EFFECT OF NITROGEN APPLICATION ON GRAIN YIELD AND WATER USE EFFICIENCY OF WINTER WHEAT UNDER ZERO TILLAGE AND SPRING WHEAT UNDER ZERO AND CONVENTIONAL TILLAGE, IN MANITOBA

B.J. Green and A.O. Ridley
Saskatchewan Rural Development - Extension Service, Kerrobert
and University of Manitoba

ABSTRACT

Five site-years of data collected from the Carberry and Manitou areas of Manitoba from 1985 to 1987 indicated that increased rates of N application increased grain yield, protein content of the grain and water use efficiency (based on grain yield) of winter wheat under zero tillage, spring wheat under zero tillage and spring wheat under conventional tillage. Although the response to N application varied between wheat-tillage regimes within and between individual site-years, spring wheat under zero tillage slightly outyielded spring wheat under conventional tillage and winter wheat under zero tillage when data for the site-years was combined. Conversely, water use efficiency was highest for winter wheat under zero tillage and lowest for spring wheat under conventional tillage. Protein content of the grain was the same for the spring wheats but substantially lower for winter wheat.

INTRODUCTION

Zero tillage and winter wheat are both relatively new to the eastern prairies. Zero tillage has been found to be an effective means of combating soil erosion, increasing spring soil moisture levels by snow entrapment (Gauer et al. 1982), slowing the evaporative loss of spring soil moisture by reducing wind speed near the soil surface (Brun, 1985), and providing for a moderation of severe winter soil temperatures through snow entrapment by stubble (Gusta et al., 1983) thereby enabling winter wheat production on the eastern prairies (Grant et al., 1985). Furthermore, winter wheat has been reported to substantially outyield spring wheat and to use water more efficiently that spring wheat, although protein content of the grain of winter wheat was lower than that of spring wheat (Fowler, 1983).

An understanding of the response to rate of N application is essential for determining both crop potential and crop management. The response to applied-N and the effect of soil moisture on this response by winter and spring wheat under conventional tillage are relatively well documented. However, winter wheat and zero tillage are relatively new to Manitoba and most of Manitoba is generally less arid than those areas where much of the research has been done. Therefore, this study was initiated to study and compare the response to rate of N application by winter wheat under zero tillage (WWZT), spring wheat under zero tillage (SWZT) and spring wheat under conventional tillage (SWCT), on the eastern Canadian prairies.

METHODS AND MATERIALS

The experiment was conducted on a Manitou CL southeast of Manitou, Manitoba, during the 1984-85, 1985-86 and 1986-87 crop years, and on a Wellwood CL northwest of Carberry, Manitoba, during the 1985-86 and 1986-87 crop years. There was also a site at Carberry in the 1984-85 crop year but data from this site-year was excluded because the winter wheat did not survive the winter. The Manitou CL and Wellwood CL soils are both Orthic Black Chernozem. Plot sites were moved for each crop year.

Non-replicated main blocks for WWZT, SWZT and SWCT were laid out on a field of barley stubble (approximately 20 cm high) once the barley crop had been harvested. Zero till main blocks were harrowed to spread the barley straw and then sprayed with 1.10 L ha^{-1} of 356 g L^{-1} glyphosate plus 0.35 L ha^{-1} of non-ionic surfactant in 112 L ha^{-1} of water the day prior to seeding to kill the existing weeds. The conventional till main block was cultivated approximately 10 cm deep and harrowed in the early fall and then tandem disced approximately 7 cm deep and harrowed in the spring just before seeding.

Six replicates of randomized subplots (2 m by 10 m) were laid out in each main block. Subplots within each tillage regime were located at least 6 m from the edge of their main block to minimize the effect of the adjacent main blocks and farmer's field on snow entrapment and wind speed. Winter wheat (c. Norstar) was sown between September 7 and 20 while spring wheat (c. Neepawa) was sown between May 7 and 27, depending on the site-year. Seeding rate was 110 kg ha^{-1} and seeding depth was approximately 3 cm. The drill used was a Versatile Noble Model 2200 hoe-press drill with 10 hoes 20 cm apart.

All subplots received 25 kg P ha^{-1}, as 11-51-0, with the seed. This also provided 12 kg applied-N ha^{-1}. Additional N, as 46-0-0, was surface-applied after seeding to establish subplot treatments of 12, 30, 60, 90, 120, 180, 240 and 300 kg applied-N ha^{-1} for WWZT and SWZT; and 12, 60, 180 and 300 kg applied-N ha^{-1} for SWCT. Fewer subplot treatments were established for the SWCT due to budget constraints. Spring soil NO_3-N levels to the 120 cm depth ranged from 41 to 72 kg ha^{-1}, depending on the site-year (Table 1). Soil K and SO4-S levels were considered adequate.

Soil moisture content at time of spring wheat seeding and at time of harvest of the respective wheats was determined gravimetrically on the 12, 60, 90, 180 and 300 kg applied-N ha^{-1} treatments of the zero till wheats and on all N treatments of the SWCT, in 3 of the 6 replicates. Soil moisture was determined in 0-15, 15-30, 30-60, 60-90 and 90-120 cm increments for both sites in the 1985-86 crop year and the Manitou site in the 1986-87 crop year. Sampling to only 60 cm in the first study year and a fire in the drying room while the Carberry samples from the third study year were being dried prevented data from these site-years being included. Water use efficiency based on grain yield (WUE) was determined according to the equation of de Jong and Rennie (1969), i.e. WUE equals grain yield divided by consumptive water use; where consumptive water use equals the spring soil moisture content plus precipitation minus the harvest soil moisture content. Daily precipitation was recorded at each plot site during the growing season using a Belfort recording rainguage, although herein it is reported on a monthly basis. Precipitation data from the nearest weather station was used to depict non-growing season precipitation as well as to what degree growing season and non-growing season precipitation differed from long-term average precipitation levels.

Herbicides were applied as necessary at recommended rates. The fungicide Tilt was applied each site-year to the winter wheat as rust and leaf diseases became evident. In 1986 very high levels of rust were encountered and thus the winter wheat was sprayed a second time with Tilt. The spring wheat was also becoming affected by rust in 1986 so it was sprayed once with Tilt.

At harvest 2 m of the centre 4 rows in each subplot (2 m in from the edge of the subplot) was cut at ground level. The sheaves were bagged, air-dried and threshed using a stationary thresher. Grain samples were weighed and tested for moisture content, and then yields were adjusted to a 13.5 % moisture content basis. Grain sampled were ground and then analyzed for total N using a modified automated micro-Kjeldahl procedure as described by Schuman et al. (1973). Percent protein content of the grain was arrived at by multiplying percent N content of the grain by 5.7.

All statistical analysis was conducted under release 5.16 of SAS on the University of Manitoba mainframe computer. The PROCEDURE REGRESSION was used to produce lines of best fit (predicted lines) by simple quadratic regression analysis, and upper and lower 95 % confidence limits of the mean value. The confidence limits allowed comparison between rates of applied-N within each wheat-tillage regime, however, statistical comparison between wheat-tillage regimes could not be made because replicate blocks were not randomized. The PROCEDURE GPLOT was used to graphically present the predicted lines.

RESULTS AND DISCUSSION

Non-growing season precipitation at the 1984-85 Manitou plot site (data was actually collected at the Morden CDA weather station) was close to the long-term average (Table 2) and this allowed the zero till main blocks to accumulate approximately 15 mm more moisture than the conventional till main block (Table 3) through greater snow entrapment by the standing stubble (Table 4). Growing season precipitation, however, was substantially greater than the long-term average (Table 2) and this provided for excellent grain yields and a highly significant response to applied-N with each wheat-tillage regime (Figure 1 and Tables 5). Grain yields increased with increasing rates of N application up to 180 to 240 kg applied-N ha^{-1} before levelling off. The SWZT outyielded the SWCT at all rates of applied-N except at the highest treatment, and outyielded the WWZT at rates of N application up to 90 kg applied-N ha^{-1}.

Non-growing season precipitation at the 1985-86 Carberry plot site (data was actually collected at the Brandon A weather station) was 35 mm above the long-term average (Table 2). However, the zero till main blocks were still able to accumulate from 11 to 15 mm more soil moisture than the conventional till (Table 3), due to greater snow entrapment by the standing stubble of the zero tillage (Table 4). Conversely, growing season precipitation during 1986 was slightly below the long-term average (Table 2). Moderate grain yields were an indication of the less than optimum amount of precipitation, however, precipitation plus stored soil moisture were still high enough that each wheat-tillage regime showed a highly significant response to applied-N and yields increased with increased rates of N application up to 180 to 240 kg applied-N ha^{-1} before levelling off (Figure 2 and Table 6). The SWZT outyielded the SWCT except, again, at the highest N treatment. Furthermore, the SWCT outyielded the WWZT although only very slightly so at low to moderate rates of applied-N. The WUE for each wheat-tillage regime also increased with increasing rates of N application up to 180 to 300 kg applied-N ha^{-1} and the response to N application was highly significant (Figure 3 and Table 7). The WUE levels for WWZT were very similar to those for SWZT except at very high rates of N application at which point the WUE for WWZT fell off. The WUE levels for SWCT were lower than those for SWZT, except at the 300 kg applied-N ha^{-1} rate.

Although non-growing season precipitation for the 1985-86 Manitou plot site was only 17 mm above the long-term average, the amount of precipitation received in April 1986 was over twice the long-term average for that month (Table 2). As a result the benefit of greater snow entrapment (Table 4) and thus greater spring soil moisture in the zero till main blocks was negated (Table 3). Growing season precipitation was substantially lower than the long-term average (Table 2), however, moderate yields and a highly significant response to applied-N by each wheat-tillage regime were still realized (Figure 4 and Table 8) due to the high spring soil moisture levels. Grain yields increased with increasing rates of N application up to 180 to 240 kg applied-N ha^{-1} before levelling off. Grain yields were similar for each wheat-tillage regime, although the WWZT did outyield the spring wheats and SWCT did slightly outyield the SWZT at all rates of applied-N except the highest. The WUE for each wheat tillage increased with increasing rates of N application up to 180 kg applied-N ha^{-1}, but the N response was significant for the WWZT only (Figure 5 and Table 9). The WUE was highest for WWZT and lowest for SWCT.

