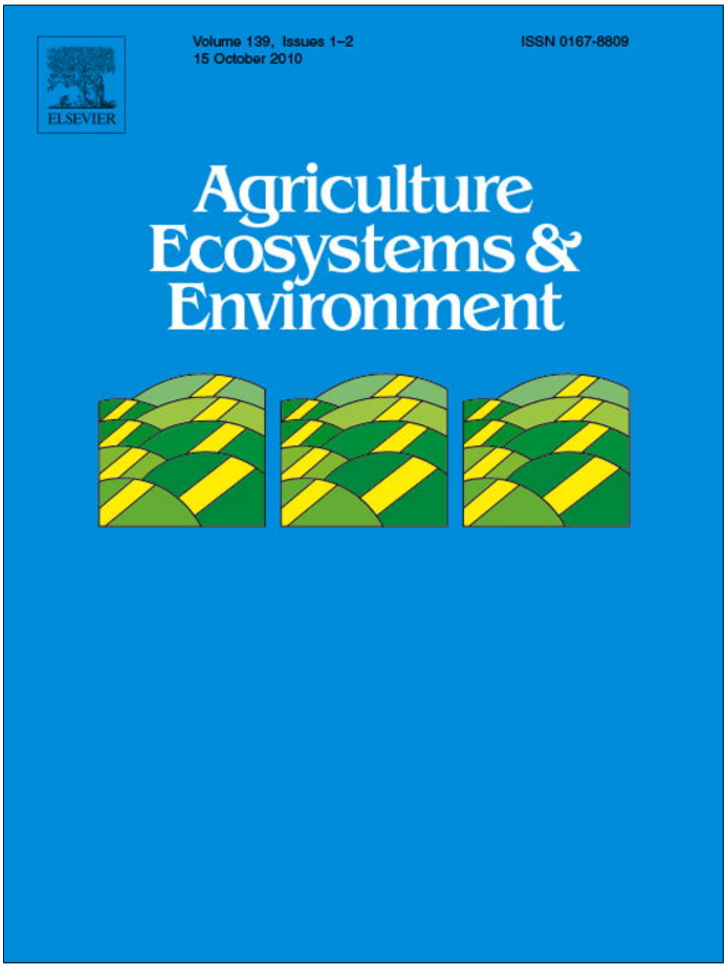
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Fifteen years of wheat yield, N uptake, and soil nitrate–N dynamics in a biosolids-amended agroecosystem

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ABSTRACT

Understanding N dynamics in biosolids-amended agroecosystems can help avoid over-application and the potential for environmental degradation. We investigated 15-years of biosolids application to dryland-wheat (*Triticum aestivum* L.) grown on Weld loam soils (fine, montmorillonitic, mesic Aridic Paleustolls) located about 25 km east of Brighton, CO, USA, questioning what is the relationship between cumulative grain yield and N uptake (N removal) and biosolids or N fertilizer rates and how many times biosolids or N fertilizer are applied? How are wheat-grain production and N uptake intertwined with residual soil NO_3–N? We found that biosolids or N fertilizer rates plus the number of applications of each material produced planar-regression (3D) models with 15-years of grain yield and N uptake data (all $R^2 > 0.93$). To evaluate how yield or N uptake impacted residual soil NO_3–N, we completed linear regressions on yield, N uptake, and soil NO_3–N. We then correlated the slopes where $P < 0.10$ for the yield and soil NO_3–N and the N uptake and soil NO_3–N. A significant negative relationship was found for biosolids application for each of these comparisons while the N fertilizer results were inconsistent. For the biosolids treatments, as yield or N uptake increased, residual soil NO_3–N decreased. Our findings show that planar-regression models could aid biosolids beneficial-use management programs when considering agroecosystem N dynamics.

1. Introduction

The USEPA regulates the recycling of biosolids (sewage sludge) through 40 CFR Part 503 regulations (USEPA, 1993). In agroecosystems, biosolids applications are based on crop N requirements, or the agronomic N rate. Consequentially, delineating the relationship between crop yields, N removal, and soil NO_3–N accumulation is crucial in avoiding over-application.

