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BIOSOLIDS AND REALISTIC YIELD EXPECTATIONS

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ABSTRACT

Municipal waste water operators question whether Realistic Yield Estimates (RYE) developed from studies of the behavior of chemical fertilizers and animal waste in soils, are valid for wastewater biosolids, which are generated by various treatment processes that affect their chemical makeup and nutrient content. This project summarized available scientific literature on differences between biosolids and other sources of plant nutrients for crop production. A series of protocols were developed to document crop yields, nutrient uptake, and estimate Plant-Available N (PAN) in biosolids and soils. A series of experiments were conducted on two relatively common soil series to validate the Realistic Yield Database for bermudagrass and its mixtures with winter cover crops. A questionnaire was developed to provide guidance on the training needs for those who manage crops receiving waste water and biosolids.

In a study of biosolids in North Carolina, PAN ranged from 4 to 39%. Other studies showed a range of 0% PAN for biosolids stored long-term in lagoons to 45% for biosolids dewatered on drying beds. In studies with corn, PAN ranged from 25 to 38% and with fescue grass from 42 to 50%. The ratio of fertilizer N to biosolids N to achieve identical yields is the N efficiency ratio (NER) of the biosolids. Review of numerous field studies showed that NER varies widely. This variation is due in part to nutrient forms in the biomass (e.g., the ratio of NH_4-N to total N in the biosolids), rainfall during the growing season, and differences among crops. NER values ranged from 0.15 to 1.38 with a mean of 0.57 and a median of 0.55. Evidence was found that NER increases if biosolids are applied over a long period of time because of the residual effect of biosolids applied in prior years. No toxic effects were found when the ration for beef cattle was supplemented with up to 12% biosolids.

The RYE data base generally over estimates the yield of bermudagrass and winter cover crops on the Alaga and Pactolus soil series. Actual yields ranged from about 45% to 95% of RYE database. Rainfall averaged from 73% to 137% of the 30-year mean, but more importantly the amount of moisture during the growing season was often severely limiting; this aspect of crop production makes it necessary to study crop responses for several years.

Apparent nitrogen recovery (ANR) ranged from 26 to 46% for the RYE levels of N and was as low as 19% when the N application rate was double the RYE suggested level. These levels of recovery indicate that significant amounts of N is not being accounted for by plant uptake and suggests that some method of assessing soil N levels should be implemented following a cropping season. A protocol was developed for use by waste water treatment operators.

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SUMMARY AND CONCLUSIONS

Municipal waste water operators question whether Realistic Yield Estimates (RYE) developed from studies of the behavior of chemical fertilizers and animal waste in soils, are valid for wastewater biosolids, which are generated by various treatment processes that affect their chemical makeup and nutrient content. This project summarized the existing literature on differences between biosolids and other sources of plant nutrients and developed protocols for determining Plant Available Nitrogen and documenting yields and nutrient composition of forage crops and developed a questionnaire that could be used to determine the training needs for those who manage crops receiving waste water and biosolids

The objectives of this project were to:

1. Summarize available scientific literature on differences between biosolids and other sources of plant nutrients for crop production.
2. Develop operational protocols for documenting crop yields, nutrient uptake, and estimation of Plant-Available N (PAN) in biosolids and soils.
3. Document forage crop production and N use efficiency for bermudagrass grown with and without winter cover crops and relate the response to RYE (Realistic Yield Expectation) database.
4. Develop a questionnaire that will provide information about crop and application management practices used on biosolids and effluent application sites.

Literature Review

From the late 1960s through the 1980s considerable research was conducted on agricultural use of biosolids. The emphasis resulted from the increase in biosolids production due to more efficient wastewater treatment processes and interest in land application as a least-cost disposal method.

Nutrient Availability

The response of crops to biosolids is largely a response to the nutrients in the biosolids, mainly nitrogen (N) and phosphorus (P). The nutrients exist in both organic and inorganic forms, so their availability to plants is not the same as the availability of nutrients in commercial fertilizer. Estimating nutrient availability is a critical step in determining biosolids application rates.

