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The effect of late-season urea spraying on grain yield and quality of winter wheat cultivars under low and high basal nitrogen fertilization

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Abstract

The late-season foliar application of urea may increase yield and grain quality of wheat (*Triticum aestivum* L.). Limited information is available regarding the effect of late urea spraying on the performance of wheat cultivars under various basal N fertilization rates. Field experiments were conducted during 2000 through 2002 to evaluate the responses of six winter wheat cultivars to foliar urea (30 kg N ha^{-1}) treatment around flowering at low (67 kg N ha^{-1}) and high (194 kg N ha^{-1}) basal N fertilization rates. Following urea spraying at low N rate, all cultivars increased grain yields to a similar extent (by an average of 7.8% or 509 kg ha^{-1}) primarily due to an increase in the 1000-kernel weight. No yield response to the late-season urea treatment occurred at high basal N rate where grain yields averaged 24.9% (1680 kg ha^{-1}) higher than those at low N rate. In contrast, late foliar urea application similarly improved grain quality at both low and high N rates by an average of 5 g kg^{-1} (4.5%) for protein content, 3.2 cm^3 (11.9%) for Zeleny sedimentation, and 20 g kg^{-1} (8.6%) for wet gluten. These quality increments were consistent in all growing seasons regardless of significant variations in grain yields and protein concentrations across years. However, most cultivars failed to achieve breadmaking standards at low N rate as quality increments associated with the urea treatment were relatively small when compared to those achieved by high basal N rate. Late urea spraying had no effect on the falling number, whereas some cultivars showed small, but significant reduction in the gluten index at both N rates. Cultivars improved the hectolitre weight with the late-season urea treatment only at low N rate. Significant cultivar × urea interactions existed for most quality traits, which were due to the cultivar differences in the magnitude of responses. Thus, late-season urea spraying consistently produced larger yields at low basal N rate, and resulted in cultivar-dependent increases in protein content, Zeleny sedimentation, and wet gluten at both low and high N rates.

Keywords: Winter wheat; N fertilization; Urea spraying; Cultivar; Yield; Grain quality

1. Introduction

The use of late-season urea spraying may increase grain yield and quality of winter wheat (*Triticum aestivum* L.). Nitrogen availability late in the season is particularly important for increased grain protein, but could be limited by low soil moisture despite adequate amount of fertilizer N added to the soil. Wheat crop in Croatia is mainly grown with low cropping inputs, primarily low N fertilization rates, despite high yielding environmental and cultivar potentials (Varga et al., 2001). The national wheat grain yield averaged 3.93 t ha^{-1} for the last decade (1991–2001) (Državni zavod za statistiku, 2002). No information is available on the effectiveness of late foliar urea application on grain yield and quality of winter wheat in Croatia.

Grain yield responses from late foliar N applications in wheat crop may vary greatly. The timing of foliar N application might also have an impact on yield responses. Thus, grain yield was significantly reduced by 5% when foliar N was applied at boot stage for hard red spring wheat, but not when sprayed after flowering (Bly and Woodard, 2003). Decreased yields for wheat crop following late urea spraying were also demonstrated by Peltonen et al. (1991)

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and Barraclough and Haynes (1996). Finney et al. (1957) found that urea applications after heading usually did not result in yield increases unless N deficiency was severe. In Oklahoma, Woolfolk et al. (2002) reported inconsistent yields responses over years and locations after late-season foliar N application. No yield benefits following urea spraying existed in a research by Dubetz (1977) and Strong (1982). However, Gooding et al. (1991) measured improved grain yield after late-season urea spraying in two out of five experiments in England. Similar results were reported by Altman et al. (1983), and Dampney and Salmon (1990). Limited information exists regarding the potential variations in the response of winter wheat cultivars to late-season urea spraying, especially when grown under various basal N fertilization rates. Altman et al. (1983) found that the magnitude of the yield response to urea spraying varied between cultivars, which contrasted the report by Gooding et al. (1991).

