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Winter Triticale: A Long-Term Cropping Systems Experiment in a Dry Mediterranean Climate

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Abstract: Triticale (*X Triticosecale Wittmack*) is a cereal feed grain grown annually worldwide on 4.2 million ha. Washington is the leading state for rainfed (i.e., non-irrigated) triticale production in the USA. A 9-year dryland cropping systems project was conducted from 2011 to 2019 near Ritzville, WA to compare winter triticale (WT) with winter wheat (*Triticum aestivum* L.) (WW) grown in (i) a 3-year rotation of WT-spring wheat (SW) -no-till summer fallow (NTF) (ii) a 3-year rotation of WW-SW-undercutter tillage summer fallow (UTF) and (iii) a 2-year WW-UTF rotation, We measured grain yield, grain yield components, straw production, soil water dynamics, and effect on the subsequent SW wheat crop (in the two 3-year rotations). Enterprise budgets were constructed to evaluate the production costs and profitability. Grain yields averaged over the years were 5816, 5087, and 4689 kg/ha for WT, 3-year WW, and 2-year WW, respectively ($p < 0.001$). Winter triticale used slightly less water than WW ($p = 0.019$). Contrary to numerous reports in the literature, WT never produced more straw dry biomass than WW. Winter wheat produced many more stems than WT ($p < 0.001$), but this was compensated by individual stem weight of WT being 60% heavier than that of WW ($p < 0.001$). Spring wheat yield averaged 2451 vs. 2322 kg/ha after WT and WW, respectively ($p = 0.022$). The market price for triticale grain was always lower than that for wheat. Winter triticale produced an average of 14 and 24% more grain than 3-year and 2-year WW, respectively, provided foliar fungal disease control, risk reduction, and other rotation benefits, but was not economically competitive with WW. A 15–21% increase in WT price or grain yield would be necessary for the WT rotation to be as profitable as the 3-year and 2-year WW rotations, respectively.

Keywords: alternative crops; straw; crop rotation; dry Mediterranean climate; economics; winter triticale

1. Introduction

The low-precipitation (<350 mm) zone of the Inland Pacific Northwest (PNW) covers two million cropland hectares in a belt through east-central Washington and north-central Oregon and is the largest contiguous crop production region in the western USA [1]. The climate is Mediterranean-like with wet winters and dry summers [2]. Since the onset of farming by pioneer settlers in the early 1880s, a monocrop 2-year WW-fallow system, where only one crop is produced every two years, has essentially been the only cropping system practiced by farmers. Researchers and farmers have for many decades sought alternative crops and rotations that are equally or more stable and profitable than the WW-fallow system. Annually, only 3% of land is planted to spring-sown crops (mostly spring wheat) [3]. A multitude of spring-sown crops so far tested by farmers and researchers in in the PNW drylands have not had stable yields nor been economically viable in the long term [4] because of heat and/or water stress encountered during their reproductive period [5]. Crop and climate models for the PNW predict future slight increases in winter precipitation but drier summers [2], which would put spring-sown crops at even further yield disadvantage compared to WW that matures earlier.

In the past 10–15 years, three relatively new winter crops have garnered interest in the region. These crops are winter triticale (WT), winter pea (*Pisum sativum* L.), and winter canola (*Brassica napus* L.) [5]. As with WW, these three new winter crops need to be planted in late August-early September into moisture accumulated in the soil after a 13-mo fallow to achieve optimum grain yield potential. Waiting to plant until the onset of fall rains in mid-October or later results in severe yield decline [6]. Winter pea and winter canola are broadleaf crops which offer farmers excellent crop rotation diversity and opportunity to control downy brome (*Bromus tectorum* L.) and other winter grass weeds. However, to date, economic returns of producing winter pea are considerably lower than those for WW [7] and winter canola, although considered economically profitable, has a small seed size that makes it difficult to establish in many years [8]. Farmers in the PNW consider WT easy to grow and believe it achieves considerably greater grain yield and straw dry biomass yield than WW. Triticale is widely reported to produce greater dry straw biomass than wheat [9–11], although this has rarely been adequately quantified in direct experimental comparisons. High straw biomass production is extremely desirable in the PNW drylands and other dry Mediterranean farming regions around the world for both carbon input into the soil [12] as well as to provide soil cover to reduce blowing dust emissions during long fallow periods [13].

Triticale is a cereal produced by crossing the female parent of either common wheat (*Triticum aestivum* L.) or durum wheat (*Triticum turgidum* L.) with the male parent rye (*Secale cereal* L.). Both forage and grain types of triticale are grown. The focus here is grain triticale. Poland, Germany, France, and Belarus are the largest triticale grain producers and account for over half of worldwide production [14,15]. In the latest USA agricultural census, 11% of the nation's rainfed triticale grain was grown in the state of Washington [16]. Triticale grain is primarily used as a feed for ruminants, pigs, and poultry as it is a good source of protein, amino acids, and B vitamins [17,18]. Triticale is widely considered to have better tolerance to both saline and low pH soil conditions compared to wheat [19,20]. Additionally, triticale is less susceptible to rusts than is wheat [21–23], including stripe rust *(Puccinia striiformis* f.sp. *tritici*) which is a major concern for WW in the PNW and other areas of the world.

