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Effects of Harvest Time on the Yield and Quality of Winter Wheat Hay Produced in Northern Italy

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Abstract: The aim of this work was to study the yield and nutritional characteristics of winter wheat hay. A selection of cultivars recommended for three main purposes: grain, whole plant (biomass) and dual purpose (grain and biomass) production were cultivated and harvested from heading to grain dough stages. Yield dry weight (YDW), dry matter (DM) and undigested neutral detergent fiber (uNDF) increased with advancing maturity, ranging from 9 t ha⁻¹, 20 and 11% of DM to 16 t ha⁻¹, 43 and 17% of DM, respectively; while crude protein (CP) and neutral detergent fiber (NDF) decreased from 11 and 59% of DM to 6 and 54% of DM, respectively. Our study showed that dual purpose winter wheat cultivars displayed similar performance of CP, NDF and net energy for lactation, when harvested at heading or grain milk stages. In addition, winter wheat recommended to be harvested as whole plant showed similar values of YDW, sugar and starch contents, when harvested at grain dough and milk stages. These characteristics are strategic in hay production, allowing a more flexible harvesting strategy. These results might be useful to improve the hay production, given useful information on harvest time and improving agricultural sustainability covering the soil in autumn and winter.

Keywords: winter wheat; hay; heading; milk stage; dough stage; crop rotation; double-crop

1. Introduction

Wheat (*Triticum* spp.) is one of the world's most important crops in term of total tonnes produced, ranking fourth after sugar cane (*Saccharum officinarum* L.), maize (*Zea mays* L.), and rice (*Oryza sativa* L.) [1]. Among the herbaceous crops, wheat is the most intensively studied, focusing mainly on grain yield, however, wheat can also be used for forage purposes [2,3]. On a worldwide scale, during 2018 wheat was cultivated on ~ 214 million of hectares, with a total production of ~ 734 million of tonnes, corresponding to an average grain yield of ~ 3.4 t ha⁻¹ [1].

Wheat is a valuable source of high-quality forage [4] that is typically available in late winter and early spring, when other forage sources are low in quantity and quality [5]. Furthermore, winter wheat (*Triticum aestivum* L.) forage, in term of crude protein (CP) ha⁻¹ and digestibility of the dry matter (DM), is comparable to alfalfa (*Medicago sativa* L.) which globally is the main crop used to produce hay for livestock production [5].

Forage crops are often exposed to environmental stresses mainly caused by inadequate availability of water and nitrogen (N) [6]. Among forage crops, wheat is particularly tolerant to abiotic stresses so it can represent an important resource in livestock production. Nevertheless, increased temperature can reduce wheat forage yield, digestibility of the dry matter, increasing leaf/stem ratio and N concentration.

On the other hand, increased carbon dioxide counteracted the elevated temperature response [6] and this point might be important considering the current climate change scenario. In fact, several published works report the effect of climate change on cereals both in Southern and Northern Europe [7,8].

When N and water are scarce, digestible dry matter production has been found to be not affected under elevated temperature [6], and increases in forage quality have been ascribed to impacts on the initiation of grain filling. Unsurprisingly an increase of N availability led to greater forage yield and quality [6].

To the authors' knowledge few works have reported on the cultivation of winter wheat used to produce hay, though some studies are available on the use of wheat straw and silage. For example, Poore et al. [9] have reported positive responses using wheat straw as a feed resource when high yielding cows are fed using diets that are deficient in fiber. Brown et al. [10] reported that replacing alfalfa hay with a low percentage of wheat straw, an increasing feed intake and milk yield was observed. Conversely, when diets are high in wheat straw [11], cows are prone to ingest inadequate feed to support a high milk yield. In particular, dry matter intake declined linearly at a rate of 2.04 kg d^{-1} at increasing levels of wheat straw in the diet.

Another interesting use of wheat in livestock production is its utilization as pasture or silage. In fact, vegetative wheat is grazed by animals like cows and sheep in several farming systems. This practice was developed in Southern Australia using wheat genotypes having long vegetative phase, allowing grazing, especially until the beginning of stem elongation with little impact on grain yield [12]. Regarding silage, both Owens et al. [13] and Keady et al. [14] found that feeding cows using fermented whole-crop led to an increased dry matter intake and improved rumen fermentation. Finally, Weinberg et al. [15] assessing wheat silage conservation suggested that prolonged storage of the silage might decrease the dry matter and NDF digestibility values.

Harvesting forage crops at different growth stages can influence both yield and quality [16]. For example, crops harvested for forage when in a vegetative state tend to have a lower yield and fiber content, but higher digestibility of the DM and CP, than at the reproductive stage [17].

Currently, farmers working within the supply chain of the PDO cheese Parmigiano Reggiano, where crop silage is not allowed, highlight a low presence of graminaceous plants in alfalfa hay. In fact, alfalfa hay with a low presence of graminaceous plants can impact on the diet of the cattle.

The lower presence of graminaceous plants is due to the improvement of the agronomic management of the alfalfa hay production (planting, weeding and harvesting).

The production of winter wheat for grain is common in crop rotations within livestock farms. In this context the cultivation of winter wheat hay in rotation with alfalfa production, might be as interesting an alternative as double-crop like *Sorghum* spp. and *Panicum virgatum* L. The advantages of including a winter cereal include: (i) exploitation of the N fixed in the soil by alfalfa, (ii) soil covered in autumn and winter, reducing the risk of soil erosion; (iii) the possibility to use existing equipment already used for alfalfa production; (iv) allow a more flexible crop rotation and not related to weather conditions and market trends in the sense that farmers have the possibility to allocate the grain product if they are unable to harvest hay in the best conditions.

To the authors' knowledge, complete and up-to-date information is not available on winter wheat hay yield and quality. Currently seed companies have been developed winter wheat cultivars suitable for three main purposes: grain yield, whole plant (biomass yield) and for dual purpose (grain and biomass yields). Considering all the information reported above, the present study was carried out to provide useful suggestions for the production of winter wheat hay, assessing the main purpose and the effect of harvest time on the yield and nutritional quality over a 2-year period in Northern Italy.