Non-growing season and growing season precipitation for the 1986-87 Carberry plot site were very close to the long-term average for that area (Table 2). Winter snow depth measurements indicate that the zero till main blocks trapped more snow than did the conventional till main block (Table 4), however, spring soil moisture measurements were not available to substantiate that this translated into greater spring soil moisture due to a soil drying oven fire that damaged many of the soil samples. Grain yields were poor for each wheat tillage regime and only the SWZT showed a highly significant response to N application (Figure 6 and Table 10). The WWZT response to N application was almost a horizontal line and the spring wheats showed only small yield increases as N application was increased to 180 kg applied-N ha^{-1}. The less than optimum precipitation levels plus the relatively high soil NO_3-N level (41 kg NO_3-N·ha^{-1}) were considered responsible for the poor responses to N application. The SWZT slightly outyielded the SWCT and both spring wheats substantially outyielded the WWZT. Less than long-term average precipitation during the months of April, May and June followed by high precipitation in July likely gave the spring wheats an advantage over the winter wheat due to their younger growth stage when the rains eventually came.

Little difference in snow depth occurred between the zero till and conventional till main blocks at the 1986-87 Manitou plot site, likely due to the greater amount of wet winter snow that remained where it fell (Table 4). Thus not only did the zero till main blocks not realize a moisture advantage over the conventional till main block but they were found to have slightly less spring soil moisture than did the conventional till main block (Table 3). Non-growing season precipitation was very close to the long-term average whereas growing season precipitation was considerably higher than the long-term average (Table 2). Moderate grain yields were realized by each wheat-tillage regime, although only the SWZT showed a highly significant response to N application (Figure 7 and Table 11). Grain yields increased slowly with increasing rates of N application up to 180 to 300 kg applied-N ha^{-1} before levelling off. The lack of significant response and the low R2 values were attributed the less than optimum precipitation coupled with a soil NO_3-N level to the 120 cm depth of 72 kg ha^{-1}. The WWZT slightly outyielded the SWCT which in turn slightly outyielded the SWZT. The WWZT would likely have shown a greater yield advantage over the spring wheats had the high level of precipitation that fell in July fallen earlier in the season when the winter wheat could have made use of it. The WUE for each wheat-tillage regime increased only slightly with increasing rates of N application and the response was not significant (Figure 8 and Table 12). This was also attributed to the less than optimum precipitation coupled with the high soil NO_3-N level. The WUE for WWZT surpassed that for the spring wheats at all rates of N application. The WUE was slightly greater for the SWCT at low to moderate rates of N application whereas the WUE for the SWZT was greater at moderate to high rates of N application.

Precipitation levels at the 5 site-years ranged from near to far above the long-term average. Figure 9 and Table 13 show the grain yield data combined for all 5 site years. Each wheat-tillage regime showed a highly significant response to N application although R2 values were very low. The low R2 values were attributed to the large difference in grain yields between site-years and the relatively high soil NO_3-N levels. The SWZT outyielded both the SWCT and WWZT at all rates of N application and even the SWCT slightly outyielded the WWZT. The SWZT outyielded the SWCT because the standing stubble of the zero till trapped more snow and thus provided for greater spring soil moisture levels in the SWZT (Staple et al., 1960; Schneider, 1979; Gauer et al., 1982) and/or the standing stubble of the zero till reduced wind speed near the soil surface and thus slowed the evaporative loss of soil moisture prior to crop canopy development in the spring (Aase and Siddoway, 1980; Brun, 1985). Other researchers have also found higher yields for SWZT than for SWCT (Bradley and Donaghy, 1977; Spilde and

Deibert, 1986), however, still others found that SWCT outyielded SWZT (Donaghy, 1973; Deibert et al., 1985; Deibert et al., 1986). Although winter wheat has been reported to outyield spring wheat (Fowler, 1983; Rourke et al., 1983; Rourke and Stobbe, 1984) the opposite occurred in this study. Winter wheat is actively growing earlier in the spring than spring wheat and this is considered by some researchers to allow for more timely use of soil moisture during the spring (Brown and Black, 1983; Fowler, 1983; Rourke et al., 1983; Rourke and Stobbe, 1984). In Saskatchewan, Gross et al. (1987) found that winter wheat rooted deeper and more extensively than spring wheat up until the flowering stage of spring wheat development; at which point in time spring wheat caught up with winter wheat. However, by the flowering stage of spring wheat growth the soil had lost much of its water reserves and thus because of its earlier growth habit winter wheat is a more efficient user of spring soil moisture. In this study, part of the reason that the winter wheat did not yield as well as the spring wheat is that 2 of the site years experienced high rainfall in July when it would benefit spring wheat growth more so than it would benefit winter wheat growth. Furthermore, the other 3 site-years experienced a level of precipitation higher than the long-term average in either the growing season or the non-growing season. Thus the high levels and timing of rainfall experienced in this study conspired against the winter wheat. A second reason the winter wheat did not yield at least as well as the spring wheat is that the winter wheat was fertilized in the early fall just after seeding whereas the spring wheat was fertilized in the spring just after seeding (Ridley, 1973; Partridge and Ridley, 1974).

The combined site-year data indicated that WUE was increased by N application, and that the WUE of WWZT surpassed that of SWZT which in turn surpassed the WUE of SWCT, at all rates of N application (Figure 10 and Table 14). As with grain yield, the WUE was greater for SWZT than for SWCT because the standing stubble of the zero tillage trapped more snow and thereby gave the zero tillage a moisture advantage and/or the standing stubble reduced wind speed near the soil surface of the zero tillage such that the soil evaporative loss was reduced. The WUE for WWZT surpassed that of the spring wheats because winter wheat is a more efficient user of moisture due to its earlier growth habit and deeper, more extensive early season rooting. That the WWZT used water more efficiently than the SWZT but did not yield as well was not considered an anomaly because the winter wheat was simply not able to use the moisture that came in July (as experienced during the last 2 site-years) as well as the spring wheat was able to. Furthermore, high levels of precipitation (as experienced during the first 3 site-years) would appear to lessen the advantage of the earlier growth habit and deeper, more extensive early season rooting by the winter wheat.

Data of protein content of the grain was not presented here on an individual site-year basis because the results did not differ markedly from the combined site-year data. In the combined site-year data (Figure 11 and Table 15) as in the case of each individual site-year, protein content increased with increasing rates of N application up to 240 to 300 kg applied-N ha^{-1}. Furthermore, the response to N application was highly significant and the response curves for SWZT and SWCT differed very little. In the first 3 site-years and in the combined site-year data the protein content of the grain of WWZT was substantially lower than that for the spring wheats. In the last 2 site-years this was the case at low to moderate rates of N application, but at high rates of N application protein content of the WWZT surpassed that of the spring wheats probably because the high July rainfall promoted grain production in the spring wheats but was too late to do so in the winter wheat. The lower protein content of winter wheat was attributed to the genetic nature of that plant.

SUMMARY AND CONCLUSIONS

Grain yield, protein content of the grain and WUE for each wheat-tillage regime generally increased with increasing rates of N application up to between 180 and 300 kg applied-N ha^{-1}. When data for the 5 site-years was combined the SWZT outyielded the SWCT and WWZT, although application of N in the fall on the winter wheat versus in the spring for spring wheat may have slightly favoured the spring wheat over the winter wheat. Protein content of the grain differed very little between SWZT and SWCT, but was substantially lower for the WWZT. The WUE was highest for WWZT because winter wheat is a more efficient user of water. The WUE was greater for the SWZT than for the SWCT because the standing stubble of the zero tillage increased and then conserved soil moisture more than the conventional tillage was able to do.

Therefore, although winter wheat can be successfully grown in Manitoba using zero tillage cropping practices, its inconsistent yield advantage, lower quality, lower value and higher cost of production (due to fungicide application) make it less attractive to the farmer than spring wheat under zero tillage. Alternatively, because the SWZT outyielded and used water more efficiently than the SWCT while maintaining grain protein content, and because zero tillage reduces wind and water erosion, it was concluded that spring wheat production using zero tillage was beneficial to the farmer and the public in general.

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Table 1. Soil NO_3-N (kg ha^{-1}) characterization[1]

	Fall		Spring	
	0-60 cm	0-120 cm	0-60 cm	0-120 cm
1984-85 Manitou	20.2	--	37.4	69.5
1985-86 Carberry	26.6	27.7	35.5	63.4
1985-86 Manitou	7.6	7.7	33.6	47.4
1986-87 Carberry	12.2	20.1	30.0	41.0
1986-87 Manitou	20.7	51.4	43.5	72.4

[1] mean of 3 samples.

Table 3. Soil moisture content (mm to 120 cm depth)[1] at time of spring wheat planting

	WWZT	SWZT	SWCT
1984-85 Manitou	232	229	215
1985-86 Carberry	379	375	364
1985-86 Manitou	522	517	535
1986-87 Carberry	---	---	---
1986-87 Manitou	410	422	426

[1] mm to 60 cm depth at 1984-85 Manitou.