Plant-available N (PAN) has been estimated in both laboratory and field studies. In laboratory studies, biosolids are added to soil and the mixture incubated for several weeks. The sum of nitrate-N (NO_3-N) plus ammonium-N (NH_4-N) present in the soil at the end of the incubation period is the PAN of the biosolids. PAN is normally expressed as a percentage of the total N originally in the biosolids. In a study of biosolids in North Carolina, PAN ranged from 4 to 39%. PAN was greater in aerobically digested biosolids than in anaerobically digested ones. Other studies showed a range of 0% PAN for biosolids stored long-term in lagoons to 45% for biosolids dewatered on drying beds.

In field studies, PAN is estimated by summing the amount of N taken up by the crop plus the amount remaining in the soil at the end of the growing season. In studies with corn, PAN ranged from 25 to 38% and with fescue grass from 42 to 50%.

Since biosolids, particularly liquid biosolids, can contain appreciable NH_4-N, estimates of N loss by ammonia (NH_3) volatilization are important in determining application rates. Field studies have shown losses up to 58% of the applied NH_4-N.

The concentration of P in biosolids and the availability of that P are affected by the wastewater treatment process. Most treatment facilities have added a process to increase P removal. Iron (Fe) and aluminum (Al) compounds may be added to react with P and form precipitates, e.g., ferric chloride [$FeCl_3$] and alum [Al_2 (SO4)$_3$]. Other facilities use a biological nutrient removal (BNR) step in which wastewater is subjected to anaerobic conditions, which increases P uptake by microorganisms.

One study showed 3.5% P in the biosolids from a facility where $FeCl_3$ was used and 1.4% from a facility where it was not. Studies estimating P availability by extracting biosolids with commonly used soil-testing extractants showed availability in the order: BNR > no additions > $FeCl_3$ additions. For example, extractable P ranged from 29 to 68 % with no additions and from 0.4 to 13% where $FeCl_3$ was added. A similar availability sequence was seen in studies measuring leaching of P from biosolids in very sandy soils.

Nutrient Loading Rates

In the past, loading rates of biosolids have been based on the N content because, among other reasons, N was considered the nutrient most likely to pose a water pollution hazard. However, because the P/N ratio in biosolids (0.25) is much greater than the ratio required by crops (0.1), this practice has led to over-application of P. A survey of biosolids application sites in North Carolina found that P rates up to 1460 kg/ha was being applied. In another study, one site had soil-test P concentrations up to 19 times higher than that required for good crop growth.

Because of concern for potential surface water pollution from erosion and runoff, 24 states now restrict loading rates based on P. Restricting loading rates based on P greatly increases disposal costs because of the greater amount of land required and greater transportation costs.

Crop Response

Since biosolids have been applied based on N content in the past, one way of evaluating crop response to biosolids is to compare the amount of fertilizer N and biosolids N required to achieve the same yield. The ratio of fertilizer N to biosolids N to achieve identical yields is the N efficiency ratio (NER) of the biosolids. A problem with this approach is that in addition to containing N, biosolids also contain a variety of other nutrients and micronutrients that could affect the yield response

Review of numerous field studies showed that NER varies widely. This variation is due in part to nutrient forms in the biomass (e.g., the ratio of NH_4-N to total N in the biosolids), rainfall during the growing season, and differences among crops. NER values ranged from 0.15 to 1.38

with a mean of 0.57 and a median of 0.55. Evidence was found that NER increases if biosolids are applied over a long period of time because of the residual effect of biosolids applied in prior years.

Since restricting loading rates based on biosolids P content is a recent development, few studies were found comparing fertilizer P rates and biosolids P rates to achieve the same yield. One study showed a P efficiency ratio (PER) of 0.77.

Tree Response

Biosolids application to trees was not very effective except on disturbed sites like barrow pits and kaolin mine spoils. Weed competition was one factor that limited the response of trees.

Effect On Grazing Animals

Since forages are the main crop on many application sites, a brief review of the effect of direct ingestion of biosolids on grazing animals was conducted. No toxic effects were found when the ration for beef cattle was supplemented with up to 12% biosolids.