2. Materials and Methods

2.1. Field Experiments

The research was performed from 2013 to 2015 in two consecutive growing seasons in the Central Po plain near Modena, Italy (Castelfranco Emilia, 44°34'40.9" N 11°02'11.7" E, altitude 40 m above sea level). Temperature and rainfall data were collected from a weather station available in the experimental farm, recording an annual mean temperature of 14.4 °C, and annual total rainfall of ~ 900 mm (Figure 1). The field trials were carried out on a silty clay loam soil with a pH measured in water of 8.1. The sand, silt, and clay contents were 130, 480, and 390 g kg⁻¹, respectively at 0–60 cm depth. The organic C was 10.7 g kg⁻¹ and total N was 1.15 g kg⁻¹. Assimilable P and exchangeable K were 17.25 and 307.25 mg kg⁻¹, respectively.

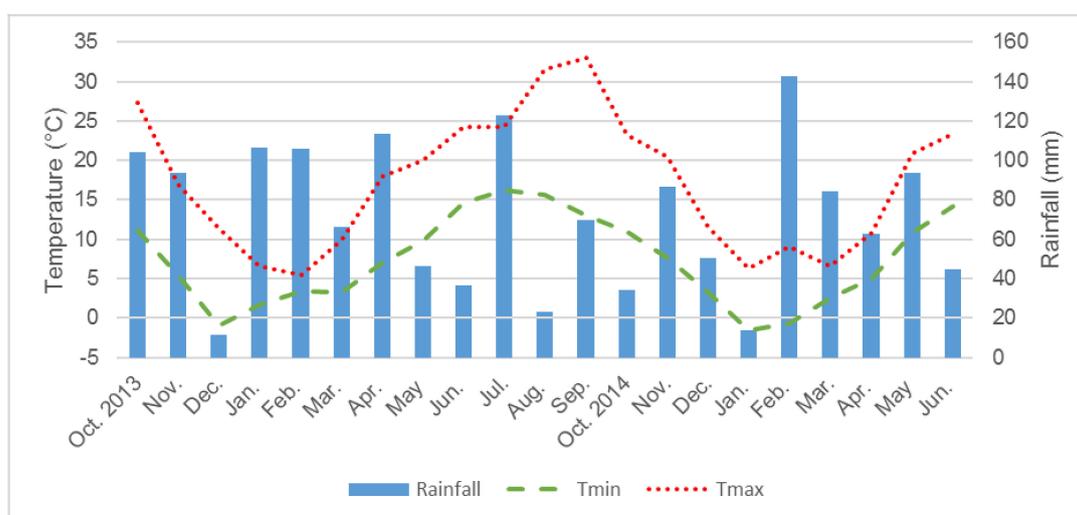


Figure 1. Monthly mean minimum (Tmin) and maximum (Tmax) air temperatures and total rainfall recorded during the two growing seasons.

2.2. Growth Condition

Eleven awnless winter wheat cultivars (Altezza, Artico, Caravaggio, Ethic, Giorgione, Ludwig, Masaccio, Norenos, Paedor, Papageno, and Sailor, Table 1) were cultivated as they were among the most widely grown commercial cultivars adapted within the investigated area, at the time of the initiation of the study.

In both the field experiments the previous crop was alfalfa (cultivated for four years). A split-plot experimental design with four replicates was used: cultivars of winter wheat (as whole-plot treatment, 4.2 m × 5 m) and the harvest times (as subplot treatment, 1.4 m × 5 m). All genotypes were sown at 450 seed m⁻² on 27 October 2013 and on 24 November 2014. The cultivars were grown in a rainfed environment and no fertilizer was applied at sowing. Nitrogen fertilization (using ammonium nitrate) was performed at an N rate of 50 kg ha⁻¹ both at the end of tillering (2.9 Zadoks scale) and at stem elongation (3.9 Zadoks scale) [18].

Weeds were controlled with a post-emergence treatment at the end of March using 20 g ha⁻¹ of tribenuron-metil 75% (SIPCAM, Milan, Italy) and pinoxaden 6.4% + cloquintocet-mexyl 1.55% (Syngenta, Padova, Italy) and no other plant protection products were applied during the two growing seasons.

Each cultivar was harvested in accordance to crop growth stage assessed in the study (heading, 5.4 Zadoks scale; grain milk stage, 7.4 Zadoks scale; grain dough stage, 8.4 Zadoks scale). Biomass samples for the yield and quality measurements were collected with a HEGE (212) forage plot harvester (Hege Equipment Inc., Colwich, KS, USA). Biomass was retained above a 7 cm harvest height.

Table 1. Cultivars investigated in the study and their main purpose.

Cultivar	Provider	Main Purpose
Altezza	APSOV sementi, Voghera, Italy	whole plant and grain
Artico	APSOV sementi, Voghera, Italy	whole plant and grain
Caravaggio	SIS, San Lazzaro di Savena, Italy	grain
Ethic	APSOV sementi, Voghera, Italy	whole plant and grain
Giorgione	SIS, San Lazzaro di Savena, Italy	grain
Ludwig	La Cerealtecnica, Mereto di Tomba, Italy	whole plant
Masaccio	SIS, San Lazzaro di Savena, Italy	whole plant and grain
Norenos	La Cerealtecnica, Mereto di Tomba, Italy	whole plant
Paledor	APSOV sementi, Voghera, Italy	grain
Papageno	Caussade Semences, Massa Finalese, Italy	whole plant
Sailor	La Cerealtecnica, Mereto di Tomba, Italy	whole plant

2.3. Recorded Agronomic Parameters on Wheat Crops

At each harvest, the whole aboveground biomass was weighed, recorded to get the yield fresh weight, and consequently oven-dried at 65 °C until constant weight to estimate the potential biomass dry weight. The accumulated growing degree days (GDD) was calculated using the following formula for each year: $\Sigma\{[(T_{max} + T_{min})/2] - 5.0 \text{ °C}\}$ until the heading time and $\Sigma\{[(T_{max} + T_{min})/2] - 7.5 \text{ °C}\}$ for the grain milk and grain dough stages as suggested by Viswanathan and Khanna-Chopra [19]; where T_{max} and T_{min} are the daily maximum and minimum temperatures, respectively, in degree Celsius. The average temperature $[(T_{max} + T_{min})/2]$ was set equal to 5.0 and 7.5 °C if less than 5.0 and 7.5, respectively [20]. Furthermore, in order to investigate N use across the treatments, the N applied efficiency (N-efficiency) index was calculated, which was obtained from the yield dry weight (t ha^{-1}) and the amount of N applied (kg ha^{-1}) and expressed as t yield kg^{-1} according to Ronga et al. [21]. During the growing season, crop water productivity (CWP) was calculated as the ratio between the yield dry weight (g) and total water used by plants (L m^{-2}) in accordance to Ronga et al. [22,23] and Cosentino et al. [24].