Table 2. Monthly precipitation (mm) at the plot sites and the Morden CDA and Brandon A weather stations during each site-year, and long-term average (1951-80 Canadian Climate Normals) monthly precipitation (mm) at the Morden CDA and Brandon A weather stations

		Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept. to April	May to Aug.
1984-85	Manitou	--	--	--	--	--	--	--	--	51	125	22	141	--	339
	Morden	32	118	23	24	9	17	13	15	60	116	40	194	251	410
1985-86	Manitou	--	--	--	--	--	--	--	--	67	59	68	23	--	217
	Morden	23	39	54	10	16	11	11	97	76	34	98	18	261	226
	Carberry	--	--	--	--	--	--	--	--	--	51	86	35	--	--
	Brandon	73	15	20	11	22	10	27	63	69	73	79	19	241	240
1986-87	Manitou	--	--	--	--	--	--	--	--	40	51	111	79	--	281
	Morden	46	14	52	3	12	60	13	0	47	62	148	63	200	320
	Carberry	--	--	--	--	--	--	--	--	15	44	79	99	--	237
	Brandon	55	23	11	8	10	33	48	5	30	60	109	67	193	266
Long-term Average	Morden	52	32	26	22	24	19	28	41	66	46	73	71	244	286
	Brandon	44	22	18	19	19	19	20	34	47	77	67	65	195	256

Table 4. Snow depth[1] (cm)

Date (month/day) at Manitou 1984-85

	12/06	12/18	01/04	01/28	02/05	02/11	02/26	03/11	03/26
WWZT	19	23	22	24	23	29	15	22	0
SWZT	16	22	24	24	23	30	13	17	0
SWCT	5	14	13	16	14	23	9	13	0

Date (month/day) at Carberry 1985-86

	11/28	12/11	12/19	01/08	01/22	02/05	02/19	03/04	03/19	04/02
WWZT	15	18	16	21	21	23	28	26	21	0
SWZT	18	19	18	20	19	21	27	26	18	0
SWCT	8	9	10	12	11	19	30	23	16	0

Date (month/day) at Manitou 1985-86

	27/11	12/10	12/18	01/07	01/21	02/04	02/18	03/05	03/18	04/01
WWZT	17	22	21	27	22	23	26	19	1	0
SWZT	22	22	19	23	21	25	29	30	16	5
SWCT	9	13	7	11	9	13	17	22	5	0

Date (month/day) at Carberry 1986-87

	11/20	12/02	12/16	01/06	01/20	02/11	02/24	03/10
WWZT	12	10	15	17	22	24	28	29
SWZT	14	13	18	14	21	22	26	27
SWCT	6	7	11	14	16	16	22	24

Date (month/day) at Manitou 1986-87

	11/21	12/03	12/17	01/07	01/21	02/10	02/25	03/11
WWZT	30	23	27	27	27	29	31	39
SWZT	30	25	25	26	32	37	38	42
SWCT	26	23	21	22	28	33	33	39

[1] each recording is the mean of 3 measurements.

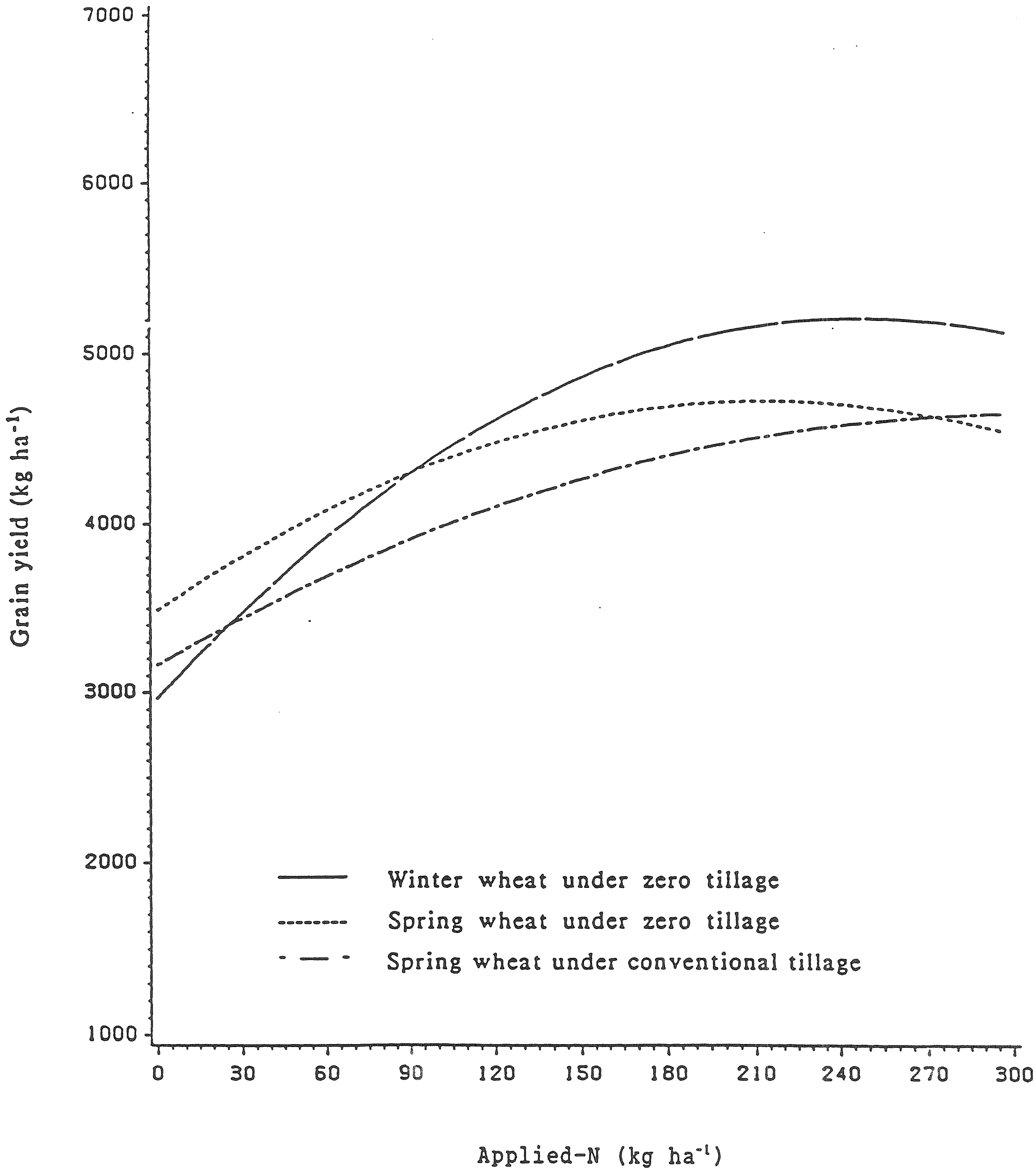

Figure 1. Lines of best fit for grain yield as affected by rate of applied-N at Manitou in 1985

Table 5. Grain yield (kg ha^{-1}) as affected by rate of applied-N at Manitou in 1985

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	3180	3539	2822	3624	3880	3368	3280	3801	2758
30	3470	3750	3190	3805	4005	3605	--	--	--
60	3912	4129	3694	4074	4230	3919	3686	4063	3309
90	4289	4521	4056	4297	4463	4131	--	--	--
120	4601	4868	4334	4472	4663	4282	--	--	--
180	5031	5320	4743	4682	4888	4476	4392	4920	3864
240	5203	5476	4931	4703	4897	4508	--	--	--
300	5117	5566	4668	4535	4855	4214	4644	5226	4063

1 $Y = 2964 + 17.95N - 3.950*10^{-2}N^2$, $R^2 = 0.61^{**}$.

2 $Y = 3488 + 11.35N - 2.620*10^{-2}N^2$, $R^2 = 0.45^{**}$.

3 $Y = 3163 + 9.66N - 1.575*10^{-2}N^2$, $R^2 = 0.42^{**}$.

