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Matching Plant-Available Nitrogen from Biosolids with Dryland Wheat Needs

C. G. Cogger, D. M. Sullivan, A. I. Bary, and J. A. Kropf

Research Question

Biosolids are stabilized solids from municipal wastewater treatment that meet federal criteria for land application. Nitrogen is usually the key nutrient for determining biosolids application rates. Biosolids producers, farmers, and regulators need good estimates of biosolids N availability to develop sustainable biosolids management programs. Our objectives were to determine the availability and downward movement of biosolids N applied to soft-white winter wheat grown in a crop-fallow rotation, and make practical recommendations for biosolids N management.

Literature Summary

Standard EPA N availability estimates for biosolids are lower than estimates published in recent literature. Using the standard estimates to set biosolids application rates could lead to over-application of N, because they may underestimate N availability. Research in Montana and Colorado indicates that even when fertilizer inputs are low, some nitrate moves below the root zone in grain-fallow cropping systems. Downward movement of nitrate is also possible in the Northwest, where precipitation falls mostly during the cooler months and soils are medium-textured. Excess applied N increases the potential for nitrate leaching. Also, excess soil N increases protein in wheat. High protein can be a problem in the Northwest, because most of the wheat grown is the soft-white type, which has highest quality at low protein levels.

Study Description

We established biosolids on-farm tests at three sites in the 9 to 12 in. rainfall zone of the Columbia Plateau of Washington, where wheat-fallow is the main cropping system. We used large (700–1000 ft long) plots to allow farmers to carry out normal field activities. We applied two to three rates (3–10 dry tons/acre; 257–853 lb total N/acre) of dewatered (21–30% solids) biosolids at the beginning of the fallow cycle, and compared biosolids treatments with aqua or anhydrous ammonia, and with unfertilized controls. Measurements included grain yield, grain protein, and grain N uptake, along with straw yield and N uptake, and flag leaf N concentration. We also measured plant-available N in the soil during the fallow, after harvest, and during the second fallow. Soils were sampled to a depth of 6 ft where possible to observe N levels throughout the soil profile.

Applied Questions

Were biosolids a reliable source of N?

Yes. Nitrogen availability from biosolids was dependable and consistent over the three sites, despite differences in environment among the sites. We found that 29% of the biosolids N was in available form by the end of the summer fallow, compared with a predicted availability of 26 to 31%, using EPA estimates. More N became available during the crop year.

Is over-application of N a potential problem?

Yes. The lowest rates of biosolids used in this study provided enough N for peak yields, with variable increases in protein and residual soil nitrate. Drawbacks to higher rates were reduced crop yield (from water stress) and

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Full scientific article from which this summary was written begins on page 41 of this issue.

quality (from increased protein), and increased risk of nitrate movement below the root zone.

What is the agronomic application rate for biosolids N?

Under the conditions of this study, agronomic rates appear to be lower than the lowest rates (257–330 lb/acre) we applied. Evaluation of lower biosolids rates (100–300 lb/acre total N) will be valuable in refining biosolids application recommendations for soft-white winter wheat grown in a dryland fallow rotation.

Matching Plant-Available Nitrogen from Biosolids with Dryland Wheat Needs

C. G. Cogger,* D. M. Sullivan, A. I. Bary, and J. A. Kropf

Biosolids are stabilized solids from municipal wastewater treatment that meet federal standards for land application. Good estimates of biosolids N availability are needed to develop sustainable biosolids management programs. We conducted this study to (i) determine the availability and fate of biosolids N applied to a dryland soft-white winter wheat (*Triticum aestivum* L.)-fallow rotation, (ii) determine if N availability predictions for biosolids are applicable under dryland conditions, and (iii) make practical recommendations for biosolids management. We applied dewatered (21–30% solids) biosolids (4.3–5.5% total N; 257–853 lb N/acre) to on-farm test plots at three locations in the 9–12 in. rainfall zone of eastern Washington. Fertilized (anhydrous or aqua ammonia [AA]) and unfertilized treatments were established at each site for comparison. We measured yield and N uptake of grain and straw at harvest, and determined soil profile nitrate N (plus ammonium N, 0–12 in. depth only) before application, during fallow, and post-harvest. We determined apparent N recovery from the soil at the end of the fallow (ANR_{fallow}). Nitrogen release from biosolids as measured by ANR_{fallow} was dependable and consistent over the three sites, despite differences in environment among the sites. ANR_{fallow} averaged 29%, similar to predicted values of 26–31%. The lowest biosolids rates (257–330 lb/acre) supplied more available N than AA. Yield, grain N, and flag leaf N all indicate that N was sufficient at the lowest biosolids rates used, and that higher levels of biosolids did not benefit the crop. Drawbacks to higher rates include risks of reduced crop yield (from moisture stress) and quality (from increased protein), and increased risk of nitrate movement below the root zone. Storage of nitrate in the soil profile does not appear to be a reliable strategy for supplying N for a second crop. Lower biosolids rates seem to reduce economic risks to the farmer and reduce leaching risk. Evaluation of low biosolids rates (100–300 lb total N/acre) and second crop response will be valuable in refining biosolids application recommendations.