2.4. Nutritional Composition of the Parameters Assessed on Wheat Crops

In order to estimate the nutritional value, at each harvest and for each cultivar, a biomass sample was oven-dried at 65 °C until constant weight [25,26], ground to 2 mm and the following parameters recorded: dry matter (DM, %), ash (% of DM), CP (% of DM), neutral detergent fiber (with amylase and sodium sulphite method, according to Fustini et al. [27]) (NDF, % of DM), acid detergent fiber (ADF, % of DM), acid detergent lignin (ADL, % of DM), undigested NDF after 240 h (uNDF, % of DM), as reported by Brogna et al. [28]), starch (% of DM), sugar (% of DM) and net energy for lactation (NEL, kcal kg DM^{-1}) using the instrument Foss NIR-System 5000 monochromator (NIR-System, Silver Spring, MD, USA) in the 1098–2500 nm spectral region. Predictions were performed using the equation developed and validated by Brogna et al. [28]. Spectral data were processed using WinISI II V1.5 software (Infrasoft International, Port Matilda, PA, USA).

2.5. Data Analysis

Agronomic and quality data recorded in each growing season were analyzed using analysis of variance (split-plot ANOVA), where cultivars, regrouped for their main purpose (grain, whole plant and dual purpose), were used as whole plot and harvest times was used as subplot. In addition, some main parameters were also analyzed considering the cultivars (not regrouped) performance, across the harvest times, and reported as Supplementary Materials. Considering the yearly variability due to different weather conditions as seen in the present study and highlighted in other works conducted in similar areas [29–31] the data were analyzed separately for each growing season. However, to give an idea of the yearly variability, all data recorded in the two growing seasons were also processed for a principal component analysis (PCA), in order to evaluate the existing relationships among cultivars, harvest times, parameters and years, a biplot was used. Experimental data were analyzed using

GenStat software (VSN International, Hemel Hempstead, UK). Means were statistically separated on the basis of the LSD test, when the 'F' test of ANOVA for treatment was significant at least at the 0.05 probability level.

3. Results

3.1. Agronomic Parameters Recorded during the Harvests Carried out in 2014 and in 2015

The main agronomic data (yield fresh (YFW) and yield dry (YDW) weights) recorded during the two growing seasons are reported in Figure 2. Winter wheat recommended to be harvested as whole plants displayed the highest values of YFW and YDW (+4 and +7%, respectively, on average across years) (Figure 2A,D)

