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Use of Dual-Purpose Winter-Grain Cover Crops as Emergency Forage and for Management of High Soil Phosphorous in Manured Fields

Samantha Glaze-Corcoran, Alexandra Smychkovich and Masoud Hashemi *

Stockbridge School of Agriculture, University of Massachusetts Amherst, 161 Holdsworth Way,
Amherst, MA 01003, USA
* Correspondence: masoud@umass.edu

Abstract: Dual-purpose cover crops can cycle nutrients on dairy farms while providing additional quality forage. However, questions remain regarding the crop species best suited to this function. A two-year field experiment with five small-grain winter cover crops, including rye (*Secale cereale*), wheat (*Triticum aestivum*), and three triticale varieties (×*Triticosecale* varieties), was conducted on an active dairy farm. The rye produced the highest yield at 4612 kg ha^{-1}, followed by the forage varieties of triticale, which averaged 4004 kg ha^{-1}, whereas the wheat and one nonforage triticale produced only 2950 and 2987 kg ha^{-1}, respectively. The wheat had the highest crude protein (CP) at 11%, and a relative feed value (RFV) of 132, and it had the greatest milk-production potential, which was 1729 kg milk/Mg of forage. Yet, the rye (CP: 10.4%; RFV: 112) had the greatest milk-production and economic potentials per hectare due to the high forage yield, valued at USD 714 ha^{-1}, whereas the nonforage triticale had the least economic value (USD 326 ha^{-1}), despite its high forage quality (CP: 9.5%; RFV: 120). The forage triticale varieties were intermediate performers compared with the rye and wheat on a yield and quality basis. Mirroring the yield, the rye also removed the most nitrogen (77.3 kg ha^{-1}) and phosphorus (20.8 kg ha^{-1}). The species differences were found to be contingent on the manure application. The results of this experiment suggested that winter rye is the most efficient cover crop for harvesting and nutrient-recycling purposes.

Keywords: dual-purpose cover crops; soil nutrient removal; forage quality; milk-production value

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1. Introduction

Agricultural operations, such as dairy farms, confined meat-finishing operations, and poultry producers, generate large amounts of manure that must be managed sustainably to minimize the potential negative environmental impacts and nutrient overaccumulation in agricultural soils. In the northeastern United States, the capacity of the manure storage is limited and is often only sufficient to hold six months or less of collected manure. The presence of large amounts of liquid in slurry manure often results in a substantial volume of waste that often exceeds the storage capacity and limits economically lucrative management options, such as composting. Thus, many farms manage their manure by applying it to their cropland, and often in excess of the crop needs [1].

To generate space for winter storage, many dairy producers apply manure in the fall to fields that may not require additional fertility. The continuous overapplication of manure results in the application of phosphorus (P) at rates that exceed the uptake capacity of cash crops, causing P overaccumulation in agricultural fields [2,3]. High levels of P in agricultural soils increase the risk of P entering the surrounding environment and contributing to the eutrophication of water systems [3–5], or, if P remains in the field, being converted into plant-unavailable forms over time [6] and rendering large amounts of this critical nonrenewable resource obsolete [7,8].

Planting winter-grain cover crops in overfertilized fields has the potential to offset overfertilization by removing excess nutrients from manured soils. However, fall manure application and cover-crop planting are often delayed, which results in insufficient time for the plant establishment and nutrient uptake. Hashemi et al. (2013) reported that a two-week delay in the planting of cover crops can result in 60% less fall nitrogen capture [9]. While the timely planting of cover crops can maximize the nutrient recovery, the termination of cover crops in spring re-releases nutrients back into the soil, providing only a short-term solution to nutrient overaccumulation.

The use of dual-purpose cover crops (DPCCs) is a proposed avenue in animal operations to mitigate nutrient overaccumulation while simultaneously producing high-quality forage [10]. Grazing or harvesting DPCCs removes excess nitrogen (N) and phosphorus (P) from agricultural fields [11], preventing the immediate re-release of nutrients into agricultural soils. Feed is known for being the greatest expense in animal operations [12–16]. The use of DPCCs as a food source for livestock can increase the efficiency of the on-farm nutrient cycling and nutrient management in dairy production systems while improving the resiliency by providing an "emergency" feed crop [8,17].

Overwintering cereal grains, such as rye (*Secale cereale*), wheat (*Triticum aestivum*), and triticale (×*Triticosecale*), have been recognized as high biomass producers and efficient nutrient scavengers [18–22]. Therefore, these crops are excellent candidates for use as DPCCs. Growers who already incorporate cover crops can easily manage these crops for forage, and farmers who do not utilize cover crops may be incentivized to do so due to the additional benefit of forage production. Furthermore, the nutrient cycling and remediation benefits of planting DPCCs can be integrated into farmers' broader nutrient management plans.

Utilizing small grains for forage is a well-established practice in the Southern Plains of the United States [23]. Interest in the practice is growing in the north, but climatically appropriate research is limited. An array of small winter grains to choose from raises questions as to which species will reliably perform to provide both high-quality forage and nutrient management. Species must be compatible with water-stress events, as climate change in the northeast brings increased periods of drought in the spring and fall during peak growth, as well as an increased intensity of precipitation events. Winters are expected to be warmer on average, which may result in reduced snow cover, but deep-freeze events will persist [24]. This threatens to leave plants exposed to extreme cold, without protective snow insulation.

Rye has long been popular due to its high stress tolerance to cold, drought, nutrient-limiting conditions, and acidic soils [25]. However, concerns persist that the high yields of rye are a tradeoff for the reduced forage quality of this crop, compared with the quality of wheat [26]. Although the use of triticale as a forage has shown promise [17,27], evaluations are limited regarding the varietal differences that pertain to the nutrient-recovery performance and feed-value characteristics of triticale as a DPCC. This study aimed to evaluate the performances of three common small winter grains (cereal rye, wheat, and triticale) and their potential for N and P recovery on an active dairy farm in a temperate climate. We hypothesized that, in general, the DPCCs could: (1) reduce the soil P levels, and (2) be used as an economically valuable forage to offset the cost of feed in dairy operations. We also hypothesized that triticale—as a hybrid of wheat and rye—would provide a superior combination of forage yield and quality, which translates to substantial milk production, while achieving the effect of N and P recovery.

2. Materials and Methods

2.1. Experimental Site

A two-year field experiment was conducted (from August 2016 to September 2018) on a small dairy farm (100+ milking cows and 100+ dry cows) in Franklin County, Massachusetts, the United States of America. The farm has been in production for over 200 years, the last 80 years of which have prioritized dairy production. The field selected for this study was 1 ha, had a history of manure application, and was traditionally used for corn-silage production. The soil in this location is categorized as a Hadley fine sandy loam (coarse–silty, mixed, superactive, nonacidic, mesic Typic Udifluvents) (Natural Resource Conservation Service, 2013). Prior to the fall manure application in 2016, the soil samples were taken from a depth of 0.2 m, and the modified Morgan extractable nutrients were quantified. The pH was 6.2, and the micro and macronutrients were in a range from optimum to above optimum, except for calcium (Ca), which was slightly low (0.965 mg/g) but typical for the region. The extractable P was more than twice the optimum level (0.0305 mg/g). The local weather conditions during this study are presented in Figure 1.