Grain protein responses to urea spraying are relatively consistent and increases are frequently reported. In North Dakota, Endres and Schatz (1993) found increasing grain protein as foliar N rate increased, with the greatest protein content at the rate of 33.7 kg N ha^{-1}. Finney et al. (1957) indicated that the largest grain protein improvements occurred when urea was applied at the flowering stage and that responses declined rapidly before or after that time. Similar findings were recently shown by Bly and Woodard (2003). Studies on wheat cultivar responses to late-season urea application in terms of grain quality traits are scarce. In greenhouse experiment, Seth et al. (1960) reported the possibility of high and low protein genotypes differing in their ability to assimilate N applied foliarly after heading. In contrast, Gooding et al. (1991) found similar cultivar responses for grain protein following urea spraying in field conditions. However, the authors indicated differential cultivar responses for SDS-sedimentation volume. In addition, late-season urea application may also affect other grain quality traits like the hectolitre weight, wet gluten content and the falling number (Pushman and Bingham, 1976; Tipples et al., 1977; Peltonen and Peltonen, 1990; Ruske et al., 2003).

The objective of our study was to evaluate the effect of late-season urea spraying on grain yield and quality of six winter wheat cultivars grown under low and high basal N fertilization rates.

2. Materials and methods

Field experiments in a winter wheat–corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] crop rotation were conducted in northwestern Croatia at the Faculty of Agriculture Zagreb experimental field during the 1999–2000 (2000), 2000–2001 (2001), and 2001–2002 (2002) growing seasons on a silt loam soil (Typic Udifluvents). The experiment was conducted using a split-strip plot design with five replications. Basal N fertilization treatments (low and high) formed 10 main plots. Low N fertilization rate consisted of 67 kg N ha^{-1} with 40 kg N ha^{-1} applied before planting and one topdressing application at growth stage (GS) 24 (Zadoks et al., 1974) with 27 kg N ha^{-1}. High N fertilization rate (total of 194 kg N ha^{-1}) included 86 kg N ha^{-1} applied before planting and topdressing of 54 kg N ha^{-1} at GS 22, 27 kg N ha^{-1} at GS 24, and 27 kg N ha^{-1} at GS 31. Subplots consisted of six winter wheat cultivars differing in their genetic potential for grain protein concentration. Chosen genotypes are widely grown in the winter wheat production systems of Croatia. Foliar urea application versus no treatment were stripped across the subplots and separated by a 1.5-m border. The application was targeted to GS 65; however, because of maturity differences cultivars were between GS 55 and GS 69 at the time of urea application (Table 1). The foliar N at the rate of 30 kg N ha^{-1} was applied as a solution of urea and water using a total volume of 300 L ha^{-1}. No precipitation occurred within 24 h of foliar urea treatment.

Previous crops (corn and soybean) were grown under low N rates to minimize the effect of residual nitrogen on subsequent winter wheat crop. In October of each year, 500 kg ha^{-1} N–P–K fertilizer (8:26:26) was broadcast before mouldboard ploughing at 30 cm. Additional urea [$(NH_2)_2CO$] (46% N) at 100 kg ha^{-1} was broadcast before seedbed preparation on plots receiving high N rate. Cultivars were planted at recommended rate (770 seeds m^{-2}). At seeding, plots consisted of 10 rows that were 11 cm apart and 7.0 m in length. Wheat was planted on 16 October 1999, 28 October 2000, and 17 October 2001 within the optimum planting-date window for the region. Herbicides amidosulfuron and bromoxynil at 225 g a.i. ha^{-1} were applied at GS 24. Granular N [27% ammonium nitrate (NH_4NO_3)] was broadcast by hand in each topdressing application for the low and high basal N fertilization rates. Fungicide

Table 1
Agronomic characteristics of winter wheat cultivars

Cultivar	Origin	Maturity	GS at urea application
Marija	Bc Institute, Zagreb, Croatia	Medium	GS 61
Žitarka	Agricultural Institute Osijek, Croatia	Medium	GS 61
Srpanjka	Agricultural Institute Osijek, Croatia	Early	GS 69
Soissons	Florimond Desprez, France	Medium	GS 59
Renan	INRA, France	Late	GS 55
Kuna	Faculty of Agriculture Zagreb, Croatia	Medium	GS 59

Table 2
Analysis of variance for grain yield, yield components, and grain quality traits

