



# Economic Value of Biosolids in a Semiarid Agroecosystem

Hubert J. Lagae,\* Michael Langemeier, Donald Lybecker, and Kenneth Barbarick

## ABSTRACT

Over half of the municipal biosolids generated in the United States are being applied to agricultural land. More information is needed on crop response to biosolids application and on the optimal level of the application from an economic perspective. With this in mind, data from two sites used in a long-term biosolids application study of an Eastern Colorado wheat (*Triticum aestivum* L.)–fallow rotation was analyzed using multiple regression analysis. The site on which biosolids had been applied since 1982 showed little significant ( $p < 0.10$ ) response to biosolids added for the years studied. These plots also averaged one third higher in total N in the top 20 cm of soil. The other site, started in 1993, showed a very significant response to biosolids. For this site, the estimated maximum wheat yield was obtained at a biosolids application rate of  $9.0 \text{ Mg ha}^{-1}$ . The economically optimal level of biosolids to apply depended on both the price of wheat and the cost of the biosolids. With wheat price of  $\$0.20 \text{ kg}^{-1}$  (USD) and a cost for biosolids (including application cost) of  $\$4.00 \text{ Mg}^{-1}$  the optimal level of biosolids applied was  $7.3 \text{ Mg ha}^{-1}$ . Given an N fertilizer price of  $\$1.10$  per kg, a producer could afford to pay  $\$7.47 \text{ Mg}^{-1}$ . Using biosolids as a soil amendment can have positive economic benefits; however, it needs to be monitored to avoid excessive nitrate accumulation or excessive levels of other nutrients or heavy metals.

IN RECENT YEARS, agricultural land application of municipal biosolids has increased and is projected to continue increasing (USEPA, 1999). Approximately 3 to 4 million dry megagrams of biosolids are applied on agricultural land in the United States (O'Connor et al., 2005). Over one half of all municipal sewage generated in the United States is applied on land for beneficial use (Epstein, 2003). From the municipalities' point of view, applying biosolids to agricultural land represents a relatively safe method to recycle biosolids. From the farmers' point of view, it becomes a resource used to supply nutrients and organic matter. However, potential environmental hazards exist since biosolids could contain trace metals. These and other environmental concerns have prompted the USEPA to establish risk-based regulations for the use of biosolids. Excessive application of biosolids may lead to  $\text{NO}_3\text{-N}$  leaching through the soil profile and into the groundwater.

Ott and Forster (1978) noted that plant nutrients found in biosolids are generally unbalanced in terms of plant requirements, resulting in an excessive amount of P when the biosolids are applied to meet the N needs of a crop. Although P does not

generally leach through the soil profile, soil erosion can transport it into lakes and rivers.

The USEPA requires trace metal analyses of municipal biosolids to determine their suitability for use on agricultural lands. Also, the USEPA 40 CFR, Part 503 regulations (USEPA, 1993) state that biosolids added to agricultural land must be applied at an "agronomic rate." Usually, the agronomic rate is based on crop N need, and in some cases on the P requirement of the crop grown on the land (Barbarick et al., 1996).

With these cautions in mind, the proper use of municipal biosolids has many benefits to farmland. Biosolids have been shown to increase plant growth through the slow release of not only the macronutrients N and P, but many micronutrients too. Also, through repeated applications of biosolids, many physical properties of soils can be improved (Gupta et al., 1977; Clapp et al., 1986; Utschig, 1985; Lagae, 1999). These improvements are largely due to the addition of organic matter, which increases aggregate stability, cation exchange capacity, water holding capacity, and water infiltration rates of soils (Waksman, 1938; Brady, 1990; Kaplan, 1983; Myśków et al., 1994; Lagae, 1999). Utschig (1985) found that biosolids increased moisture retention in the plow layer (top 20 cm) by 0.8 cm over a 2-yr period. Gupta et al. (1977) found that the use of biosolids increased soil water retention and saturated hydraulic conductivity and decreased bulk density. They also found that biosolids lowered thermal conductivity while increasing the specific heat of the soil. Wei et al. (1985) applied a single application of biosolids at rates of 0, 11.2, 22.4, 44.8, and  $112.0 \text{ Mg ha}^{-1}$  (dry solids basis), with a sixth treatment of  $22.4 \text{ Mg ha}^{-1}$  applied annually for 5 yr. Five years after the first applications (the fifth year of the annual application), all treatments with application rates  $\geq 44.8 \text{ Mg ha}^{-1}$  (and the  $22.4 \text{ Mg ha}^{-1}$  annual application