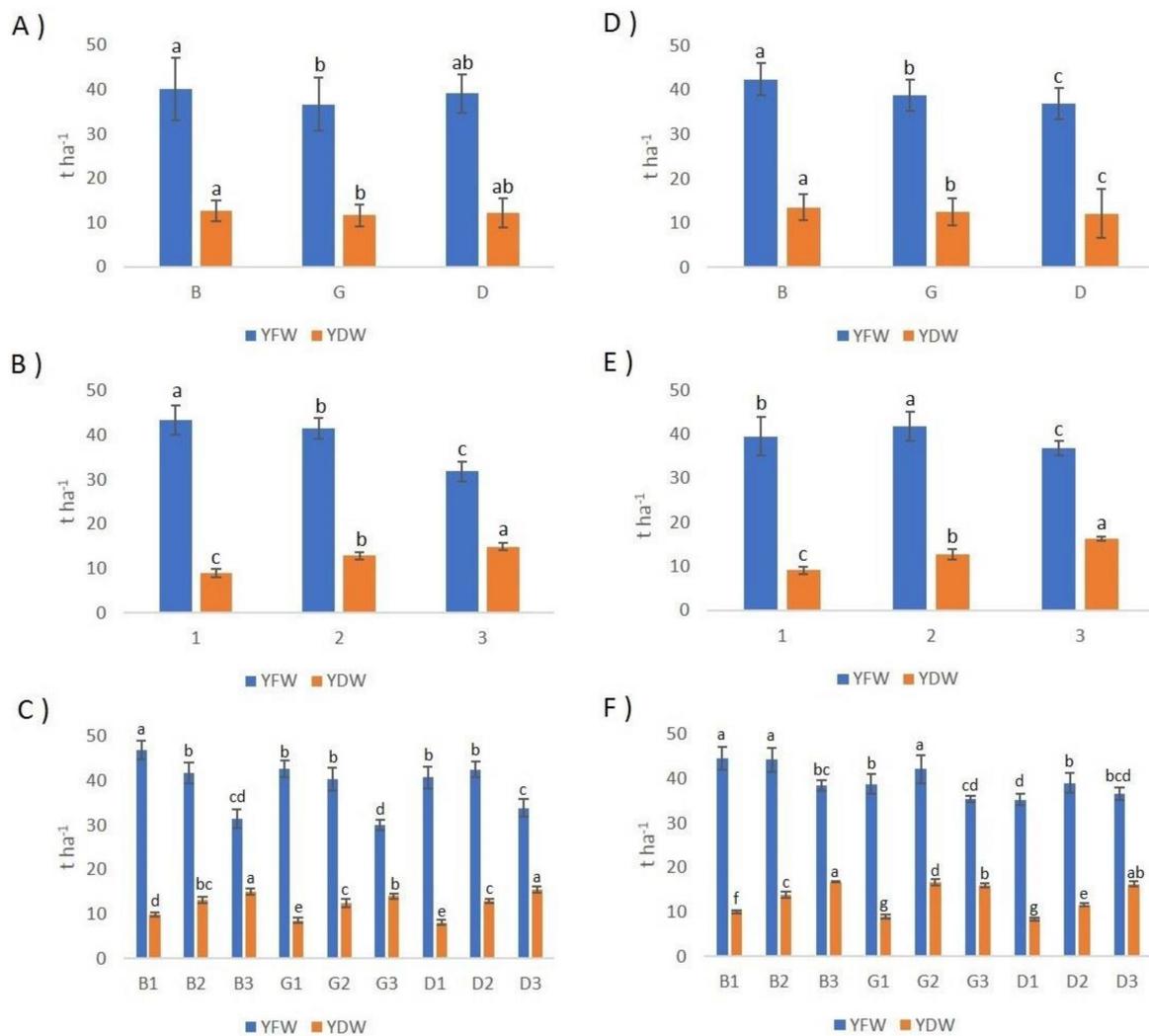


Figure 2. Main agronomic parameters (yield fresh (YFW) and yield dry (YDW) weights) recorded during the two growing seasons. (A) = winter wheat purpose (year 2014); (B) = harvest time (year 2014); (C) = interaction between winter wheat purpose and harvest time (year 2014); (D) = winter wheat purpose (year 2015); (E) = harvest time (year 2015); (F) = interaction between winter wheat purpose and harvest time (year 2015); The cultivar suitability is indicated as follows: B = for harvest as whole plant; G = for grain; D = dual purpose, while the harvest date is indicated as: 1 = winter wheat harvest at heading stage; 2 = winter wheat harvested at grain milk stage; 3 = winter wheat harvested at grain dough stage. Different letters indicate statistically significant differences (within a variable) at $p < 0.05$. Bars indicate the standard deviation.

Considering the effect of the harvest time, when winter wheat was harvested at grain dough stage the lowest YFW and the highest YDW were recorded in both years (Figure 2B,E).

Regarding the interaction between winter wheat purpose and harvest time, winter wheat suitable to be harvested as whole plant at heading time showed the highest value of YFW and when harvested at grain dough stage produced the highest value of YDW in both the years (Figure 2C,F).

Table 2 summarizes other important agronomic parameters (nitrogen efficiency, crop water productivity (CWP) and growing degree days (GDD)), that relate to crop growth and relative physiological performance. Considering the two harvesting seasons, winter wheat suitable to be harvested as whole plant showed the highest value of N-efficiency and GDD (+6 and +5%, respectively, on average across years). Looking the effect of the harvest time, winter wheat harvested at grain dough stage highlighted the highest values of N-efficiency, CWP and GDD (+25, 21 and 13%, respectively, on average across years). Finally, considering the interaction between winter wheat purpose and harvest time, the cultivars suitable to be harvested as whole plant when harvested at grain dough stage recorded the highest values of N-efficiency and GDD (+28 and +17%, respectively, on average across years).

Table 2. Agronomic parameters linked with physiological performance, recorded during the two growing seasons.

Purpose/Harvest Date	Harvest 2014						Harvest 2015					
	N-Efficiency (t DM kg N ⁻¹)		CWP (g DM L m ⁻²)		GDD (°C)		N-Efficiency (t DM kg N ⁻¹)		CWP (g DM L m ⁻²)		GDD (°C)	
B	0.13	a	2.34	a	1488	a	0.14	a	2.96		1335	a
G	0.12	b	2.17	b	1380	b	0.13	b	2.78		1242	b
D	0.12	ab	2.22	ab	1381	b	0.12	c	2.80		1249	b
<i>p-value</i>	<0.01		<0.05		<0.05		<0.001		n.s.		<0.05	
1	0.09	c	1.67	c	1247	c	0.09	c	2.36	c	1092	c
2	0.13	b	2.34	b	1414	b	0.13	b	2.79	b	1293	b
3	0.15	a	2.72	a	1588	a	0.16	a	3.40	a	1441	a
<i>p-value</i>	<0.001		<0.001		<0.001		<0.001		<0.001		<0.05	
B1	0.10	d	1.84		1324	d	0.10	f	2.39	c	1171	c
B2	0.13	bc	2.42		1483	c	0.14	c	2.96	b	1340	b
B3	0.15	a	2.756		1658	a	0.17	a	3.53	a	1494	a
G1	0.09	e	1.63		1206	d	0.09	g	2.26	c	1055	c
G2	0.12	c	2.30		1382	e	0.13	d	2.61	b	1264	b
G3	0.14	b	2.58		1550	b	0.16	b	3.47	a	1427	a
D1	0.08	e	1.54		1211	e	0.08	g	2.43	c	1051	c
D2	0.13	c	2.29		1377	d	0.12	e	2.79	b	1274	b
D3	0.156	a	2.84		1556	b	0.16	ab	3.19	a	1402	a
<i>p-value</i>	<0.05		n.s.		<0.05		<0.01		<0.05		<0.05	

N-efficiency = nitrogen efficiency; CWP = crop water productivity; GDD = growing degree days. The cultivar suitability is indicated as follows: B = for harvest as whole plant; G = for grain; D = dual purpose, while the harvest date is indicated as: 1 = winter wheat harvest at heading stage; 2 = winter wheat harvested at grain milk stage; 3 = winter wheat harvested at grain dough stage. Different letters indicate statistically significant differences (within a variable) at $p < 0.05$. n.s. = not significant.

3.2. Nutritional Composition of Winter Wheat Harvested in 2014 and 2015

The main nutritional parameters (crude protein (CP % of DM), neutral detergent fiber (NDF, % of DM) and undigested NDF (uNDF, % of DM)), assessed during the harvests carried out in 2014 and 2015 are reported in Figure 3. Winter wheat recommended for grain and dual purposes displayed the highest value of CP (+4%, on average across years) (Figure 3A,D); while winter wheat suitable to be harvested as whole plant showed the highest values of NDF and uNDF (+4 and +3%, respectively, on average across years) (Figure 3A,D).