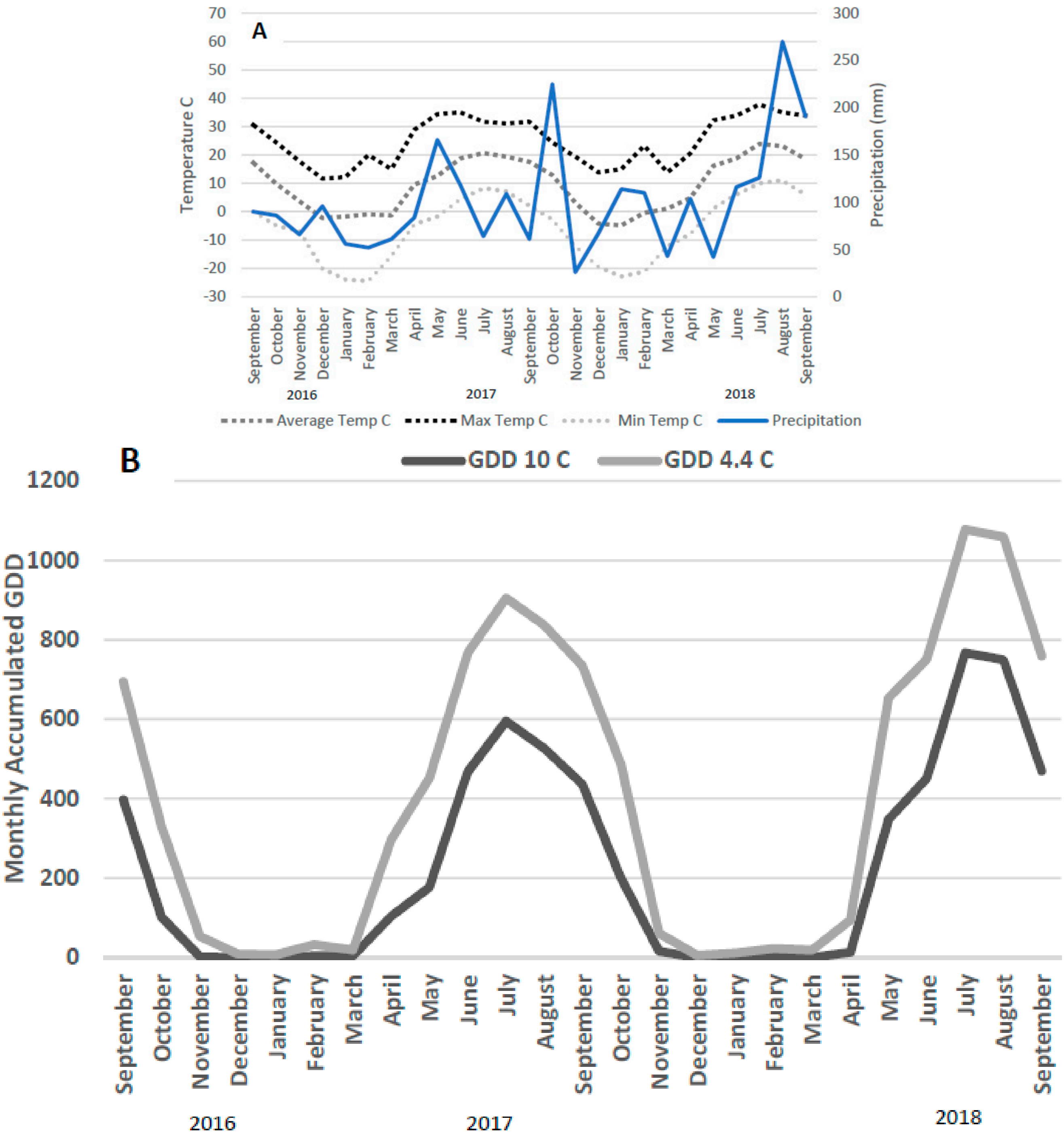

Figure 1. (**A**) Minimum, maximum, and average temperatures (°C) at experimental site (2016–2018); (**B**) accumulated GDDs at experimental site (2016–2018). GDDs: growing-degree days.

In the first year of the experiment, the monthly precipitation alternated between increased precipitation (up to 60% more than average) and decreased precipitation (up to 40% less than average). This extreme variation continued into the fall of Year Two. In the winter through spring of Year Two, the precipitation pattern was predominantly in line with the historical precipitation average. In Year One, there were increased durations between precipitation events, intense rainfall events, and periods of drought. Throughout the entirety of the experiment, the monthly maximum and minimum temperatures were, on average, 10 degrees higher and 10 degrees lower, respectively, than the historical average. Both the temperature and precipitation fell within the expected variation, which is in line with climate change predictions.

2.2. Experimental Design and Management

The experimental plots were planted and harvested by the farmer. Each of the five crops was planted in a 0.2 ha strip, approximately 12 m wide and 167 m long. All samples were collected from the centers of the strips to minimize edge effects. Rye (Wheeler), wheat (Emerson), and three varieties of triticale (Trical 815 (T1); NE426GT (T2); T3 (variety not stated)) were broadcast on 23 September 2016 and 27 September 2017 using a fertilizer spreader at a rate of 109 kg ha^{-1}. In 2016, the DPCCs were seeded several days after the corn-silage harvest. Manure, in the form of slurry, was surface applied at a rate of 37,400 L ha^{-1} on October 5, 2016, containing 30 kg total nitrogen and 10.5 kg orthophosphate. Due to management constraints, no manure was applied in the fall of 2017. In both years, each DPCC species was planted in one 2500 m^2 strip.

DPCCs were harvested on 17 May 2017 and 15 May 2018. Ten 0.1 m^2 samples were taken per strip prior to harvest with a flail chopper. Samples were collected from a height of 7.6 cm above the soil surface to mimic the blade height of the flail chopper. The remainder of the DPCCs in the field were harvested by the farmer. The field was then prepared for corn planting via tillage, manure application (74.8 thousand liters ha^{-1}), and the use of a disc harrow. A 92-day-mature corn hybrid for silage was planted at a rate of 86,500 plants ha^{-1} approximately one week following the DPCC harvest and termination. Information about the corn planting is provided only to give a better picture of a conventional cover-crop–corn-silage system in the region.