Protocol For Plant Available Nitrogen Of Biosolids And Soils

An estimate of the plant availability of nitrogen (N) in biosolids is required to ensure that biosolids loading rates will supply sufficient N for optimum yields, but will not create a ground water pollution hazard. The protocol consists of maintaining samples of soil and biosolids-amended soil at moisture and temperature levels suitable to sustain microorganisms that convert organic N to ammonium and nitrate. The accumulation of these two inorganic N forms over a period of 12 or more weeks is an estimate of the PAN the soil or biosolids will supply during a growing season.

A flow chart of the suggested protocol for estimating PAN is shown. It could be incorporated into the regular monitoring program that wastewater treatment facilities use to assess the performance of treatment systems.

Soil samples would be collected from each field receiving biosolids. Each sample would be split for specific analyses:

Sample 1 would be submitted to the Agronomic Division of the NC Department of Agriculture for routine soil testing. Results of these tests would be use to determine rates of supplemental fertilizer and/or lime required by specific crops.
Sample 2 would be analyzed to determine soil nitrate content after crop harvest or at the end of growing season. Excessive soil nitrate would indicate the previous biosolids rate was too high and subsequent rates should be adjusted accordingly. Low concentrations could indicate (1) the rate was appropriate if yields were good; or (2) the rate was too low if yields were poor.
Sample 3 would be used in a laboratory incubation study to estimate PAN.

a. Soil samples, with and without biosolids additions, would be incubated for 12 or more weeks and assayed periodically for ammonium-N (NH_4-N) and nitrate-N

(NO_3-N). This inorganic N that accumulated during the study period would be an estimate of:

1. the PAN the soil would supply during the subsequent growing season
2. the PAN the biosolids would supply.

The data from samples 2 and 3 would provide the information needed to determine the biosolids loading rate for the subsequent growing season. This procedure would be repeated each year as a regular part of the wastewater treatment facility's monitoring program.

Protocol For Monitoring Yields And Nutrient Uptake

Yields for a particular field or farm may vary from the reported RYE database due to variation in soil characteristics, management skills, cropping history, and environmental conditions, namely rainfall for a given year. Yield and nutrient composition from crop fields should be documented for a minimum of three years but due to unpredictable weather patterns it is best to monitor yields every year.

Sample a representative number of bales within any of the above parameters that can impact weight, moisture content and number of bales. As a general rule, sample a minimum of 10 bales or 10% of the bales within a management unit to achieve repeatable and consistent results.

Choose representative bales and weigh them in the field using load bars or truck scale. Immediately after weighing each bale, use a commercial hay probe to extract at least one core from the bale to be used for moisture determination. Combine the core samples of 10 bales or 10% of the bales in the management unit into a "ziplock" bag for moisture content determination and nutrient analysis. Calculating the dry weight per acre example:

Dry weight yield per acre = (avg bale weight * avg dry matter %) * number of bales /acre

Protocol For Estimating The Botanical Composition Of Forage Crops.

Nutrient management plans are based on RYE values for specific crop species and mixtures. Therefore, one must know the botanical composition of application sites before selecting the appropriate agronomic rates of nutrients or the proper harvest or grazing management practices.

The Point-Step method provides a reasonable estimate of botanical composition. The procedure is based on making a number of specific contact points with the vegetation across a field and recording the number of times a particular plant specie is contacted relative to the number of potential contacts. Use a systematic way of collecting the data by recording a "contact" at some predetermined interval while crossing the field. For example, make a reading at every 10th step while walking the field.

For many fields it is necessary to make at least 300 points. The botanical composition is determined for each specie**s** by dividing the number of times it was "contacted" by the total number of times all plants were "contacted" during the walk.

Using Crop Growth Curves To Time Nutrient Applications

Nutrient uptake by crops is strongly related to the daily growth rate of the plant. Plants have fairly characteristic growth patterns that can be used to strategically apply nutrients so that the rapid growth of the plant can be matched with nutrient applications that maximize uptake and minimize the risk of nutrient loss from the root zone. Data is presented to show monthly distribution of growth for various forage species and suggested application dates are presented.

Documenting RYE and Apparent Nitrogen Recovery On Alaga And Pactolus Soil Series.