Few studies have investigated plant yield or N uptake and residual soil NO_3–N interactions. Binder et al. (2002) measured little NO_3–N accumulation when biosolids were applied at rates to maximize corn (*Zea Mays* L.) and sorghum (*Sorghum bicolor* L.) grain production in a Sharpsburg silty clay loam (Argiustoll). Cogger et al. (2001) found an inconsistent relationship between tall fescue (*Festuca arundinacea* Schreb.) yield and residual soil NO_3–N over 7 years of biosolids application to a Puyallup fine sandy loam (Haploxeroll). Jurado-Guerra et al. (2006) showed that tobosagrass [*Hilaria mutica* (Buckl.) Benth.] yields in a Stellar sandy loam (Calciargid) were determined by soil NO_3–N release as related to biosolids residence time. Mendoza et al. (2006) found that N leaching losses and residual NO_3–N did not account for up to 61% of the N input in biosolids-amended Blue Point loamy sand (Torripsamment). Barbarick et al. (1996) applied biosolids to either a Weld (Argiustolls) or Platner loam (Paleustolls), showing for dryland-wheat an inability to explain the fate of 28–71% of biosolids-applied N with lowest accountability occurring with higher biosolids rates.

Our hypotheses were:

1. A planar (3D) regression using number of biosolids or N fertilizer applications and biosolids or N fertilizer rates would predict cumulative wheat grain yields or cumulative N uptake in a dryland agroecosystem with an $R^2 > 0.75$ (to explain 75% of the variability) and provide superior predictability (higher R^2-value and lower SE) than a simple linear model.
2. Correlation between the linear-regression slopes for grain yield or N uptake and residual soil NO_3–N will be negative and significant at the $P < 0.10$ level. In other words, we believe that larger grain yields or N uptake will reduce soil NO_3–N accumulation.

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Table 1
The solids, organic N, NH_4–N, and NO_3–N content of the Littleton/Englewood, Colorado biosolids applied to dryland winter wheat at two sites near Bennett, CO, USA from 1993 to 2008.

Year applied	Site receiving	Solids (mg kg^{-1}) (wet basis)	Organic N (mg kg^{-1}) (dry basis)	NH_4–N (mg kg^{-1}) (dry basis)	NO_3–N (mg kg^{-1}) (dry basis)
1993	A	880	30.9	5.0	<0.1
1994	B	880	26.7	5.5	<0.1
1995	A	600	25.4	5.0	<0.1
1996	B	730	12.4	8.6	<0.1
1997	A	530	34.4	0.6	<0.1
1998	B	680	11.2	4.3	<0.1
1999	A	640	7.0	3.4	0.14
2000	B	800	18.0	5.9	<0.1
2001	A	740	21.0	4.0	<0.1
2002	B	930	53.0	10.4	<0.1
2003	A	550	19.0	2.6	0.11
2004	B	920	30.0	3.6	<0.1
2005	A	930	30.0	3.6	<0.1
2006	B	800	42.8	5.2	<0.1
2007	A	930	45.4	4.2	<0.1

2. Materials and methods

We started our biosolids research near Bennett, CO, USA (latitude 39.9563, longitude 104.462) in the summer of 1993. Mean maximum and minimum temperatures are 19 and 2 °C, respectively, mean annual precipitation is about 350 mm and the annual growing season is about 150 d (NRCS, 1974). Since the crop rotation was hard red winter wheat-summer fallow, we used two sets of plots on the same farm (designated A for those established in 1993; B for those established in 1994).

A Weld loam (fine, smectitic, mesic Aridic Argiustoll; NRCS, 2010a) comprises both sites. The Weld soil series occupies 3.2×10^5 ha in eastern Colorado (NRCS, 2010b). Initial soil characteristics were: organic matter content ~1% to a depth of 150 cm; surface (0–20 cm) soil pH of 6.9, and subsoil pH ranged from 7.2 to 8.3 from 20 to 150 cm. The electrical conductivity of saturated-soil extracts were <1 dS m^{-1} to the 150 cm depth.