Due to efforts of a small group of PNW farmers and university faculty, subsidized federal crop insurance was recently made available for triticale grain production, first in the PNW and later extended throughout the USA [24]. Indeed, the long-term grain yield data reported in this paper were instrumental for documenting "proven yield" for this effort. Farmers who produce triticale now have the same federal crop insurance safety net available for wheat and other major commodity crops.

A long-term comparison of WW and WT for grain yield, straw biomass production, soil water dynamics, and their effects on subsequent crop performance has not been previously reported in the PNW nor anywhere in the literature; although Beres et al. [25] reported spring triticale performance when grown in rotation with two broadleaf crops in Canada. In this paper we describe and discuss a 9-year field study on WT in the low-precipitation (<350 mm annual) rainfed cropping zone of east-central Washington. Our objective was to provide a long-term term assessment of the agronomic and economic feasibility of producing WT in lieu of monoculture wheat.

2. Materials and Methods

2.1. Overview

An 9-year dryland cropping systems field experiment was conducted during the 2011–2019 crop years at the Ronald Jirava farm (46°59′41.1468″ N, 118°28′18.4908″ W) near Ritzville, WA to compare the agronomic and economic feasibility of WT compared to WW. Soil at the experiment site is a Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls) (US classification system), also known as a Haplic Kastanozems [26]. Soil is >2 m deep with no rocks or restrictive layers and slopes are <1%.

The study was part of a large-scale and long-term dryland cropping systems experiment initiated in 1997 to investigate the feasibility of alternative crops and rotations as well as no-till and conservation-till soil management. During the first 12 years of this study (1997–2009) numerous spring-sown crops were direct-seeded into the standing and undisturbed stubble of the previous crop. None of the continuous spring crop rotations were economically profitable [27]. Therefore, a long 13-mo fallow period was introduced into a portion of the experiment using both no-till fallow (NTF) and undercutter minimum tillage fallow (UTF) methods. Experience by regional farmers and scientists had demonstrated the potential feasibility NTF after soil had undergone several years with no tillage. Historically, at least one tillage during late spring of the fallow year was considered essential to sever soil capillary pores and channels to retard water evaporation during the hot, dry summer months to allow establishment of WW from deep sowing depths in late summer [28,29]. Both UTF and NTF were used during the 13-mo fallow period preceding sowing of WW and WT, respectively (details in Section 2.3). In the two 3-year rotations, spring wheat (SW) was sown directly into the standing and undisturbed stubble of the previous WT or WW crop. Beginning in September 2010, the following treatments rotations were introduced for comparison:

(i) 3-year WT-SW-NTF
(ii) 3-year WW-SW-UTF
(iii) 2-year WW-UTF

Experimental design was a randomized complete block with four replications. Individual plot size was 9 × 150 m. All phases of all rotations were present every year (total = 32 plots).

2.2. Soil Water and Precipitation

Water content in the soil to a depth of 180 cm was measured three times each year. These times were: (i) early August after the harvest of WT, WW, and SW; (ii) at the end of the 13-month fallow in late August; and (iii) in late March. Volumetric soil water content in the 0–30 cm depth was determined from two 15-cm core samples with gravimetric procedures [30] using known soil bulk density values. Soil volumetric water content in the 30-to 180-cm depth was measured in 15 cm increments with an InstroTek CPN 503® neutron moisture probe (Intsrotek Inc., Research Triangle Park, NC, USA) [31].

Precipitation was measured on site during all years with a computerized tipping-bucket weather station that was owned and operated by the WSU AgWeatherNet program (https://weather.wsu.edu/). We knew that the AgWeatherNet weather station at the site underestimated several precipitation events, therefore precipitation data reported here (Table 1) was recorded manually every day by the Adams Conservation District in the town of Ritzville located 8 km east of the experiment site. Historically, the town of Ritzville receives 6-to 12-mm greater annual precipitation than at the experiment site.

Table 1. Crop-year (1 September–31 August) precipitation (mm) at Ritzville, Washington from 2011 to 2019.

Crop Year	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Total
2011	26	43	34	54	32	11	40	21	57	6	6	0	330
2012	4	19	17	0	23	27	64	39	11	67	20	2	293
2013	0	38	66	40	18	15	17	14	24	52	0	35	319
2014	30	2	23	10	15	40	51	30	7	34	2	13	256
2015	2	31	31	42	43	27	41	17	24	0	0	3	261
2016	24	12	20	93	56	30	78	12	23	13	16	3	370
2017	9	123	36	35	40	64	71	31	22	8	0	0	440
2018	19	36	57	49	59	27	34	49	26	8	1	2	367
2019	1	20	39	59	54	47	18	23	31	16	3	9	319
9-year avg.	13	36	36	42	38	32	46	26	25	23	5	7	328

2.3. Fallow Management

After harvest of all plots in early August, residue was left standing and undisturbed throughout the fall and winter. When Russian thistle (*Salsola tragus* L.) was present after harvest (mostly only in SW stubble), 0.42 kg active ingredient (ai)/ha paraquat herbicide was applied. Paraquat is a contact herbicide which provides more effective control of Russian thistle than does the systemic herbicide glyphosate in mid-July and later when this weed is hardened off by the hot and dry weather and difficult to control with glyphosate [32].