Source of variation	d.f.	Grain yield	Ears per square meter	Grain weight per ear	1000-kernel weight	Kernels per ear	Hectolitre weight	Protein content	Zeleny sedimentation	Wet gluten content	Gluten index	Falling number
Year (*Y*)	2	***	***	***	***	***	***	***	***	***	*	**
R/*Y*	12	–	–	–	–	–	–	–	–	–	–	–
Basal nitrogen (N)	1	***	***	***	***	***	***	***	***	***	*	***
Y × N	2	**	**	**	***	NS	***	NS	**	NS	*	NS
Error *a*	12	–	–	–	–	–	–	–	–	–	–	–
Cultivar (C)	5	***	***	***	***	***	***	***	***	***	***	***
Y × C	10	***	***	***	***	***	***	***	***	***	**	***
N × C	5	**	***	***	***	***	***	***	**	*	NS	***
Y × N × C	10	***	NS	***	***	***	***	NS	**	**	*	NS
Error *b*	120	–	–	–	–	–	–	–	–	–	–	–
Urea (U)	1	***	NS	*	**	NS	***	***	***	***	*	NS
Y × U	2	NS	NS	NS	NS	NS	**	NS	NS	**	NS	NS
Error *c*	12	–	–	–	–	–	–	–	–	–	–	–
N × U	1	**	NS	*	**	NS	***	NS	NS	NS	NS	NS
Y × N × U	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Error *d*	12	–	–	–	–	–	–	–	–	–	–	–
C × U	5	NS	NS	NS	NS	NS	***	**	*	*	*	NS
Y × C × U	10	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
N × C × U	5	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y × N × C × U	10	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Error *e*	120	–	–	–	–	–	–	–	–	–	–	–

NS: not significant.
* Significant at $P = 0.05$.
** Significant at $P = 0.01$.
*** Significant at $P = 0.001$.

tebuconazol (250 g a.i. ha^{-1}) was applied as a foliar spray in a 200 L ha^{-1} water approximately one week before the urea treatment.

Ear density was determined from a central 0.55-m^2 plot-area just before harvest. Thirty spikes were randomly handpicked and threshed to determine grain production per ear and the 1000-kernel weight. Average 1000-kernel weight was determined by counting and weighing two 100-kernel samples. The kernel number per ear was calculated from the ear number, grain production per spike, and the 1000-kernel weight. Plots were harvested by a combine, and total grain yields are expressed on a kilogram per hectare basis at a 130 g kg^{-1} moisture basis. Harvest dates were 2 July 2000, 5 July 2001, and 4 July 2002.

The hectolitre weight was determined using standard procedures (Schopper chondrometer). Grain nitrogen was measured by Kjeldhal analysis (ICC 105/2, International Association for Cereal Chemistry, 1994), and protein content was calculated as 5.7 × percent N in dry matter. Zeleny sedimentation and Hagberg falling number were determined using ICC methods 116/1 and 107/1, respectively (International Association for Cereal Chemistry, 1994). Wet gluten content and the gluten index were measured on a Perten Glutomatic 2200 System according to standard method ICC 155 (International Association for Cereal Chemistry, 1994).

The experiment consisted of three treatment factors: two basal N fertilization rates (main plots), six winter wheat cultivars (split-plots), and foliar urea spraying versus non-treated plots (strip-plots), with five replications. Data were analyzed using mixed model procedures (SAS Institute, 1997). Combined analysis of variance was computed with year, basal N fertilization rate, cultivar, and urea management considered fixed effects. Mean differences were assessed using the LSD values if the F-test was significant at $P = 0.05$.

3. Results and discussion

3.1. Grain yield and yield components

When averaged over all treatments, late-season urea spraying significantly affected grain yield, grain weight per ear, and 1000-kernel weight (Table 2). A significant urea × N interaction indicated that yield responses to foliar urea application at flowering varied across the two basal N fertilization rates. Under low basal N fertilization, late-season urea spraying produced yields significantly larger by an average of 509 kg ha^{-1} (7.8%), primarily because of a 3.6% increase in the 1000-kernel weight (Table 3). Pushman and Bingham (1976), and Strong (1982) also found that late N application at flowering may increase the kernel weight. The number of kernels per ear tended to increase only slightly after urea treatment at low N rate (Table 3). In contrast, no yield difference between the urea-sprayed and the untreated plots existed at high basal N rate where grain yields averaged 24.9% (1680 kg ha^{-1}) larger than those at

Table 3
Average grain yields and yield components of winter wheat cultivars with or without late-season urea treatment at low (67 kg N ha^{-1}) and high (194 kg N ha^{-1}) basal N rates, Zagreb, 2000–2002