Considering the effect of the harvest time, winter wheat recorded the highest values of CP and NDF (+28 and +6%, respectively, on average across years) when harvested at heading (Figure 3B,E); while winter wheat harvested at grain dough stage showed the highest value of uNDF (+17%, on average across years) (Figure 3B,E).

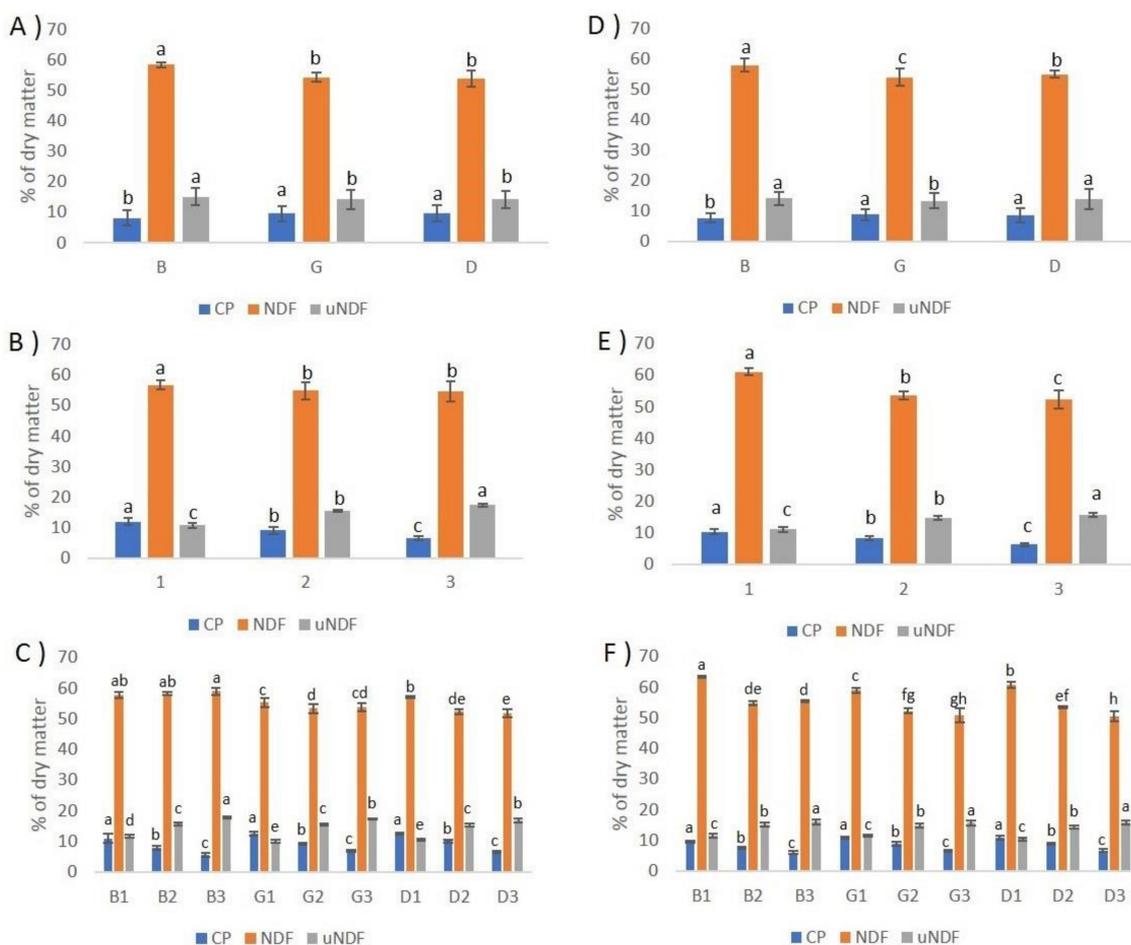


Figure 3. Main nutritional parameters, like crude protein (CP), neutral detergent fiber (NDF) and undigested NDF (uNDF), recorded during the harvests performed in 2014 and in 2015. (A) = winter wheat purpose (year 2014); (B) = harvest time (year 2014); (C) = interaction between winter wheat purpose and harvest time (year 2014); (D) = winter wheat purpose (year 2015); (E) = harvest time (year 2015); (F) = interaction between winter wheat purpose and harvest time (year 2015); The cultivar suitability is indicated as follows: B = for harvest as whole plant; G = for grain; D = dual purpose, while the harvest date is indicated as: 1 = winter wheat harvest at heading stage; 2 = winter wheat harvested at grain milk stage; 3 = winter wheat harvested at grain dough stage. Different letters indicate statistically significant differences (within a variable) at $p < 0.05$. Bars indicate the standard deviation.

Regarding the interaction between winter wheat purpose and harvest time, winter wheat (for all purposes) showed the highest value of CP when harvested at heading; on the other hand winter wheat suitable to be harvested as whole plant produced the highest value of NDF when harvested at heading (Figure 2C,F), while showed the highest values of uNDF when harvested at grain dough stage (Figure 3C,F).

Table 3 presents results for other important nutritional parameters (dry matter (% DM), ash, ADF, ADL, starch and sugar contents (% of DM) and net energy for lactation (NEL, kcal kg DM⁻¹)) used to program correct cattle diets. Considering the two harvesting seasons, winter wheat suitable to be harvested as whole plant showed the highest values of ADF and ADL (+3 and +5%, respectively, on average across years). On the other hand, winter wheat suitable for dual purpose recorded the highest values of starch and sugar contents and NEL (+21, +11 and +3%, respectively, on average across years).