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**Abbreviations:** CBIO, the sum of biosolids applied to a plot in previous years; CN, carbon–nitrogen ratio; Y, estimated grain yield.

rate treatment) showed significant decreases in bulk density, increases in hydraulic conductivity of saturated soil cores, enhancement of aggregate stability, an increase in the volume of large pore spaces, and increased organic matter content. There was also an increase in the in situ volumetric moisture content, especially after a period of dry weather.

The increase in organic matter obtained through biosolids application also increases the microbial biomass of a soil and adds energy and nutrients required by the soil microorganisms (Brady, 1990). Cogger et al. (1998) indicated that dryland wheat farmlands are ideally suited for the application of biosolids because of a large land base, low risk of runoff, minimal metal uptake by plants when applied at agronomic rates, and deep root zones that allow more efficient  $\text{NO}_3\text{-N}$  uptake. However, without proper management, these lands can be subject to soil erosion by wind, which could potentially transport the applied biosolids off site (Wagner and Hagen, 2001; Tibke, 2006).

Research examining the economics of applying biosolids is limited. With the concern on heavy metal uptake, researchers often were most concerned with reporting the chemical constituents of the crops with little attention on yields. Epstein (2003) indicates that information pertaining to the economic benefits of biosolids application is needed. Estimating crop yield response to production inputs (in this case, biosolids) is a necessary ingredient for determining the optimal amount of input to apply. Lacking this information can lead to either under- or overapplication of biosolids. In either case, profits are diminished. Also, overapplication of biosolids can be harmful to the environment. In their analysis of the effect of biosolids on farm income, Lerch et al. (1990b) found a quadratic response of winter wheat yields to biosolids application. Sabey and Hart (1975) found that biosolids application rates of 25 and 50  $\text{Mg ha}^{-1}$  (dry weight basis) resulted in increased grain yields compared with check plots, but at rates of 100 and 125  $\text{Mg ha}^{-1}$ , yields declined significantly and, on average, were less than yields from check plots. Day et al. (1988) found that 10  $\text{Mg ha}^{-1}$  of dried sewage sludge supplied 157  $\text{kg ha}^{-1}$  of N. Barbarick and Ippolito (2000) showed that 1  $\text{Mg}$  of biosolids provided an equivalent of about 8  $\text{kg N}$  fertilizer, while the USEPA (1983) estimated the 1  $\text{Mg}$  of biosolids provided an equivalent of 6 to 7  $\text{kg}$  of N fertilizer. Because of this, one would expect the response of grain yield to biosolids to follow a similar response as other N fertilizers. Halvorson and Reule (1994) derived a quadratic response for relative grain yield as a function of N fertilizer applied to winter wheat in a dryland cropping system. In a study of the effect of N and irrigation water on winter wheat, Eck (1988) found a quadratic grain yield response to N.

Soulsby et al. (2002) calculated the fertilizer replacement value of biosolids in a 3-yr crop rotation consisting of 2 yr of winter wheat followed by oilseed rape. They found that after 3 yr the biosolids + fertilizer treatments showed a significant yield increase compared with the use of mineral N fertilizer alone. This, combined with the fertilizer replacement value, resulted in a 7% increase in the gross margin for the rotation. They also estimated the value of various environmental impacts or externalities associated with the production and use of mineral fertilizer and biosolids. They concluded that, when the external costs and yield increases are considered together, there

is a net economic benefit in the use of biosolids as compared with mineral fertilizer. They estimated this total benefit of 10.85 British pounds (\$21.98 USD)  $\text{Mg}^{-1}$  (92% dry matter) of granulated biosolids.

The objective of this study was to estimate winter wheat grain yield response to biosolids application using data from a long-term agronomic study in which biosolids were used in a winter wheat-fallow rotation. Then, using this estimated yield response, determine the economically optimal level of biosolids application given alternative input and output price assumptions. This economically optimal level assumes profit maximization as the primary objective of the producer, and does not include any externalities (costs external to the market) related to its use. This does not imply that there are no externalities associated with the use of biosolids, but simply that these factors are outside the scope of this study.

