoFR †**	**HazletFR**	**PikaWT**	**Barley-BonoFR**	**Barley-HazletFR**
			——————\$ ha^{-1} ——————		
Cropping Costs					
Cultivate	22.23	22.23	22.23	22.23	22.23
Spraying	12.35	12.35	12.35	24.70	24.70
Herbicide	4.80	4.80	4.80	9.60	9.60
Seeding	56.81	56.81	56.81	113.62	113.62
Barley seed	–	–	–	53.22	53.22
Winter triticale/Fall rye seed	150.18	26.71	83.16	150.18	26.71
Fertilizer	–	–	–	27.75	27.75
Land Rent	123.5	123.50	123.50	123.5	123.50
Total cropping costs	369.87	246.40	302.85	524.79	401.33
Haying Costs					
Cutting	49.4	49.40	49.40	98.80	98.80
Baling	20.13	22.41	16.53	122.07	115.47
Hauling	9.15	10.18	7.52	55.49	52.48
Total haying costs	78.68	81.99	73.45	276.36	266.75
Total forage costs	448.55	328.39	376.30	801.15	668.08

Note. † BonoFR, fall rye cv. Bono; HazletFR, fall rye cv. Hazlet; PikaWT, winter triticale cv. Pika; Barley-BonoFR, double cropping treatment barley (cv. Maverick) followed by BonoFR; Barley-HazletFR, double cropping treatment of spring barley followed by HazletFR, All dollar (\$) values are in Canadian dollars (Can\$1.25 = US\$1).

The greenfeed haying (cut, bale, and haul) costs varied due to variations in DMY; costs averaged \$78 ha^{-1} for single cropping and \$272 ha^{-1} for double cropping systems (Table 9). Total forage costs (grow + haying costs) averaged \$384 ha^{-1} for single cropping and \$735 ha^{-1} for double cropping systems. The cost of the Bono fall rye seed was the highest, at \$150 ha^{-1} and the costs for the other crops were \$27, \$53, and \$83 ha^{-1} for Hazlet fall rye, barley, and Pika winter triticale, respectively. The average RFQ-adjusted market value was \$138 Mg^{-1} across all treatments, ranging from \$121 Mg^{-1} for Hazlet fall rye to \$162 Mg^{-1} for Pika winter triticale.

The returns averaged \$160 ha^{-1} for the single cropping treatments and \$984 ha^{-1} for double cropping treatments (Table 10). The net returns were positive for the two double cropping treatments, \$248 ha^{-1} for Barley-HazletFR and \$251 ha^{-1} for Barley-BonoFR, but they were negative for all three single cropping treatments, −\$166 ha^{-1} for Hazlet fall rye, −\$215 ha^{-1} for Pika winter triticale, and −\$291 ha^{-1} for Bono fall rye.

Table 10. Returns and net returns of winter cereals in single and double cropping systems over 2 years.

	Single Cropping (SC)			Double Cropping (DC)	
Item	**BonoFR †**	**HazletFR**	**PikaWT**	**Barley-BonoFR**	**Barley-HazletFR**
Forage RFQ-adjusted price, \$ Mg^{-1}	130.28	121.21	162.33	143.80	132.41
Returns (forage market value), \$ ha^{-1}	157.16	162.73	160.82	1051.77	916.05
Net returns, \$ ha^{-1}	−291.39	−165.67	−215.48	251.76	249.12

Note. † BonoFR, fall rye cv. Bono; HazletFR, fall rye cv. Hazlet; PikaWT, winter triticale cv. Pika; Barley-BonoFR, double cropping treatment barley (cv. Maverick) followed by BonoFR; Barley-HazletFR, double cropping treatment of spring barley followed by HazletFR; RFQ, Relative forage quality; All dollar (\$) values are in Canadian dollars (Can\$1.25 = US\$1).

The break-even yields (*ceteris paribus*) for the single cropping treatments are 4, 3.1, and 2.6 Mg ha^{-1} for Bono fall rye, Hazlet fall rye, and Pika winter triticale, respectively. The break-even prices (*ceteris paribus*) for the single cropping treatments are \$380 Mg^{-1}, \$372 Mg^{-1}, and \$245 Mg^{-1} for Pika winter triticale, Bono fall rye, and Hazlet fall rye, respectively.

4. Discussion

4.1. Soil Nutrients

The soil nitrate-N in the current study was comparable, but phosphate-P was higher than the average surface soil N levels across Alberta, Saskatchewan, and Manitoba (9.0 kg ha^{-1}) and soil P (11.0 kg ha^{-1}) [26].