2.3. Laboratory Analysis

Immediately following harvest, the samples were weighed for the fresh weight, and were then dried in a forced-air oven (Gruenberg Oven Company, Williamsport, PA, USA) at 80 °C until their weights remained constant, indicating that all the moisture had evaporated. The difference between the fresh weight and dry weight was used to estimate the water removal from the field at the time of harvest. The dried samples were weighed to obtain the total biomass, and they were ground using a Foss Mill (Foss Cyclotec 1093, Hilleroed, Denmark) with a 0.42 mm screen to prepare them for laboratory analysis.

A total of 0.2 g of each DPCC subsample was used to analyze the N and crude protein via the Kjeldahl method (Standard Method 4500-N(Org) C. Semi-Micro-Kjeldahl). Following digestion, the samples were analyzed with a Lachat 8500 flow-injection-analysis spectrophotometer, using the Lachat total Kjeldahl nitrogen (TKN) method (Number 13-107-06-2-D) (Zellweger Analytical, Milwaukee, WI, USA).

A total of 0.2 g of each DPCC subsample was used for the quantification of the orthophosphate. Samples were weighed into porcelain crucibles and placed in a combustion oven for 24 h at a temperature of 500 °C. Following a cooling period, 20 mL of 10% hydrochloric acid was added to each crucible to bring phosphorus into the solution. Orthophosphate samples were analyzed using the same Lachat 8500 flow-injection-analysis spectrophotometer (Lachat Orthophosphate Method Number 10-115-01-1-V). Except for the crude-protein and total-digestible-nutrient analyses, the feed analysis on the cover-crop samples was completed by near-infrared-reflectance (NIR) spectroscopy (Unity Scientific, Milford, MA, USA). Milk 2006 [28] was used to estimate the milk values of the cover crops.

2.4. Statistical Analysis

Statistical analyses were performed using the GLM procedure in SAS, Version 9.4 (SAS Institute, Cary, NC, USA). The model was assessed as a two-way analysis for the effects of the year and cover crop, with multiple observations. The experiment did not include block replications due to the practical limitations of a farmer-managed field experiment on a working farm. The authors acknowledge the potential failure to capture site-based field variation, and this is considered in the data interpretation. The year was treated as a fixed variable to represent the different effects in the first and second years of a new management strategy in a continuous cropping system. The mean separation for the statistically significant main effects was performed using Tukey's HSD, while the ten pair-wise comparisons for significant interactions were separated using least significant differences (LSDs), sliced for the year, using a Bonferroni corrected significance level of $p \leq 0.005$.

Authors' note: The work presented in this study is based on research that is also presented in a dissertation chapter [29].

3. Results

3.1. DPCC Yields, Heights, Moisture Contents, and Water Recoveries

The DPCC yields were significantly influenced by the year, cover-crop species, and interaction of these two main effects. Overall, the cover crops produced nearly three times as much biomass in 2017 (5442 kg ha^{-1}) than in 2018 (1866 kg ha^{-1}) (Table 1). The rye, T1, and T2 outyielded the wheat and T3 (Table 2). There were no significant differences among the crops in Year Two, as evidenced by the mean separation of the interaction.

Table 1. Biomass yields, moisture contents, nutrient recoveries, and quality of harvested DPCCs. Means separated by Tukey's HSD range test. Within the same row, values followed by different letters are statistically different.

	2016–2017	2017–2018	Pr > F
Dry matter (kg ha^{-1})	5442 a	1866 b	<0.0001
Height (cm)	95 a	54 b	<0.0001
Percent moisture at harvest	74 b	82 a	<0.0001
Water removed (m^3 ha^{-1})	16.7 a	8.7 b	<0.0001
N concentration (%)	1.55 b	1.90 a	<0.0001
P concentration (%)	0.39 b	0.47 a	<0.0001
N:P ratio	4.06	4.07	0.7649
N removed (kg ha^{-1})	83.2 a	35.3 b	<0.0001
P removed (kg ha^{-1})	21.9 a	8.8 b	<0.0001
Relative feed value	111 b	126 a	<0.0001
Crude protein (%)	11.9 b	9.7 a	<0.0001
Milk (kg ha^{-1})	4402 a	1563 b	<0.0001
Milk (kg Mg^{-1})	1621 b	1715 a	0.0044
Dollar value of milk ha^{-1} of DPCC (USD)	845 a	300 b	<0.0001

The DPCC heights were significantly affected by both main effects and their interaction. The DPCCs in Year One were almost twice as tall (95 cm) as the plants in Year Two (54 cm) (Table 1). Rye was the tallest crop, followed by T1 and T3, and then T2, with the wheat being the shortest of all the DPCCs (Table 2). There were significant height differences among the DPCCs when the interaction was parsed by year. Overall, the same trends were observed in both years, with the exception of T2, which was taller than the wheat in Year One, but not in Year Two (Figure 2).

The DPCCs contained 8% more water in the second year than in the first year (Table 1). Moreover, the cover-crop species demonstrated significant differences in the water contents, with the greatest difference between the wheat and rye (Table 2). However, there were no significant differences in the water contents among the cover crops in the second year.

Table 2. Biomass yields, moisture contents, nutrient recoveries, and quality of DPCC species at harvest. Means separated by Tukey's HSD range test. Within the same row, values followed by different letters are statistically different. Values are averages of two years. Trical 815 (T1); NE426GT (T2); T3 (variety not stated).

	T1	**T2**	**T3**	**Wheat**	**Rye**	**Pr > F**
Dry matter (kg ha^{-1})	4056 a	3953 a	2987 b	2950 b	4612 a	<0.0001
Height (cm)	74 b	66 c	74 b	56 d	106 a	<0.0001
Percent moisture at harvest	78 ab	80 a	77 b	73 c	81 a	<0.0001
Water removed (L ha^{-1})	14,000 bc	15,250 b	9520 c	7745 c	18,455 a	<0.0001
Nitrogen concentration (%)	1.66 b	1.65 b	1.71 b	1.90 a	1.69 b	0.0004
Phosphorous concentration (%)	0.45 a	0.44 a	0.44 a	0.38 b	0.45 a	<0.0001
Ratio of N:P	3.68 b	3.71 b	3.95 b	5.2 a	3.79 b	<0.0001
Nitrogen removed (kg ha^{-1})	62.4 b	57.9 b	48.4 c	53.7 b	77.3 a	0.0002
Phosphorous removed (kg ha^{-1})	17.3 ab	16.6 b	12.4 c	10.2 c	20.8 a	<0.0001
Relative feed value	112 b	116 b	120 b	132 a	112 b	<0.0001
Crude protein (%)	8.6 b	8.8 b	9.5 b	11.0 a	10.4 b	0.0004
Milk (kg ha^{-1})	3080 a	2992 a	2470 b	2718 b	3713 a	0.0216
Milk (kg Mg^{-1})	1543 b	1636 ab	1729 a	1759 a	1677 ab	0.0005
Dollar value of milk ha^{-1} of DPCC (USD)	590 ab	576 ab	326 b	474 b	714 a	0.0216