Undercutter tillage fallow was used in the WW-UTF and WW-SW-UTF rotations in mid-May to mid-June. A Haybuster® undercutter (DuraTech, Jamestown, ND, USA) with wide, narrow pitch, overlapping sweep blades on two ranks was used for primary spring tillage plus simultaneous injection of 67 kg/ha aqua NH_3-N + 11 kg/ha thiosulfate S liquid fertilizer. The undercutter sweep blades were operated at approximately 13 cm depth. The undercutter method is considered a best management conservation practice for primary spring tillage during fallow because it effectively breaks soil capillary continuity to effectively retain soil moisture during the dry summer while leaving most residue on the soil surface and does not pulverize surface clods [33]. One, and sometimes two, rotary rod weeding operations (also a noninversion implement) were conducted at 7–10 cm depth during late spring and/or summer to control broadleaf weeds.

No-till fallow was used in the WT-SW-NTF rotation. The soil in these plots had been in no-till with no soil disturbance except for sowing of crops since 1997. Glyphosate herbicide was applied 3–4 times from March through August of the fallow year at rates ranging from 0.43 to 1.29 kg acid equivalent (ae)/ha. As WT was sown into NTF, N and S fertilizer was stream jetted in Solution 32 formulation (urea ammonium nitrate N + thiosulfate S) onto established WT seedlings in late October or early November just prior to an expected substantial rain event. Fertility requirements for WT and WW are similar [34], thus, N and S fertilizer application rates for these two crops were held constant at 56 kg/N/ha and 11 kg/S/ha every year with a starter fertilizer of P, Zn, and B applied in the seed row with the deep-furrow drill (see Section 2.4) at sowing.

2.4. Sowing

2.4.1. Winter Triticale and Winter Wheat

For the two UTF rotations, WW was sown every year within the first 10 days of September as adequate seed-zone moisture for germination and emergence is available essentially 100% of the time with the UTF method at this location. Adequate seed-zone moisture was available in both NTF and UTF all nine years, therefore WT and WW were always sown on the same day and with the same deep-furrow drill.

Certified seed of WT (cv. Trimark 099) and WW [cv. Xerpha (2011–2016) or Otto (2017–2019)] were sown between 1 and 10 September during all years. Trimark 099 was bred in Poland and released as a commercial WT cultivar in the USA by ProGene Plant Development, Othello, WA. Both Xerpha and Otto were released by Washington State University (WSU) and are among the highest yielding WW cultivars available to farmers in east-central Washington. All seed was treated with a broad-spectrum fungicide and an insecticide for wireworm (*Agriotes lineatus*) control. A custom-built deep-furrow drill with 43 cm spacing between rows was used to place seed into moisture with 10–13 cm of soil covering the seed. Sowing rate for WT and WW was always held constant at 56 kg/ha. Successful stand establishment of WT and WW was achieved every year.

2.4.2. Spring Wheat

Spring wheat (cv. Louise) was sown as soon as soil conditions allowed on dates ranging from 15 March to 7 April. Sowing rate was 78 kg/ha. A custom-built hoe-opener drill with 10 cm paired rows with 30 cm row spacing was used to direct sow SW into the undisturbed standing stubble of the previous WT or WW crop. Liquid fertilizer was delivered in a deep band between the paired seed rows.

Solution 32 was used as the carrier to apply an average of 47, 7, and 7 kg/ha of N, P, and S, respectively. Fertilizer rates varied each year depending on soil test results and expected SW yield potential based on residual fertilizer and available soil water. The fertilizer rates for SW following both WT and WW were always the same.

2.5. In-Crop Weed and Stripe Rust Control

Several in-crop herbicide formulations were applied at labeled rates over the nine years to control broadleaf weeds in WT, WW, and SW. These formulations were bromoxynil, 2–4-D ester, ethylhexyl ester, dicamba, and thifensulfuron + tribenuron. Some of these herbicides have different modes of action which is required to slow/reduce the development of herbicide resistant weeds [35]. For WW, the fungicide propiconazole for control of stripe rust (*puccinia striiformis*) was tank mixed with the broadleaf herbicide in all but two years. Fungicide was not required for WT as no stripe rust lesions were observed in any year. Fungicide was also not applied to SW as the warmer, drier weather conditions during its active growth was not conducive to stripe rust infection. Broadleaf herbicides (plus fungicide for WW) were applied mid-April for WT and WW and mid-to-late May for SW.

The grass-weed herbicide propoxycarbazone was applied at labeled rates to WT and WW in 5 of 9 years to control downy brome (*Bromus tectorum* L.). This herbicide was applied during the tillering stage of plant growth during the mid-fall to mid-to-late winter.

2.6. Grain Yield

Winter triticale, WW, and SW were harvested every year in early August. A commercial-size combine with 6.1-m-wide cutting platform was used to harvest the entire 150 m length of each plot. After harvest of each plot, grain was augured into a weigh wagon and grain weight measured on built-in digital scale.