## MATERIALS AND METHODS

A long-term study was initiated in August 1982 to evaluate the use of Littleton and Engelwood, CO, municipal biosolids on a dryland winter wheat-fallow rotation at two locations near Bennett, CO (Utschig, 1985; Utschig et al., 1986). Another site (North Bennett) was established in 1992 (Barbarick and Ippolito, 2000). The primary purpose of the long-term study was to evaluate the effects of biosolids compared with inorganic N fertilizer on winter wheat grain yield, protein content, and various elemental concentrations of both grain and plant material (Barbarick et al., 1995, 1996; Utschig, 1985; Utschig et al., 1986; Lerch et al., 1990a, 1990b). On one set of treatment plots, various quantities of N from an inorganic fertilizer were applied; on the second set, various quantities of biosolids from the Littleton and Engelwood, CO, wastewater treatment plant were applied. A randomized complete design with four replications was used on all experimental sites (Barbarick et al., 1995, 1996). This paper only reports data for the crops grown during 1994 to 1997 from the original Bennett site (West Bennett), which was discontinued after 1997, and from 1994 to 2000 for the North Bennett site. Due to dry conditions and poor management, there was no harvest from the West Bennett site in 1996.

Table 1 summarizes the biosolids and N fertilizer rates used on the West Bennett and North Bennett sites. The biosolids rates for each application ranged from 0 to 26.8  $\text{Mg ha}^{-1}$  (0–12 tons  $\text{acre}^{-1}$ ) on the West Bennett plots and from 0 to 11.2  $\text{Mg ha}^{-1}$  (0–5 tons  $\text{acre}^{-1}$ ) on the North Bennett plots. The biosolids were applied to the plots in late summer. The N application rates ranged from 0 to 134  $\text{kg ha}^{-1}$  (0–120 lbs  $\text{acre}^{-1}$ ) and 0 to 112  $\text{kg ha}^{-1}$  (0–100 lbs  $\text{acre}^{-1}$ ) on the West Bennett and North Bennett plots, respectively (Barbarick et al., 1995, 1996; Utschig, 1985; Utschig et al., 1986; Lerch et al., 1990a, 1990b; Barbarick and Ippolito, 2000). All the annual pollutant loading rates in the years analyzed were at least an order of magnitude below the USEPA limits.

The West Bennett and the North Bennett sites were analyzed separately to account for differences in the number of years biosolids had been applied, the amount applied, and any management differences. The analysis was done using either year identifier variables for each year or by using climatic variables such as precipitation and temperature. Climatic variables would not vary appreciably between the two sites in

a given year since they were only about 7 km apart, but could vary considerably from year to year. Since the present study combined several years of data, this climatic variation needed to be accounted for using either year identifier variables or climatic variables.

Multiple regression analysis was used to estimate the effect of various independent variables, including biosolids, on the dependent variable, wheat grain yield. This approach is similar to that taken by Mjelde et al. (1991) and Arce-Diaz et al. (1993). Besides biosolids and N fertilizer, the other independent variables included the carbon–nitrogen ratio (CN) in the plow layer (0–20 cm), precipitation in May and June (just preceding July harvest), the total August and September precipitation just before planting, and the 15-mo fallow period precipitation preceding planting. Weather data was collected at the station located at Byers, CO, approximately 50 km SE of the plots. However, from the 1997 through 2000 crop year, climate data were not available from the Byers station, so the recently opened weather station at Denver International Airport (approximately 16 km from the plots) was used.

Organic C and total N content in the top 20 cm of soil (the plow layer) were determined using a LECO 1000 CHN auto analyzer (Miller et al., 1998).

One of the difficulties encountered in an analysis of the use of biosolids, or most other organic types of soil amendments such as livestock manure, is the additive effect of its use over time. Each year, only part of the nutrient content of the biosolids is mineralized. The remainder is released for plant use in subsequent years. Barbarick and Ippolito (2000) estimated the North Bennett first-year net mineralization rate to be 25 to 32% for application rates up to 11.2 dry Mg ha<sup>-1</sup> (5 tons acre<sup>-1</sup>). With this in mind, two sets of biosolids variables were included. The first set accounted for the amount applied for each crop year. The second set accounted for the cumulative amount of biosolids applied in previous years.