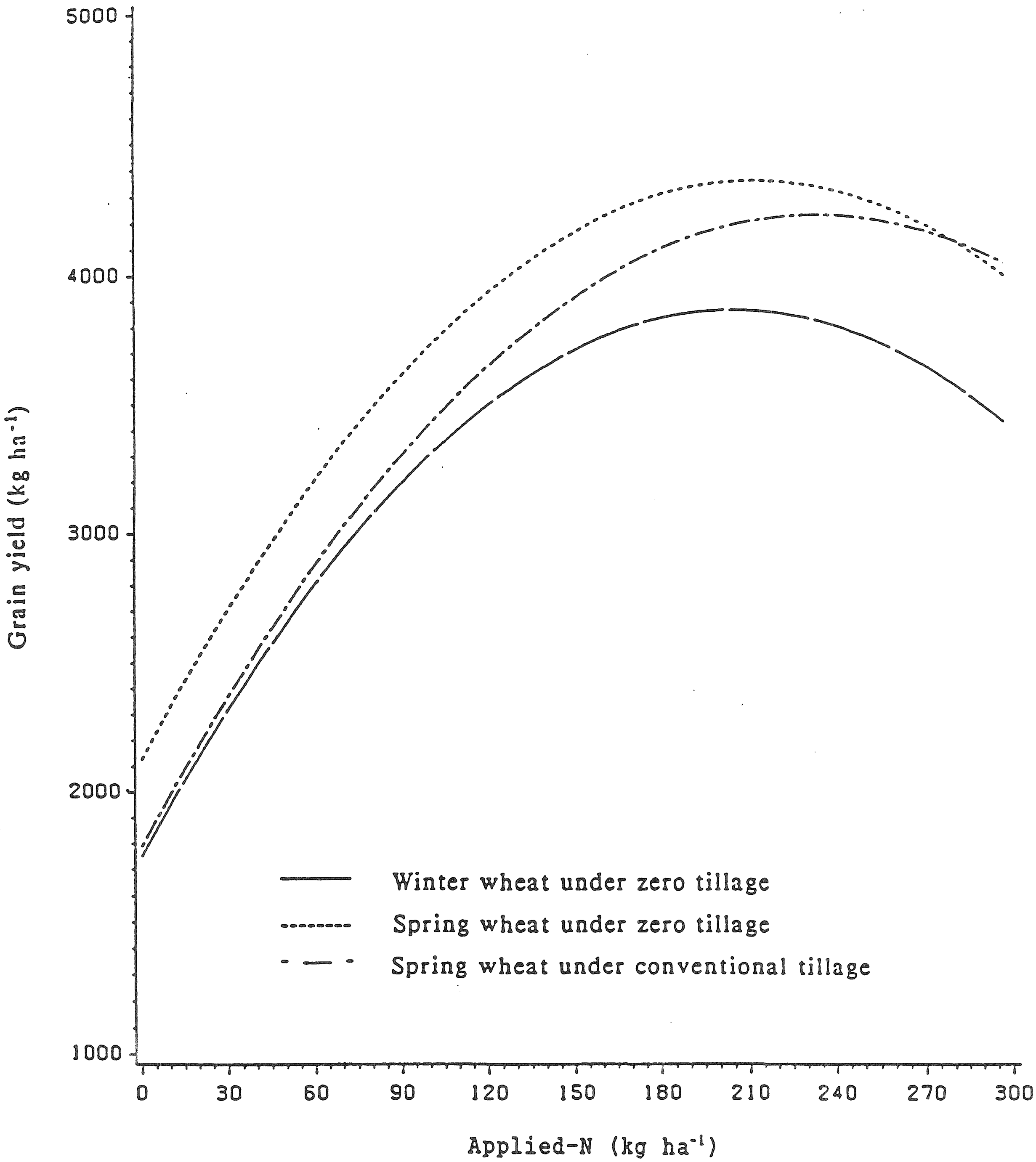

Figure 2. Lines of best fit for grain yield as affected by rate of applied-N at Carberry in 1986

Table 6. Grain yield (kg ha^{-1}) as affected by rate of applied-N at Carberry in 1986

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	1995	2336	1653	2375	2557	2194	2038	2300	1776
30	2320	2586	2053	2708	2849	2566	--	--	--
60	2001	3008	2594	3202	3312	3092	2874	3064	2685
90	3192	3413	2971	3608	3726	3491	--	--	--
120	3493	3748	3239	3927	4062	3792	--	--	--
180	3827	4102	3553	4299	4445	4153	4091	4357	3826
240	3802	4062	3543	4318	4456	4180	--	--	--
300	3418	3845	2991	3985	4212	3758	4035	4327	3742

1 $Y = 1749 + 20.52N - 4.985 \times 10^{-2}N^2$, $R^2 = 0.57^{**}$.

2 $Y = 2125 + 20.89N - 4.896 \times 10^{-2}N^2$, $R^2 = 0.84^{**}$.

3 $Y = 1788 + 20.76N - 4.423 \times 10^{-2}N^2$, $R^2 = 0.87^{**}$.

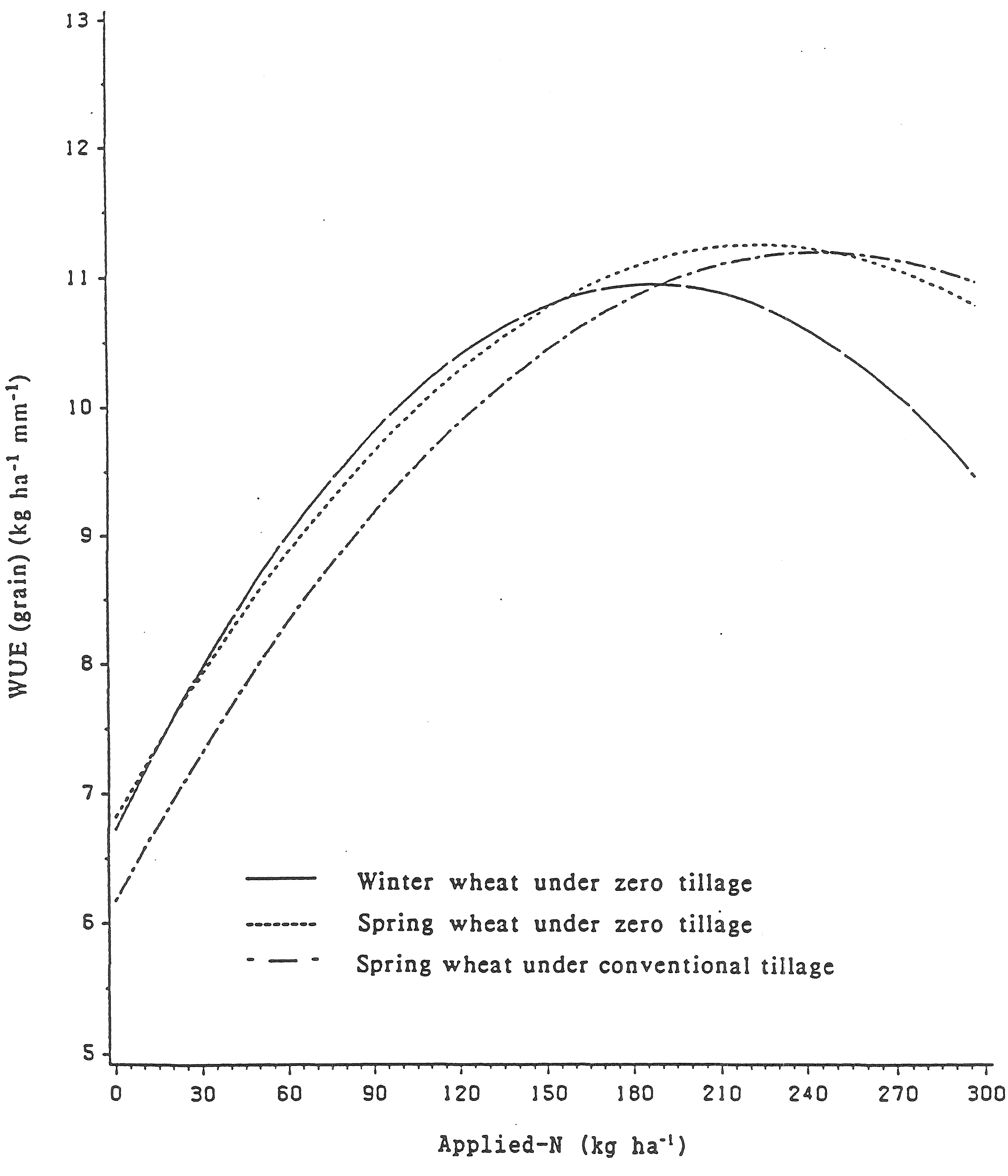

Figure 3. Lines of best fit for water use efficiency (WUE) based on grain yield as affected by rate of applied-N at Carberry in 1986

Table 7. Water use efficiency (WUE) based on grain yield (kg ha^{-1} mm^{-1}) as affected by applied-N at Carberry in 1986

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted WUE[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	7.3	8.9	5.7	7.3	8.3	6.2	6.7	8.3	5.0
30	--	--	--	--	--	--	--	--	--
60	9.0	10.0	8.0	8.9	9.5	8.2	8.3	9.5	7.1
90	9.8	10.9	8.7	9.6	10.3	8.9	--	--	--
120	--	--	--	--	--	--	--	--	--
180	10.9	12.3	9.5	11.0	12.0	10.1	10.8	12.5	9.2
240	--	--	--	--	--	--	--	--	--
300	9.4	11.2	7.6	10.8	11.9	9.6	10.9	12.8	9.1

[1] $Y = 6.7 + 4.48*10^{-2}N - 1.19*10^{-4}N^2$, $R^2 = 0.46^{*}$.

[2] $Y = 6.8 + 3.91*10^{-2}N - 8.66*10^{-5}N^2$, $R^2 = 0.73^{**}$.

[3] $Y = 6.2 + 4.07*10^{-2}N - 8.27*10^{-5}N^2$, $R^2 = 0.68^{**}$.