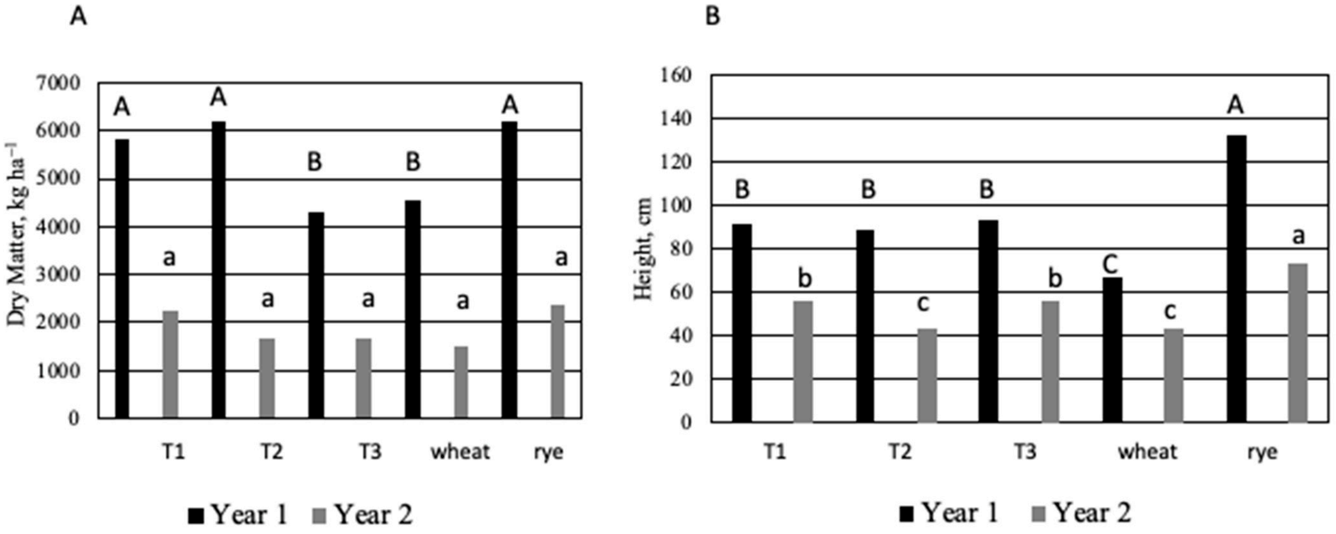

Figure 2. (**A**) Dry matter produced by DPCCs each year. (**B**) Heights of DPCCs within each experimental year. Means separated by Tukey's HSD range test. Within the same row, values followed by different letters are statistically different. Uppercase letters are associated with values in year 1; lowercase letters are associated with values in year 2.

The amount of water removed from the field was a reflection of the water contents in the plants at the time of harvest. This parameter was affected by the cover crop, year, and interaction of these main effects. Nearly twice as much water was removed in Year One as in Year Two (Table 1). The rye removed the most water at 18 thousand liters ha^{-1}, followed by T1 and T2, while T3 and the wheat removed less than 10 thousand liters ha^{-1} (Table 1). Notably, T2 and the rye removed more than twice as much water in Year One than in Year Two, while the other three cover crops only exhibited approximately 50% more water removal in the first year (Figure 2).

3.2. N and P Recovery

The N and P concentrations in the DPCCs were affected by the cover crop, year, and interaction of these main effects. The concentrations of both nutrients in the DPCCs were greater in the second year than in the first: 1.55% and 1.99% N and 0.39% and

0.47% P in Years One and Two, respectively (Table 1). There were no differences in the N and P concentrations among the cover crops (Table 2), with the exception of the wheat, which contained a significantly lower concentration of P, but a higher concentration of N, compared with the other cover-crop treatments.

The cover-crop species accumulated different amounts of P in the two years of the study. In the first year, the rye had the highest P concentration, followed by T1 and T2 (Figure 3B). However, in Year Two, all three triticale varieties were more efficient in P accumulation. In both years, the wheat accumulated the lowest P concentration among the DPCC species.