N rate	Urea	Grain yield (kg ha^{-1})	Ears per square meter (no.)	Grain weight per ear (g)	1000-kernel weight (g)	Kernels per ear (no.)
Low	No	6485	672	1.09	41.3	26.4
	Yes	6994	681	1.16	42.8	27.1
High	No	8425	806	1.22	39.3	31.5
	Yes	8414	809	1.22	38.7	31.7
LSD (0.05)[a]		193	NS[b]	0.045	0.58	NS
LSD (0.05)[c]		282		0.051	0.54	

[a] LSD values for comparing means within the same basic N fertilisation.
[b] Not significant for N rate × urea interaction at $P = 0.05$.
[c] LSD values for comparing means across N rates and urea management.

low N rate (Table 3). The lack of yield response to late-season foliar N applications was found by many authors (Dubetz, 1977; Strong, 1982; Rawluk et al., 2000; Woolfolk et al., 2002; Bly and Woodard, 2003). Although the urea treatment caused some scorch at both N rates, only 10% or less of the flag leaf area was affected; consequently, no reductions in grain yields were observed in our research. Scorch of between 30% and 40% of the flag leaf area is possible from high applications of foliar N, in which case yield depressions are likely to occur (Dampney and Salmon, 1990).

The absence of year × urea and year × urea × N interactions (Table 2) indicated that specific yield responses to urea spraying observed at low and high N rates were constant over a range of growing conditions, even though significant variations in grain yields existed across years. The largest yields (averaging 8521 kg ha^{-1}) were produced in the most favourable growing conditions of 2002. Significantly lower yields occurred in the two previous growing seasons, which averaged 7366 kg ha^{-1} in 2000 and 6881 kg ha^{-1} in 2001. These lower yields in 2000 and 2001 were attributed to the dryer than normal conditions in spring (Table 4). Consistent yield increases in all three growing seasons at low N rate following urea spraying were somewhat surprising and rarely found in previous studies. Only few authors reported occasional yield increases following the late foliar urea application (Finney et al., 1957; Pushman and Bingham, 1976). A significant response to the urea treatment at low N rate existed even in the most favourable growing conditions of 2002 despite relatively large yields in non-treated plots (7642 kg ha^{-1}), which clearly demonstrated suboptimal N fertilization earlier in the vegetation. Thus, our findings may indicate the potential use of late-season foliar N application to increase yields in winter wheat crop if previous N application to the soil was suboptimal for the maximum yield potential in given environmental conditions.

Cultivars significantly differed for grain yields and all yield components (Table 2), thus demonstrating their genetic differences in the yield potential. Moreover, cultivars produced various grain yield responses across growing seasons and two basal N fertilization rates (Table 2). However, the non-significant cultivar × urea interaction indicated that all cultivars showed similar responses to urea treatment regardless of their observed differences in the grain yield. In England, Pushman and Bingham (1976) also found non-significant cultivar × urea interaction in their one-year field experiment using 10 winter wheat cultivars. In contrast, Altman et al. (1983) reported significant differences in grain yield responses to late-season foliar N using genotypes of widely different germplasm. Interestingly, the magnitude of yield improvements after urea spraying at low N rate was consistent among a relatively wide range of cultivars used in our study and in spite of varying growing conditions over three years (Table 2).

Table 4
Monthly mean temperature and total rainfall during growing seasons from 2000 to 2002

Month	Mean temperature (°C)				Total rainfall (mm)			
	2000	2001	2002	30-year	2000	2001	2002	30-year
October	11.7	13.4	14.3	10.4	100	92	8	74
November	3.6	9.2	3.6	5.3	71	109	86	78
December	1.7	4.6	−1.6	1.1	99	118	24	57
January	−1.6	4.0	1.7	−0.6	17	79	22	44
February	4.6	4.9	6.5	1.8	18	13	47	41
March	7.8	10.4	8.8	6.1	46	10	33	57
April	14.2	10.6	10.8	10.5	54	79	131	59
May	17.5	17.8	18.4	15.3	39	71	86	75
June	21.6	18.4	21.1	18.6	47	118	71	98

Table 5
Average grain quality traits of winter wheat cultivars with or without late-season urea treatment at low (67 kg N ha^{-1}) and high (194 kg N ha^{-1}) basal N rates, Zagreb, 2000–2002

N rate	Urea	Hectolitre weight (kg hl^{-1})	Protein content (g kg^{-1})	Zeleny sedimentation (cm^3)	Wet gluten content (g kg^{-1})	Gluten index (%)	Falling number (s)
Low	No	79.7	100	20.4	189	95	293
	Yes	80.9	106	24.1	215	92	303
High	No	79.8	123	33.5	277	91	322
	Yes	79.9	127	36.3	291	88	318
LSD (0.05)[a]		0.22	NS[b]	NS	NS	NS	NS
LSD (0.05)[c]		0.23					

[a] LSD values for comparing means within the same basic N fertilisation.
[b] Not significant for N rate × urea interaction at $P = 0.05$.
[c] LSD values for comparing means across N rates and urea management.