DRYLAND WHEAT is an excellent crop for beneficial reuse of biosolids in the Pacific Northwest, because: (i) there is a low risk of runoff or public contact with pathogens, (ii) metal uptake is small at agronomic application rates (Barbarick et al., 1995), (iii) wheat has a deep root zone that can capture some deep-moving nitrate, and (iv) a large land base is available. Wheat farmers have become interested in biosolids because they are an inexpensive form of N, and they perceive potential additional benefits from the organic matter in biosolids.

Repeated application of low levels of organic N can benefit soft-white winter wheat grown in a crop-fallow rotation. In a summary of a 55-yr experiment in Oregon, Rasmussen and Parton (1994) reported higher grain yields and better maintenance of soil organic matter with low rates of cattle manure (100 lb N/acre per crop cycle) than with synthetic fertilizer.

Little research data is available for one-time applications of higher rates of organic N (300 lb N/acre or more) in a wheat-fallow cropping system. Dryland farmers need this information to know whether biosolids application will meet the N needs of their crop, without increasing risks of yield or grain quality loss from excess N.

Guy et al. (1995) observed yield and quality loss from increased protein, moisture stress, and lodging after over-application of N in northern Idaho. Sowers et al. (1994) hypothesized that excess levels of N deep in the root zone increased the risk of high protein in soft-white winter wheat, while excess N levels shallow in the root zone increased the risk of moisture stress.

Availability and downward movement of biosolids N are also important environmental factors, because excess N that leaches below the root zone is a wasted resource, and may become a groundwater contaminant. Biosolids producers (wastewater treatment plants), farmers, and regulators all need good estimates of biosolids N availability to develop sustainable biosolids management programs.

Researchers have estimated N availability from biosolids using lab incubations and field mineralization experiments. Results have varied widely among studies (Barbarick et al., 1996). Standard mineralization estimates used in the USA (USEPA, 1995) use values at the lower end of the range reported in the literature.

In a dryland wheat-fallow rotation in Colorado, Barbarick et al. (1996) used changes in soil N in a long-term (11-yr) biosolids experiment to estimate biosolids N mineralization rates. Their estimates ranged from 13 to 43% for first-year biosolids N mineralization to 25 to 57% for long-term cumulative biosolids N mineralization, when biosolids were applied at 3 dry tons/acre per crop cycle. First-year mineralization estimates were as high as 67% when 12 dry tons/acre of biosolids were applied. The first-year mineralization estimates were for liquid biosolids with variable N content, while the cumulative rates were for a mixture of liquid and drying bed biosolids. These ranges are too wide to be useful in estimating agronomic application rates for biosolids.

A dryland wheat-fallow rotation should be well-suited for a more direct estimate of first-year N availability, by applying biosolids at the start of the fallow, and comparing N recovery from biosolids-treated and unfertilized soil at the end of the fallow. This estimate would include both miner-

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C.G. Cogger and A.I. Bary, Washington State Univ. Puyallup Research and Extension Center, 7612 Pioneer Way E., Puyallup, WA 98371-4998; D.M. Sullivan, Dep. of Crop and Soil Science, Oregon State University, Corvallis, OR 97331; J.A. Kropf, WSU Cooperative Extension, Pierce County, WA. WSU Crop and Soil Sciences Departmental Paper No. 9708-04 *Corresponding author (cogger@wsu.edu).

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Abbreviations: AA, anhydrous or aqua ammonia.

alization and ammonium recovery, and can be compared with USEPA (1995) or other estimates of N availability.

The Colorado studies also evaluated the fate of biosolids N applied to dryland wheat (Lerch et al., 1990a, b; Barbarick et al., 1996). They found the lowest rates of biosolids applied (3 dry tons/acre per crop cycle) were sufficient to maintain or increase yields and increase protein compared with commercial fertilizer applications. Higher biosolids rates sometimes depressed yields. All rates of biosolids increased post-harvest residual nitrate in the soil profile. The increase was small at the 3 ton/acre rate, but substantial at 12 tons/acre.

Evans et al. (1994) noted evidence of movement of small amounts of nitrate below the root zone in dryland wheat in eastern Colorado. In Montana, Bauder et al. (1993) reported elevated levels of nitrate in groundwater in areas predominantly farmed in crop-fallow rotation for dryland cereal grains. In some cases nitrate N levels in domestic wells were greater than 10 ppm. Some of the areas with elevated nitrate received average precipitation of less than 12 inches per year.

The leaching observed in the studies above occurred in areas that received zero to moderate levels of N fertilizer. In a Colorado study where high rates of biosolids were repeatedly applied, Barbarick et al. (1996) found nearly 30 ppm nitrate N at 60 to 80 in., but did not sample deeper in the profile.