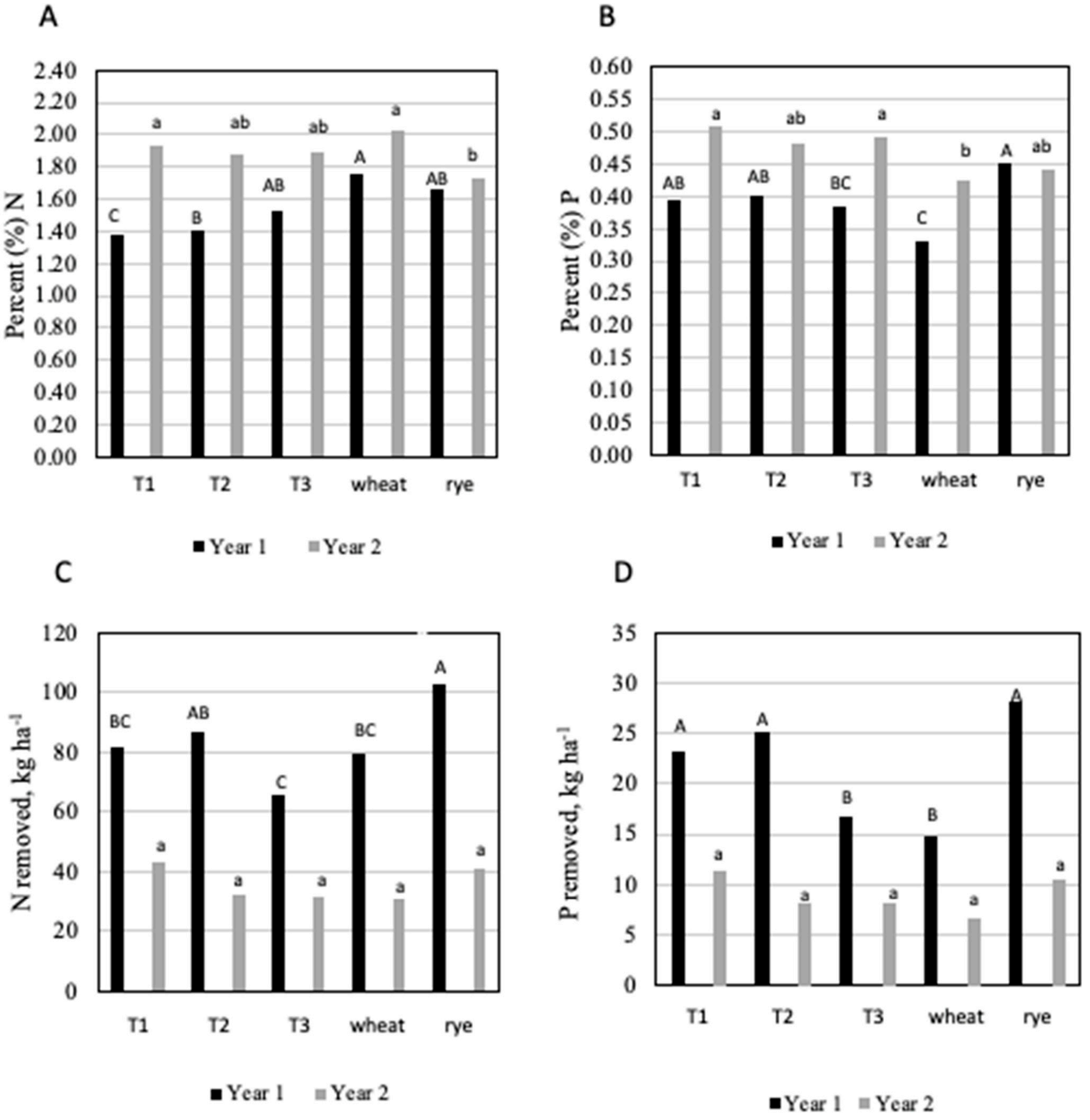

Figure 3. (**A**) Percent N of DPCCs in each experimental year. (**B**) Percent of P of each crop in each experimental year. (**C**) N removed by DPCCs in each experimental year. (**D**) P removed by DPCCs in each experimental year. Means separated by Tukey's HSD range test. Within the same row, values followed by different letters are statistically different. Uppercase letters are associated with values in year 1; lowercase letters are associated with values in year 2.

Unlike P, the wheat cover crop accumulated more N than the other DPCC species in both years (Figure 3A). In Year Two, the rye accumulated the lowest amount of N, and the three triticale varieties had intermediate N concentrations (Figure 3A). In Year One, the concentration of N in the rye was statistically equivalent to the concentration in the wheat. Similar to the rye with regard to the N accumulation, the three triticale varieties performed differently in the two years of the experiment. While the triticale varieties demonstrated the lowest N accumulation in the first year, they were as efficient as the wheat in the second year (Figure 3A).

The influence of the year, cover crop, and interaction of these main effects on the total N and P removal were significant (Tables 1 and 2). Overall, the DPCCs collectively captured considerably more N and P in the first year than in the second year. In Year One, 74 and 22 kg ha^{-1} of N and P, respectively, were removed, whereas in Year Two, only 31.5 and 8.8 kg ha^{-1} of N and P, respectively, were captured (Table 1). Rye was the most efficient cover-crop species, recovering 70 kg N ha^{-1} and 21 kg P ha^{-1}. T1 and T2 performed better at removing the N and P from the soil, compared with T3 and the wheat (Table 2).

The differences in the N and P removal among the cover-crop species were more pronounced in the first year. For example, in the first year, the rye removed 57% more N than T3, whereas in the second year, the difference between the most and least efficient species in terms of the N removal was only 42%. Similar trends were observed in Years One and Two with regard to the P removal. In Year One, the rye, T1, and T2 removed approximately 25 kg ha^{-1} of P, while the wheat and T3 removed only 15 kg ha^{-1} (Figure 3D). The rye removed the most N at 100 kg ha^{-1}, although it was not significantly different than T2, which captured an average of 80 kg ha^{-1}, along with T1 and the wheat. T3 captured the least amount of N, although it was not significantly different from the wheat at 65 kg ha^{-1} (Figure 3).

3.3. Soil P and Organic Matter Changes

Table 3 demonstrates the amount of P in the soil at the beginning of the experiment in September 2016 (baseline), and the amount of P that remained in the soil at the conclusion of the experiment in September 2018. Averaging all the cover-crop species, the amount of P before and after remained the same as the baseline, indicating that the cover crops captured the P released from the manure. The change in the soil organic matter after two years was minimal, and it increased by only 0.1% compared with the baseline value (Table 3).

Table 3. Phosphorous levels (mg/g) in the field at the beginning of the experiment in September 2016 (baseline), and the levels in the soil following each crop at the conclusion of the experiment in September 2018.

	Phosphorus (mg/g)	**Soil Organic Matter (%)**
Baseline	0.031	3.9
T1	0.029	3.1
T2	0.032	4.2
T3	0.031	3.9
Wheat	0.030	3.9
Rye	0.029	4.7
Average of all DPCCs	0.030	4

3.4. DPCC Forage-Quality Characteristics

The relative feed value (RFV) was significantly impacted by the year, cover crop, and interaction of the two. The RFV was higher in the second year, with a value of 126, compared with 111 in the first year. Among the DPCCs, the wheat had the highest RFV at 132, while the other cover-crop treatments ranged between 120 in T3 and 112 in the rye and T1 (Table 2). The interaction of the year and crop was significant. While all the cover-crop species had almost similar RFVs, the wheat had a significantly higher RFV than the other DPCC species (Figure 4).

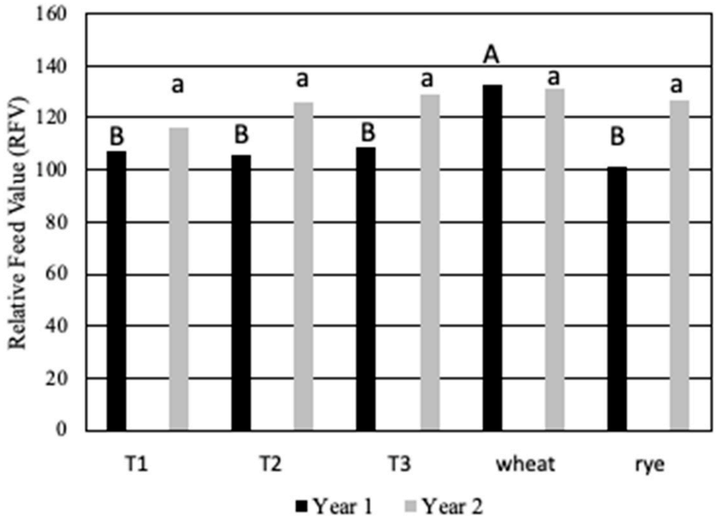

Figure 4. Relative feed values (RFVs) of DPCCs in each experimental year. Means separated by Tukey's HSD range test. Within the same row, values followed by different letters are statistically different. Uppercase letters are associated with values in year 1; lowercase letters are associated with values in year 2.