The yields of bermudagrass alone or with overseeded winter cover crops varied widely from year to year. Using observed yields and regression analysis it was determined that most of the variation in yield could be attributed to N level. However soil moisture and rainfall variation were most likely the factors limiting yields on the two soils evaluated in this study.

The RYE data base generally over estimates the yield of bermudagrass and winter cover crops on the Alaga and Pactolus soil series. Actual yields ranged from about 45% to 95% of RYE database. Rainfall averaged from 73% to 137% of the 30-year mean, but more importantly the amount of moisture during the growing season was often severely limiting; this aspect of crop production makes it necessary to study crop responses for several years.

Apparent nitrogen recovery (ANR) ranged from 26 to 46% for the RYE levels of N and was as low as 19% when the N application rate was double the RYE suggested level. These levels of recovery indicate that significant amounts of N is not being accounted for by plant uptake and suggests that some method of assessing soil N levels should be implemented following a cropping season.

A Questionnaire About Crop And Application Management Practices

A detailed questionnaire was developed that could be used by managers to assess the current status and activities describing management practices on waste application sites. A review of the answers will provide information that may be useful in designing educational needs and or changes that can impact nutrient management on sites.

RECOMMENDATIONS

1. Do not select an availability factor to use for all biosolids and all soils because estimates of N and P availability varied widely among biosolids.
2. Do not select a value of NER for all biosolids because crop response to biosolids-applied N is quite variable. NER values varied not only among studies but also within studies but it increases as the years of treatment continue.
3. Wastewater treatment facilities should estimate PAN by conducting incubation studies with biosolids and soil from their respective sites as a regular part of their land application program. A protocol was developed for conducting incubation studies.
4. Use PAN incubation of soils from application sites at the end of the growing season to adjust nutrient loading rates in the subsequent season.
5. Monitor crop yields for weight (dry matter composition) and nutrient (N, P, and perhaps Cu, Zn) concentration as a means of documenting nutrient removal from application sites. A protocol was developed for documenting yields and nutrient composition.
6. It appears that the RYE database may be overestimating the yield potential for many soils, therefore additional research should be initiated to further validate the crop removal of N and P on biosolids application sites.
7. Validating the RYE database should be continued for many other soils and for more than three year periods.
8. Due to wide variation in seasonal rainfall it would be best to provide supplemental irrigation water to application sites during the active growing season as a way to maximize crop growth and nutrient uptake.
9. To enhance crop yields and nutrient uptake consider split applications of biosolids or waste water based on monthly crop growth curves.
10. Since P buildup is a strong possibility on some sites, research should be initiated to determine the amount of fertilizer N needed for satisfactory crop growth.
11. PLAT (Phosphorus loss assessment tool) should be used on sites to determine the potential for P loss from the application site, especially on sites that have received biosolids for several years. See http://www.soil.ncsu.edu/nmp/ncnmwg/index.htm
12. Assess the need for additional education and training in the area of crop management on biosolids application sites. Use the questionnaire to gather information to alert managers and educators to specific needs regarding crop management relative to biosolids application.

ABBREVIATIONS

Al: aluminum
BNR: biological nutrient removal
Ca: calcium
Cd: cadmium
Cl: chlorine
Cu: copper
dm: decimeter
Fe: iron
g: gram
H: hydrogen
ha: hectare (2.47 acres)
kg: kilogram (2.2 pounds); kg/ha = 1.12 x pounds/acre
Mehlich 1 and 3 = extractants used in soil testing laboratories
mg: milligram
N: nitrogen
NER: Nitrogen efficiency ratio, fertilizer N rate/biosolids N rate that results in the same yield.
NH_3: ammonia
NH_4-N: ammonium nitrogen
NO_3-N: nitrate nitrogen
NUE: Nitrogen use efficiency, the ratio of N taken up by the crop to the amount of N applied by fertilizer or biosolids.
O: oxygen
P: phosphorus
PAN: plant-available N. Estimated from laboratory incubation studies or from field studies where crop and soil N are determined
Pb: lead
PER: Phosphorus efficiency ratio, fertilizer P rate/biosolids P rate that result the same yield.
S: sulfur

CHAPTER 1

CROP RESPONSE TO BIOSOLIDS: A LITERATURE REVIEW

Introduction

Definition of Biosolids

Municipal wastewater contains about 99.9% water and 0.1% solids. One of the main objectives of wastewater treatment is the removal of the solids. Most of the solids are removed in "clarifiers", large tanks where wastewater is held to allow heavy particles to settle to the bottom and light particles to float to the top. In the past these solids were referred to as sewage sludge. The newer term is "biosolids". The biosolids are removed from the clarifiers and stabilized prior to land application.