Anaerobically digested biosolids were obtained from the Littleton/Englewood, CO Wastewater Treatment Plant (L/E) after approximately 60 d of sand-bed drying. Biosolids samples were collected prior to application and kept refrigerated at approximately 3 °C until analyses were completed. Table 1 shows the solids and N content for the biosolids applied to both plots. Biosolids were applied at rates of 0, 2.24, 4.48, 6.72, 8.96, and 11.2 dry Mg biosolids ha^{-1} to 1.8 m × 17.1 m plots in 1993, 1995, 1997, 1999, 2001, 2003, 2005, and 2007 at site A and in 1994, 1996, 1998, 2000, 2002, 2004, and 2006 at site B. Barbarick and Ippolito (2007, 2008) provide further research-site details. The 4.48 Mg biosolids ha^{-1} rate is our recommended agronomic rate for dryland winter wheat since it supplies ~35 kg N ha^{-1} (Barbarick and Ippolito, 2007), the requirement for optimal dryland winter wheat yields. In late July or early August (about 50 d before planting), we weighed the L/E biosolids (solids content of 530–930 g kg^{-1}), evenly spread over the plots utilizing a front-end loader, hand raked to improve the uniformity of distribution, and immediately rototilled to a depth of 10–15 cm. We uniformly hand-applied urea fertilizer at rates of 0, 22.4, 44.8, 67.2, 89.6, and 112 kg N ha^{-1} to fertilizer only plots at the same time as biosolids application. We arranged the research in a randomized complete block design with four replications of each treatment at each site.

Each July from 1994 through 2008, we harvested a 1.8 m × 15.2 m area for yield determinations and grain sampling. Hail destroyed the 2000-1 crop. We determined grain protein content with a Dickey John (Colombes, France) GAC III near infrared analyzer and then calculated N concentrations by dividing protein content by 5.7. We determined grain N uptake as follows:

$$\text{N uptake} = \text{N concentration} \times \text{yield} \quad (1)$$

where N uptake is expressed in kg ha^{-1}, grain concentration in g kg^{-1}, and yield in Mg ha^{-1}.

Immediately following each wheat harvest, we collected composite soil samples (two to three cores per plot) from the 0 to 20 cm (tillage layer) and 20 to 60 cm depth near the center of each plot to avoid biosolids redistribution problems that can occur following tillage operations over many cropping years (Ippolito et al., 2007; Yingming and Corey, 1993). The soil samples were immediately air-dried and crushed to pass a 2-mm sieve. We determined soil NO_3–N concentrations using a 2 M KCl extraction (Mulvaney, 1996) for both soil depths. We calculated a weighted average for the NO_3–N levels in the 0–60 cm depth. We statistically analyzed the yield and N uptake data for both sites together using a planar-regression model:

$$\text{Cumulative yield or cumulative N uptake} = a + bx + cy \quad (2)$$

where: cumulative yield is expressed in Mg ha^{-1} or cumulative N uptake in kg ha^{-1}; a, b, c = non-linear curve fitting parameters; x = number of biosolids or N fertilizer applications; y = biosolids rates in Mg ha^{-1} of N fertilizer rates in kg ha^{-1}.

We also calculated linear regressions for cumulative yield vs. cumulative biosolids or N fertilizer application so that we could compare the linear to the planar model.

$$\text{Cumulative yield or cumulative N uptake} = \text{slope}(x) + \text{intercept} \quad (3)$$

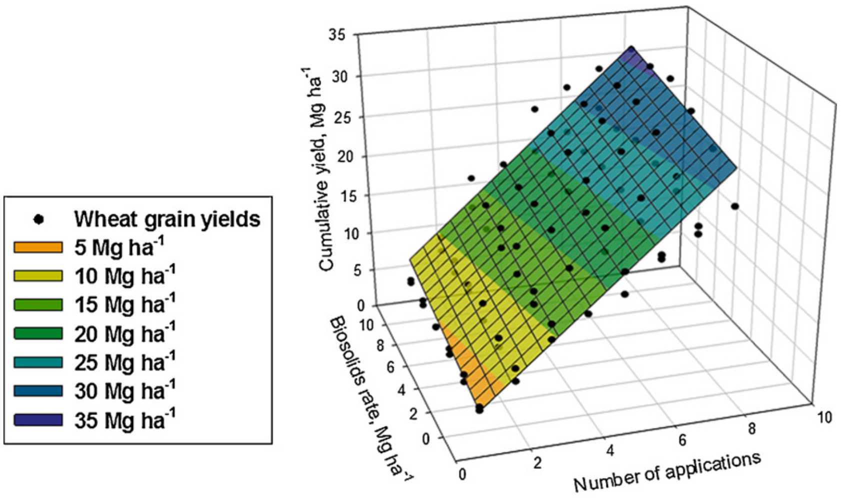
where cumulative yield is expressed in Mg ha^{-1} or cumulative N uptake in kg ha^{-1}; x = cumulative biosolids rates in Mg ha^{-1} or cumulative N fertilizer rates in kg ha^{-1}.