The amount of the estimated milk production from one hectare, and the amount of estimated milk production from one megaton of forage, varied only by the year and cover crop (Tables 1 and 2). When assessed by feed per hectare, and influenced by the yield, the rye, T1, and T2 resulted in the greatest milk production. When assessed as milk per megagram, which emphasizes the forage quality, the wheat and T3 had the highest milk-production potentials. The rye and T2 were intermediates, but they were not significantly different from the wheat or T3. Because the feed quality was better in Year Two, the milk-production potential was greater in Year Two (1715 kg Mg^{-1}) than in Year One (1621 kg Mg^{-1}).

The estimated dollar value of the milk that could be produced per hectare of the DPCC forage was significantly affected by the year and crop. In Year Two, the dollar value of the milk per hectare of the DPCCs was USD 300, which was significantly less than the USD 845 value in Year One (Table 1). When assessed by cover-crop treatment (Table 2), the rye was worth the most at USD 714 ha^{-1}, followed by T1 and T2, which were valued at USD 590 and USD 576 ha^{-1}, respectively. The wheat and T3 were the least profitable in this assessment, valued at USD 474 and USD 521 ha^{-1}, respectively.

4. Discussion

4.1. DPCC Yields, Heights, and Moisture Contents

The rye and forage triticale varieties (T1 and T2) produced substantial yields, while the wheat and T3 produced the least amount of biomass (about 25% less than the rye, T1, and T2 (Table 2). Rye is a cover crop that is often chosen for its high biomass production, and so it is unsurprising that it produced high yields in the current experiment. Furthermore, the particular variety chosen for this experiment was intentionally bred for use in forage production. T1 and T2 are the products of breeding programs that were tasked with developing triticale cultivars for the purpose of DPCCs. T1 was released in 2004, and it was bred for dual-purpose use for grain production and fall forage, which is a function that requires excellent spring growth [30], while T2 was developed for its excellent forage and yield characteristics. T3, a VNS seed, did not have the selected genetic background for the performance, as did the curated profiles of T1 and T2 [31].

The three triticale varieties were selected to respond to the increasing interest among local growers. The purchased varieties were deemed to be the most readily available in the experiment area at the time of this study, and they were thus suitable for this intent.

While VNS seeds may be compelling due to the reduced seed cost, and may be suitable for standard cover cropping, this result suggests the importance of selecting a seed variety bred for the dual-use purpose.

The lag in the wheat yield can, in part, be ascribed to the delayed maturity compared with the other species. In addition, other studies have also found that wheat routinely produces less biomass than rye [32–34]. The Emerson wheat variety is not bred for forage use, and it is instead known for its resistance to Fusarium head blight, as well as for its winter hardiness. It was selected because it offered the potential for both quality protein levels and yields (Canterra Seeds, 2016). Greater yields may have been achieved if the wheat had had more time to mature, as the wheat matured much slower than the other DPCCs in the spring. At the time of harvest, the wheat was in the jointing and early-flag-leaf stages in Year One, and it was still in the tillering stage in Year Two; all the other crops were in the more advanced-flag-leaf to early-boot stages in both years. These findings do suggest that the harvest delay associated with the wheat DPCC may be promising for typically wet fields due to the soil type or topography, which cannot be worked until later in the spring.

Rye is generally known to grow well under high-stress environments—including drought and extreme cold—while the wheat performance declines under similar stress; triticale offers an intermediate performance [35]. This may, in part, explain the variation in the yields among the species in Year One of this experiment, during which the fall and winter were dryer than usual, thus subjecting the plants to drought stress during the establishment and early spring regrowth due to the lack of snow melt (Figure 2A). Although the winter temperatures did not vary between Year One and Year Two, the snowfall was reduced in the first winter. As a result, the reduced snow cover may have also subjected the plants to more extreme temperature variations and extended periods of cold exposure due to the lack of the insulating property of snow cover. While the precipitation was substantial in the spring of Year One, the rye and triticale may have begun the growing season in a superior condition to the wheat due to their stress tolerance.

The wheat also had a significantly lower moisture content than all the other crops overall, and notably in Year One, during the dry conditions. In Year One, the fresh wheat was 65% moisture, but in Year Two, the wheat reached 80% moisture (Figure 5A). This suggests that the reduced moisture content was not a biological limitation, but it may further reflect an inferior ability to adapt to or tolerate dry conditions compared with the other species in this study. While the rye and triticale demonstrated the ability to withstand these environmental factors, the performance of the wheat in this study suggests that it is unreliable as a substantial source of forage in this variable climate.

The height was not a strong predictor of the biomass. While the rye was consistently the tallest plant with the greatest yield, TI and T2 were shorter but did not produce smaller yields than the rye. Similarly, although T3 was taller than the wheat, it did not produce more. Differences in the amount of tillering and leaf width, and not the crop height, could be responsible for the observed yield differences by both cover crop and year (Figure 2). However, these two parameters were not measured in the field.

DPCCs may help to alleviate the wet field conditions that are common in spring by capturing and removing excess moisture. Although the water-removing properties of DPCCs can be problematic in climates where water is limited [17,36], they could provide an advantage in the northeast. The precipitation in the first year was nearly double that of the second year for the months of March–May (NOAA, 2019). This precipitation was reflected in almost twice as much water removal at the spring harvest in Year One than in Year Two overall (Table 1). Among the species, the rye resulted in the greatest water removal from the field at harvest (Table 2), while the wheat removed the least. Had the wheat been allowed to grow longer to a more advanced developmental stage, more water may have been removed. The triticale varieties remained consistent, with T3 removing the least water, which was comparable to the wheat, and T1 and T2 performing as intermediates to the wheat and rye. Interestingly, the pattern of water removal held true in both Years One and

Two, regardless of the difference in the spring rainfall (Figure 5B), and despite differences in the percent moisture of the plant matter itself (Figure 5A).