The dryland wheat areas of the Pacific Northwest differ from those in Colorado and Montana in several important ways. Although rainfall is less is many parts of the Northwest, more of the precipitation falls during the fall and winter when the leaching potential is higher. Most of the Northwest soils are coarser-textured (loams and silt loams) than the soils in the Colorado studies (clay loams), which could also increase leaching potential. While high protein is desirable in the hard-red wheat grown in the Colorado study (Lerch et al., 1990b), increased protein is not desirable in the soft-white wheat grown in the Pacific Northwest (Rao et al., 1993). These differences mean that over-application of biosolids may have greater negative effects in the Northwest, and local information on the availability and fate of biosolids N is important to sound biosolids management.

We conducted this study to improve our ability to manage biosolids applied to dryland grains in the Pacific Northwest and similar areas. Our specific objectives were: (i) to determine the availability and downward movement of biosolids N applied to a soft-white winter wheat-fallow dryland rotation, (ii) to determine whether N availability predictions for biosolids are applicable under Northwest dryland conditions, and (iii) make practical recommendations for biosolids management to meet the needs of farmers, biosolids producers, and regulators.

MATERIALS AND METHODS

Sites and Soils

We established on-farm experimental plots at one location in Douglas County (site D92), 110 mi west of Spokane, WA, and two locations in Adams County (sites A92 and A93), 60 and 80 mi southwest of Spokane. The sites represent a range of soil and environmental conditions found in the 9 to 12 in. precipitation zone of the dryland soft-white wheat-fallow belt of eastern Washington. The site code indicates the county (D = Douglas and A = Adams) and year of biosolids application.

Table 1. Climate summary for on-farm test locations.†

Site	County	Mean Jan. temp	Mean July temp.	Mean precip.	Mean snowfall
		—— °F ——		—— in. ——	
D92	Douglas	23	67	11.2	51
A92	Adams	27	71	11.3	15
A93	Adams	28	72	9.9	16

† 30-year mean (1961–1990).

The Adams County soils are derived from loess and are silt loam in texture. Although the soils at both Adams sites are in the Ritzville series (coarse-silty, mixed, mesic Calciorthidic Haploxerolls), the soil at site A93 is sandier than site A92. The Douglas County soil is a mixture of till and loess. It is classified as Touhey loam (coarse-loamy, mixed mesic Aridic Duric Haploxerolls). Touhey soils are weakly cemented in the substratum and contain more clay and coarse fragments than the Ritzville soils.

Soils at all sites had low organic matter levels (1.4–1.7% in the 0–4 in. depth), and had been farmed without manure or other organic inputs for at least 50 yr before biosolids applications, making them responsive to N fertilization. Before biosolids application, mean bicarbonate soil test phosphorus (0–12 in.) ranged from 12 to 18 ppm across sites, exchangeable potassium ranged from 450 to 750 ppm, and soil pH from 6.4 to 6.6, all adequate for wheat production (Halvorson et al., 1986).

Precipitation and temperatures were taken from stations at Ritzville (5 mi E of site A92), near Hatton (7 mi W of site A93), and at Waterville (20 mi SW of site D92). Thirty-year mean temperatures are about 5°F cooler at site D92 and snowfall is considerably higher, compared with sites A92 and A93 (Table 1). The cooler temperatures and higher snowfall at site D92 increase available moisture but also increase the risk of snow mold (*Fusarium nivola* and *Typhula* spp.). Site A93 has the least available moisture because of its lower precipitation, warmer temperatures, and sandier soil texture.

Precipitation is usually not enough to support annual cropping, so a typical crop rotation is a fallow year followed by soft-white winter wheat. Sometimes fall canola (*Brassica napus* L. var. *napus*) or spring wheat are grown. The purpose of the fallow year is to store moisture and control weeds. Biosolids are applied early in the fallow year, either in the fall after harvest of the previous crop, or during the following spring. Wheat is planted at the end of fallow in late summer, and harvested the following July or August. Applying biosolids early in the fallow season reduces soil compaction, and allows a relatively long window (fall and spring) for application. Early application has the disadvantage of loss of stubble, because the biosolids usually are incorporated shortly after application.

Experimental Design

Treatments included two to three biosolids rates, one rate of AA and an unfertilized check. Plots measured 50 by 1000

Table 2. Biosolids N content and application rates.†

Site	Biosolids applied	TKN	NH_4 N	Total N applied	Date applied
	ton/acre	%		lb/acre	
D92	5, 10	4.3	1.5	426, 853	15 Oct. 92
A92	3, 6, 9	4.3	1.2	257, 513, 770	19 Oct. 92
A93	3, 4.5, 6	5.5	1.1	330, 495, 660	30 Nov. 93

† Biosolids rates and N analyses are on a dry weight basis.

ft at sites D92 and A92, and 70 by 700 ft at site A93. Each site had a randomized complete block design, with three replications at site D92 and four replications at sites A92 and A93. All sites were in a wheat-fallow rotation. Cooperating farmers managed the plots, doing all tillage and weed management according to their normal practices.