Common methods of stabilization include anaerobic digestion, aerobic digestion, and lime stabilization. Digestion involves holding biosolids in air-tight structures (anaerobic) or open basins (aerobic) for 20 to 30 days to allow microbial decomposition of the readily decomposable components of the biosolids. Lime stabilization involves dewatering the biosolids and adding lime [calcium hydroxide, $Ca(OH)_2$] to raise the pH to approximately 12 to kill essentially all the microorganisms in the biosolids. Another highly alkaline material, cement kiln dust, is also used for stabilization. Because of the lime content, these biosolids have a liming effect on soil. For example, the liming potential of lime-stabilized biosolids may range from 21 to 52% of that of agricultural limestone; liming potential of biosolids stabilized with cement kiln dust may rang from 47 to 68% (Jakobsen 1986; Simard 1986; Willett 1986; Sloan 1995).

Biosolids aerobically or anaerobically digested usually are applied to land in a liquid form (e.g., 5% solids). The organic matter contend of these biosolids is about 45% (King 1977; King 1981). Lime-stabilized biosolids are usually applied as a cake material (e.g., 20-30% solids). Because of the high lime content (up to 66% of the solids), the organic matter content is greatly reduced by dilution.

History of Interest in Land Application

Early reports on the agricultural value of biosolids include publications by Anderson (Anderson 1955) and Bear and Prince (Bear 1955). Interest in application to agricultural land increased in the mid 1960s and continued into the 1980s. This interest was stimulated by increased biosolids production because of more efficient wastewater treatment processes, a desire for cheaper disposal methods, phasing out of land filling and ocean dumping, and environmental concerns like nitrate leaching and uptake of heavy metals by crops. Application to agricultural land is now a widely accepted method of biosolids disposal/utilization.

Purpose

The purpose of this report is to summarize the literature on the response of crops to biosolids applications. From the information collected, it is desired to determine if sufficient knowledge is available to establish biosolids application rates for crops in North Carolina or if more research is needed

Scope

The review placed emphasis on the availability of N and P in biosolids and crop response to biosolids applications. The fate of heavy metals and pathogens in biosolids was not included in this review of literature. Also, biosolids produced during treatment of industrial wastewater were not included in the review.

Information sources

Initially, the Internet was used to conduct electronic searches of a variety of databases. Websites of scientific journals such as the *Journal of Environmental Quality, Soil Science Society of America Journal, and Transactions of the American Society of Agricultural Engineers* provide online search capabilities. Similarly, the websites of the D. H. Hill Library at North Carolina State University and the State Library of North Carolina provide online search capabilities. Also the D. H. Hill Library provides databases such as Agricola, which can be searched online. Initial searches of these sources yielded about 55 references (articles, books, or reports) pertaining to crop response to biosolids.

The references available at the D. H. Hill Library were accessed and reviewed. Literature citations in these references led to additional references of interest. The greatest numbers of references were found in the *Journal of Environmental Quality* (24 articles).

Nutrient Availability

The response of crops to application of biosolids is mainly a response to the nutrients applied. Yields may be enhanced by improved soil physical properties resulting from organic matter additions. For example, a biosolids application supplying 110 kg /ha of plant-available N might also supply 1000 kg/ha organic matter(King 1977; King 1981; King 1983). However, since the main response is to the applied nutrients, the availability of the nutrients must be estimated so rates can be chosen to supply adequate but not excessive nutrients for good crop growth.

Nitrogen

Estimates of Effectiveness of Biosolids N

Several methods have been used to estimate the effectiveness of biosolids N as a nutrient source for crops. These methods produce estimates like *plant-available N* (PAN), *N use efficiency* (NUE) and *N efficiency ratio* (NER). The methods of determining these three estimates will be discussed briefly.