The general form of the multiple regression production function that included the year identifier variables was

$$Y = f(\text{CN}, \text{BIO}, \text{BIO}^2, \text{NIT}, \text{NIT}^2, \text{CBIO}, \text{DVN4}, \text{DVN5}, \text{DVN6}, \text{DVN7}, \text{DVN8}, \text{DVN9}) \quad [1]$$

where Y = estimated grain yield (kg ha<sup>-1</sup>); CN includes the top 20 cm of soil; BIO = biosolids applied in current year, dry weight (Mg ha<sup>-1</sup>); NIT = N applied from inorganic fertilizer (kg ha<sup>-1</sup>); CBIO = total biosolids applied in previous years, dry weight (Mg ha<sup>-1</sup>); and DVN4 to DVN9 = year identifier variables for 1994 to 1999.

The multiple regression production function that used climatic variables had the following general form:

$$Y = f(\text{CN}, \text{BIO}, \text{BIO}^2, \text{NIT}, \text{NIT}^2, \text{CBIO}, \text{PCP56}, \text{PCP89}, \text{PCPFAL}, \text{PFALP89}) \quad [2]$$

where PCP56 = precipitation (cm) received in May and June, PCP89 = precipitation (cm) received in August and September just before planting, PCPFAL = precipitation (cm) received over the 15-mo fallow period, and PFALP89 = interaction term (PCPFAL × PCP89).

**Table 1. Description by site—Years, treatments, and observations.**

	West Bennett	North Bennett
Years	1994 1995 1997	1994 1995 1996 1997 1998 1999 2000
Management	conventional tillage	minimum tillage
Biosolids rates, Mg ha <sup>-1</sup>	0 6.72 13.44 26.88	0 2.24 4.48 6.72 8.96 11.2
N fertilizer rates, kg ha <sup>-1</sup>	1994 0 33.6 67.2 100.8 137.4	1995, 1997 0 28 56 112
No. of observations	100	336

It is important to note that there were no plots that had a combination of biosolids and N fertilizer applied. All plots had either biosolids or N fertilizer applied, excepting the control plots that had neither. For the North Bennett site, when years (1994–2000) and all treatments were combined, the total number of observations was 336. For the West Bennett site, the years included in the analysis were 1994, 1995, and 1997 (1996 was not harvested due to crop failure). The total number of observations for this site was 100.

The variables in Eq. [1] and [2] were evaluated for their effect on wheat yield using multiple linear regression analysis. This analysis was done using both EViews (Quantitative Micro Software, Irvine, CA) and SigmaStat (Stystat Software, San Jose, CA). The same results were obtained using both of these statistical software packages.

Optimal biosolids and N rates and wheat yields were determined using a profit equation and the estimated production function (Beattie and Taylor, 1985). Specifically, output price was multiplied by the production function and the nutrient costs were then subtracted:

$$\pi = pY - rB \quad [3]$$

where  $\pi$  is profit (i.e., net return over biosolids cost),  $p$  is wheat price,  $Y$  is the production function (estimated yield per hectare),  $r$  is the price of biosolids, and  $B$  is the biosolids rate.

Taking the first derivative of the profit equation yields the factor demand function:

$$B^* = a - b(r/p) \quad [4]$$

where an asterisk indicates the optimal input level, and  $a$  and  $b$  are computed using the production function coefficients. The factor demand function can be used to examine the sensitivity of optimal biosolids use to changes in input and output prices.

Substituting the factor demand function into the production function yields the wheat supply function:

$$Y^* = c - d(r/p)^2 \quad [5]$$

where the asterisk denotes the optimal output level, and  $c$  and  $d$  are computed using the factor demand coefficients. The wheat supply function can be used to examine the sensitivity of wheat yields to changes in input and output prices.

The functional forms for the factor demand and supply functions are dictated by the functional form of the production function. With a quadratic production function the ratio of input to output prices is linear in the factor demand function and quadratic in the supply function.