For the soil NO_3–N data, we first calculated the slopes from the linear regression analyses (Eq. (4)) of yield, N uptake, and soil NO_3–N compared to biosolids or N fertilizer rate.

$$\text{Yield or N uptake} = \text{slope}(x) + \text{intercept} \quad (4)$$

where yield is expressed in Mg ha^{-1} for any given harvest or N uptake in kg ha^{-1} for any given harvest; x = soil NO_3–N immediately following any given harvest.

Once the slopes for each individual linear regression were determined, we correlated the slopes from the significant linear effects for soil NO_3–N with those for yield and N uptake. We used a P of 0.10 to determine significance for all statistical tests. Model equations, R^2 values, and standard errors were determined using SigmaPlot® (2009) version 11.2.



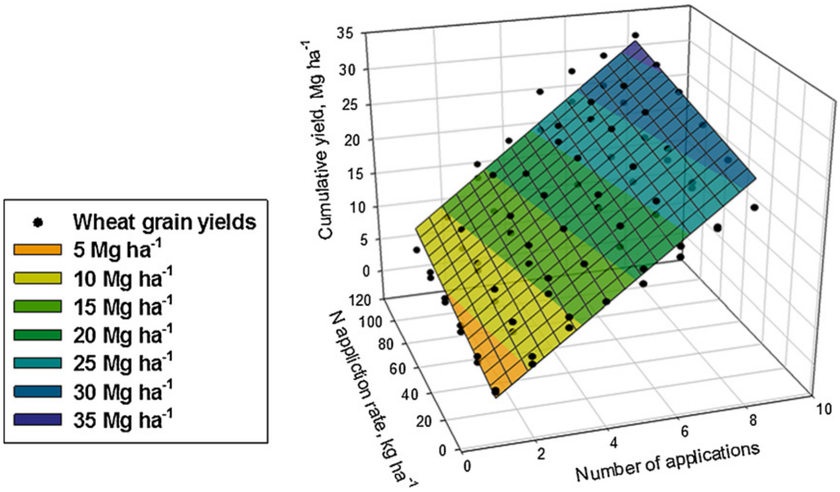
$$\mathit{cumulative\ \ yield} = -1.0 + 3.5(\mathit{apps.}) + 0.38(\mathit{biosolids\ \ rate})$$
$$R^2 = 0.934;\ P < 0.001;\ SE = 2.2$$

Fig. 1. Cumulative wheat-grain yields as a function of number of applications and biosolids rate at North Bennett, 1993–2008.