Table 3. Nutritional composition of the biomass produced in the two growing seasons

Harvest 2014														
Purpose/ Harvest Date	DM (%)	Ash (% of DM)		ADF (% of DM)		ADL (% of DM)		Starch (% of DM)		Sugar (% of DM)		NEL (kcal kg DM ⁻¹)		
B	31.3	a	8.0	39.5	a	5.3	a	2.6	c	9.2	c	1214	c	
G	30.5	b	8.0	37.2	b	5.0	b	3.8	b	10.3	b	1274	b	
D	29.8	c	7.9	36.8	b	4.8	c	4.4	a	11.5	a	1289	a	
<i>p-value</i>	<0.001		n.s.	<0.001		<0.001		<0.001		<0.001		<0.001		
1	18.9	c	8.8	36.3	c	4.3	c	1.5	c	9.2	b	1294	a	
2	28.8	b	7.7	37.0	b	5.1	b	2.5	b	10.8	a	1265	b	
3	44.0	a	7.4	40.2	a	5.8	a	6.6	a	11.1	a	1217	c	
<i>p-value</i>	<0.001		<0.001	<0.001		<0.001		<0.001		<0.001		<0.001		
B1	19.5	c	8.7	37.9	d	4.9	e	1.5	e	9.1	d	1264	d	
B2	29.6	b	7.7	38.7	cd	5.3	cd	1.5	e	9.5	d	1215	e	
B3	44.9	a	7.5	42.0	a	6.2	a	4.6	c	9.1	d	1162	f	
G1	18.6	c	8.8	35.0	g	4.1	f	1.6	e	9.4	d	1326	a	
G2	2.7	b	7.9	36.7	e	5.2	d	3.0	d	10.6	c	1268	cd	
G3	44.1	a	7.5	39.7	b	5.8	b	6.9	b	10.9	c	1216	e	
D1	18.5	c	9.1	36.1	ef	4.2	f	1.5	e	9.1	d	1290	bc	
D2	28.1	b	7.6	35.5	fg	4.7	e	3.1	d	12.2	b	1314	ab	
D3	42.9	a	7.1	38.9	bc	5.4	c	8.5	a	13.2	a	1262	d	
<i>p-value</i>	<0.05		n.s.	<0.05		<0.001		<0.001		<0.001		<0.001		
Harvest 2015														
Purpose/ Harvest Date	DM (%)	Ash (% of DM)		ADF (% of DM)		ADL (% of DM)		Starch (% of DM)		Sugar (% of DM)		NEL (kcal kg DM ⁻¹)		
B	30.3		7.2	b	38.7	a	5.0	a	3.4	b	11.5	b	1257	b
G	30.2		7.3	ab	37.1	b	4.8	b	4.7	a	12.5	a	1302	a
D	30.6		7.6	a	37.5	b	4.7	b	4.9	a	12.7	a	1294	a
<i>p-value</i>	n.s.		<0.05		<0.001		<0.001		<0.001		<0.001		<0.001	
1	21.5	c	8.1	a	38.8	a	4.5	c	1.0	c	9.4	b	1272	b
2	28.2	b	6.7	c	36.3	c	4.8	b	3.6	b	13.5	a	1314	a
3	41.5	a	7.3	b	38.1	b	5.2	a	8.3	a	14.0	a	1266	b
<i>p-value</i>	<0.001		<0.001		<0.001		<0.001		<0.001		<0.001		<0.001	
B1	21.0	c	8.3	a	40.5	a	4.9	bc	0.6	e	8.2	e	1221	g
B2	28.8	b	6.2	d	36.4	ef	4.8	c	3.2	d	13.6	bc	1307	bc
B3	41.1	a	7.3	b	39.0	b	5.3	a	6.4	b	12.7	c	1242	f
G1	21.9	c	7.9	a	37.3	de	4.3	d	1.0	e	10.0	d	1311	ab
G2	27.6	b	6.7	c	36.1	f	4.8	c	3.8	cd	13.5	bc	1329	a
G3	41.1	a	7.4	b	37.8	cd	5.3	a	9.3	a	14.1	ab	1265	e
D1	21.5	c	8.1	a	38.5	bc	4.4	d	1.3	e	9.8	d	1283	de
D2	28.2	b	7.2	b	36.6	ef	4.7	c	3.9	c	13.3	bc	1308	bc
D3	42.3	a	7.3	b	37.3	de	5.0	b	9.4	a	15.0	a	1291	cd
<i>p-value</i>	<0.05		<0.05		<0.001		<0.001		<0.001		<0.01		<0.001	

DM = dry matter, ADF = acid detergent fiber; ADL = acid detergent lignin; NEL = net energy for lactation; The cultivar suitability is indicated as follows: B = for harvest as whole plant; G = for grain; D = dual purpose, while the harvest date is indicated as: 1 = winter wheat harvested at heading stage; 2 = winter wheat harvested at grain milk stage; 3 = winter wheat harvested at grain dough stage. Different letters indicate statistically significant differences (within a variable) at $p < 0.05$. n.s. = not significant.

Winter wheat showed the highest value of ash content (+3%, on average across years) when harvested at heading; but when harvested at grain dough stage produced the highest values of DM, ADL, starch and sugar contents (+40, +7, +90 and +11%, respectively, on average across years).

Considering the interaction between winter wheat purpose and harvest time, winter wheat (for all purposes) showed the highest values of DM (+40%, on average across years) when harvested at grain dough stage. Winter wheat suitable to be harvested as whole plant recorded the highest values of ADL (+11%, on average across years) when harvested at grain dough stage. On the other hand, winter wheat suitable for dual purposes (for grain or whole plant biomass) gave the highest values of starch and sugar (+127% and +25%, respectively, on average across years) when harvested at grain dough stage. Finally, winter wheat suitable for grain purpose recorded the highest values of NEL (+3%, on average across years) when harvested at heading.

3.3. Relationships Among Cultivars, Harvest Times, Years and Evaluated Parameters for the Harvests Performed in 2014 and 2015

The correlations among winter wheat purposes (harvest for grain, whole plant biomass and for dual purpose), harvest times, years and parameters measured were studied by PCA analysis and result is shown in Figure 4 as biplot. The contributions of the two first principal components were 62.78% (PC1) and 21.88% (PC2) and their sum explained the 84.66% of the total variability. Associations among cultivars, harvest times, years and measured parameters were easily appreciated on biplot. The first principal component indicated the effect of harvest time. Indeed, winter wheat harvested at heading is displayed on the negative side of PC1 and associated with high values of CP, YFW, ash content (AS), NEL and NDF. On the other hand, winter wheat harvested at grain dough stage is shown on the positive side of PC1 and associated with high values of sugar (SU), starch (ST), N-efficiency (NE), CWP, YDW, DM, uNDF, GDD, ADL and ADF. In addition, winter wheat suitable for dual purpose displayed similar performance, both when harvested at heading and at grain milk stage and the trend was also confirmed across the two years. Finally, also winter wheat suitable to be harvested as whole plant showed a similar performance, both when harvested at grain dough and milk stages and the trend was also confirmed across the two years.