Biosolids (input) prices of \$2.00 and \$4.00 Mg<sup>-1</sup> (including application costs) and wheat (output) prices of \$0.15, \$0.20, and \$0.25 kg<sup>-1</sup> were used to determine the optimal biosolids rate. In addition to computing the optimal biosolids rates for specific combinations of input and output prices, the prices that a farmer could afford to pay for biosolids given N prices of \$1.10 and \$2.20 per kg, and a wheat price of \$0.20 kg<sup>-1</sup> were determined using Excel's Solver Add-in (Microsoft Corporation, Redmond, WA). This breakeven analysis was conducted by first computing the profit obtained with the profit maximizing levels of N fertilizer. These profit levels were then used along with a wheat price of \$0.20 kg<sup>-1</sup> to compute the prices that a farmer could afford to pay for biosolids that would give the farmer the same profit levels as those obtained with the profit maximizing levels of N fertilizer.

## RESULTS AND DISCUSSION

The regression results for the West Bennett site indicated that there was not a significant yield response to either the biosolids application or the N fertilizer applied. Looking at the yield response to biosolids by individual year, 1994, 1995, and 1997, indicated that only 1995 had a significant response (Fig. 1). Another factor that may have contributed to the poor response of yield to biosolids was the difference in the total N content of the top 20 cm of soil. Total N includes a large amount organic N unavailable to plants so should not be confused with available N. For West Bennett the N content averaged 1.04 g kg<sup>-1</sup>, while at the North Bennett it averaged only 0.78 g kg<sup>-1</sup>. The CN was 9.08 and 10.66 for the West and North Bennett sites, respectively. Since the West Bennett soil had a much higher N content, it is not surprising to find that

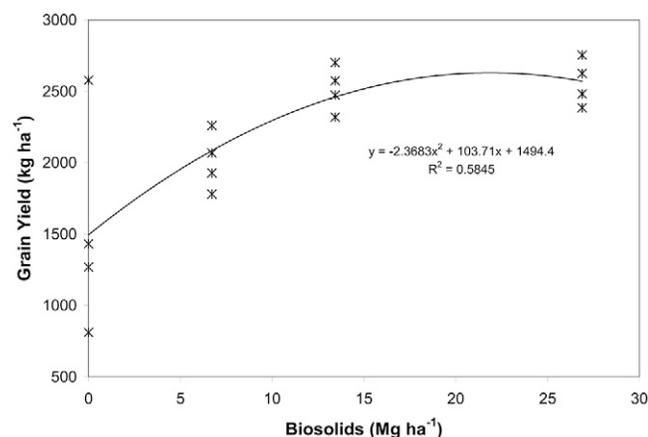


Fig. 1. Wheat yield response to biosolids, West Bennett site, 1995.

wheat yield on this site was not as responsive to additional N applied as either biosolids or fertilizer. This might also help explain why in 1995, which had the highest May–June precipitation, the response was more significant since with the added moisture the crop was better able to use the N.

For the North Bennett site, the data were analyzed using two regression models. The first used the year identifier variables and the second used the climatic (precipitation) variables. These results are shown in Tables 2 and 3, respectively. Overall, both regressions had reasonable results.

The model using the year identifier variables (Table 2) worked well in terms of having the highest  $R^2$  of 0.84. The small difference between the  $R^2$  and the adjusted  $R^2$  is a result of the large number of observations (336) and relatively few explanatory variables. The graph of the actual versus the predicted observations shows the overall fit of the model visually (Fig. 2). The year identifier variables are all significant except for DVN6. The constant ( $y$  intercept) term represents the crop harvested in 2000. A negative coefficient for one of the year identifier variables indicates that response for that year was lower than in 2000 while a positive coefficient indicates a higher response than in 2000. The coefficient on DVN4 is

Table 2. North Bennett regression analysis results (with year identifier variables). Dependent variable is wheat yield (kg ha<sup>-1</sup>).

Variable†	Coefficient	t value	Probability
Intercept	1863.67	12.56	0.0000
CN	25.29	2.99	0.0030
BIO	107.16	3.61	0.0004
BIO <sup>2</sup>	-5.97	-2.29	0.0226
NIT	11.81	4.18	0.0000
NIT <sup>2</sup>	-0.057	-2.18	0.0299
CBIO	18.47	2.35	0.0194
DVN4	-476.61	-4.12	0.0000
DVN5	492.13	4.26	0.0000
DVN6	64.61	0.63	0.5309
DVN7	852.87	8.55	0.0000
DVN8	691.66	6.90	0.0000
DVN9	2783.68	99.95	0.0000
$R^2 = 0.836$		No. of observations = 336	
Adjusted $R^2 = 0.830$		Durbin–Watson Stat. = 3.97	

† CN = carbon–nitrogen ratio, BIO = biosolids (Mg), NIT = nitrogen (applied as fertilizer), CBIO = total previous years biosolids application (Mg), DVN4 = 1994 year identifier, DVN5 = 1995 year identifier, DVN6 = 1996 year identifier, DVN7 = 1997 year identifier, DVN8 = 1998 year identifier, DVN9 = 1999 year identifier.