3.2. Grain quality

Late-season urea spraying at flowering displayed significant effect on all grain quality traits, except Hagberg falling number (Table 2). This lack of response for the falling number agrees with the findings of Gooding et al. (1991). In field conditions, Ruske et al. (2003) reported that foliar urea (40 kg N ha^{-1}) applied at anthesis improved the falling number in one out of three growing seasons, which was not found in our study because of the non-significant year × urea interaction (Table 2).

The significant interaction between urea spraying and basal N fertilization rate existed for the hectolitre weight only (Table 2). Following urea treatment, the hectolitre weight significantly improved at low N rate and averaged 80.9 kg hl^{-1} compared to 79.7 kg hl^{-1} in untreated plots, whereas no difference existed between sprayed and untreated plots at high N rate (Table 5). Pushman and Bingham (1976) also reported a possible increase in the hectolitre weight with the late-season foliar urea application, whereas Finney et al. (1957) found that urea spraying did not greatly affect the hectolitre weight. In untreated plots (Table 5), average hectolitre weight was similar across two basal N fertilization rates despite a lighter 1000-kernel weight at high N rate (39.3 g) compared to that at low N rate (41.3 g). Thus, the hectolitre weight may vary depending not only on the 1000-grain weight but also on grain size and texture.

In contrast to hectolitre weight responses, other quality traits showed similar improvements with late-season urea spraying at both N rates (Table 2) by an average of 5 g kg^{-1} (4.5%) for protein content, 3.2 cm^3 (11.9%) for Zeleny sedimentation, and 20 g kg^{-1} (8.6%) for wet gluten (Table 5). Tipples et al. (1977) and Peltonen and Peltonen (1990) also reported improved protein content and wet gluten content after late foliar urea application. The non-significant year × urea × N interaction indicated that the grain quality improvements in protein content, Zeleny sedimentation and wet gluten after the urea treatment were consistent in all three growing season (Table 2). Rawluk et al. (2000) also reported consistent protein increases with foliar N application at anthesis across a range of conditions. Improved grain quality even at high N rate, despite no yield benefits from late-season urea treatment, indicated that optimum N fertilization for maximum yields may differ from that for maximum grain quality traits, as also reported by Garrido-Lestache et al. (2004).

The increases in grain protein concentrations following urea spraying resulted in larger proteins yield per ha (grain yield × protein concentration). Despite similar increments in grain protein concentrations at both basal N rates after urea treatment (Table 5), the improvements in protein yield averaged 93 kg ha^{-1} at low N rate compared to only 32 kg ha^{-1} at high N rate. This greater increase in protein yield per ha at low N rate was because of yield increases that were not observed at high N rate (Table 3). Consequently, late-season foliarly applied urea (30 kg N ha^{-1}) brought about a small increment in grain N (5.7 kg N ha^{-1}) at high N rate compared to that at low N rate (16.3 kg N ha^{-1}). Reported recoveries of foliar N in grain range from only 4.5% (Rawluk et al., 2000) up to 64% (Powlson et al., 1989) for applications made between anthesis and grain milky ripe.

The gluten index exhibited a small, but significant decline following late-season urea treatment (Table 2), which was similar under both basal N rates (Table 5). Finney et al. (1957) pinpointed the incomplete gluten protein synthesis to explain why loaf volume from the flour with 19% protein was similar to that for flour with only 11% protein. This incomplete protein synthesis was associated with the large increase in the water-soluble protein for wheat frequently sprayed with urea. However, Ćurić et al. (2001) demonstrated that the gluten index higher than 75% is satisfactory for good breadmaking quality. Therefore, small decrease in the gluten index associated with late foliar urea application in our study should not be detrimental to wheat breadmaking quality (Table 5).