Biosolids Applications

Biosolids were produced by anaerobic digestion and dewatering of primary and secondary municipal wastewater sludge at the King County Department of Natural Resources East Division Reclamation Plant, Renton, WA. Trace metal concentrations in the biosolids were all within USEPA Table 3 Pollutant Concentration limits (USEPA, 1993). We applied the biosolids (21–30% total solids) in the fall of the fallow season, using a rear-delivery, hydraulic ram manure spreader. Biosolids were incorporated using a chisel or disc within 1 d of application at sites D92 and A93, and 5 mo after application at site A92. Biosolids application rates and N content are summarized in Table 2. The AA plots received 50 lb N/acre injected at sites D92 and A92, and 45 lb N/acre at site A93.

Wheat was planted on 27 Aug. 1993 at site D92, 8 Sep. 1993 at site A92, and 25 Aug. 1994 at site A93. Portions of the field at site A93 had poor emergence, and were replanted on 25 Oct. 1994. The biosolids plots at site A93 had the best emergence, and most of the replanting was done in the unfertilized and AA treatments.

Harvest and Soil Sampling

The farmers harvested a single combine pass (Sites D92 and A92) or double combine pass (Site A93) from the center of each plot. We measured grain yield using a weigh wagon or weigh pads, and collected a 2-lb subsample from each plot for grain test weight and N content. Harvest dates were 25 July 1994 for site A92, 26 July 1994 for site D92, and 24 July 1995 for site A93.

Immediately before combine harvest, we hand-harvested two 36-in. sections of row from each plot for straw yield and straw N content. Straw samples were threshed to remove the grain, and then dried, ground, and subsampled for N analysis. Straw included the chaff from threshing grain. When plants were at heading (Feekes 10.5) at site A92 and early heading (Feekes 10.1) at site A93, we collected 30 flag leaves per plot for N concentration.

We collected soil samples using a 1-in. hammer probe, a 1.5-in. hydraulic hollow-core probe, or a 1.5-in. hydraulic auger probe, depending on soil conditions and depth of sampling. We collected samples five times: before biosolids application at the beginning of fallow, during the spring of the fallow year, at the end of fallow (planting), after harvest, and during the spring or summer of the second fallow year. We sampled 12-in. increments to a depth of 36 in. through fallow, and to 72 in. when possible for the post-harvest and second fallow samples. Sampling was limited to 48 in. at site D92 because of dense, rocky soil, and to 36 in. at site A92 post-harvest because we could not recover samples below that depth in the dry soil. Each sample was a composite of 20 cores (0–12 in. depth) or 6 to 10 cores (samples below 12 in.). Soil samples were dried (80°F), ground, sieved (0.08 in.), and analyzed for ammonium N (0–12 in. only), and nitrate N (all depths).

Sample Analysis

When biosolids were applied, we collected six composite biosolids subsamples at each site. Three subsamples were dried at 130°F for determining total solids, and three subsamples were acidified to pH 4 to 5 by addition of 1 M H_2SO_4 and dried at 130°F before N analysis. Sample preparation by acidification and drying yielded similar biosolids N analyses to established methods using fresh biosolids (APHA, 1992) in a preliminary experiment.

Total N was determined for biosolids and plant materials using a combustion N gas analyzer (LECO Instruments, St. Joseph, MI, model FP-428; Sweeney, 1989). Biosolids ammonium N was determined by steam distillation and titration (APHA, 1992). Soil nitrate N and ammonium N were extracted with 2M KCl and determined by automated colorimetric methods (Gavlak et al., 1994).

Statistical Analyses and Calculations

Statistics were computed using established procedures (SAS Institute, 1985). Least-significant differences were compared following a significant ($P < 0.05$) F-test. Data for soil profile nitrate N and post-harvest soil N recovery were transformed to a log10 distribution, because in most cases these data had a large positive skew. The log10 transformations produced normally distributed data.

Apparent recovery of biosolids N from soil during the first fallow (ANR_{fallow}) was calculated as:

$$ANR_{fallow} = [(A - B)/C] \times 100 \qquad [1]$$

where

A = [Soil profile nitrate N (lb/acre) + soil ammonium N (lb/acre, 0–12 in. only)] from treatment of interest,
B = [Soil profile nitrate N (lb/acre) + soil ammonium N (lb/acre, 0–12 in. only)] from the unfertilized treatment.
C = Total N applied as fertilizer or biosolids.

Apparent N recovery from the soil and crop at harvest ($ANR_{harvest}$) was calculated similarly, except that N uptake in the grain and straw was also included:

$$ANR_{harvest} = [(D - E)/C] \times 100 \qquad [2]$$

where

D = [N uptake in grain (lb N/acre) + N uptake in straw (lb N/acre) + soil ammonium N (lb/acre, 0–12 in.

only) + soil profile nitrate N (lb/acre)] from treatment of interest,

E = [N uptake in grain (lb N/acre) + N uptake in straw (lb N/acre) + soil ammonium N (lb/acre, 0–12 in. only) + soil profile nitrate N (lb/acre)] from the unfertilized treatment.

RESULTS AND DISCUSSION

Nitrogen Release in Fallow Year

Since biosolids are applied early in the fallow-wheat cycle, N released from biosolids during both the fallow and crop years will be available to the wheat crop. We can estimate N release from biosolids during the fallow year by comparing available N accumulations in the soil in the treated and unfertilized plots (ANR_{fallow}, Eq. 1).