Table 3. North Bennett regression analysis results (with precipitation variables). Dependent variable is wheat yield (kg ha<sup>-1</sup>).

Variable†	Coefficient	t value	Probability
Intercept	-4025.57	-1.93	0.055
CN	36.17	3.49	0.001
BIO	80.86	2.13	0.034
BIO <sup>2</sup>	-5.84	-1.75	0.082
NIT	11.90	3.28	0.001
NIT <sup>2</sup>	-0.058	-1.72	0.086
CBIO	40.47	4.16	0.000
PCP56	63.12	3.66	0.000
PCP89	291.87	1.12	0.2625
PCPFAL	112.18	4.43	0.000
PFALP89	-6.85	-1.94	0.053
$R^2 = 0.728$		No. of observations = 336	
Adjusted $R^2 = 0.719$		Durbin–Watson Stat. = 1.62	

† CN = carbon–nitrogen ratio, BIO = biosolids (Mg), NIT = nitrogen (applied as fertilizer), CBIO = total previous years biosolids application (Mg), PCP56 = May and June precipitation, PCP89 = August and September precipitation, PCPFAL = 15-mo fallow period precipitation, PFALP89 = PCPFAL × PCP89.

negative and significant, and the coefficients on DVN5, DVN7, DVN8, and DVN9 are significant and positive. Since DVN6 was not significant, the response in 1996 was similar to that in 2000.

For the climatic model (Table 3) all of the precipitation terms are positive and significant, with the exception of PCP89. Because of the overlap in the time periods of PCP89 (August and September precipitation at or before planting) and the PCPFAL (the precipitation over the 15-mo fallow period) the interaction term PFALP89 was included. The PCP56, May–June precipitation, was positive and highly significant. Neghassi et al. (1975) found that, in winter wheat production, the relative sensitivity of the crop to water stress was highest from the soft dough to maturity stages, which generally corresponds to May and June in eastern Colorado. This would support the results obtained demonstrating that precipitation received during this time has a robust effect on yield. The next coefficient (PCPFAL) represents the precipitation received during the fallow period (the 15-mo period from July during or after the previous harvest until September before or during planting). This coefficient, as expected, was positive and very significant. Although the practice of summer fallow, leaving a field without any crop for a certain period of time to store up soil water for the next crop, may only store a fraction of the precipitation received (Greb et al., 1967; Farahani et al., 1998), the precipitation received in this period results in increased yields for the subsequent crop.

The coefficients for the linear and quadratic terms for biosolids and N fertilizer were significant in both the North Bennett year identifier and climatic variable regressions. Due to the higher  $R^2$  measure, the discussion below focuses on the regression using the year identifier variables.

As was stated earlier in the introduction, yield response to fertilizer inputs have been shown to be quadratic. Again, it should be emphasized that the treatments involved either N fertilizer or biosolids treatments, with no treatments having combinations of the two inputs. For the biosolids and N fertilizer coefficients, the linear terms were both highly significant ( $p < 0.01$ ) and the squared terms were both significant at  $p < 0.05$ . To better understand the response of winter wheat yield to biosolids, the mean values for CN and CBIO were substituted into the estimated regression equation and the constant term representing the crop harvested in 2000, was used. Once this is done, the response of grain yield to biosolids applied can be reduced to

$$Y = 2252 + 107.16(\text{BIO}) - 5.97(\text{BIO})^2 \quad [6]$$

Using the results presented in Eq. [6], Fig. 3 shows this response surface graphically.

Maximum production can be found by taking the first derivative of Eq. [6] and setting it equal to zero. For the North Bennett site, the estimated maximum production was achieved when 8.98 Mg ha<sup>-1</sup> of biosolids was applied, resulting in a yield of 2733 kg ha<sup>-1</sup>. The yield response to biosolids increases at a decreasing rate until it reaches the maximum yield.