2.7. Grain Yield Components and Straw Weight

For WT and WW in both 2-year and 3-year rotations, spike density was measured by counting the number of grain-bearing spikes from a randomly selected 1-m row section in each plot just prior to grain harvest. The entire aboveground portion of plants from these same 1-m row sections was then hand clipped and collected. Plants were then placed in a hot, low-humidity greenhouse for at least one week then weighed. Kernels per spike was calculated based on number of spikes/m^2 and 1000-kernel weight after passing spikes through a hand-fed thresher and then counting kernels in an automated kernel-counting devise. Straw dry biomass was determined by subtracting the weight of the grain from the whole aboveground plant weight.

2.8. Economic Assessment

Enterprise budgets were constructed for each rotation with annual costs based on actual inputs and field operations used each year, and with annual income based on observed yields. Fertilizer, seed, and pesticide input costs were based on 2019 prices from local suppliers, reflecting the prices that local farmers would pay. Machinery costs were from WSU budgets [36] and were updated to 2019 values using 2019 fuel and labor costs, and with other costs components updated using the USDA-NASS machinery prices paid index [37]. Machinery costs were estimated for farm-scale equipment and included repairs, labor, fuel and lube, depreciation, and overhead costs (interest, taxes, housing, insurance, licenses). In order to compare costs for each phase of the rotations on an equitable basis, the costs for fertilizer and fertilizer application were included in the fallow (UTF or NTF) phase of each rotation, even though fertilizer applications in the WT-SW-NTF rotation occurred after WT sowing.

To focus the economic analysis on crop production impacts, crop prices were fixed at eight-year (2012–2019) average of local market prices on September 1 of each year. Note that economic analysis was only conducted over eight years to include all rotation phases for all years as eight years of production data were available for SW versus nine years of data for WT and WW. Average wheat and triticale grain prices used for the economic analysis were $171 and $135/Mg, respectively. No land or management charges were included, so net returns represent returns to land and management. Rotation-average costs and returns were calculated as the average of costs and returns for each phase of the rotation.

Since results of the economic analysis may be sensitive to market conditions, additional economic analysis was conducted using annual crop prices. Annual crop prices are reported in supplemental Table S1. In addition, break-even analysis was conducted to identify the triticale and wheat price levels at which average net returns for the WT-SW-NTF were equal to the WW-SW-UTF and WW-UTF rotations. Also, to investigate the sensitivity of results to differing fallow (UTF and NTF) practices, additional analysis was conducted using UTF costs instead of NTF costs in the WT rotation. Finally, economic risk can be an important factor influencing whether a farmer is willing to adopt a practice. The standard deviation of rotation-average annual net returns across years was included as a measure of economic risk.

2.9. Statistical Procedures

Analysis of variance (ANOVA) was conducted for soil water content, grain yield, grain yield components (i.e., spikes per unit area, kernels per spike, 1000-grain weight), aboveground dry straw weight per unit area, costs, gross returns, and net returns using a randomized complete block design ANOVA for each year and a split-plot in time ANOVA across years with treatment as the fixed-effect factor and year as the random-effect factor. Additionally, an analysis of covariance (ANCOVA) was conducted to determine any differences in relative grain yield response among WT and 3-year and 2-year WW as affected by crop-year precipitation. The Tukey's honest significant difference (HSD) was used to detect statistical differences in treatment means and control the experiment-wise error rate for multiple comparisons. All ANOVA and ANCOVA tests were conducted at the 5% level of significance using Statistix 10® software (Analytical Software, Tallahassee, FL, USA) for the agronomic data analysis and JMP PRO 13® (SAS Institute, Buckinghamshire, UK) for the economic data analysis.

3. Results

3.1. Crop-Year Precipitation

Crop-year (September 1–August 31) precipitation ranged from 256 to 440 mm and averaged 328 mm over the nine years (Table 1). The 2014 and 2015 crop years were the only periods with considerably below-average precipitation. Much greater than average precipitation fell in the 2016 and 2017 crop years (Table 1).

3.2. Soil Water Storage and Water Depletion by Crops

Averaged over the years, WW in the 3-year rotation used 5 mm more soil water than WT by time of grain harvest in early August. Although these water use differences were minor, they were statistically significant ($p = 0.019$, Table 2). Stubble was left standing and undisturbed through the winter and, by late March, soil water content in the WT and WW stubble averaged 320 and 307 mm, respectively ($p = 0.014$, Table 2). Although this was a net overwinter soil water gain of 8 mm for WT vs. WW stubble, this difference in net water gain was not statistically significant (Table 2).

Spring wheat was direct sown into both WT and 3-year WW stubble in late March-early April. By time of SW harvest in early August, soil water content between these two treatments averaged over years was essentially equal (Table 2).

3.3. Straw Weight and Stem Number of WT Versus WW

There were no statistical differences in the weight of dry WT straw/m^2 compared to 3-year and 2-year WW. The 3-year WW, however, produced a much greater quantity of dry straw than did 2-year WW ($p < 0.010$, Table 3).

Table 2. Soil water content: (i) in August at time of harvest of winter triticale (WT) and winter wheat (WW), (ii) in the standing and undisturbed stubble of WT and WW in early spring, and (iii) at the time of spring wheat (SW) harvest in August. Data are averaged over eight years (2012–2019). ns = not significant.