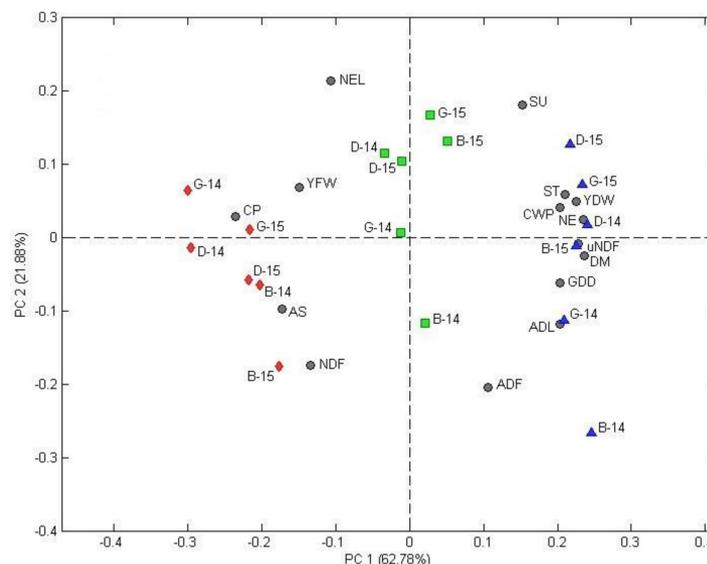


Figure 4. Biplot of Principal Component Analysis of the harvests carried out in 2014 and 2015. The studied parameters (grey circles) are: YFW = yield fresh weight; YDW = yield dry weight; DM = dry matter, CP = crude protein, NDF = neutral detergent fiber (with amylase and sodium sulphite method); ADF = acid detergent fiber; ADL = acid detergent lignin; uNDF = undigested NDF after 240 h; ST = starch; SU = sugar; NEL = net energy for lactation; AS = ash; CWP = crop water productivity; NE = N-efficiency; GDD = growing degree days. Red diamonds = winter wheat harvested at heading stage; Green Squares = winter wheat harvested at grain milk stage; Blue triangles = winter wheat harvested at grain dough stage. B-14 = winter wheat suitable to be harvested as whole plant and harvested in 2014; G-14 = winter wheat suitable for grain purpose and harvested in 2014; D-14 = winter wheat suitable for double purposes and harvested in 2014; B-15 = winter wheat suitable to be harvested as whole plant and harvested in 2015; G-15 = winter wheat suitable for grain purpose and harvested in 2015; D-15 = winter wheat suitable for double purposes and harvested in 2015.

4. Discussion

Considering the current rising prices of maize due to its use in biofuel production as well as its higher consumption of irrigation water, wheat forage might be an interesting alternative for livestock production in many areas around the world [32]. Hence, it is important to provide useful information on the cultivation and utilization of winter wheat as a source of forage and the present study was carried

out to assess its potential yield and quality in the production of hay. Winter wheat hay productivity and its related nutritive changes were investigated at different harvest times, from heading to grain dough stages. This study was carried out in an important livestock area dedicated for the production of the PDO cheese Parmigiano Reggiano, where the use of silage is not allowed.

Alfalfa is one of the most important forage crops globally produced, and haymaking is the most common method of conservation [28]. On the other hand, among forage crops, wheat can be an important source of high-quality forage in livestock production [4]. In addition, winter wheat used as forage is usually harvested in late winter (in dry or semi-arid climate areas) and early spring (in Continental climate areas), when other forage crops are both lower in quantity and quality. Furthermore, wheat forage, in term of nutritive parameters like CP ha⁻¹ and DM digestibility, is comparable to alfalfa [5].

To increase cattle feed efficiency, the best strategy should be adopted; to do this, a rapid assessment of the nutritional composition of the forage should be available by farmer. From this point of view, near infrared reflectance spectroscopy (NIRS) has been widely identified as a valuable and not time consuming technology to predict in an accurate way the chemical composition of different forages [33,34], and in the prediction of several parameters [35,36].

In our study, FYW decreased with the advancing harvest time, confirming the existing literature on several herbage crops, that ascribed this trend to the leaf senescence and remobilization of storage carbohydrates, leading into a reduction of the plant biomass after flowering [37]. On the other hand, YDW increased from heading to grain dough stages, as expected and in accordance to the data reported by Delogu et al. [38] and Bocchi et al. [39] on triticale (*Triticosecale* Wittmack) cultivated in similar areas of Northern Italy. Increased YDW with advancing harvest time has been well-documented for several forage crops like perennial ryegrass (*Lolium perenne* L.), Italian ryegrass (*Lolium multiflorum* Lam.), tall fescue (*Festuca arundinacea* Schreb.), cocksfoot (*Dactylis glomerata* L.), timothy (*Phleum pratense* L.) and red clover (*Trifolium pratense* L.) [40]. These findings are related to advancing of the plant growth cycle and to the storage of photosynthates in the grain.

Considering cultivars with different purposes, winter wheat suitable to be harvested as whole plants showed the highest values of YFW and YDW and related agronomic performances, in particular in term of CWP and N-efficiency. In addition, among the investigated cultivars suitable to be harvested as whole plant, cultivar “Norenos” showed higher agronomic performance than the others in both the assessed years (Table S1).

At each harvest time, nutritive composition displayed, as expected, significant differences. When going from early heading to grain dough stages, the majority of the investigated parameters increased as already suggested in previous works [2,41].