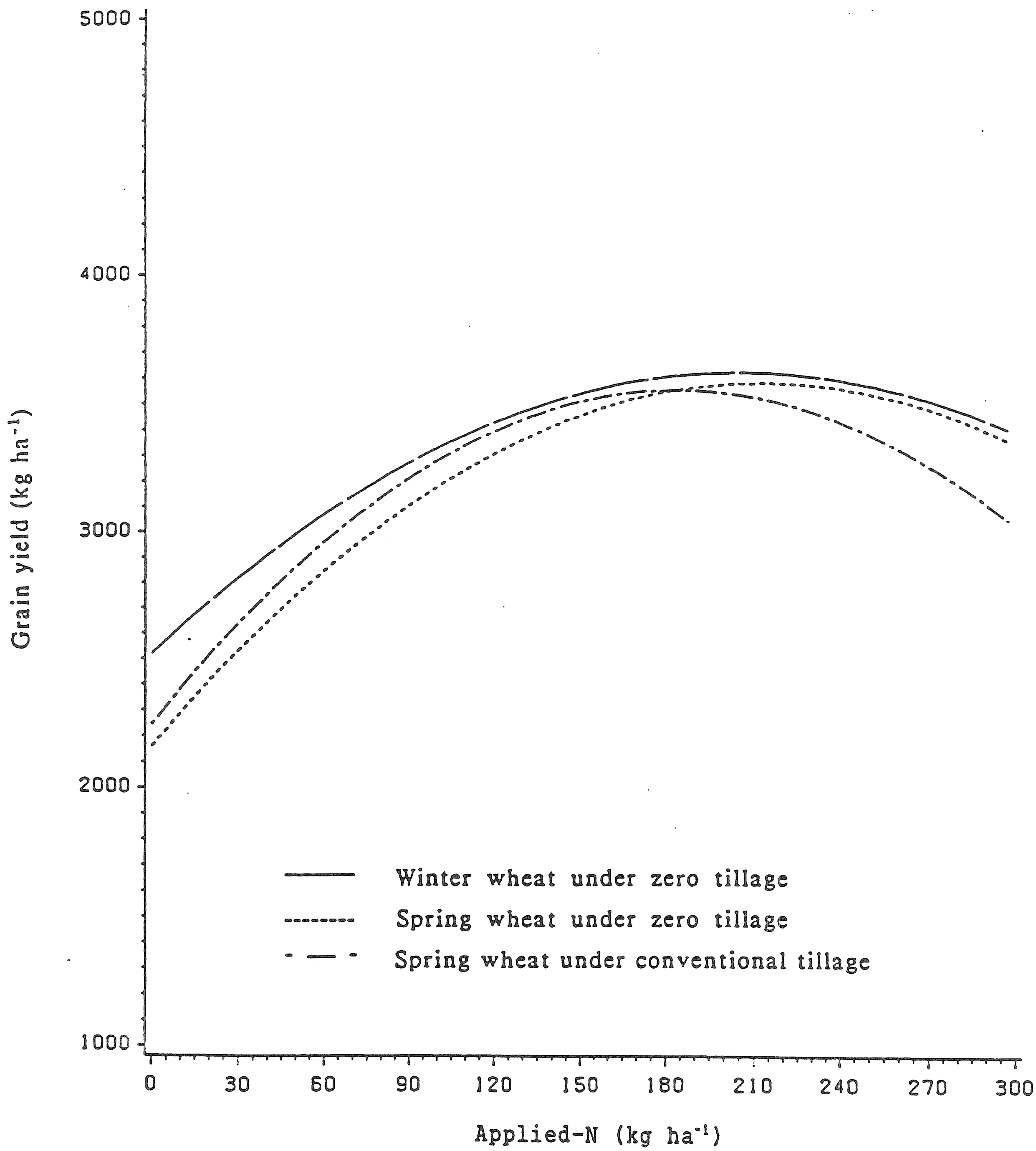

Figure 4. Lines of best fit for grain yield as affected by rate of applied-N at Manitou in 1986

Table 8. Grain yield (kg ha^{-1}) as affected by rate of applied-N at Manitou in 1986

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	2647	2880	2413	2317	2528	2105	2412	2664	2160
30	2815	2998	2632	2527	2692	2362	--	--	--
60	3064	3207	2921	2841	2970	2713	2955	3137	2772
90	3267	3419	3115	3099	3236	2962	--	--	--
120	3424	2598	3250	3302	3459	3144	--	--	--
180	3598	3785	3412	3540	3710	3370	3548	3803	3293
240	3587	3764	3411	3556	3717	3395	--	--	--
300	3391	3682	3101	3349	3614	3084	3033	3315	2752

1 $Y = 2519 + 10.63N - 2.573*10^{-2}N^2$, $R^2 = 0.44^{**}$.

2 $Y = 2158 + 13.24N - 3.091*10^{-2}N^2$, $R^2 = 0.61^{**}$.

3 $Y = 2243 + 14.17N - 3.846*10^{-2}N^2$, $R^2 = 0.62^{**}$.

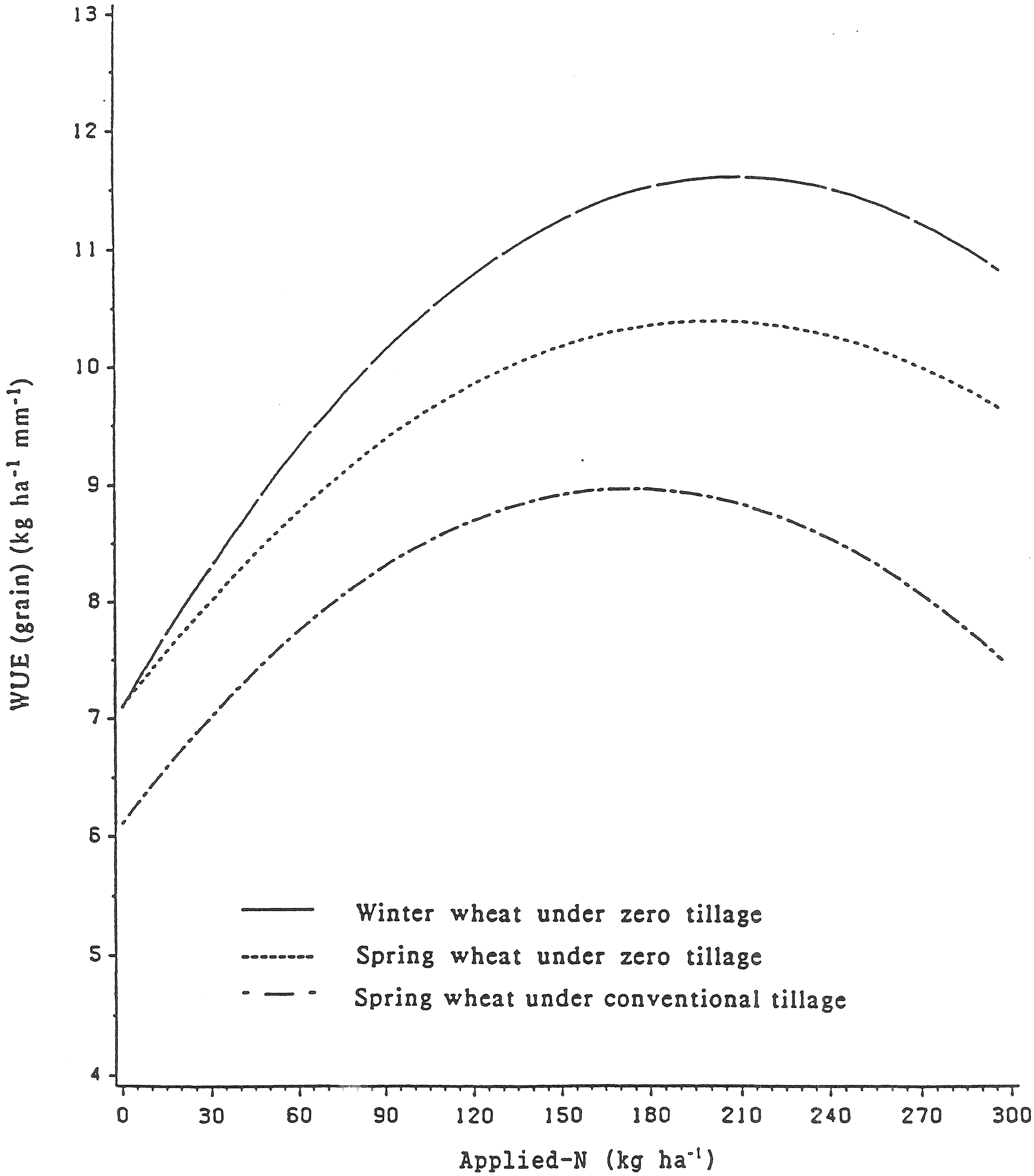

Figure 5. Lines of best fit for water use efficiency (WUE) based on grain yield as affected by rate of applied-N at Manitou in 1986

Table 9. Water use efficiency (WUE) based on grain yield (kg ha^{-1} mm^{-1}) as affected by applied-N at Manitou in 1986

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted WUE[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	7.6	8.9	6.4	7.5	9.0	5.9	6.5	8.1	4.9
30	--	--	--	--	--	--	--	--	--
60	9.3	10.1	8.5	8.8	9.7	7.8	7.7	8.9	6.6
90	10.1	11.0	9.3	9.4	10.4	8.3	--	--	--
120	--	--	--	--	--	--	--	--	--
180	11.5	12.6	10.4	10.3	11.7	9.0	9.0	10.5	7.4
240	--	--	--	--	--	--	--	--	--
300	10.8	12.2	9.4	9.6	11.3	7.9	7.5	9.2	5.7

[1] $Y = 7.1 + 4.26*10^{-2}N - 1.01*10^{-4}N^2$, $R^2 = 0.67^{**}$.

[2] $Y = 7.1 + 3.23*10^{-2}N - 7.99*10^{-5}N^2$, $R^2 = 0.37$.

[3] $Y = 6.1 + 3.28*10^{-2}N - 9.42*10^{-5}N^2$, $R^2 = 0.36$.