	Baseline after WT/WW	Spring	Over-Winter Gain	At Time of SW Harvest
	mm			
3-year WT	152	320	168	168
3-year WW	147	307	160	166
p-value	0.019	0.014	ns	ns

Table 3. Straw dry biomass weight, stem number and stem weight for winter triticale and winter wheat averaged over five years (2015–2019) at Ritzville, WA. Within-column letters followed by a different letter are significantly different. HSD = honest significant difference.

	Straw wt. (kg/ha)	Stems/m^2	Wt. (g)/Stem
Winter triticale (3-year)	7276 ab	284 c	2.36 a
Winter wheat (3-year)	7517 a	486 a	1.47 b
Winter wheat (2-year)	6489 b	398 b	1.51 b
Significance (*p*-value)	<0.010	<0.001	<0.001
Tukey HSD (0.05)	887	50	0.16

There were huge differences between WT and WW in the number of stems/m^2 ($p < 0.001$) and individual stem weight ($p < 0.001$, Table 3). Winter triticale produced an average of only 284 stems/m^2 compared to 486 and 398 stems/m^2 for 3-year and 2-year WW, respectively. Individual stems of WT were much thicker and heavier than those of WW with individual stem weight of 2.36 g for WT compared to 1.47 g for 3-year WW and 1.51 g for 2-year WW (Table 3). There were never any within-year differences in individual stem weight between 3-year and 2-year WW, but 3-year WW always produced significantly more stems/m^2 than 2-year WW and in the long-term average as summarized in Table 3.

3.4. Grain Yield of Winter Triticale and Winter Wheat

Over the nine years, WT produced 14 and 24% greater grain yield than 3-year and 2-year WW, respectively. Winter triticale grain yield ranged from 4400 to 7426 kg/ha and averaged 5812 kg/ha (Table 4). Grain yield of 3-year WW averaged 5099 kg/ha and 2-year WW 4700 kg/ha. Winter triticale grain yield was significantly greater than either WW system in all but two years and the 9-year average grain yield differences were highly significant with WT > 3-year WW > 2-year WW ($p < 0.001$, Table 4). There were no significant differences in grain yield among WT and both 3-year and 2-year WW in 2012 and 2014. Statistical comparison of regression coefficients for grain yield using ANCOVA showed that, although the magnitude of grain yield response (i.e., y-intersect) among WT, 3-year WW, and 2-year WW were different, the relative differences, or slope, in grain yield among the three treatments did not change in dry or wet crop years ($p = 0.89$).

Table 4. Grain yield of winter triticale (WT) and 3-year and 2-year winter wheat (WW) for nine years and averaged over years at Ritzville, WA. Within-year letters followed by a different letter are significantly different. ns = not significant.

	2011	2012	2013	2014	2015	2016	2017	2018	2019	9-Year Avg.
	Grain Yield (kg/ha)									
WT	6976 a	5048	5533 a	4400	4245 a	7426 a	6215 a	6652 a	5848 a	5816 a
WW (3-year)	4918 b	5310	5423 a	3688	3760 ab	6330 b	5475 b	5890 b	4985 b	5087 b
WW (2-year)	5060 b	5008	4220 b	3696	3144 b	6313 b	5211 b	4946 c	4608 b	4689 c
p-value	0.00 7	ns	<0.001	ns	0.012	0.020	<0.001	<0.001	<0.001	<0.001
HSD (0.05)	1396	625	577	1160	755	976	384	575	514	218

3.5. Grain Yield Components of Winter Triticale and Winter Wheat

As reported in Section 3.3 and shown in Table 3, spike density (e.g., stems/m^2) was significantly different (<0.001) among treatments with 3-year WW > 2-year WW > WT. Winter triticale produced an average of 46 kernels/spike vs. 34 kernels/spike for both 3-year and 2-year WW ($p < 0.001$, data not shown). Average 1000 kernel weight was 44, 31, and 33 g for WT, 3-year WW and 2-year WW, respectively ($p < 0.001$). Thus, the higher grain yield achieved by WT was due to greater number of kernels/spike and heavier kernel weight despite having much fewer spikes/m^2 compared to the WW treatments. The 3-year WW produced significantly greater straw/m^2 as well as spikes/m^2 compared to 2-year WW (Table 3); this likely a positive "rotation effect" of having SW in the WW-SW-UTF system.

3.6. Grain Yield of Spring Wheat

Spring wheat grain yield ranged from 1410 to 3398 kg/ha (Table 5). Note that SW yields are reported for 8 years (versus 9 years for WT and WW) because one year was required to first grow WT and WW to get SW in rotation. All spring-sown crops grown in the PNW drylands have highly variable grain yields over years due to frequent water and heat stress during reproductive development [4,33,38] whereas WT and WW complete reproductive phase considerably earlier. Spring wheat yields were especially meager in the low-precipitation years of 2014 and 2015 (Tables 1 and 5). The highest SW grain yields were achieved in 2016 when crop-year precipitation was relatively abundant, timely rains occurred in May and June (Table 1), and May and June air temperatures were moderate. There were no treatment differences in SW grain yield after WT versus WW in any year but, averaged over the years, yield of SW after WT was slightly but significantly greater than SW after WW ($p = 0.022$, Table 5). Average grain yield of SW was considerably less than half of that of WT and WW (Tables 3 and 5).