Cultivars significantly differed among themselves for the hectolitre weight, grain protein, Zeleny sedimentation, wet gluten content, gluten index and falling number (Table 2). The significant cultivar × urea interactions also occurred for all quality traits, except the falling number (Table 2). This was because none of the six cultivars showed any

Table 6
Average grain quality traits of winter wheat cultivars with or without late-season urea treatment, Zagreb, 2000–2002

Cultivar	Hectolitre weight (kg hl^{-1})		Protein content (g kg^{-1})		Zeleny sedimentation (cm^3)		Wet gluten content (g kg^{-1})		Gluten index (%)		Falling number (s)	
	No urea	Urea	No urea	Urea	No urea	Urea	No urea	Urea	No urea	Urea	No urea	Urea
Marija	78.5	79.4	112	115	23.9	26.8	225	242	93	90	337	338
Žitarka	80.7	81.3	110	118	26.5	29.9	257	275	83	77	301	298
Srpanjka	79.6	80.3	110	117	26.5	31.7	223	251	96	96	351	363
Soissons	78.8	79.7	106	110	23.8	26.8	207	225	98	98	329	338
Renan	79.7	80.2	115	121	30.8	33.6	242	268	96	94	327	314
Kuna	81.1	81.6	117	120	30.4	32.5	245	258	90	85	202	211
LSD (0.05)[a]	0.33		2.7		1.93		11.0		3.8		NS[b]	
LSD (0.05)[c]	0.35		2.7		1.95		11.4		4.0			

[a] LSD values for comparing means within the same cultivar.
[b] Not significant for cultivar × urea interaction at $P = 0.05$.
[c] LSD values for comparing means within the same urea management.

significant decrease or increase in the falling number following urea treatment at flowering (Table 6). In contrast, Peltonen and Peltonen (1990) in a greenhouse study found a significant increase in the falling number for two out of four spring wheat cultivars after foliar urea application at flowering.

The significant cultivar × urea interaction existed for the hectolitre weight because the average increments with urea spraying ranged from 1.7 kg hl^{-1} (2.2%) for cultivar Soissons to only 0.7 kg hl^{-1} (0.9%) for cultivar Renan (Table 6). The non-significance of cultivar × urea × N interaction (Table 2) indicated that none of the tested cultivars had an increased hectolitre weight at high basal N fertilization. However, cultivar-dependent responses to the urea treatment for the hectolitre weight varied across years (Table 2), and were mainly associated with the differences in the magnitude in responses and not in directions (data not shown).

Significantly increased grain protein after the urea treatment was observed in all cultivars (Table 6). The greatest increase of 8 g kg^{-1} accumulated cultivar Žitarka, whereas the smallest of 3 g kg^{-1} occurred in cultivars Marija and Kuna. Pushman and Bingham (1976) also reported different increases in grain protein content among 10 winter wheat cultivars given foliar urea application at anthesis, which was in contrast to the report by Gooding et al. (1991). In a greenhouse experiment, Seth et al. (1960) showed that an increase in grain protein was greater in the high-protein genotypes than in low-protein ones following foliar application of N after heading. However, in our research, cultivar-dependent increases in protein content after urea spraying could not be related to their genetic background for grain protein concentration. This is because some high-protein cultivars like Kuna exhibited a smaller increase in grain protein concentration than low-protein cultivar Srpanjka (Table 6) and vice versa (Marija versus Renan). Interestingly, these cultivar-specific responses for grain protein after late foliar urea application were not affected by two basal N fertilization rates and various growing conditions over three years (Table 2).

Similarly to grain protein responses, all cultivars significantly increased Zeleny sedimentation with foliar urea treatment at flowering (Table 6). The significant cultivar × urea interaction existed because of differences in the magnitude of responses. Similar results for SDS-sedimentation were shown by Gooding et al. (1991), despite the fact that cultivars used in their research responded similarly in terms of grain protein content. The highest increment in Zeleny sedimentation following urea spraying was found in cultivar Srpanjka (5.2 cm^3), which was more than 2-fold larger than that found for Kuna (2.1 cm^3). Wet gluten content also significantly improved in all cultivars after urea treatment (Table 6). Similarly to responses for Zeleny sedimentation, the largest increase was exhibited by Srpanjka (2.8%), whereas the lowest occurred for Kuna (1.3%). Although all cultivars tended to have a smaller gluten index following late foliar urea application, these reductions were significant only for Žitarka and Kuna (Table 6).