Before biosolids application, residual soil nitrate N levels were low (Fig. 1, pre-application). Total residual nitrate N in the upper 36 in. of the soil ranged from 30 lb/acre at sites A92 and A93 to 60 lb/acre at site D92. These levels are low enough that a N response by wheat was expected at all sites.

Biosolids application increased soil inorganic N during the fallow year (Table 3). Most of this N had accumulated by the fallow-spring sampling date. Farmers establish a tillage mulch during the summer fallow by disking or sweep plowing to 4 to 6 in. during the spring, followed by two to four rod-weedings to 2 to 4 in. Low soil moisture in this tillage mulch probably limited N mineralization during summer.

ANR_{fallow} measured at planting was about 30% of total biosolids N applied (Table 3). Recovery was similar across sites, although the fallow year at site A93 (1993–1994) was much drier than the fallow year at sites D92 and A92 (1992–1993). The ANR_{fallow} of 30% is nearly identical to the amount predicted using standard N mineralization and ammonium retention estimates for biosolids (USEPA, 1995).

It appears that most of the nitrate remained in the surface soil (0–12 in. depth) during the fallow year, with little leaching below 12 in. (Fig. 1, planting). This may be because biosolids were applied to cool, dry soil in the fall, limiting mineralization and nitrification of biosolids N until the following spring, after the end of the leaching season.

Indicators of Crop N Sufficiency

Yield, grain N, and flag leaf N all indicate that available N was sufficient at the lowest biosolids rates used in this study (Table 4), and that higher levels of biosolids did not benefit the crop. Table 3 shows fallow N biosolids availability ranging from 79 to 196 lb/acre over application rates of 330 to 660 lb N/acre (3–6 dry tons/acre), for an average of 27 lb/dry ton. Even at the lowest biosolids rates, available N from the fallow year alone is greater than N applied to the AA plots (45–50 lb/acre). Yield was apparently near maximum in the AA treatments because biosolids did not significantly increase yield over AA, except for one rate at site A93 (Table 4).

Some of the additional biosolids N went into the grain, increasing protein. Grain protein at the lowest biosolids rate was greater than for the AA treatment at all sites (Table 4). The increased protein is generally not a benefit for soft-white wheat production, because low protein (<10%) is pre-

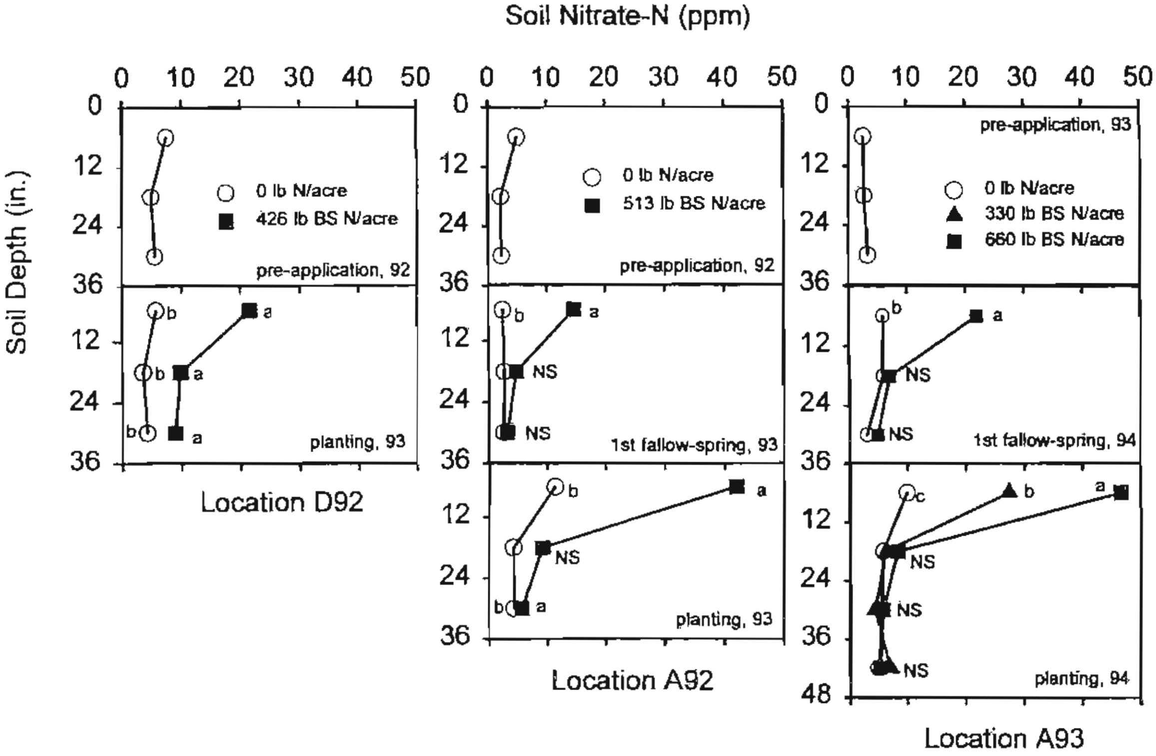

Fig. 1. Mean soil profile nitrate N concentrations at sites D92, A92, and A93 before biosolids application, and during fallow year after application. Means within a site and depth followed by different letters are significantly different at $P < 0.05$ by protected LSD on log10 transformed data. NS = no significant difference among means ($P < 0.05$).