Plant-available N (PAN) in biosolids consists of the NH_4-N and NO_3-N initially in the biosolids plus the amounts of these compounds formed as the organic N in the biosolids is mineralized. Organic N will mineralize at a rate dependent on the form of the organic N (e.g., easily mineralizable proteins vs. recalcitrant lignin-bound N compounds), temperature, and oxygen supply. PAN can be estimated from laboratory studies in which soil amended with biosolids and unamended soil are incubated for several weeks. The unamended soil is included so the NH_4-N and NO_3-N that accumulates due to mineralization of native soil organic N can be deducted from the amount that accumulates in biosolids-amended soil. The difference in the amount of NH_4-N and NO_3-N that accumulates in the amended and unamended soil is assumed the PAN, i.e.:

$$\text{PAN} = \frac{(NH_4\text{-N and } NO_3\text{-N in biosolids-amended soil}) - (NH_4\text{-N and } NO_3\text{-N in unamended soil})}{\text{Total N added by biosolids}}$$

PAN also can be estimated in greenhouse or field studies in which the amount of N taken up by a crop, plus the amount of NH_4-N and NO_3-N remaining in the soil after crop harvest are determined. PAN is the sum of the N uptake plus the soil NH_4-N and NO_3-N from treatments receiving biosolids minus the same N pools from unamended treatments:

$$\text{PAN} = \frac{(\text{N uptake} + \text{soil } NH_4\text{-N \& } NO_3\text{-N}) \text{ with biosolids} - (\text{N uptake} + \text{soil } NH_4\text{-N \& } NO_3\text{-N}) \text{ without biosolids}}{\text{Total N added by biosolids}}$$

N use efficiency (NUE) is the ratio of the amount of N taken up by a crop to the amount supplied by biosolids. The amount of N uptake by an unamended crop is assumed to be the amount of soil N taken up by the biosolids-amended crop. Thus, NUE is calculated:

$$\text{NUE} = \frac{(\text{N uptake by biosolids amended crop}) - (\text{N uptake by unamended crop})}{\text{N supplied by biosolids}}$$

Note that NUE is similar to PAN estimated from field studies except that soil NH_4-N and NO_3-N are not included in the NUE calculation. Thus, while NUE is a measure of efficiency of crop use, it gives no indication of the potential groundwater pollution hazard posed by residual NH_4-N and NO_3-N in the soil after crop harvest.

N efficiency ratio (NER) is simply the ratio of the rates of fertilizer N and biosolids N that result in the same crop yield. For example, if 100 kg/ha of fertilizer N resulted in the same crop yield as did 400 kg/ha of total N supplied by biosolids, NER would be 100/400 or 0.25. Note that NER does not address the efficiency of uptake of biosolids N nor the pollution potential from residual NH_4-N and NO_3-N in the soil after crop harvest.

A word of caution in interpreting NER: Biosolids supply a variety of elements in addition to N, so the response to biosolids may be a response to more than the N applied. Comparing response to N from biosolids and fertilizer is not like comparing the response to different fertilizer N sources, e.g., ammonium nitrate (NH_4NO_3) vs. sodium nitrate ($NaNO_3$).

Plant-available N

A laboratory study was conducted to estimate the PAN in biosolids from selected North Carolina cities (King 1984). Biosolids were added to samples of Cecil sandy loam soil at rates to supply 500 mg total N/kg soil. The mixtures were kept moist and incubated for 16 weeks. PAN was defined as the NH_4-N and NO_3-N present in the amended soils at 16 weeks minus that in an unamended control soil sample. PAN was reported as a percentage of the organic N originally in the biosolids (Table 1). PAN of biosolids from drying beds was quite variable and probably reflects the length of time the biosolids had been on the drying beds prior to sampling. PAN of solids separated from liquid biosolids was higher than that for biosolids from drying beds and was not greatly affected by type of digestion.

Table 1.1. Availability of organic N in biosolids from selected North Carolina cities. Data from King (1984).