Similarly, substituting mean values of CN and CBIO into the estimated regression that includes the year identifier variables results in the following response to N fertilizer:

$$Y = 2252 + 11.81(\text{NIT}) - 0.057(\text{NIT})^2. \quad [7]$$

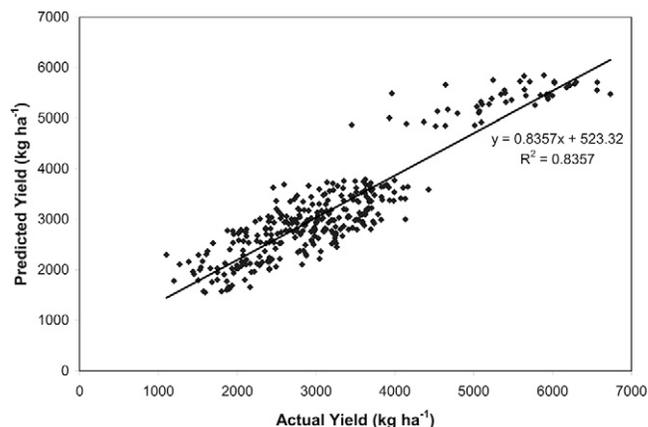


Fig. 2. Actual and predicted observations for year identifier regression, North Bennett site.

The maximum yield is attained when 103.6 kg ha<sup>-1</sup> of N fertilizer are applied, with a resulting yield estimated to be 2865 kg ha<sup>-1</sup>. As it did with the biosolids, the yield increases at a decreasing rate up to maximum yield.

Unless the input is free, the profit maximizing input level is less than the production maximizing input level. The estimated production function for biosolids (Eq. [6]) can be used along with the profit equation (Eq. [3]) to determine the optimal biosolids application rates for alternative biosolids and wheat prices. Substituting the biosolids production function into the profit equation, taking the first derivative, and solving for B yields the factor demand for biosolids:

$$B^* = 8.98 - 0.084(r/p) \quad [8]$$

The optimal biosolids application rate is negatively related to input price and positively related to output price.

If we substitute this equation into Eq. [6], we obtain the wheat supply function:

$$Y^* = 2733 - 0.0421(r/p)^2 \quad [9]$$

Wheat yield is thus negatively related to input price and positively related to output price.

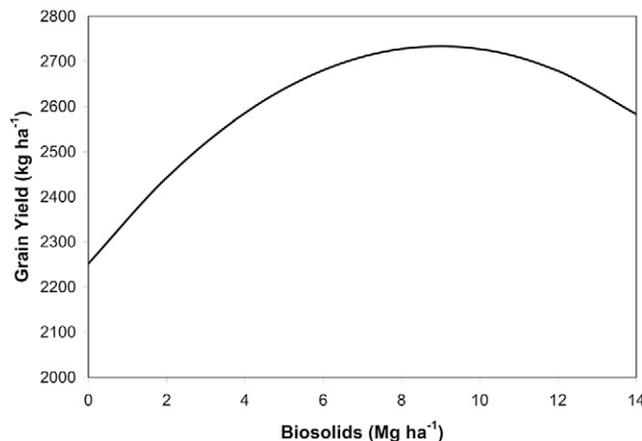


Fig. 3. Wheat yield response to biosolids for year identifier regression, North Bennett site (with all other independent variables set at their means).

**Table 4. Optimal biosolid application rates and yields.**

Input prices (r)	Wheat prices (p)	Biosolid rates (B*)	Wheat yield (Y*)	Profit (π)
USD	\$ kg <sup>-1</sup>	Mg ha <sup>-1</sup>	kg ha <sup>-1</sup>	\$ ha <sup>-1</sup>
2.00	0.15	7.86	2726	393
2.00	0.20	8.14	2729	530
2.00	0.25	8.31	2730	666
4.00	0.15	6.74	2703	379
4.00	0.20	7.30	2716	514
4.00	0.25	7.64	2722	650