Table 3. Measured and predicted apparent N recovery during the fallow year.

Time	Site	Total N applied	Measured $\mathrm{ANR}_{\mathrm{fallow}}$†		Predicted $\mathrm{ANR}_{\mathrm{fallow}}$‡
		lb/acre	lb/acre§	%	%
Fallow-spring	A92	513	130	25	–
	A93	660	105	16	–
Planting	D92	426	127	30	31
	A92	513	156	30	28
	A93	330	79	24	26
	A93	660	196	30	26

† Measured $\mathrm{ANR}_{\mathrm{fallow}}$ from Eq. 1 (0–36 in. depth).

‡ Predicted $\mathrm{ANR}_{\mathrm{fallow}}$ = [(0.2 × biosolids organic N + 0.5 × biosolids NH_4 N)/ biosolids total N] × 100, from USEPA (1995). Predicted $\mathrm{ANR}_{\mathrm{fallow}}$ computed only for sampling at planting (1 year after biosolids application).

§ Difference between treatment and unfertilized check significant at $P < 0.05$ for all sites.

Table 4. Indicators of N sufficiency in wheat crop.

Site	N source†	Total N applied	Grain yield‡	Grain protein§	Straw N	Flag leaf N¶
		lb/acre	lb/acre	%	%	%
D92	none	0	38 b*	8.1 c	0.31 b	–
	AA	50	57 a	9.9 c	0.36 b	–
	BS	426	56 a	14.4 b	0.57 ab	–
	BS	853	59 a	16.5 a	0.99 a	–
A92	none	0	46 c	7.7 c	0.31 NS	2.5 b
	AA	50	51 abc	8.3 c	0.32 NS	2.6 b
	BS	257	55 a	11.4 b	0.52 NS	4.4 a
	BS	513	51 ab	12.9 a	0.55 NS	4.6 a
	BS	770	50 bc	13.2 a	0.50 NS	4.8 a
A93	none	0	36 d	11.9 c	0.37 b	3.4 b
	AA	45	42 bc	11.4 c	0.39 b	3.7 b
	BS	330	45 ab	13.1 b	0.37 b	4.5 a
	BS	495	46 a	14.2 a	0.42 ab	4.5 a
	BS	660	40 c	14.4 a	0.64 a	4.6 a

* Means within a site and column followed by different letter are significantly different at $P < 0.05$ by protected LSD.

† N source: AA = aqua ammonia at site A92, anhydrous ammonia at sites D92 and A93; BS = biosolids.

‡ Grain yield at 10% moisture.

§ Grain protein estimated via total N analyses. Grain protein (%) = grain total N (% dry wt) × 5.75.

¶ Flag leaves sampled at Feekes growth stage 10.5 for site A92 and Feekes 10.1 at site A93.

Table 5. Nitrogen recovered from crop and soil at harvest.

Site	N source†	Total N applied	Crop N uptake		Post-harvest soil N‡		Total N recovered§	Total N $\mathrm{ANR}_{\mathrm{harvest}}$¶
			Grain N	Straw N	0–36 in.	>36 in.		
		lb/acre	lb/acre	lb/acre	lb/acre	lb/acre	lb/acre	% of applied
D92	none	0	28 d*	12 b	28 bc	5 c	73 c	–
	AA	50	49 c	24 b	22 c	4 c	99 c	52#
	BS	426	73 b	52 ab	56 b	9 b	189 b	27
	BS	853	85 a	82 a	202 a	36 a	406 a	39
A92	none	0	34 c	11 NS	39 c	--	84 c	
	AA	50	41 b	15 NS	46 c	--	102 c	36
	BS	257	60 a	29 NS	109 c	--	197 b	44
	BS	513	62 a	27 NS	208 a	–	297 a	41
	BS	770	61 a	28 NS	279 a	–	368 a	37
A93	none	0	39 d	17 NS	35 bc	57 bc	148 c	
	AA	45	48 c	16 NS	33 b	40 c	137 c	–25
	BS	330	55 b	16 NS	52 b	60 bc	183 bc	11
	BS	495	60 a	21 NS	83 a	85 ab	249 b	20
	BS	660	53 b	34 NS	111 a	120 a	318 a	25

* Means within a site and column followed by different letters are significantly different at P <0.05 by protected LSD. NS = no significant difference among means ($P < 0.05$).

† N source: AA = aqua ammonia at site A92, anhydrous ammonia at sites D92 and A92; BS = biosolids.