Stabilization method and source of biosolids	Initial organic N content	PAN[1]
Anaerobically digested	% of dry wt.	% of initial organic N
1. Solids from drying beds		
Charlotte	2.86	16
Kings Mountain	2.80	4
Pilot Creek (Kings Mountain)	3.76	18
Washington	1.60	8
Wilmington	0.6	14
2. Solids from liquid sludge[2]		
Clayton	4.55	21
High Point	3.37	30
Aerobically digested		
1. Solids from dewatered sludge[2] (Raleigh)	4.14	27
2. Solids from liquid sludge[2]		
Albermarle	3.89	26
Morganton	7.17	39

[1] PAN: plant-available N

[2] To estimate the PAN of liquid sludge, the N in the liquid fraction (mainly NH_4-N, data not shown) must be included in the calculation.

Laboratory incubation studies provide an estimate of PAN for the first growing season, but do not provide an estimate of PAN in subsequent growing seasons. Multi-year field studies noted below do provide information on PAN over several growing seasons.

An estimate of PAN in biosolids from the Neuse River Wastewater Treatment Plant (City of Raleigh, NC) was obtained through a 3-year field study with corn (King 1983). Research plots were amended with several rates of biosolids. PAN was estimated as the N taken up by the corn crop plus any NO_3-N remaining in the soil at the end of the growing season. The assumption was made that N losses by leaching were minimal during the study period. When biosolids were applied only once at a rate to supply 1300 kg total N/ha, PAN was 19% of the applied N at the end of the first growing season, 46% at the end of the second, and 53% at the end of the third.

At the end of the third growing season, annual applications of biosolids and NH_4NO_3 fertilizer resulted in PAN values shown in Table 2. Surface application of biosolids resulted in higher PAN than did subsurface injection. The fact that PAN of fertilizer N was less than 100%, indicates that some N was not recovered because of (a) leaching losses (contrary to the assumption of no leaching loss during the period), (b) ammonia volatilization, or (c) denitrification or (d) incorporation into the soil organic N.

Table 1.2. Plant-available N from biosolids and fertilizer applications at the Neuse River Wastewater Treatment Plant. Data from King 1983.

N source	N application	Mean annual PAN at end of third growing season
Biosolids	kg/ha	%
Subsurface injected	640	25
Surface-applied	640	38
NH_4NO_3 fertilizer	170	59

A field study in the state of Washington estimated biosolids PAN by comparing yield and N content of fescue grass fertilized with several rates of biosolids or fertilizer N (Cogger 2004). Biosolids from 14 sources varied in the range of treatment and dewatering/drying processes. Biosolids were applied in May and yield and N uptake were monitored through September of the following year. Using crop uptake of N from fertilizer or biosolids, fertilizer efficiency regression equations were developed and used to calculate biosolids PAN from N uptake data. Results are shown in Table 3. PAN was relatively low in lagoon biosolids. Also, heat drying resulted in low PAN after the first summer. Previous experiments similar to this one showed no increase in soil NO_3-N above background concentrations and thus no soil NO_3-N had to be factored into PAN calculations (personal communication with Craig Cogger).

Table 1.3. Plant-available N (PAN) in biosolids as determined from a field study with fescue grass. Data from Cogger (2004).

Biosolids type	May-Sept	Oct-April	May-Sept	Cumulative
	-------- PAN as % of total N applied ---------------			
Fresh	37	7	6	50
Fresh, heat dried	36	4	2	42
Lagoon (2-17yr)	8 to 25	0 to 5	0 to 3	---

Henry et al. (Henry 1999) compiled data from several field studies in western Washington and Oregon. In these studies PAN was estimated by measuring net N in harvested grass receiving either 200 kg/ha fertilizer N or 400 kg/ha total N from biosolids. Results are shown in Table 4. For a given type of biosolids, differences among grass types were greater than differenced among biosolids. These differences may be due to variations in climatic conditions at the different sites.

Table 1.4. Cumulative plant-available (PAN) in biosolids as determined from a field study with perennial ryegrass, prairiegrass, and fescue grass. Data from Henry (1999).