3. Results and discussion

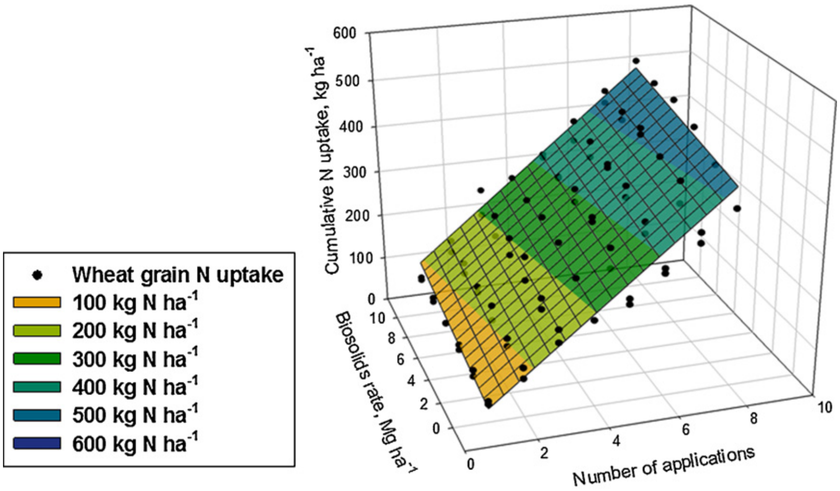
Figs. 1–4 show that the relationship between cumulative yield or cumulative N uptake and number of applications of biosolids or N fertilizer rates produced R^2 values >0.93. Barbarick and Ippolito (2008, 2009) found that planar- (R^2 values between 0.62 and 0.92) or parabolid-regression models (3D; R^2 values between 0.32 and 0.87) predicted soil extractable and grain elemental concentrations, respectively. By contrast, the linear-regression parameters for cumulative yields and N uptake vs. cumulative biosolids or N fertilizer rates produced R^2 values between 0.48 and 0.54 (Table 2) with larger standard errors than the planar models. Consequently, we accepted our first hypothesis.

The 3D models allow viewing trends involving multiple rates and applications, and supply better predictions than linear models. As an example from the prediction model shown in Fig. 1, two applications of 6.72 Mg biosolids ha^{-1} would produce a cumulative grain yield of 8.6 Mg ha^{-1}. Six applications of 2.24 Mg biosolids ha^{-1} would produce a cumulative grain yield of 24.8 Mg ha^{-1}. In both cases, a total of 13.44 Mg biosolids ha^{-1} would have been added; however, the predicted cumulative yields differ because of how the biosolids would be distributed. By contrast, utilizing the parameters in Table 2 and a cumulative 13.44 Mg biosolids ha^{-1} application amount, the linear-regression model would predict a cumulative grain yield of 13.4 Mg ha^{-1}. Using the model shown in Fig. 4, one application of 112 kg N fertilizer ha^{-1} would result in a cumulative N uptake of 98 kg ha^{-1}. Five applications of 22.4 kg N fertilizer ha^{-1} would generate a cumulative N uptake of 248 kg N uptake ha^{-1}. For a cumulative N fertilizer rate of 112 kg N fertilizer ha^{-1}, the cumulative N uptake would be 148 kg ha^{-1} using the linear-regression model provided in Table 2. The planar-regression model captures the biosolids or N fertilizer dynamics over time, indicating that it would be a more useful approach for a biosolids-management program than a simple linear-regression prediction.



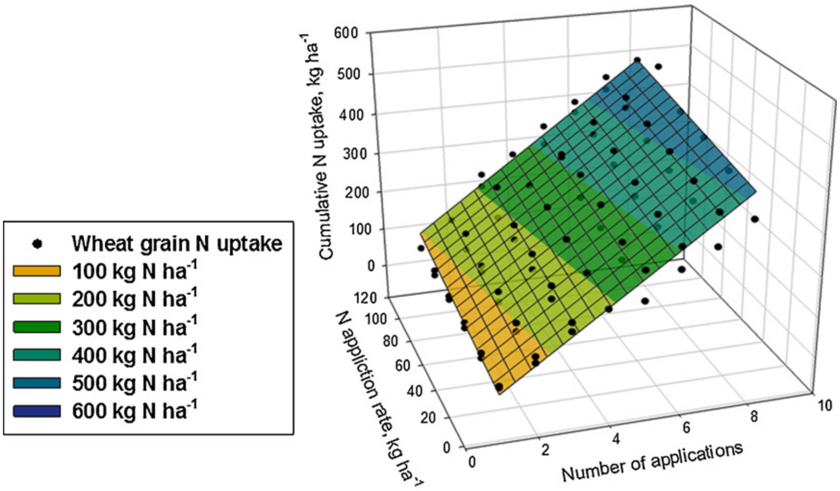
$$\mathit{cumulative\ \ yield} = -1.6 + 3.5(\mathit{apps.}) + 0.048(N\ \ \mathit{rate})$$
$$R^2 = 0.953;\ P < 0.001;\ SE = 1.8$$

Fig. 2. Cumulative wheat-grain yields as a function of number of applications and N fertilizer rate at North Bennett, 1993–2008.