Growing conditions significantly affected cultivar performance for grain quality (Table 2). Significantly smaller average grain protein concentration occurred in 2000 (106 g kg^{-1}) and 2001 (111 g kg^{-1}) compared to that observed in 2002 (125 g kg^{-1}), following a similar trend as grain yield responses. In 2000, grain protein concentrations for Soissons, Srpanjka and Žitarka were below the baseline level for breadmaking wheat (>114 g kg^{-1}) even at high basal N fertilization. Following urea spraying, these

Table 7
Grain protein (g kg^{-1}) of winter wheat cultivars following urea spraying at low (67 kg N ha^{-1}) and high (194 kg N ha^{-1}) basal N fertilisation, Zagreb, 2000–2002

Cultivar	Growing season					
	2000		2001		2002	
	Low N	High N	Low N	High N	Low N	High N
Marija	100[a]	111	110	127	109	131
Žitarka	101	121	105	123	117	141
Srpanjka	93	115	113	128	115	142
Soissons	98	115	94	113	108	132
Renan	104	125	101	125	126	147
Kuna	108	124	105	125	117	144

[a] Non-significant cultivar × N × urea interaction at $P = 0.05$.

cultivars achieved protein content sufficient for breadmaking quality (Table 7). Thus, late-season urea spraying might be important practice even under high basal N fertilization because it may provide low-protein cultivars with satisfactory breadmaking quality in years when N availability in soil is limited by drought. However, most cultivars failed to achieve breadmaking standard at low N rate because quality increments arising from urea treatment were relatively small when compared to those achieved by high N versus low N rate (Table 5). Grain protein averaged 125 g kg^{-1} at high N rate in comparison to only 103 g kg^{-1} at low N rate, a relatively large increase of 21.4%, whereas protein increase due to the late-season urea spraying averaged only 5 g kg^{-1} (4.5%) when compared to untreated plots. The decline in grain protein concentration if the amount of added N was inadequate for potential yield was also shown McNeal and Davis (1954) and Terman et al. (1969). Consequently, at low N rate only four cultivars in the most favourable growing conditions of 2002 succeeded to achieve grain protein above 114 g kg^{-1} following foliar urea application at flowering (Table 7). Although quality increments resulting from late-season urea spraying were consistent at both N fertilization rates (Table 2), our findings demonstrated the importance of optimum N fertilization earlier in the season to achieve high yields and especially good breadmaking quality. Cassman et al. (1992) also emphasized the importance of both preplant and in-season N fertilizer management for optimizing yield and protein content in wheat. The non-significance of year × urea × cultivar interaction for all grain quality traits indicated that cultivar-dependent increases in protein content, Zeleny sedimentation and wet gluten content following urea spraying were relatively constant across varying growing conditions over three years (Table 2).

4. Conclusions

Our findings indicated the potential use of late urea spraying for improved grain yields in winter wheat crop if previous N applications were suboptimal for maximum yield potentials. Following urea spraying, grain quality increments for protein content, Zeleny sedimentation, and wet gluten content were consistent at both low and high basal N fertilization regardless of variations in grain yields and protein concentrations across years. Cultivars differed in their magnitude of responses to urea spraying for most grain quality traits.

References

Altman, D.W., McCuistion, W.D., Kronstad, W.E., 1983. Grain protein percentage, kernel hardness, and grain yield of winter wheat with foliar applied urea. Agron. J. 75, 87–91.

Barraclough, P.B., Haynes, J., 1996. The effect of foliar supplements of potassium nitrate and urea on the yield of winter wheat. Fertil. Res. 44, 217–223.

Bly, A.G., Woodard, H.J., 2003. Foliar nitrogen application timing influence on grain yield and protein concentration of hard red winter and spring wheat. Agron. J. 95, 335–338.

Cassman, K.G., Bryant, D.C., Fulton, A.E., Jackson, L.F., 1992. Nitrogen supply effects on partitioning of dry matter and nitrogen to grain of irrigated wheat. Crop Sci. 32, 1252–1258.

Ćurić, D., Karlović, D., Tušak, D., Petrović, B., Đugum, J., 2001. Gluten as a standard of wheat flour quality. Food Technol. Biotechnol. 39, 353–361.

Dampney, P.M.R., Salmon, S., 1990. The effect of rate and timing of late nitrogen applications to breadmaking wheats as ammonium nitrate or foliar urea-N, and the effect of foliar sulphur application: I. Effect on yield, grain quality and recovery of nitrogen in grain. Aspects Appl. Biol. 25, 229–241.

Državni zavod za statistiku, 2002. Statistički ljetopis. Državni zavod za statistiku, Zagreb, Croatia.