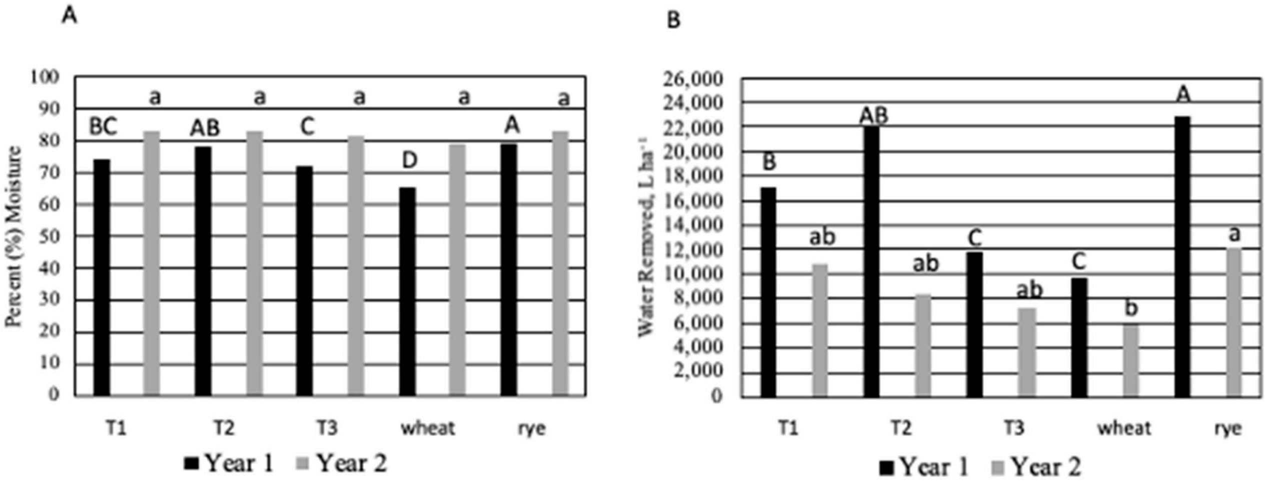

Figure 5. (**A**) Percent moisture of DPCCs in each experimental year. (**B**) Water removed by DPCCs during each experimental year. Means separated by Tukey's HSD range test. Within the same row, values followed by different letters are statistically different. Uppercase letters are associated with values in year 1; lowercase letters are associated with values in year 2.

The ability of cover crops to mitigate rainfall and wet field conditions in the spring, and the nature of DPCCs that harvests moisture from the field rather than returning it in an incorporated traditional cover crop, may be desirable to combat water-induced delays to corn planting. Of course, the total water removed at harvest does not reflect the water transpired by plants. To better understand the possibility of using cover crops to speed up the spring access to historically wet fields, the transpiration rates and soil water levels should be assessed. The large amounts of water removed by the rye at harvest indicate that this species would be a good candidate for such an approach. Conversely, rye could magnify the water stress in the succeeding cash crop in the event of a drought. Further research should focus on the impacts of the DPCC soil moisture removal on subsequently planted cash crops.

The percent moisture of the crops at the time of harvest underlies the water-removal potential and influences the fermentation process and dry-down period if ensiled [37]. On average, the moisture content of the plants was 8% higher in Year Two than in Year One (Table 1). Considering the precipitation difference between the two experimental years, the higher moisture content may be attributed to differences in the maturity at the time of harvest in each year, rather than to the amount of rainfall.

The moisture-content variation by cover-crop species, both as a main effect and the Year One interaction (Table 1, Figure 5A), could be indicative of the water-uptake capacity and transpiration-rate capacity, and it may be linked to the crop N uptake [38]. In the first year, the plant percent moisture (Figure 5) and plant N removal ha^{-1} (Figure 3) followed the same trend. N is highly soluble, and it is passively brought into plants along with water [30], which explains the trend similarity. These observations do not appear to provide a yield advantage, at least to plants in the vegetative stage, but they do provide information about DPCC ecosystem services.

However, many differences among the characteristics of the wheat, rye, and triticale varieties were found overall, which were clearly discernible in Year One, and disappeared in Year Two. A similar phenomenon was observed by Coblentz et al. (2020) [32], and the authors attributed it to both the environmental and field conditions. In this study, it is probable that two major factors contributed to the lack of yields and height responses among the cover crops: (1) the lack of manure application in Year Two, which resulted in lower soil fertility, and (2) the late-season planting of the DPCCs. It has been previously established that seeding after 15 September in this region can result in considerable biomass penalties, and thus the efficiency of the soil-nutrient-removal penalties in winter rye crops [9]. It is likely that other cover crops are negatively impacted by delayed planting, although how wheat and triticale are influenced by fall planting dates in the northeast United States has yet to be established.

The combination of the lack of manure application plus the delayed planting date in the second year may have uniquely contributed to the observed results, as opposed to if only one or the other had occurred, such as in Year One, when only the planting was delayed. Aside from the implications of the experimental results, the results of the current study provide an important context for interpreting how DPCC varieties will function in dairy production systems. Differences in the weather and harvest conditions can impact the annual management, and they can prevent fields from receiving manure application or timely DPCC planting, which is often delayed in favor of managing other needs on a farm. This experiment captured the behavior of this system when managed as a convenient, but not critical, opportunity for additional forage production. Our results provide a realistic framework for the basic management requirements to translate DPCC research into practical approaches for farmers.

The overall suppressed DPCC yields in Year Two (Table 1) can most likely be attributed to the lack of fall manure application, resulting in a reduction in the nutrient availability, rather than to the delayed planting date, as the planting dates were similar in both years. However, part of the yield reduction may be attributed to the increased metabolic investments in the root proliferation to support nutrient scavenging [39]. In addition, the variation among the crops in Year One showed the differing potentials of the plants to capture and efficiently utilize abundant nutrients. The lack of variation in the second year (Figure 2A) suggests that, under the nutrient-limiting conditions, no particular DPCC displayed an advantage or unique adaptation to the reduced soil fertility.

4.2. N and P Recovery

In this study, the yield differences did not appear to be affected by the differences in the total N removal, and vice versa. In Year One, although the wheat yielded the least, the wheat was associated with a nitrogen capture equal to T1, and it was not statistically different from T2. This indicates that the total biomass is not the sole driver of N removal, at least in the vegetative stage. Conversely, the crops with the largest amounts of P capture also yielded the most in this study. It is unclear whether the increased P-uptake ability resulted in higher yields, or if other biological factors contributing to increased yields also impacted the P uptake by the DPCCs. More research is needed to understand the relationship between the DPCC biomass yield and P-uptake dynamics. In addition, the year did not affect the N-to-P ratio, despite affecting the N and P concentrations in the plants, which suggests the consistent biological homeostasis of this ratio by crop, or at least by stage of maturity, with the latter being more likely. Despite the reduced nutrient availability in the second year, the DPCCs collectively had greater concentrations of N and P (Table 1).

However, when averaged across both years, the rye was superior to all the other DPCCs in both N and P nutrient capture (Table 2). T1 and T2 were the second most effective at N and P capture. T3 (VNS) functioned the poorest in this regard, and the wheat underperformed in P recovery. It is likely that the delayed maturity of the wheat was responsible for the differences from the other DPCCs, including in the N and P removal. The ratio of N to P was significantly greater in the wheat compared with all the other crops, indicating a level of biological variation (Table 2), which can include differences in cell division, protein synthesis, DNA replication, and other metabolic processes [40].