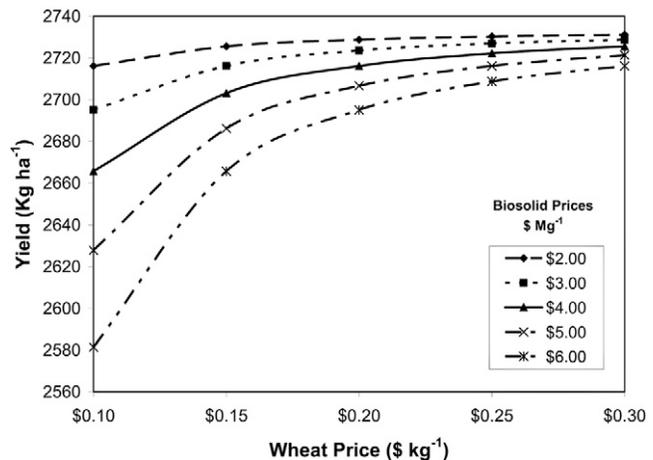
Using the factor demand function, the wheat supply function, and input and output price combinations, the optimal level of biosolids can be derived. Table 4 shows the optimal levels of biosolids, yields, and the resulting profit for several input and output combinations. It must be remembered that these profits take into account only the cost of the biosolids. All the other costs associated with producing wheat on a per-hectare basis must still be subtracted. Figure 4 provides a graphical representation of the profit maximizing yields with six different prices of biosolids and a range of wheat prices. It is apparent that, when prices of wheat are low, the profit maximizing yields are much more sensitive to changes in biosolids prices than when wheat prices are higher.

Using the results in Table 4, the optimal biosolids application rate varies from 6.74 Mg ha<sup>-1</sup> for an input price of \$4.00 Mg<sup>-1</sup> and an output price of \$0.15 per kg to 8.31 Mg ha<sup>-1</sup> for an input price of \$2.00 Mg<sup>-1</sup> and an output price of \$0.25 per kg. Within this price range, wheat yield was not very sensitive to changes in input and output prices. Optimal wheat yield in Table 4 ranges from 2703 to 2730 kg ha<sup>-1</sup>. From Fig. 4 it is apparent that, given higher costs of biosolids, the optimal wheat yield would be more sensitive to price changes.

Excel's Solver Add-in (Microsoft Corporation, Redmond, WA) was used to examine the maximum prices a farmer could afford to pay for biosolids given N fertilizer prices of \$1.10 and \$2.20 per kg, and a wheat price of \$0.20 per kg. With an N fertilizer price of \$1.10 per kg and a wheat price of \$0.20 per kg, profit above N costs was \$485 ha<sup>-1</sup> at the profit maximizing level of N fertilizer. At this profit level, a farmer could afford to pay \$7.47 Mg<sup>-1</sup> for biosolids. With an N fertilizer price of \$2.20 kg<sup>-1</sup> and a wheat price of \$0.20 kg<sup>-1</sup>, profit above fertilizer costs was \$451 and a farmer could afford to pay \$11.65 Mg<sup>-1</sup> for biosolids.

## SUMMARY AND CONCLUSIONS

Data from long-term biosolids application study on a Colorado 2-yr wheat-fallow rotation were analyzed using multiple regression analysis. For the site that recently initiated the application of biosolids, the biosolids response function explained >83% of the wheat yield variation. Maximum wheat yield was achieved at a biosolids application rate of 9.0 Mg ha<sup>-1</sup> when all variables in the regression equation other than biosolids were set at their mean. The economically optimal level of biosolids to apply depends on both the price of the output, wheat, and the cost of the input, biosolids, and any costs associated with its application. With a wheat price of \$0.20 kg and a cost of biosolids of \$4.00 Mg<sup>-1</sup>, the optimal level of biosolids would be approximately 7.3 Mg ha<sup>-1</sup> (see Table 4).



**Fig. 4. Profit maximizing yields at various prices of biosolids and wheat prices.**

When biosolids are applied at or below the agronomic recommended rate, there would be few if any negative externalities (Lerch et al., 1990a). At levels above the agronomic recommended rate, however, the potential for negative externalities may be quite substantial. Monitoring the soil periodically for nutrient levels would be prudent to avoid any excess levels on N or other plant nutrient. Municipal biosolids, when properly applied in a wheat-fallow agro-ecosystem, can be beneficial to farmers while providing an opportunity to recycle them in an environmentally sound manner.

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