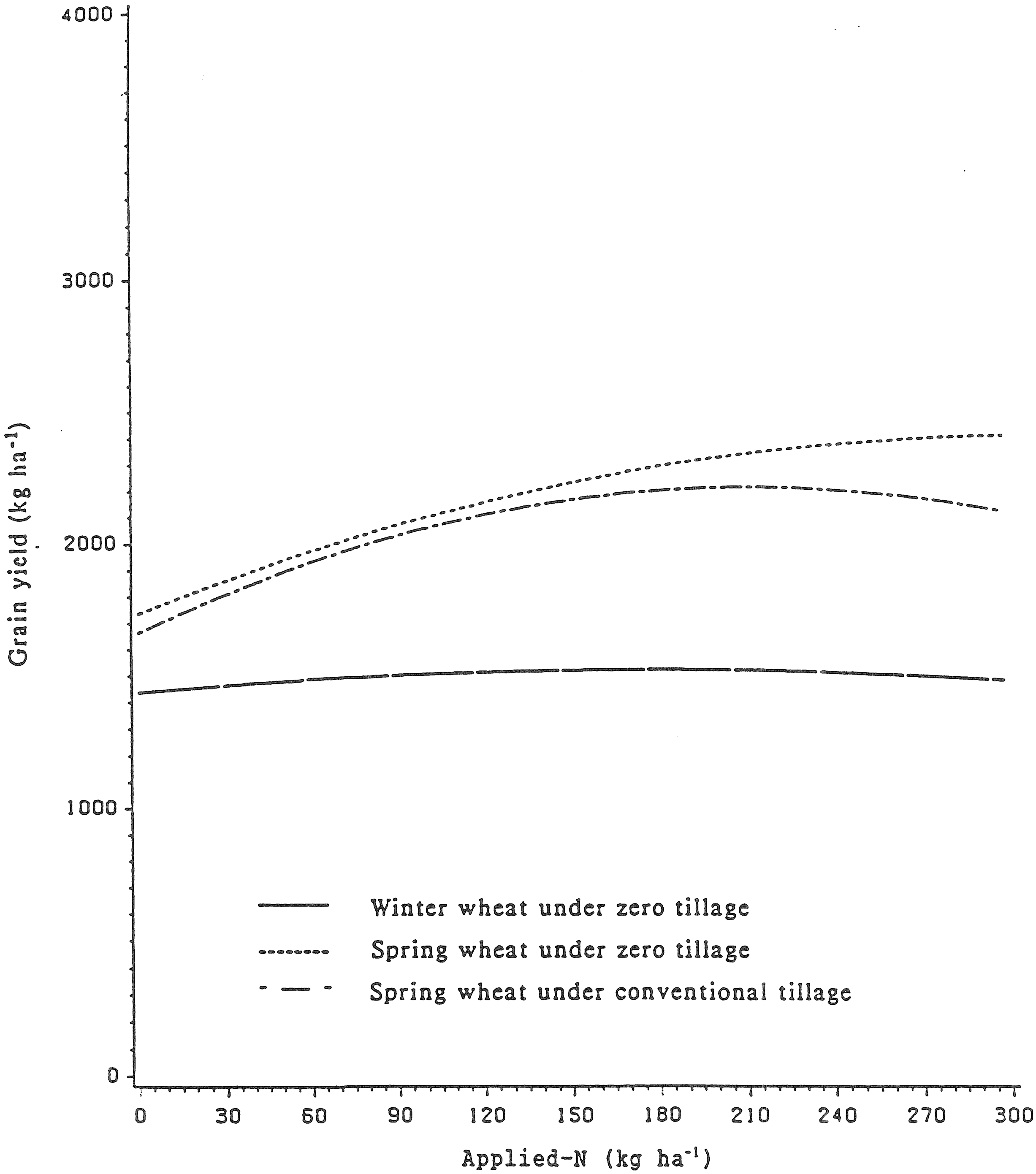

Figure 6. Lines of best fit for grain yield as affected by rate of applied-N at Carberry in 1987

Table 10. Grain yield (kg ha^{-1}) as affected by rate of applied-N at Carberry in 1987

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	1449	1676	1222	1788	2000	1575	1724	2010	1438
30	1464	1641	1287	1859	2025	1693	--	--	--
60	1485	1623	1348	1970	2099	1841	1929	2136	1722
90	1502	1649	1355	2069	2206	1931	--	--	--
120	1513	1682	1344	2155	2313	1997	--	--	--
180	1521	1704	1338	2289	2459	2118	2198	2488	1909
240	1508	1681	1336	2372	2533	2210	--	--	--
300	1476	1760	1191	2404	2670	2138	2115	2434	1797

[1] $Y = 1438 + 0.965N - 2.791*10^{-3}N^2$, $R^2 = 0.004$.

[2] $Y = 1735 + 4.342N - 7.044*10^{-3}N^2$, $R^2 = 0.28^{**}$.

[3] $Y = 1662 + 5.183N - 1.224*10^{-2}N^2$, $R^2 = 0.21$.

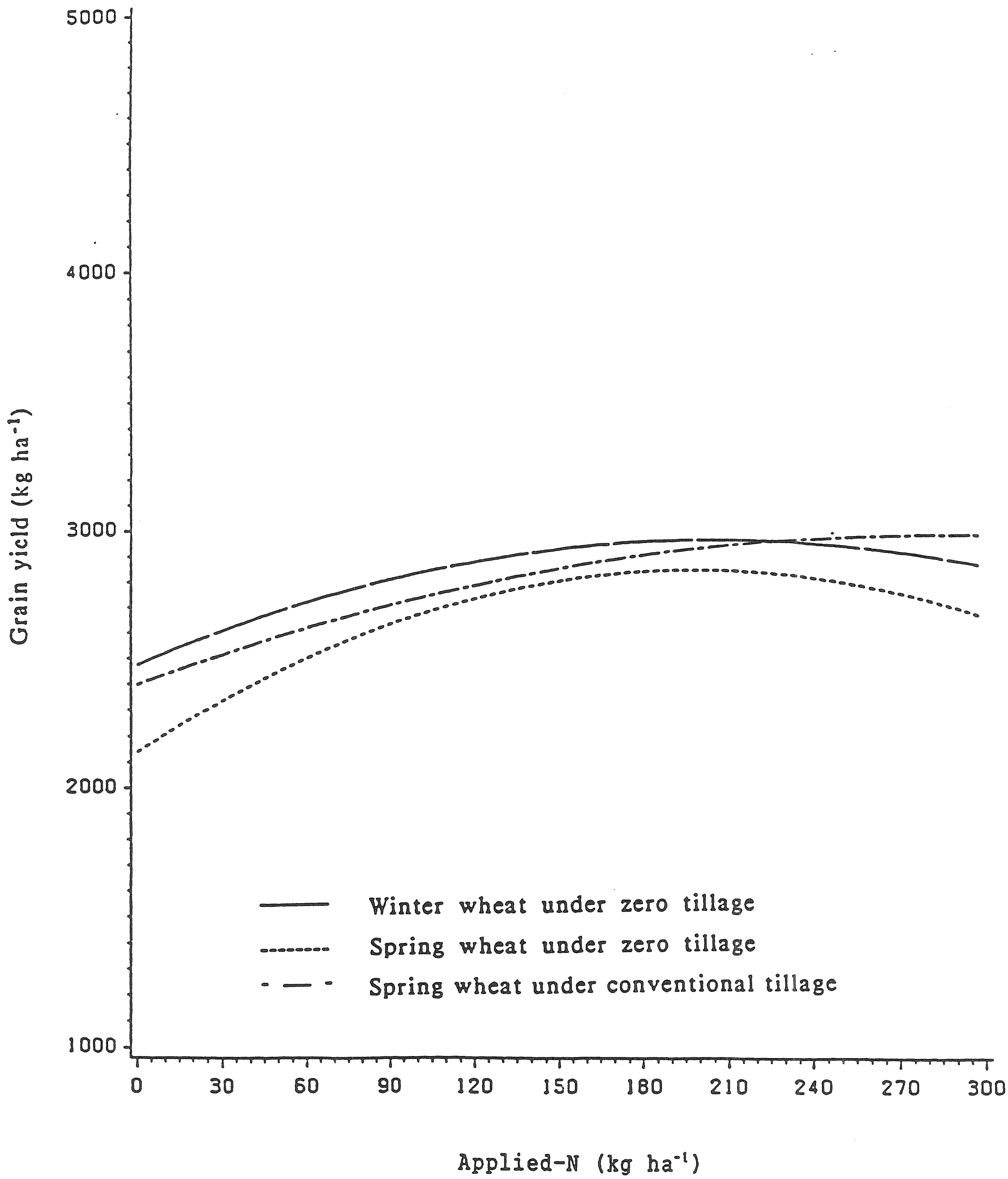

Figure 7. Lines of best fit for grain yield as affected by rate of applied-N at Manitou in 1987

Table 11. Grain yield (kg ha^{-1}) as affected by rate of applied-N at Manitou in 1987

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	2533	2858	2207	2223	2452	1995	2449	2888	2009
30	2608	2862	2353	2335	2514	2157	--	--	--
60	2719	2916	2521	2500	2639	2361	2618	2937	2300
90	2809	3020	2598	2633	2781	2485	--	--	--
120	2879	3121	2636	2734	2904	2564	--	--	--
180	2957	3218	2695	2839	3023	2655	2903	3348	2458
240	2951	3199	2704	2816	2991	2642	--	--	--
300	2864	3271	2456	2665	2952	2379	2983	3473	2493

1 $Y = 2476 + 4.737N - 1.148*10^{-2}N^2$, $R^2 = 0.07$.

2 $Y = 2138 + 7.099N - 1.781*10^{-2}N^2$, $R^2 = 0.24^{**}$.

3 $Y = 2399 + 4.080N - 7.111*10^{-3}N^2$, $R^2 = 0.14$.