‡ Post harvest soil N (0–36 in.) = NH_4 N (0–12 in.) + NO_3 N (0–36 in.); post harvest soil N (>36 in.) = NO_3 N at 36–48 in. at site D92 and 36–72 in. at site A93.

§ Total N recovered = crop N uptake + post-harvest soil N.

¶ $\mathrm{ANR}_{\mathrm{harvest}}$ from Eq. 2.

$\mathrm{ANR}_{\mathrm{harvest}}$ for AA plots is less precise than for BS plots because of low rate of total N application for the AA plots.

ferred by most of the major importers of soft-white wheat (Rao et al, 1993). Grain protein for soft-white wheat producing near-maximum yield is usually less than 12% (Sowers et al., 1994; Guy et al., 1995). Straw N content also tended to increase with biosolids (Table 4). Straw N concentrations for dryland soft-white wheat producing near-maximum yields are usually 0.4% or less (Rasmussen, 1996; Rasmussen and Parton, 1994).

Flag leaf N concentration increased significantly at the lowest rate of biosolids compared with AA, but did not increase further with increasing biosolids rate (Table 4). Flag leaf N concentrations at the lowest biosolids rate at all sites were within the range of sufficiency (>4.0–4.2%) reported by Tindall et al. (1995) for high-protein irrigated hard-red wheat. Bauer et al. (1987) reported leaf N concentrations for hard-red spring wheat between 3.5 and 4.5% at the growth stages sampled in our study. Sufficiency levels for soft-white wheat are likely to be similar to or lower than those for hard-red spring wheat.

Table 5 shows apparent N recovery from the soil and above-ground crop at harvest ($\mathrm{ANR}_{\mathrm{harvest}}$). $\mathrm{ANR}_{\mathrm{harvest}}$ from biosolids averaged 38% at sites D92 and A92, but was only 19% at site A93. $\mathrm{ANR}_{\mathrm{harvest}}$ probably underestimated cumulative N availability from the biosolids, because some soil nitrate may have moved below the sampling depth during the crop season, and only the above-ground portion of the N taken up by the crop was measured. The low recovery from site A93 may have been because of leaching of available N during the wet winter of 1994–1995.

Movement of N in Soil

Most of the additional N available at the higher biosolids rates accumulated in the soil. At all sites, post-harvest soil available N increased significantly with biosolids rate (Table 5).

Nitrate from biosolids moved into the soil profile during the crop year at all sites (Fig. 2, post-harvest). At sites D92 and A93, there was little difference in nitrate distribution among the lowest biosolids rate, the AA treatment, and the unfertilized treatment (Fig. 2). The lowest biosolids application rate significantly increased nitrate accumulation below the 0-12 in. depth only at site A92. At the higher rates, biosolids increased soil nitrate concentration at all sites (Fig. 2, post-harvest). Additional nitrate may have moved deeper than the lowest depths sampled.

Crop year precipitation was 30 to 35% below the 30-year (1961–1990) average at sites D92 and A92, with most of the deficit occurring during the fall and winter. Despite the low precipitation, some downward movement of nitrate was apparent at the high biosolids rates (Fig. 2, post-harvest). Because dry soil at site A92 limited sampling to 36 in., and rocks and dense soil at site D92 limited sampling to 48 in., we do not know if movement occurred deeper in the profile during the crop year at these sites.

The crop year at site A93 (1994–1995) had 50% more precipitation than the 30-yr average, and increased downward movement of N beneath high biosolids rates is apparent throughout the 72-in. profile (Fig. 2, post-harvest). Movement at least to the bottom of the sampled profile also occurred the same year beneath sites D92 and A92, when they were in the second fallow since biosolids application (Fig. 2, second fallow).

Precipitation as great as 1994–1995 occurs less than 1 yr in 10 at sites A92 and A93 and less than 1 yr in 5 at site D92, so 1994–1995 had an unusually high potential for nitrate movement. Even during the dry year of 1993–1994, we saw evidence of nitrate movement beneath sites D92 and A92, at least to the 36 to 48 in. depth sampled that year (Fig. 2, post-harvest).

Implications for Biosolids Users and Producers

In Douglas County, where biosolids are available at a cost of $1/wet ton (including application), demand for biosolids now exceeds supply. In 1992 three farmers received biosolids. By 1995, 75 wheat farmers had signed up to become part of the biosolids program.

Farmers and biosolids managers could benefit if enough biosolids were applied to meet the N needs of two crops. This would reduce field work, save N application costs for the second crop, and help compensate for the changes in management caused by biosolids application. The increased residual soil nitrate coupled with increased N mineralization potential from the higher rates may have the potential to supply N for two crops. But, drawbacks to higher rates include risks of reduced yield and quality (from increased protein) of the first crop, and increased potential for nitrate movement below the root zone. Lower biosolids rates appear to reduce agronomic risks and reduce leaching risk.

SUMMARY AND CONCLUSIONS

Nitrogen release from biosolids was dependable and consistent over the three sites, despite different environments among the sites. Nitrogen release during the fallow year was similar to estimates using EPA equations. Second year N release also appeared to be substantial, but was difficult to measure accurately.