4.2. Crop Yield in Single and Double Cropping Systems

In the current study, no yield difference between the winter cereals corresponded to Jefferson et al. [27] in Saskatoon, SK, Canada and Bishnoi and Hughes [28] in Alabama, USA, who found winter triticale(s) having forage yields equal to fall rye, or fall rye from Ontario pasture produced an average of 1.0–1.5 Mg ha^{-1} and winter triticale at 1.0–1.25 Mg ha^{-1} [29]. Likewise, Juskiw et al. [30] evaluated spring seeded winter triticale, fall rye, and mixtures of these cereals with spring barley at different ratios, where mean DM yields for triticale were generally as high as the fall rye treatments (5.9 Mg DM ha^{-1}). In southern Ontario, cereal rye (cv. Common) produced equal DMY (2.0 Mg ha^{-1}) to triticale (cv. Pika) when harvested at flag leaf or close to (2.7 vs. 2.6 Mg ha^{-1}) at boot stage, whereas at heading it yielded less than triticale (3.6 vs. 4.5 Mg ha^{-1}) [31].

Similar DMY of fall rye cultivars in single and double cropping systems that were observed in the current study contradicted to Bono yielding 125 to 138% of Hazlet [9] or to Bono producing more than Hazlet (5.4 vs. 3.0 Mg ha^{-1}) in north-central Iowa, USA [4]. Furthermore, the current study results conflicted with an earlier study in Guelph, ON, Canada, that determined higher forage yields for winter rye (cv. Frontier) than wheat or triticale (4.1 vs. 1.9 Mg ha^{-1}) regardless of treatment [32]. In contrast to this Ontario study [32], in Virginia, USA, when harvested at boot stage KWS Progas fall rye produced 8.4 Mg ha^{-1} or 3.0 Mg less DM per ha than Trical triticale [33] and in Manitoba, Canada, 'Hazlet' fall rye was consistently within the lower yielding annuals and ranged from 1.5 to 3.2 Mg ha^{-1} harvested in late summer [34]. Greater winter rye phytomass in a double cropping system with corn (*Zea mays* L.) was recorded by Tollenaar et al. [35] at 2.7 and 4.5 Mg ha^{-1} mid-May after corn harvest in Elora and Woodstock, ON, respectively, and 5.4 Mg ha^{-1} at the end of May in Elora. In addition, greater total DM forage productions than in the current study were reported in central Saskatchewan, 4.3 Mg ha^{-1} for fall rye [36], 6.4 Mg ha^{-1} for 'Prima' fall rye [37], Hazlet fall rye produced in the spring (2.3 Mg ha^{-1}) or in the fall (2.2 Mg ha^{-1}) in the Parkland area of Saskatchewan [38], or higher grain yields of Hazlet fall rye at Swift Current (3.9 Mg ha^{-1}) [10] and Saskatoon, SK (5.8 Mg ha^{-1}) [39]. Although whole-crop Hazlet fall rye, in the current study, yielded much lower than others reported, both fall ryes yielded higher than the mean grain yield (0.9 Mg ha^{-1}) of Puma fall rye seeded in early September in Southwestern Saskatchewan [8]. Researchers in Southern Manitoba, establishing double crops after winter cereals, documented extremely variable biomass production of these crops, ranging from 0.10 to 2.4 Mg ha^{-1} for double-cropped black lentil, hairy vetch, and field pea [40,41].

The relatively lower DMYs of winter cereals in the present study compared to others [27,28,30–39], were likely related to the differences in environmental conditions, cultivar, and cropping management. Another possible reason for the lower yield in the current study could be the late seeding date (17 and 18 September), as McCartney et al. [12] noted that delayed seeding (15 September) of winter cereals (fall rye and winter triticale) resulted in later forage production, smaller plants and decreased DM, and did not produce sufficient DM for early grazing the following spring. Similar to McCartney et al. [12], Kibite et al. [42] in central Alberta evaluated the effect of seeding date (May vs. June) and harvest stage and concluded that on average, DM yield of early-seeded cereals produced nearly 5.0 Mg DM ha^{-1} or 35% more forage yield than late-seeded cereals, most notably at Black Soil locations. Additionally, the inability of fall ryes to achieve sufficient yield in the present study indicates their limitations for summer and fall grazing under dryland farming conditions, especially in dryer than usual years. This was evidenced by greater DMY for fall ryes in the first production year than in the second year (avg. 2.3 vs. 0.4 Mg ha^{-1}; data not shown), when there were drought conditions (54% of LTA precipitation).