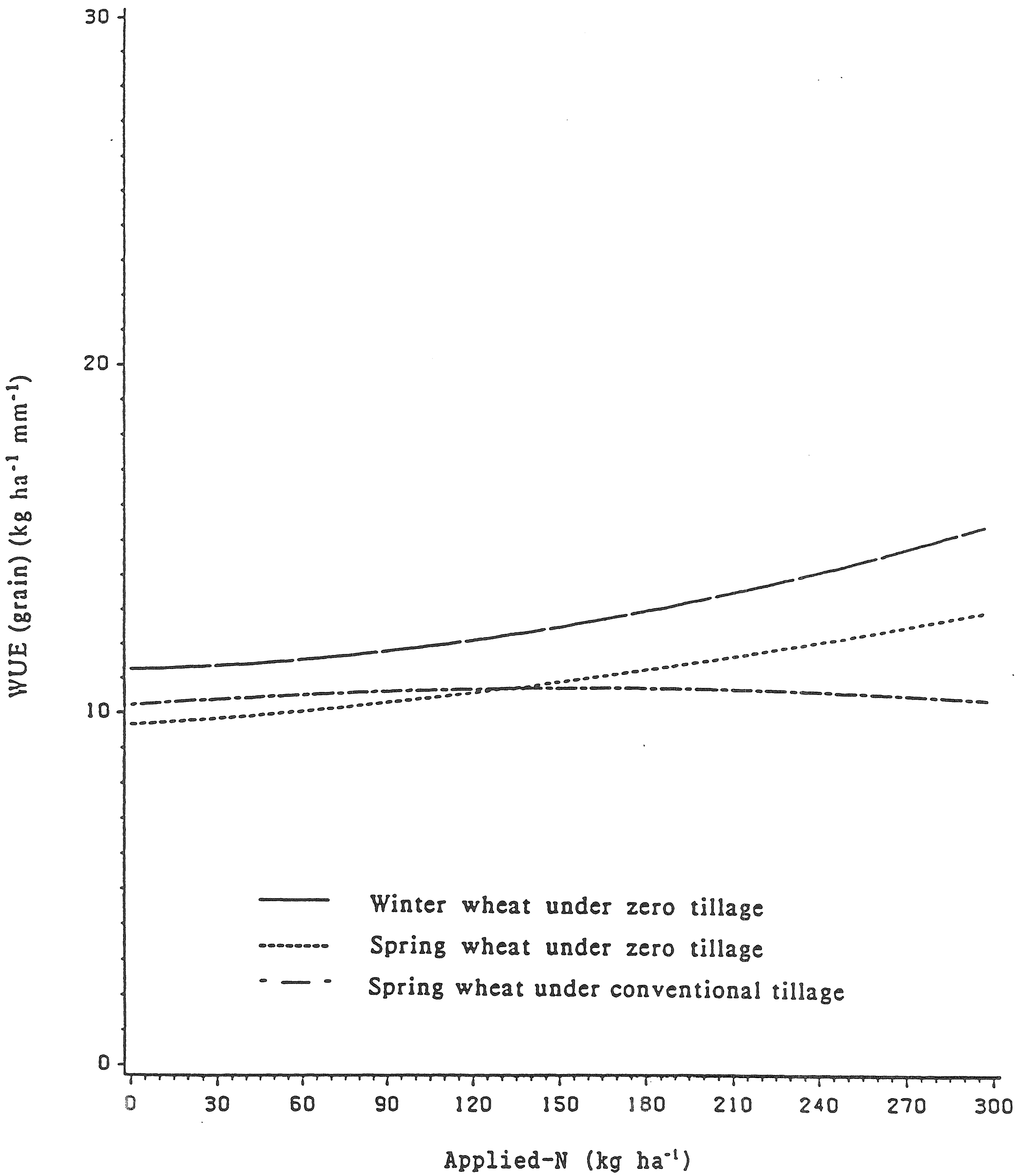

Figure 8. Lines of best fit for water use efficiency (WUE) based on grain yield as affected by rate of applied-N at Manitou in 1987

Table 12. Water use efficiency (WUE) based on grain yield (kg ha^{-1} mm^{-1}) as affected by applied-N at Manitou in 1987

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted WUE[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	11.3	16.4	6.2	9.7	13.4	6.1	10.3	14.2	6.4
30	--	--	--	--	--	--	--	--	--
60	11.5	14.7	8.4	10.1	12.3	7.8	10.5	13.4	7.7
90	11.8	15.2	8.3	10.3	12.8	7.8	--	--	--
120	--	--	--	--	--	--	--	--	--
180	12.9	17.4	8.4	11.2	14.5	8.0	10.7	14.7	6.7
240	--	--	--	--	--	--	--	--	--
300	15.4	21.1	9.6	12.9	17.9	7.9	10.3	14.7	6.0

[1] $Y = 11.3 + 2.38{*}10^{-3}N + 3.77{*}10^{-5}N^2$, $R^2 = 0.12$.

[2] $Y = 9.7 + 5.44{*}10^{-3}N + 1.78{*}10^{-5}N^2$, $R^2 = 0.11$.

[3] $Y = 10.2 + 6.03{*}10^{-3}N - 1.91{*}10^{-5}N^2$, $R^2 = 0.003$.

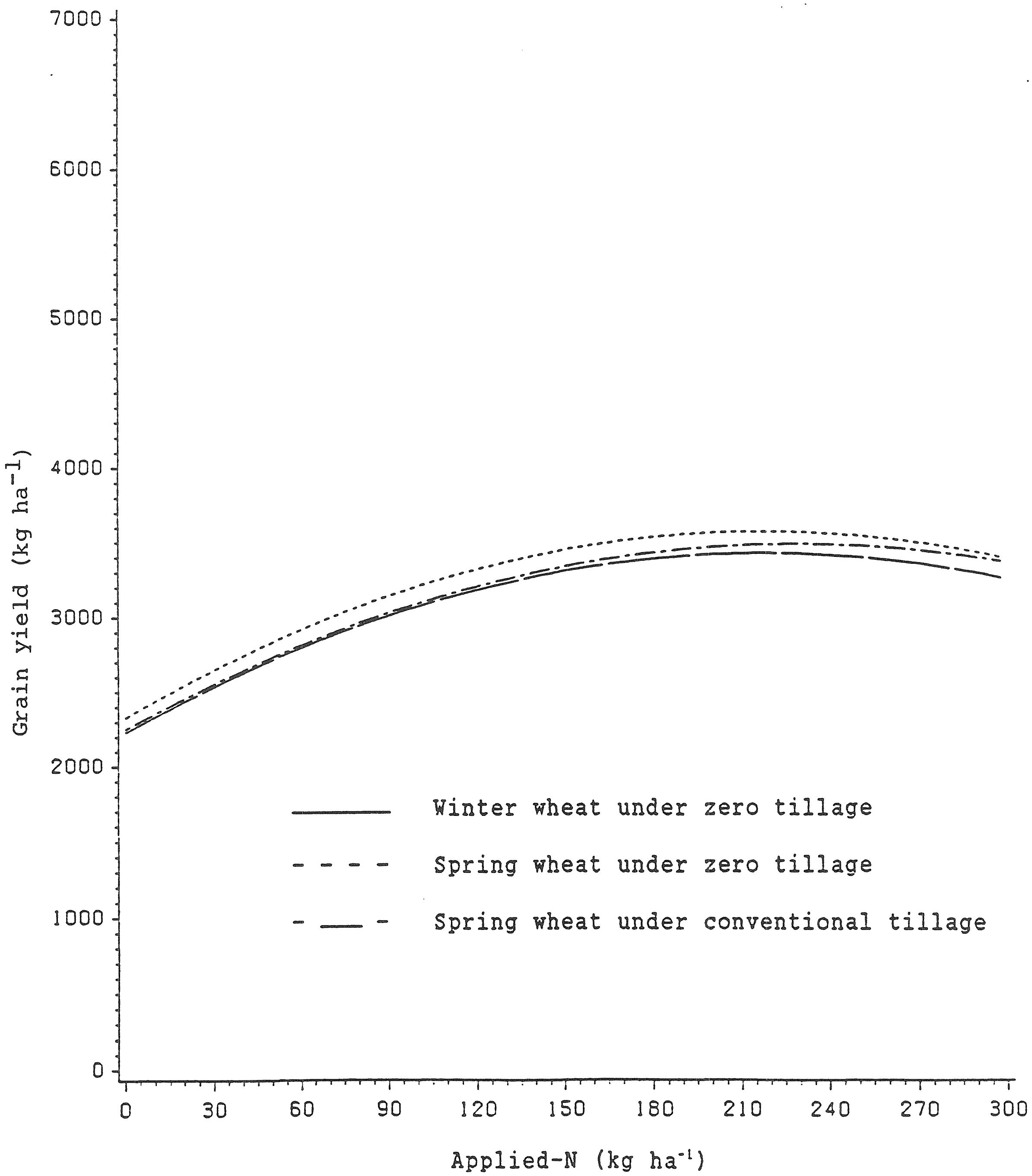

Figure 9. Lines of best fit for grain yield as affected by rate of applied-N for all site-years combined

Table 13. Grain yield (kg ha^{-1}) as affected by rate of applied-N for all site-years combined

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted yield[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted yield[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	2359	2642	2076	2465	2687	2243	2380	2655	2106
30	2534	2754	2313	2647	2820	2473	—	—	—
60	2794	2966	2623	2918	3053	2783	2812	3011	2614
90	3010	3193	2827	3141	3285	2997	—	—	—
120	3181	3391	2970	3318	3483	3152	—	—	—
180	3386	3613	3159	3530	3708	3351	3427	3704	3149
240	3410	3625	3196	3553	3722	3384	—	—	—
300	3254	3607	2900	3388	3666	3109	3362	3668	3056

[1] $Y = 2227 + 10.96N - 2.513 \times 10^{-2}N^2$, $R^2 = 0.11^{**}$.

[2] $Y = 2329 + 11.39N - 2.618 \times 10^{-2}N^2$, $R^2 = 0.17^{**}$.

[3] $Y = 2251 + 10.77N - 2.356 \times 10^{-2}N^2$, $R^2 = 0.21^{**}$.