Wrobel et al. [42] evaluated the production and chemical composition of wheat hay, cv. BRS UMBU produced in Brazil at two harvest stages (pre-flowering and grain dough). The authors reported that hay harvested at dough stage had higher DM and lower NDF and CP levels, in accordance with our results obtained in Northern Italy. Also Beck et al. [43] reported that advanced maturity increased wheat forage DM and decreased CP concentrations. In addition, MacKown et al. [44] highlighted that CP was inversely related to YDW as well as displayed in our work in the PCA biplot.

The results of the present study regarding YDW and CP are in accordance with investigation performed on other crops that can be used as a source of alternative forage. In fact, Borreani et al. [45] studying the yield and quality of semi-leafless grain peas (*Pisum sativum* L.) reported that YDW increased with advancing maturity, while the CP decreased.

A decrease of CP with advancing maturity was also reported by other papers, which investigated the effect of: harvest time on alfalfa [46]; the intercropping between winter wheat and bean (*Vicia faba* L.) [47]; the kernel milkline stage of maize forage [48].

The information derived from the present study regarding nutritive parameters highlights that the best time to harvest winter wheat is until grain milk stage, in agreement with data reported on maize and cow pea (*Vigna unguiculate* L.) [49]. Our results are also in agreement with authors which

reported that wheat silage might be harvested at flowering to achieve the highest nutritive value as suggested by Weinberg et al. [32] and Arieli and Adin [50] due to its greater field yields and degradable NDF, and ensuring a better ensiling quality [51].

In our research winter wheat harvested at heading time had significantly greater NDF concentrations compared with those harvested at the grain milk and dough maturity stages in agreement with Weinberg et al. [32]. This occurred because mature plants contained grains filled with starch, that diluted the NDF concentration in the whole plants. In our work, winter wheat suitable to be harvested as whole plant demonstrated the highest value of NDF when harvested at heading time.

In the present study, as showed in the biplot, ADL was one of the most important parameters impacting on NDF digestibility (reported as uNDF) as already suggested by Weinberg et al. [32]. In addition, uNDF was affected by harvest time and increased from heading to grain milk stage. This result suggests again that an early harvest time of winter wheat, from heading to grain milk stages, is fundamental to achieve the best forage quality. Moreover, value of uNDF can be also used to estimate NDF digestibility, impacting on the performance of dairy cows. In fact, a one-unit increase in NDF digestibility was related with a 0.17 kg increase in dry matter intake and a 0.25 kg increase in 4% fat-corrected milk [52].

Another parameter that suggests an early harvest is best is ADL; this increased with the harvest time in our study. In fact, highly lignified crops remain in the rumen for more time due to their slower rate of digestion, decreasing the dry matter intake and in turn animal performance [53,54]. Thus, forage crops harvested at early growth stages are more appropriate to feed cow while ensuring high animal performance [55,56].

Our study highlighted that winter wheat suitable for dual purpose displayed a similar performance, both when harvested at heading and at grain milk stages. And similar trend was also observed for winter wheat suitable to be harvested as whole plant, both when harvested at grain dough and milk stages. These characteristics are fundamental and strategic in hay production, allowing a more elastic harvesting and haymaking. In addition, considering the two investigated years, among the cultivars suitable to be harvested as whole plant, cultivar “Norenos” displayed the highest values of NDF and uNDF, while cultivars “Artico” and “Ethic” recorded the highest values of NEL (Table S1).

Several agronomic factors can impact on yield and quality of crops used as forage [57]. As highlighted in our work on winter wheat hay, the most important factor is the harvest time. However, while YDW increased until grain dough stage, some important nutritional parameters like CP and NDF decreased [38,57]. These trends might be a serious dilemma between farmer that only produce hay and farmers that both produce hay and use it in their livestock production.

Our results indicate that winter wheat hay harvested from heading to grain milk stages show nutritive values, especially in term of CP and NEL, comparable to that one of alfalfa hay reported in literature [58]. In addition, both in term of DM and NDF, the results showed in the present work are in similar to those showed on winter wheat silage [59,60].

Farmers harvesting winter wheat at heading-milk stage might maximize yields *per* unit area *via* double-cropping [61]. Because winter wheat forage can be cultivated before summer crops such as maize or soybean [62,63], it represents a good opportunity to generate diversified incomes, and decreases the risk related to winter wheat production in areas where growing conditions are not optimal for grain production [64]. Finally, it is also possible to grow winter wheat as pasture in winter and then cut it for hay production during spring [62].

In livestock production, winter wheat cultivation allows a more flexible crop rotation, not related to weather conditions and market trends with farmers having the possibility to produce the grain if are unable to harvest wheat hay in the best conditions. In addition, interestingly there is much interest in Australia on identifying area of frost damage in wheat crops—as harvesting for hay is a valuable alternative output if the damaged areas can be rapidly identified [65].

Further future study is needed to validate our results in real farms as well as also in other European environments as it is well known that cultivar, seasonal temperature, solar radiation, rainfall, soil type and external inputs, can all affect the yield and nutritional values of cereal crops [38,66–68].

5. Conclusions

Autumn-sown cereals can be a very important source of nutrients for livestock production and could help to improve the self-sufficiency of dairy farms, in terms of homegrown forages. Among the various cereals, winter wheat is interesting for its potential quality–quantity characteristics used as whole-plant to produce hay. Our results showed that the yield dry matter of winter wheat hay increased, and its nutritive quality decreased, with advancing maturity. Yield and quality were most stable across the years for those cultivars deemed suitable for whole-plant harvest or as dual purpose varieties. Our results show that winter wheat has a good potential for hay production in Northern Italy in a period when other forages are lower in quantity and quality, improving in turn the agricultural sustainability. In addition, winter wheat hay may therefore be a valid alternative in the supply chain of the PDO cheese Parmigiano Reggiano where silage is not allowed. Further research is needed to assess the potential of winter wheat for hay production in real farm situations and in other European environments.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4395/10/6/917/s1>, Table S1: The main agronomic parameters and nutritional composition of the biomass recorded on the assessed cultivars, across the harvest times, during the two growing seasons

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