Table 5. Spring wheat grain yield grown in a 3-year rotation after winter triticale (WT) or after winter wheat (WW).

	2012	2013	2014	2015	2016	2017	2018	2019	8-Year Avg. †
	Grain Yield (kg/ha)								
After WT	1882	3128	1513	1607	3398	2557	3052	2462	2451
After WW	1866	2720	1410	1699	3472	2444	2857	2192	2332
p-value	ns	ns	ns	ns	ns	ns	ns	ns	0.022
Tukey HSD	138	491	731	454	553	140	335	280	100

† Spring wheat grain yield is reported for 8 years (versus 9 years for WT and WW) because WT and WW had to be first grown so that SW could follow in the rotation. ns = not significant.

3.7. Economic Analysis

Production costs for the WT phase were not significantly different from the WW phases of the rotations (Table 6). Costs for NTF were $32/ha higher than for UTF. This was due to higher costs for herbicide applications to control weeds in NTF compared to use of the rod weeder implement in UTF. The total cost for the SW phase was the same for the 3-year rotations. Rotation average costs were $10/ha higher for WT-SW-NTF than for WW-SW-UTF due to the higher cost of NTF. Rotation average costs for the 3-year rotations were both higher than for the 2-year rotation, due to the higher cost of the SW phase of the 3-year rotations compared to the other rotation phases.

Average gross returns for WT and 2-year WW were $105 and $79/ha lower than for 3-year WW (Table 7). Even though WT yields were higher than WW yields, gross returns for WT were lower due to the lower price of triticale compared to wheat. These differences in gross returns also were reflected in lower net returns for WT and 2-year WW than for 3-year WW. Average gross returns were $13/ha higher for SW after WT than for SW after WW, which was also reflected in higher SW net returns after WT than after WW. It should be noted that net returns for WT and WW represent returns over a 2-year period, since costs for the fallow year were included in these values, while net returns for SW represent returns over a single year. Nonetheless, net returns on an annual basis were lower for SW than WW or WT.

Table 6. Average annual costs for winter triticale (WT), 3-year and 2-year winter wheat (WW), spring wheat (SW), no-till fallow (NTF), undercutter tillage fallow (UTF), and rotation averages over eight years (2012–2019).

	WT	WW (3-Year)	WW (2-Year)	SW	NTF	UTF	WT-SW-NTF	WW-SW-UTF	WW-UTF
	Cost ($/ha)								
Labor	22 a †	22 a	22 a	25	9 a	9 a	18 a	19 a	16 b
Repairs	17 a	17 a	17 a	18	1 b	3 a	12 b	13 a	10 c
Fuel	13 a	13 a	13 a	16	8 a	8 a	12 a	12 a	11 b
Materials	85 a	87 a	87 a	170	119 a	82 b	124 a	113 b	84 c
Interest	7 a	7 a	7 a	9	12 a	10 b	9 a	9 b	8 c
Depreciation	17 a	17 a	17 a	17	0 b	2 a	11 b	12 a	9 c
Overhead	12 a	12 a	12 a	12	0 b	2 a	8 b	9 a	7 c
Total Cost	173 a	175 a	175 a	266	148 a	116 b	196 a	186 b	146 c

† Different letters within each row indicate significant difference in costs ($p < 0.05$) between winter crops (WT, WW), between fallow types (NTF, UTF), and between rotations (WT-SW-NTF, WW-SW-UTF, WW-UTF).

Table 7. Gross returns and net returns for winter triticale (WT), 3-year and 2-year winter wheat (WW), spring wheat (SW) after WT, and SW after WW averaged over eight years (2012–2019). Costs for fallow were included in the net returns for the winter crops, so returns for the crops represent the returns over two years.

	WT	WW (3-Year)	WW (2-Year)	SW after WT	SW after WW
	Returns ($/ha)				
Gross Returns	767 b †	872 a	793 b	419 a	398 b
Net Returns	446 b	581 a	502 b	153 a	132 b

† Different letters within each row indicate significant differences ($p < 0.05$) between winter crops (WT, WW) and between SW rotations (after WT and after WW).

Looking at rotation averages, net returns for WW-UTF were numerically higher than for WT-SW-NTF in every year except 2013 and 2018, with significant differences in 2012, 2014, 2017, and 2019 (Table 8). Similarly, net returns were numerically higher for WW-SW-UTF than for WT-SW-NTF in every year, with significant differences in 2012 and 2017. As a result, average net returns over the entire study period were significantly higher for WW-UTF and WW-SW-UTF than for WT-SW-NTF, by $52 and $39/ha, respectively. Net returns for WW-UTF were significantly lower than for WW-SW-UTF in 2013 but were significantly higher than WW-SW-UTF in 2017, and 2019. Average net returns over the 8-year period were not significantly different between WW-SW-UTF and WW-UTF. Inter- annual variation in net returns was higher for the 3-year rotations than for WW-UTF. If the same WT yields had been obtained using UTF instead of NTF, the cost reduction of $32/ha for UTF relative to NTF would have increased average net returns for the WT rotation by $11/ha to $210/ha. This is still significantly lower than the net returns for WW-UTF but not significantly lower than for WW-SW-UTF.