Low rates of biosolids provided sufficient N for peak yields, with variable increases in protein and residual soil nitrate. High rates of biosolids greatly increased protein and post-harvest residual soil nitrate at all sites. The agronomic rate for biosolids at these sites appears to be lower than the lowest rates applied.

We did not see much downward movement of N during the first fallow year, suggesting that biosolids application early in the fallow does not increase leaching risk. Downward movement of N was evident during the crop year, however, both in the dry year of 1993–1994 and wet year of 1994–1995. Nitrogen moved into the 36 to 72 in. depth, and likely deeper, by the end of the second fallow. Nitrogen in the 36 to 72 in. depth would contribute much less to the growth of wheat than shallower N, because it would not be accessible until later in the growing season,

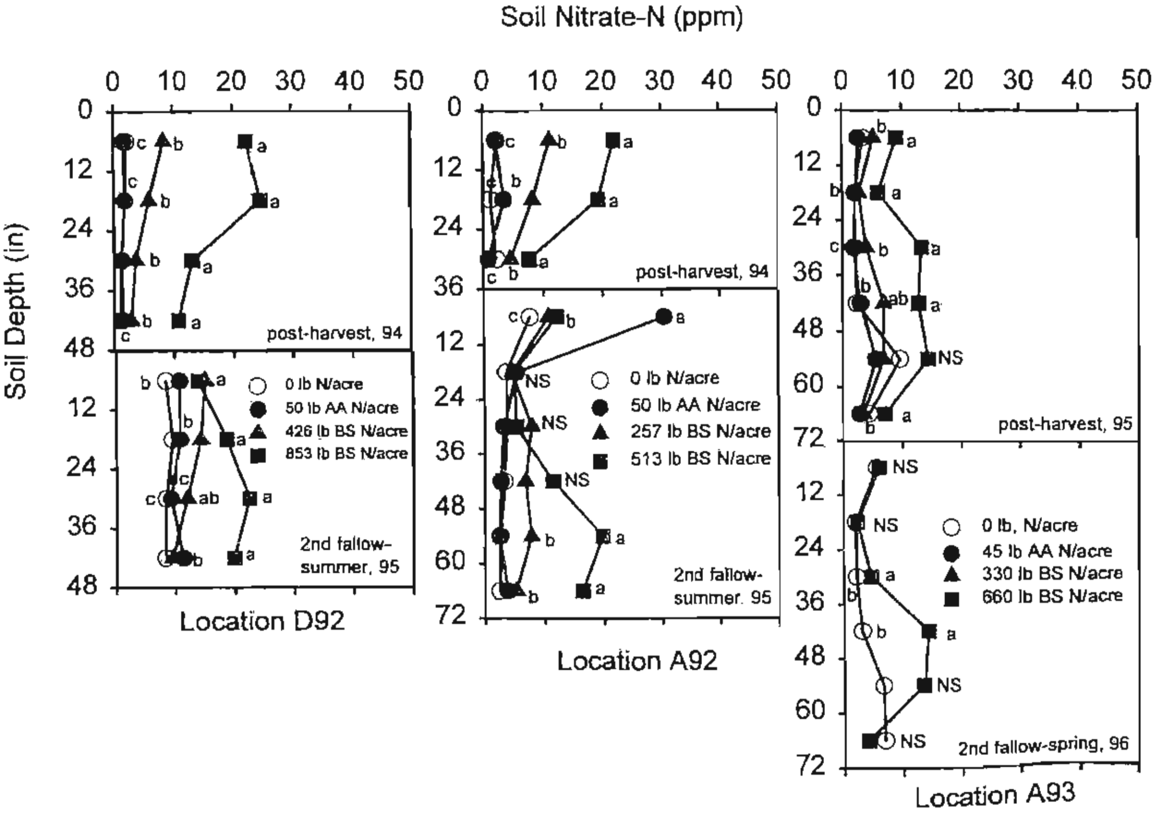

Fig. 2. Post-harvest and second fallow soil profile nitrate N concentrations at sites D92, A92, and A93. Means within a site and depth followed by different letters are significantly different at $P < 0.05$ by protected LSD on log10 transformed data. NS = no significant difference among means ($P < 0.05$).

when the crop was nearly mature. The deep N would be more likely to increase protein, but have little effect on yield (Cochran et al., 1978; Sowers et al., 1994). Thus, soil storage of available N does not appear to be a dependable source of N for a second crop.

Low rates of biosolids seem to provide the most practical benefits for wheat production, by reducing agronomic and environmental risks, and spreading benefits over a larger acreage of farmland. The current timing of applications early in the fallow cycle is acceptable from a N leaching standpoint, and allows a long period for application. Farmers do not like the loss of stubble associated with early incorporation of biosolids, however.

Evaluation of lower biosolids rates (100–300 lb total N/acre) and determining fertility requirements for a second crop following biosolids will be valuable in refining the biosolids application program for soft-white winter wheat in the Pacific Northwest. Other future research needs include flag leaf N as an indicator of N sufficiency and biosolids management in reduced tillage cropping systems.

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