Barley as the first crop in a double cropping system, in the current study, produced in the range of 3.9 to 9.5 Mg DM ha^{-1} barley (cv. Ranger) yield in Saskatchewan [43], 4.4 to 7.4 Mg ha^{-1} in Virginia, USA [33], and similar to the average forage DMY (5.0–7.5 Mg ha^{-1}) of barley for greenfeed production in the Black Soil zone of Saskatchewan [2]. The current study observed greater barley yield than barley (1.0–4.4 Mg ha^{-1}) harvested in New Liskeard, ON [44], but lower than Ranger barley in two locations in Saskatchewan (6.7 and 6.9 Mg ha^{-1}) and Alberta (6.3 and 6.8 Mg ha^{-1}) [42], Maverick barley in Manitoba (8.3 Mg ha^{-1}) [40], and cereal forage barley in New Liskeard, ON (6.9 Mg ha^{-1}) harvested at milk stage [44].

Several environmental factors appeared to have affected forage production in the present study, including available soil moisture as the poor spring moisture experienced in spring to summer of 2019, cooler months in 2020 (lower April and October temperatures than LTA), and drought conditions in 2021.

Despite these conditions, double cropping of barley and fall rye cultivars increased ($p < 0.01$) total DMY (barley DMY + fall rye DMY) by 83.1% and barley with Bono fall rye by 84.9% compared to single cropping, a greater increase in the current study than elsewhere. Thus, in Idaho, USA, Brown [45] reported that double cropping of fall planted winter barley, winter and spring genotypes of wheat, and triticale followed by silage corn increased cumulative forage production from 8.4 to 15.9% compared to corn alone, while in Pennsylvania, USA, Ranck et al. [46] reported double cropping winter annuals (winter rye, winter triticale, and winter wheat) and corn increased DMY per ha by 19% compared with no double cropping. Binder et al. [47] reported double cropping forage cereal rye with silage corn increased total forage production 29–44% compared to an early terminated rye cover crop.

4.3. Crop Nutritive Value and Digestible Nutrients in Single and Double Cropping Systems

As the results of the current study indicated, the new fall rye cv. Bono was similar in nutrient profile or energy values with the conventional cv. Hazlet in either of the cropping systems, as opposed to Bono, differing from Hazlet with 88.0 vs. 104.0 g kg^{-1} CP [11] or 112.0 vs. 122.0 g kg^{-1} CP reported by others [9].

In contrast, a Virginia, USA study observed no difference ($p > 0.05$) between KWS Progas hybrid rye and Trical triticale in CP or RFQ when harvested at early heading [33]. Crude protein contents of fall ryes, in the present study, were higher compared to that of Hazlet fall rye (106 g kg^{-1} CP) grown in Saskatchewan [39] and of cereal rye in Ontario (145, 115, and 97 g kg^{-1} CP at flag leaf, boot, and heading stages, respectively) [31], and was in the lower end of 154–234 g kg^{-1} CP range of fall rye grown in Manitoba [34]. In the current study, winter cereals, however, contained lower CP as compared to winter triticale or winter rye (280 g kg^{-1} CP) in Saskatoon, SK [27] and dry green forage protein that ranged from 240 to 270 g kg^{-1} among 7 triticale cultivars, 'Wintergrazer 70′ rye, and 'Arthur' wheat in the southeastern United States [28]. Fall rye cultivars, in the current study, had higher NDF and ADF as compared to Hazlet fall rye, as reported in the Manitoba study (NDF < 450 g kg^{-1} DM and ADF < 300 g kg^{-1} DM) [34]. The potassium levels of fall ryes detected in the current study were comparable to the K range of Hazlet fall rye (17.35 to 28.65 g kg^{-1}) in Manitoba [34], whereas the P contents of all three winter cereals were lower than the P range of 3.55 to 4.43 g kg^{-1} the same study documented [34]. The correlation analysis on CP and TDN with the nutrient yields indicated forage yield was the main source to nutrient yield obtainable per unit land. Protein yield obtained from double cropping, in the current study, was higher, but CPY from single cropping was much below the level Hazlet fall rye produced (649 kg ha^{-1}) in a Western Canadian study [39].

Here it should be noted that the first barley crop was the major contributor to these increases in the double cropping system. The phosphorus uptake increase obtained from double cropping in the current study, in comparison, was twice as high as the increase reported by Brown [45] in P removal (by 29.8 to 42.2%), on double cropping of winter cereals and silage corn, although the opposite was true (i.e., twice as low) on the actual P removal by crops, 15.6 kg ha^{-1} in our study vs. 30 to 42 kg ha^{-1} in the same study [45].