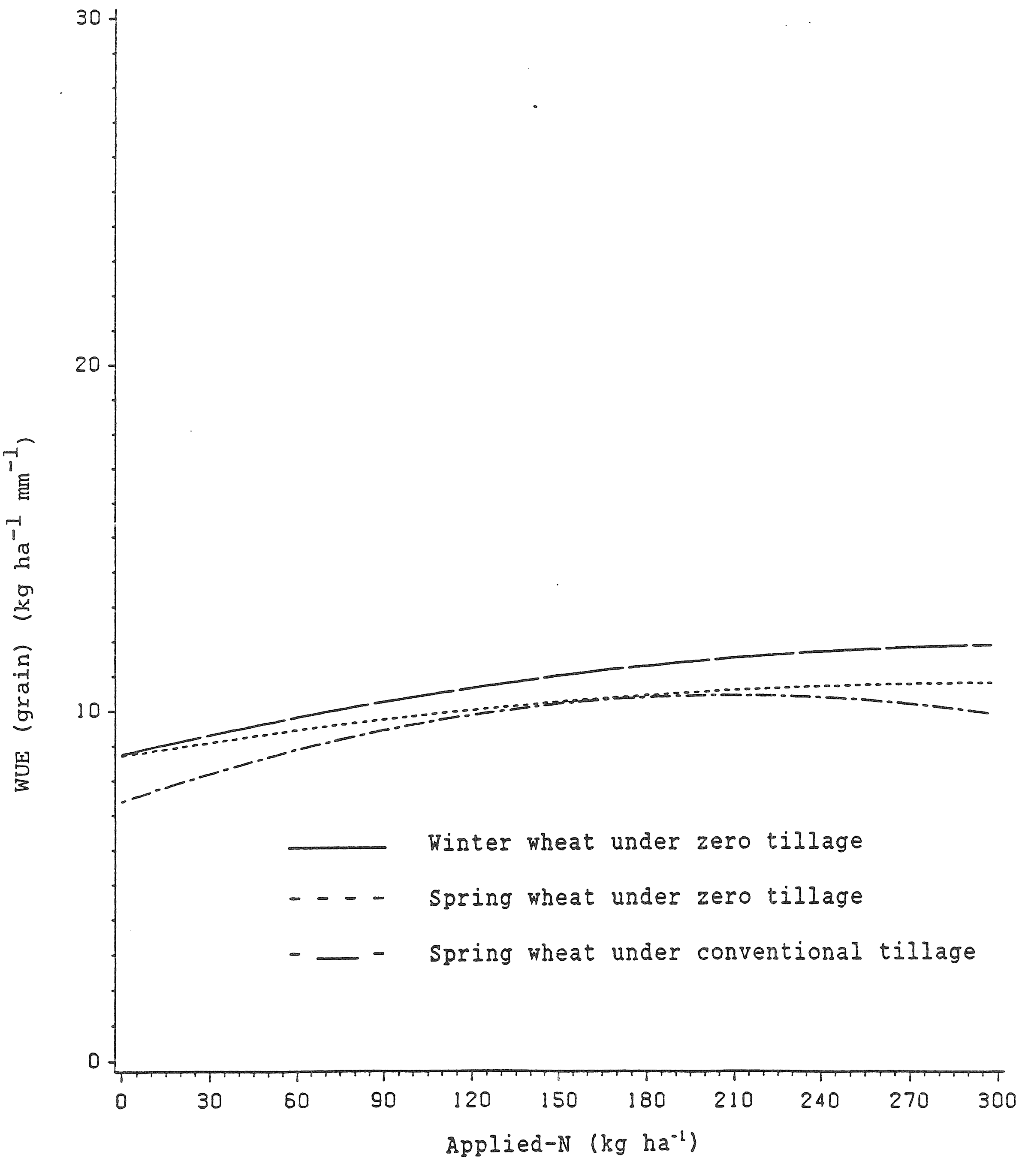

Figure 10. Lines of best fit for water use efficiency (WUE) based on grain yield as affected by rate of applied-N for all site-years combined

Table 14. Water use efficiency (WUE) based on grain yield (kg ha^{-1} mm^{-1}) as affected by rate of applied-N for all site-years combined

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha^{-1})	Predicted WUE[1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted WUE[3]	Upper 95% confidence limit	Lower 95% confidence limit
12	9.0	10.7	7.3	8.9	10.2	7.6	7.7	9.1	6.3
60	9.8	10.9	8.8	9.5	10.3	8.7	8.9	9.9	7.9
90	10.3	11.5	9.1	9.8	10.6	8.9	—	—	—
180	11.3	12.8	9.8	10.5	11.6	9.3	10.4	11.8	9.0
300	11.9	14.0	9.8	10.8	12.3	9.3	9.9	11.5	8.3

[1] $Y = 8.8 + 1.96*10^{-2}N - 3.05*10^{-5}N^2$, $R^2 = 0.10$.

[2] $Y = 8.7 + 1.38*10^{-2}N - 2.28*10^{-5}N^2$, $R^2 = 0.09$.

[3] $Y = 7.4 + 2.92*10^{-2}N - 6.94*10^{-5}N^2$, $R^2 = 0.16^{*}$.

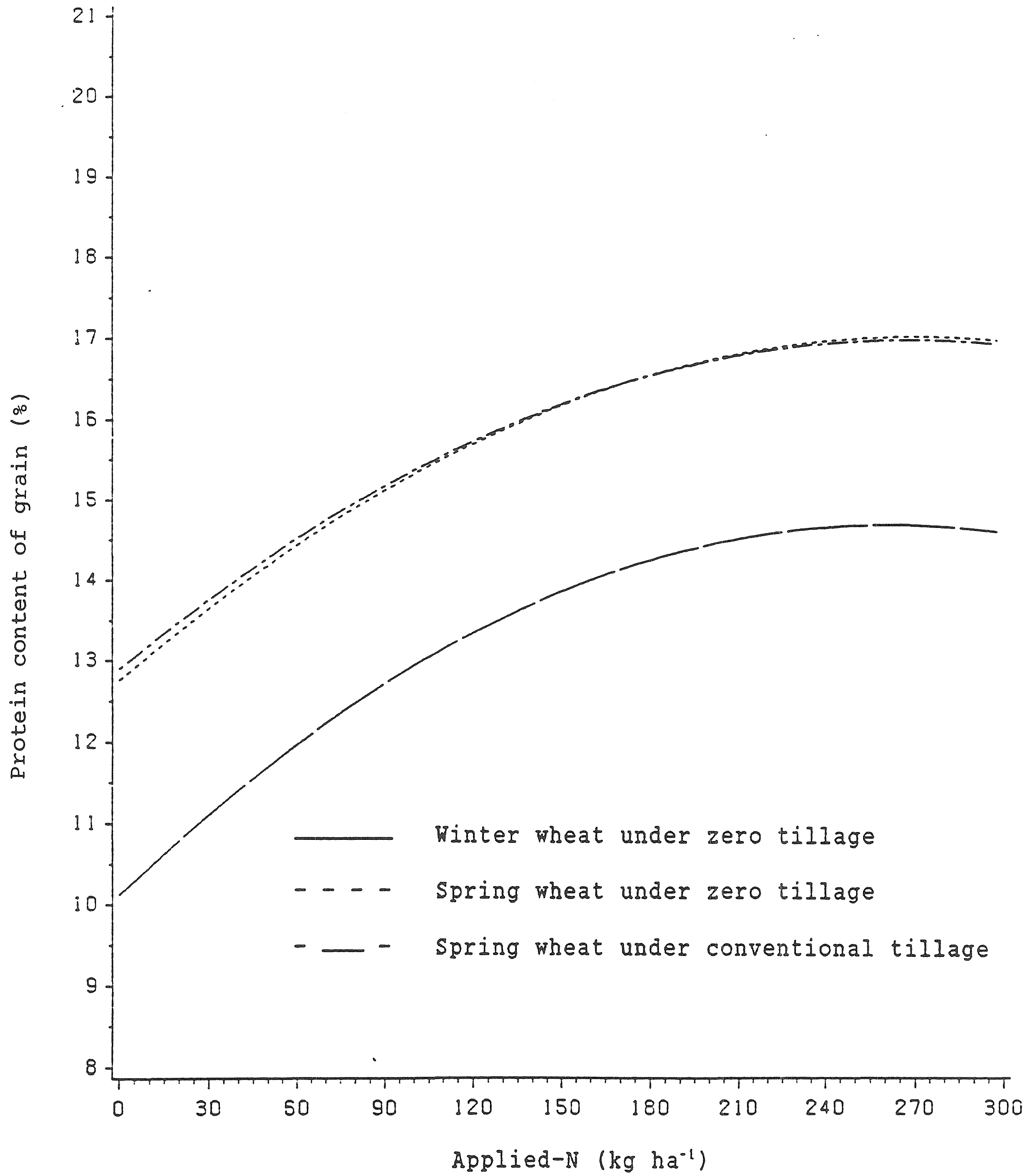

Figure 11. Lines of best fit for protein content of the grain as affected by rate of applied-N for all site-years combined

Table 15. Protein content (%) of grain as affected by rate of applied-N for all site-years combined

	Wheat-till regime								
	Winter wheat zero till			Spring wheat zero till			Spring wheat conventional till		
Applied-N (kg ha $^{-1}$)	Predicted protein content [1]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted protein content [2]	Upper 95% confidence limit	Lower 95% confidence limit	Predicted protein content [3]	Upper 95% confidence limit	Lower 95% confidence limit
12	10.5	11.2	9.8	13.1	13.5	12.8	13.3	13.6	12.9
30	11.1	11.7	10.6	13.6	13.9	13.4	—	—	—
60	12.0	12.4	11.5	14.4	14.6	14.2	14.5	14.8	14.2
90	12.7	13.2	12.3	15.1	15.3	14.9	—	—	—
120	13.3	13.9	12.8	15.7	15.9	15.4	—	—	—
180	14.2	14.8	13.7	16.5	16.8	16.3	16.5	16.9	16.1
240	14.6	15.2	14.1	17.0	17.2	16.7	—	—	—
300	14.6	15.5	13.7	17.0	17.4	16.6	16.9	17.3	16.5

[1] $Y = 10.1 + 3.48*10^{-2}N - 6.65*10^{-5}N^2$, $R^2 = 0.24^{**}$.

[2] $Y = 12.8 + 3.14*10^{-2}N - 5.79*10^{-5}N^2$, $R^2 = 0.56^{**}$.

[3] $Y = 12.9 + 3.03*10^{-2}N - 5.64*10^{-5}N^2$, $R^2 = 0.62^{**}$.