Supplemental analysis showed that adding the variation in crop prices across years generally did not change net return rankings within years or the average over the 8-year period (data not shown). As expected, adding variation in crop prices across years increased inter-annual variation in net returns. However, WT-SW-NTF was less variable than either WW-SW-UTF or WW-UTF.

The relative profitability of WT-SW-NTF compared to WW-UTF and WW-SW-UTF may change as wheat and triticale prices change. The price relationships where net returns for the WT-SW-NTF rotation are equal to the net returns for the WW-UTF rotation are denoted by the solid line in Figure 1. Similarly, the breakeven price relationships for the WT-SW-NTF rotation compared to the WW-SW-UTF rotation are denoted by the dashed line in Figure 1. For the wheat price of $171 Mg^{-1} used in the economic analysis, the triticale price would need to be $163 and $156 Mg^{-1} for the WT-SW-NTF rotation to be as profitable as the WW-UTF and WW-SW-UTF rotations, respectively at the average observed yield level. Alternatively, average WT yield would have needed to be 6.83 or 6.54 Mg to equal the profitability of the WW-UTF and WW-SW-UTF rotations, respectively. These breakeven triticale prices or yields are higher by 21 and 15%, respectively, than the average triticale price of \$135 Mg^{-1} and triticale yield of 5.67 Mg/ha used in the economic analysis. If the same WT yields had been obtained using UTF instead of NTF in the WT rotation, triticale prices or yields would need to be 16 and 11% higher for the WT rotation to be as profitable as the WW-UTF and WW-SW-UTF rotations, respectively.

Table 8. Rotation average annual net returns, and average standard deviation over eight years (2012–2019) based on average crop prices.

Rotation	2012	2013	2014	2015	2016	2017	2018	2019	8-Year Avg.	SD
	Net Returns (\$/ha)									
WT-SW-NTF	143 b [†]	230 b	89 b	88 a	349 a	220 c	285 a	192 b	199 b	92
WW-SW-UTF	217 a	270 a	106 ab	127 a	388 a	260 b	320 a	215 b	238 a	94
WW-UTF	272 a	215 b	157 a	126 a	399 a	308 a	279 a	251 a	251 a	86
p-value	0.001	0.010	0.048	0.108	0.246	0.000	0.113	0.003	0.006	
HSD (0.05)	56	37	67	53	86	25	54	31	36	

WT = winter triticale, WW = winter wheat, SW = spring wheat, NTF = no-till fallow, UTF = undercutter tillage fallow. SD = standard deviation. [†] Different letters within each year indicate significant differences in net returns ($p < 0.05$).

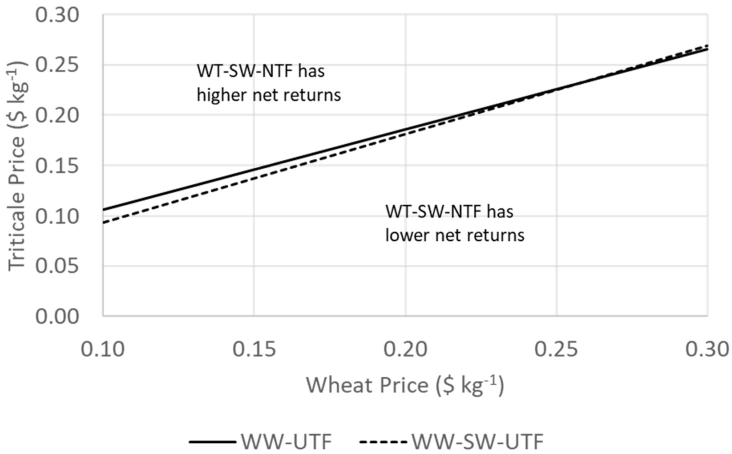

Figure 1. Breakeven winter triticale price as related to wheat price for the WT-SW-NTF rotation to be as profitable as the winter wheat (WW)- spring wheat (SW)-undercutter tillage fallow (UTF) rotation or the WW-UTF rotation. Winter triticale and wheat price combinations above and to the left of the WW-UTF or WW-SW-UTF breakeven lines would have higher average (8-year average) WT-SW-NTF net returns than the respective winter wheat rotation. Winter triticale and wheat price combinations below and to the right of the WW-UTF or WW-SW-UTF breakeven lines would have lower average (8-year average) WT-SW-NTF net returns than the respective winter wheat rotation.

4. Discussion

Triticale is widely reported to consistently produce higher grain yields compared to wheat [39–41]. This held true in our study where yield differences between WT and 3-year WW were highly statistically different. In addition, 3-year WW achieved significantly greater average yield than 2-year WW. We grew only one WT cultivar and two WW cultivars throughout the 9-year study. A separate study conducted from 2015 to 2017 at Lind, WA (22 km from the Ritzville site) evaluated grain yield of five WT numbered lines from Germany and Poland as well as Trimark 099. There were no statistical differences in grain yield among Trimark 099 and other top entries in any year or when averaged over the three years [42], thus we feel good about the decision to use Trimark 099 in the Ritzville study.