Dubetz, S., 1977. Effects of high rates of nitrogen on Neepawa wheat grown under irrigation. I. Yield and protein content. Can. J. Plant Sci. 57, 331–336.

Endres, G., Schatz, B., 1993. Foliar N applied post-anthesis to enhance wheat grain protein.. Misc. Publ. North Dakota State Univ., Carrington Res. Ext. Cent, Carrington, ND.

Finney, K.F., Meyer, J.W., Smith, F.W., Fryer, H.C., 1957. Effect of foliar spraying on Pawnee wheat with urea solutions on yield, protein content, and protein quality. Agron. J. 49, 341–347.

Garrido-Lestache, E., Lopez-Bellido, R.J., Lopez-Bellido, L., 2004. Effect of N rate, timing and splitting and N type on bread-making quality in hard red spring wheat under rainfed Mediterranean conditions. Field Crops Res. 85, 213–236.

Gooding, M.J., Kettlewell, P.S., Hocking, T.J., 1991. Effects of urea alone or with fungicide on the yield and breadmaking quality of wheat when sprayed at flag leaf and ear emergence. J. Agric. Sci. 117, 149–155.

International Association for Cereal Chemistry, 1994. Standard methods of the ICC. Verlag Moritz Schafer, Detmold, Germany.

McNeal, F.H., Davis, D.J., 1954. Effect of nitrogen fertilization on yield, culm number, and protein content of certain spring wheat varieties. Agron. J. 46, 375–378.

Peltonen, J., Peltonen, P., 1990. Effect of apical-timed urea spraying on yield components and quality properties of spring wheat (*Triticum aestivum* L.) in greenhouse experiments. Acta Agric. Scan. 40, 33–43.

Peltonen, J., Kittila, S., Peltonen-Sainio, P., Karjalainen, R., 1991. Use of foliar-applied urea to inhibit the development of *Septoria nodorum* in spring wheat. Crop Prot. 10, 260–264.

Powlson, D.S., Poulton, P.R., Moller, N.E., Hewitt, M.V., Penny, A., Jenkinson, D.S., 1989. Uptake of foliar applied urea by winter wheat (*Triticum aestivum*): the influence of application time and use of a new ^{15}N technique. J. Sci. Food Agric. 48, 429–440.

Pushman, F.M., Bingham, J., 1976. The effects of a granular nitrogen fertilizer and a foliar spray of urea on the yield and bread-making quality of ten winter wheats. J. Agric. Sci. 87, 281–292.

Rawluk, C.D.L., Racz, G.J., Grant, C.A., 2000. Uptake of foliar or soil application of ^{15}N-labelled urea solution at anthesis and its affect on wheat grain yield and protein. Can. J. Plant Sci. 80, 331–334.

Ruske, R.E., Gooding, M.J., Jones, S.A., 2003. The effects of adding picoxystrobin, azoxystrobin and nitrogen to a triazole programme on disease control, flag leaf senescence, yield and grain quality of winter wheat. Crop Prot. 22, 975–987.

SAS Institute, 1997. SAS/STAT software: changes and enhancements through release 6.12. SAS Inst., Cary, NC.

Seth, J., Hebert, T.T., Middleton, G.K., 1960. Nitrogen utilization in high and low protein wheat varieties. Agron. J. 52, 207–209.

Strong, W.M., 1982. Effect of late application of nitrogen on yield and protein content of wheat. Aust. J. Exp. Agric. Anim. Husb. 22, 54–61.

Terman, G.L., Ramig, R.E., Dreier, A.F., Olson, R.A., 1969. Yield–protein relationships in wheat grain as affected by nitrogen and water. Agron. J. 61, 755–759.

Tipples, K.H., Dubetz, S., Irvine, G.N., 1977. Effects of high rates of nitrogen on Neepawa wheat grown under irrigation: II. Milling and baking quality. Can. J. Plant Sci. 57, 337–350.

Varga, B., Svečnjak, Z., Pospišil, A., 2001. Winter wheat cultivar performance as affected by production systems in Croatia. Agron. J. 93, 961–966.

Woolfolk, C.W., Raun, W.R., Johnson, G.V., Thomason, W.E., Mullen, R.W., Wynn, K.J., Freeman, K.W., 2002. Influence of late-season foliar nitrogen applications on yield and grain nitrogen in winter wheat. Agron. J. 94, 429–434.

Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for growth stages of cereals. Weed Res. 14, 415–421.