Plants that are efficient in absorption and utilization of nutrients greatly enhance the efficiency of applied fertilizers, reducing the cost of inputs and preventing losses of nutrients to ecosystems [48]. The N use efficiency values of fall ryes in both cropping systems observed in the current study (Table 8), were in the typical range of N use efficiency common values (30–60) for cereals [49] and greater in comparison to the value (38.3) for annual wheat reported by Huggins [50] or to the worldwide N use efficiency of approximately 33 percent for cereal production (wheat, *Triticum aestivum* L.; corn, *Zea mays* L.; rice, *Oryza sativa* L. and O. *glaberrima* Steud.; barley, *Hordeum vulgare* L.; sorghum, *Sorghum bicolor* (L.) Moench; millet, *Pennisetum glaucum* (L.) R. Br.; oat, *Avena sativa* L.; and rye, *Secale cereale* L.) [51].

According to NASEM [52], the CP and TDN requirements for mature cows and first-calf heifers at pre-calving, postpartum, pregnant, mid-gestation, and lactating periods range from 62 to 129 g kg^{-1} and 449 to 645 g kg^{-1} total diet, respectively. In the current study, CP and TDN values for double and single cropping systems were above the CP range and above or at the higher end of the TDN range of NASEM [52] requirements, thus would meet the nutritional requirements of beef cattle. Further, as Van Soest [53] suggested, when NDF concentration increases to more than 550 to 600 g kg^{-1} of the diet DM, it may limit intake because of rumen fill. Forages in both cropping systems, in the present study, contained <550 g kg^{-1} NDF averaging at 536.8 ($\pm$ 50.4) g kg^{-1} for the fall rye cultivars, thus were of high nutritive value according to NASEM [52] nutrient requirements. Likewise, feeds with an RFQ of 115 to 130 are suitable for 635 kg beef cows, and a RFQ of 125 to 150 is considered suitable for 300 kg yearling steers [23]. In the current study, RFQ values for single and double cropping systems were met or above the nutritional requirements of beef cows or yearling cattle.

Overall, the new fall rye cultivar 'Bono' appeared to be distinctive from the conventional cultivar 'Hazlet' in terms of CP yield, copper content, N, P, and K uptakes, but from winter triticale in soluble protein, K, iron, and manganese concentrations, as well as by N use efficiency.

4.4. Economic Evaluation of Single and Double Cropping Systems

Fall rye seed was valued at \$172 ha^{-1} in the 2020 Saskatchewan Crop Planning Guide [54]. The cost of the Bono fall rye seed (\$150 ha^{-1}) added significant costs to the two treatments using that cultivar. The break-even yields (*ceteris paribus*) for the single cropping treatments are 4, 3.1, and 2.6 Mg ha^{-1} for Bono fall rye, Hazlet fall rye, and Pika winter triticale, respectively. The break-even prices for the single cropping treatments may not be attainable. In fall 2021, locally published greenfeed prices reached \$238 Mg^{-1} under drought conditions, which is close to the break-even price required for Hazlet fall rye but well below those needed for Pika winter triticale and Bono fall rye [21].

Overall, under drought conditions, the single cropping system did not have the yield and price sufficient to cover production costs, while the double cropping system did. In the double cropping system, 80% of the value (yield $\times$ price) was due to the barley greenfeed. When producers consider adopting a new forage system and cultivars, they will need to consider the costs and returns associated with it, in addition to the nutritional requirements of their animals, and whether the forage meets these requirements.

5. Conclusions

The new cultivar of Bono fall rye shows some potential to be used in single and double cropping systems, resulting in adequate forage biomass for beef cattle production in western Canada, with its lower nutritive value compared to winter triticale being compensated by the higher efficiency of N use and protein and total digestible nutrients accumulated per hectare. Double cropping of Bono and Hazlet fall ryes with spring barley increased total protein, digestible nutrients, and N, P, and K uptakes obtainable on a per hectare basis. This, consequently, improved N use efficiency, in addition to being economically feasible as opposed to a single cropping system. Spring barley as the first crop in the double cropping system contributed greatly to the total accumulated yield and nutrients available, mineral uptake, and N use efficiency, providing substantial forage for greenfeed during summer. When producers consider adopting new forage systems and cultivars, they will need to consider the costs and returns associated with them, in addition to the nutritional requirements of their animals. Overall, as the present study demonstrated, even though it has not reached our expectations due to the drought conditions, Bono fall rye could still be an equal quality alternative to Hazlet fall rye; however, the higher seed price currently may delay its adoption. Large-scale research (with multiple years) needs to be conducted to make a more definite conclusion.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy12061382/s1; Table S1: One-way ANOVA results of spring barley nutrient composition; Table S2: One-way ANOVA results of winter cereal nutrient composition; Table S3: One-way ANOVA results for dry matter yield, nutrient yield and uptake, and N use efficiency of barley and winter cereals.

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