It is difficult to know whether the substantial production of aerial biomass by rye results in root exploration that allows for nutrient capture, or if effective nutrient capture drives the ample aerial biomass production. Sheng and Hunt (1991) found that rye had less root biomass than wheat or triticale prior to anthesis, and so a more extensive root system is unlikely to be the cause. Mugwira et al. (1980) concluded that rye, wheat, and triticale did not demonstrate differences in the nitrogen-uptake effectiveness [41]. However, Pandey et al. (2003) found a strong response in the P uptake by rye when associations were formed with arbuscular mycorrhizal fungi (AMF); the genes mediating this strong response are found in rye, and triticale typically inherits less responsive genes from wheat [42]. While speculative, it is possible that if rye makes associations with AMF that enhance the P uptake, the plants will then favor a root architecture with deep roots that can scavenge for N, rather than forming lateral roots that scavenge for P [43]. Characterizing the root architecture and AMF associations in the field in future research would provide valuable insight into the nutrient-capture differences among these three species.

The lack of differences among the species in Year Two (Figure 3) suggests that the crops do not have different nutrient-capturing strategies in low-soil-fertility conditions, and that the differences in the nutrient capture are environmentally stimulated. The DPCCs in Year Two had greater concentrations of both water and nutrients (Figures 3A and 4A,B), accumulated more growing-degree days [44] than the plants in Year One, and were harvested at the same time and maturity both years, yet the plants in the second year demonstrated conserved growth at the time of harvest. Overall, 58% more N and 60% more P were removed in Year One compared with Year Two (Table 1). Consistent with other results, this can be attributed to the lack of manure application in 2017–2018.

4.3. DPCC Forage Quality

The relative feed value is derived from acid-detergent fiber (ADF) and neutral-detergent fiber (NDF), as they affect both the dry matter intake and digestible dry matter (energy). The RFV is largely a function of the plant structural development, and it increases with age as changes occur in the cellulose, hemicellulose, and lignin content [33].

The wheat, the lowest-yielding crop, displayed the highest RFV overall (Table 2). As plants age and the biomass increases, their feed quality drops due to the structural-fiber development necessary to support upright growth and stem elongation [45]. As the wheat was the most immature crop, it is unsurprising that it presented the best RFV. The rye, T1, and T2 were of a more advanced maturity, and their reduced RFVs reflect this development. However, while T3 was developmentally comparable to the rye, T1, and T2, the RFV of T3 was comparable to that of the wheat. As T3 performed so similarly to the wheat in all parameters, and as it was not a well-bred seed, it is possible that T3 possesses more dominant genes from wheat than from rye, which explains its similarities to the wheat.

The RFV of the rye in Year One (Figure 4), which was acceptable but not ideal for forage production, emphasizes the importance of appropriate DPCC management, and suggests that prioritizing the time of harvest is critical when developing management plans on dairy farms. These findings are consistent with the conclusions of recent DPCC studies, which emphasize the importance of considering the yield–quality tradeoff when making management decisions, including the timing of the harvest [17,46].

In Year Two, the RFVs were not significantly different among the cover crops. It is possible that the lack of manure and nutrients limited the cell-wall development, thus affording higher RFVs. While a greater RFV is desirable, the substantial yield penalty observed in Year Two is not.

The wheat and T3 were the best-performing DPCCs when evaluating the crop quality for milk production. However, due to their low biomass yields, they were outperformed by all the other DPCCs when evaluated on the basis of the milk production per hectare of forage produced, which is a more practical basis on which to assess the value (Table 2). Due to the high yield of the rye and the quality forage characteristics of the rye and T3, these crops resulted in the greatest milk-production potentials on a per hectare basis. Yet, due to the cheaper cost of rye seed as compared with T3 seed, the rye was the most economically valuable crop on a per hectare basis.

The dollar value for the milk was assessed based on July 2019 milk prices [47]. Overall, the crops and their milk-producing potentials were far more valuable in Year One than in

Year Two when assessed based on the milk Mg^{-1} (Table 1). As previously mentioned, this can be attributed to the lower yields driven by the lack of manure in Year Two. However, the net value estimate of USD 845 ha^{-1} in Year One demonstrates the considerable economic potential of incorporating DPCCs into dairy cropping systems. The higher-yielding DPCCs (winter rye, T1, and T2) were of greater economic value than T3 and the wheat, which were monetarily worth the least due to their low yields (Table 2). These findings emphasize the importance of considering the region and intended use when selecting the DPCC species and variety. Moreover, despite advances in the breeding of triticale, the cheap seeds and high yields of the rye set it apart as an excellent candidate for forage production, thus refuting our hypothesis, which favored triticale.

The variation in the RFVs by year (Table 2) can be attributed to slight differences in the maturities in Year One versus Year Two, despite the fact that the DPCCs were harvested at the same time and were evaluated to be at comparable physiological stages from year to year. The DPCCs were also smaller in the second year, as demonstrated by both the yield and height parameters (Table 1), which lends credence to this hypothesis.

4.4. Final P and Soil-Organic-Matter Levels

The DPCCs removed an average of 30 kg P ha^{-1} in total over the two years of this experiment. Despite this figure, as well as the lack of manure application in the second year, the P levels in the soil remained unchanged at the conclusion of the experiment in September 2018, compared with the baseline soil test. Such a result indicates the challenge of remediating fields with high levels of P, which lends credibility to the practice of harvesting cover-crop biomass as a standard practice to prevent the further accumulation of P in soils.

No changes in the soil organic matter were observed over the course of this study, despite the DPCC biomass being removed from the field and the field remaining under conventional tillage, which can result in the destruction of the soil organic matter. Our findings suggest that the residue of the incorporated stubble was adequate to maintain the soil organic matter, offering some alleviation of the farmer concerns that harvesting DPCCs could have an adverse effect on the soil-organic-matter levels. Long-term studies must be conducted to ensure that the SOM and soil health are not compromised after a greater duration of the practice.

5. Conclusions

- DPCCs, in general, are an effective addition to the nutrient management strategies of manured systems. DPCCs should be considered as a tool for the recovery of the N residue in soil, thus preventing N loss and remediating or preventing P accumulation. DPCCs also contribute to on-farm nutrient cycling, and they keep the orthophosphate active in the biological cycle, rather than it becoming fixed by aluminum and iron and lost to the chemical cycle;
- Wheat may not be as quick to mature in the northeast as rye and triticale. This may be desirable for wet fields that are entered later in the spring, or for fields in rotations with other summer crops, such as squash. Conversely, in fields that must be ready for harvest from early to mid-spring, the slow maturity of wheat is likely to result in low DPCC yields and a limited nutrient-scavenging capacity, and thus, both ecosystem services and the economic value of DPCCs are compromised;
- Varieties bred for use as forage should be used. Many varieties have been bred for dual-purpose use as a grain crop, but these varieties appear to perform well as the sole forage crop in corn-silage rotations;
- Winter annual rye is already a popular cover crop, and it offers excellent yields, quality, and nitrogen capture. This study demonstrates that rye is a superior crop for dual-purpose use. With small changes to management practices, such as the planting date or seeding method, many growers can readily begin using rye cover crops for forage.

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