$$cumulative\ \ N\,uptake = -27 + 56(apps.) + 5.9(biosolids\ \ rate)$$
$$R^2 = 0.967;\ P < 0.001;\ SE = 23.9$$

Fig. 3. Cumulative N uptake by wheat grain as a function of number of applications and biosolids rate at North Bennett, 1993–2008.



$$cumulative\ \ N\,uptake = -34 + 56(apps.) + 0.68(N\ \ rate)$$
$$R^2 = 0.964;\ P < 0.001;\ SE = 24.9$$

Fig. 4. Cumulative N uptake by wheat grain as a function of number of applications and N fertilizer rate at North Bennett, 1993–2008.

Increasing biosolids rates often leads to both grain yield increases and higher residual soil NO_3–N; however, higher grain yields often result in less NO_3–N accumulation. These observations infer that the slopes of the linear response curves for yield or N uptake and soil NO_3–N over either biosolids or N fertilizer rate would probably be positive but the magnitude of the slopes will differ as yields differ. Consequently, a negative correlation should result between the slopes for yield or N uptake and soil NO_3–N.

Table 3 shows that negative correlations ($P < 0.002$) were found for the slope of yield or N uptake and soil NO_3–N with the biosolids treatment. The same comparisons for N fertilizer produced inconsistent results. Consequently, we accept hypothesis

Table 2
Regression coefficients and statistics for linear-regression slopes between grain yield or N uptake and cumulative biosolids or cumulative N fertilizer rates at North Bennett, 1993–2008.

Parameters	Cumulative yield vs. cumulative biosolids rate	Cumulative yield vs. cumulative N fertilizer rate	Cumulative N uptake vs. cumulative biosolids rate	Cumulative N uptake vs. cumulative N fertilizer rate
Slope	0.26	0.027	4.1	0.42
Intercept	10	9.4	147	143
R^2	0.476	0.540	0.489	0.516
Probability level	<0.001	<0.001	<0.001	<0.001
SE	6.1	5.6	93	92

Table 3
Correlation data between slopes for linear regressions between soil NO_3–N and grain yield and soil NO_3–N and N uptake at North Bennett, 1993–2008.

Slopes comparison	*r*-Value	Probability level	Standard error
Soil NO_3–N vs. grain yield			
Biosolids	−0.867	0.002	0.072
N fertilizer	+0.649	0.082	0.026
Soil NO_3–N vs. N uptake			
Biosolids	−0.944	<0.001	0.12
N fertilizer	−0.367	0.371	0.067

2 when biosolids were applied but reject it when N fertilizer was applied. The slow-release nature of the biosolids vs. immediate and rapid availability from the N fertilizer (Barbarick and Ippolito, 2000) may explain the differences. If crop removal is small, slow and continual N release by the biosolids probably provided a more consistent opportunity for NO_3–N accumulation compared to inorganic N fertilizer. Knowing the dynamics of grain production and N uptake and residual soil NO_3–N will ensure best management practices and a reduction in the potential for environmental degradation (i.e. leaching and offsite NO_3–N movement) for a biosolids-application program.

4. Conclusions

Planar-regression equations (3D) using number of biosolids or N fertilizer applications plus application rates provided superior models (higher R^2 values, lower SE) for grain yield production and N uptake than a simple linear-regression model involving cumulative application amounts. Also, comparison of the slopes from linear-regression models between yield or N uptake and soil NO_3–N accumulation indicated that biosolids application produced a negative correlation while N fertilizer provided inconsistent results. These observations should offer information that will help with biosolids-application best management practices and reduce the potential for offsite NO_3–N transport. For example, if a grain yield is less than would be predicted by the planar model, an increase in NO_3–N would be expected. Consequently, the operators would probably have to reduce their next biosolids application rate. Also, as reported by Barbarick and Ippolito (2009), the Weld soil encompasses 3.2×10^5 ha in eastern Colorado and soils with the same soil taxonomy to the family level (fine, smectitic, mesic, Aridic Argiustolls) comprise 2.3×10^6 ha in 25 soil series in 10 U.S. states. Responses on these soils to biosolids management would probably be very similar to our results on the Weld soil.

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