There are many statements in the literature that WT produces more dry straw biomass than WW, but these have been largely based on visual observations and rarely quantified. Winter triticale grows taller than WW and farmers tend to cut WT straw at harvest at a greater height than for WW. In our study, the thick WT stems that weighed 60% more than those of WW visually masked the fact that WT had far fewer stems. Although straw production of WT versus WW has been quantified in very few studies, both winter and spring types of triticale are reported to produce a significantly greater quantity of straw (sometimes double) compared to WW and SW, respectively [9–11,43]. In our study, we consistently found no differences in quantity of straw produced between WT and WW. This information is important because farmers in low-precipitation Mediterranean environments, want and need to produce as much straw as possible [12,13].

Winter wheat produced significantly more spikes/m^2 than WT. Should we have increased the sowing rate of WT? Separate multiple-year field studies in central and southern Alberta, Canada showed no differences in grain yield of early-sown WT as affected by sowing rate [44,45]. Field studies on early-sown WW in east-central Washington showed little effect of sowing rate on grain yield [46]. Such studies on early-planted WT are currently being conducted at Lind, WA but no data are yet available. Estrada-Campuzano et al. [43] argued that fewer spikes/m^2 of triticale compared to wheat is not a yield hindrance as it allowed for enhanced accumulated intercepted radiation and radiation use efficiency compared with thicker stands of triticale.

Winter triticale grew much more rapidly than WW in late winter-early spring, flowered earlier that WW, and was ripe for harvest at least seven days earlier than WW every year in the study. Although row spacing was wide (43 cm), WT had a closed canopy in most years by early April. Below freezing nighttime air temperatures occurred some years during anthesis of WT, but frost damage was rarely observed; whereas it is well understood that substantial plant injury and subsequent grain yield decline occurs with frosts during anthesis of WW.

Some PNW dryland farmers have expressed reluctance to plant WT because its male parent is cereal rye whose seed can lay dormant in/on the soil for several years and be a weed that requires hand roughing in the subsequent wheat crops(s). Such "feral" cereal rye and WT are somewhat similar in appearance and both grow ≥10 cm taller than semi-dwarf WW; therefore, volunteer plants are easily seen in a WW field. However, importantly, unlike cereal rye, triticale seed has little to no primary dormancy and, like wheat, does not persist in the seed bank [47]. Thus, the concern of some farmers that WT will become a feral weed is unfounded.

The early maturity of WT is favorably viewed by dryland farmers in east-central Washington as it allows for its harvest before WW is ripe for cutting. Farms are large and many farmers own or rent two or three combines. As the region is almost exclusively in 2-year WW-fallow, including WT on some farmland hectares would spread the optimum period for grain harvest over a longer time window which would likely allow some farmers to reduce the number of combines needed.

Although WT produced an average of 14 and 24% greater grain yield than 3-year and 2-year WW, respectively, it was not economically competitive with either WW system primarily since it fetched a considerably lower market price, but also in part due to the higher cost of NTF compared to UTF. If UTF had been used with WT instead of NTF, and assuming the same yields were attained, the cost reduction would have increased average net returns for the WT rotation to where it was not significantly lower than for WW-SW-UTF, but still significantly lower than the net returns for WW-UTF. Even with this cost reduction, the WT gross returns would need to be 11–16% higher than the average gross returns observed in the economic analysis to produce the same net returns as the WW rotations. This could be attained by 11–16% higher WT price or 11–16% higher WT yield or a combination of price and yield increases.

The SW phase of the 3-year rotations is not as profitable as the WT or WW phase of these rotations. While the cost of SW production is similar to the cost for WW, the annualized cost for WW including the cost of fallow is lower than the cost of SW production, while the annualized yield for WW is higher than for SW. However, the lack of profitability for SW is partially offset by yield and profitability benefits to the WW phase of the WW-SW-UTF rotation. As a result, net returns for WW-UTF were not significantly different from net returns for WW-SW-UTF.

5. Conclusions

Winter triticale is an easy-to-grow and hardy crop that produced significantly greater grain yield than WW. Spring wheat grain yield was slightly, but significantly, greater after WT versus after WW. Unlike essentially all reports to the contrary, WT did not produce greater dry straw biomass than WW. The WT rotation was less profitable than the WW rotations due to the lower price of WT. Pairing WT production with UTF in addition to the cost savings realized in eliminating fungicide applications may help improve the profitability by reducing production costs. Additional yield improvements or development of higher value uses for WT that increase the price of WT relative to wheat would help WT be economically competitive with WW rotations. This may be feasible in future years due, for example, to recent promising research with selected 1R chromosomes and known wheat alleles to improve protein, hardness, and gluten strength of triticale grain for bread making [48,49].

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/11/1777/s1, Table S1: Annual (September 1) soft white wheat and triticale market prices in US dollars from 2012-2019 at Ritzville, Washington.

Author Contributions: W.F.S. designed the experiment and performed all field and laboratory work. D.W.A. conducted the economic analysis. Both W.F.S. and D.W.A. performed statistical analysis and evaluated the data and both contributed to drafting the manuscript and writing the final version. All authors have read and agreed to the published version of the manuscript.

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