Biosolids	Grass	1st year	2nd year
		--- % of applied N ---	
Dewatered	Per. ryegrass	17	60
	Prairiegrass	35	43
	Tall fescue	37	59
	Mean	30	54
Heat dried	Per. ryegrass	23	57
	Per. ryegrass	27	61
	Tall fescue	40	40
	Mean	30	53
Liquid	Tall fescue	27	42
	Overall mean	29	53

A study that included laboratory and field experiments and computer simulation was used to estimate the PAN of biosolids from 25 cities in the United States (Gilmour 2003). In the laboratory incubation study, mean PAN was 30% and the range was 0% for biosolids from long-term lagoon storage to 45% from anaerobically digested biosolids dewatered on drying beds. In the field study, relationships were developed between the total N uptake by plants and the amount of fertilizer N required to produce these same values. Mean PAN was 37% and the range was 9 to 74%.

Ammonia volatilization

Loss of N by NH_3 volatilization will affect biosolids PAN. In the field studies noted above, this loss is included in the PAN estimates. However, if data from incubation studies are used to estimate PAN, then NH_3 volatilization must be factored into the estimate.

A study was conducted in Ontario to estimate NH_3 volatilization from biosolids applied on a field scale (Beauchamp 1978). Liquid biosolids were applied via a tank truck to a field that recently had been disked. The experiment was conducted in May and again in October. Results are shown in Table 5. Average loss was 58% of the applied NH_4-N.

Table 1.5. Ammonia volatilization from surface-applied liquid biosolids. Data from Beauchamp (1978).

Days after application	NH_3-N loss May	NH_3-N loss October
	--- kg/ha ---	
1	22	16
2	36	14
3	14	4
4	9	4
5	5	4
6	3	2
7	---	3
8	---	2
Total NH_3-N loss	91	50
Total NH_4N applied	150	89
% loss	60	56

Robinson and Roper (Robinson 2003) measured NH_3 volatilization from biosolids applied to pine forest in New Zealand. From 44 to 55% of the applied NH_4-N volatilized, the majority of it on the first day. After 5 days, 95% of the loss had occurred. The loss was 12% of the total N applied.

Phosphorus

The availability of P in biosolids is influenced by the wastewater treatment process and the method of biosolids stabilization. Several methods are used to remove P from wastewater during the treatment process. Additions of chemicals that react with P to from insoluble compounds have been used for many years, e.g., ferric chloride [$FeCl_3$] and alum [$Al_2(SO_4)_3$]. In contrast to chemical additions, biological nutrient removal (BNR) is also used. In this process wastewater is treated in an anaerobic environment and then in an aerobic environment. The result is that microorganisms take up P at higher than normal rates and thus sequester P in their biomass.

Once biosolids are separated from wastewater, they are stabilized by anaerobic or aerobic digestion or by addition of $Ca(OH)_2$ to raise the pH to around 11 (lime stabilization). Phosphorus in the biosolids may react with Ca to form relatively insoluble Ca phosphates.

Penn and Sims (Penn 2002) estimated the availability of P in several biosolids. They found that in biosolids not lime-stabilized, most of the P was associated with Fe and Al. The amount of P extracted from biosolids with Mehlich 1 or 3 or with water was greatly reduced by the addition of $FeCl_3$ during the wastewater treatment process (Table 6).

Table 1.6. Effect of additions of $FeCl_3$ during wastewater treatment on extractability of P from biosolids. Data from Penn (2002).

$FeCl_3$ addition	% of USEPA 5030[1] P extracted		
	Mehlich 3	Mehlich 1	Water
None	29-68	17-52	10-45
Added	0.4-13	0.3-6	0.4-5

[1] The US Environmental Protection Agency 5030 procedure is an acid peroxide digestion method that extracts metals absorbed by biosolids constituents. It does not include metals associated with silicates, but often extracts 75 to 90% of total metals measured by more complex digestion procedures. Also called "total sorbed P".

When the biosolids were applied to soil, relative P availability was: biosolids from treatment facilities using BNR > biosolids from facilities using no chemical additions > biosolids for facilities using $FeCl_3$ additions and lime stabilization > biosolids for facilities using $FeCl_3$ additions. The greater availability with Fe+lime compared with Fe only probably results from greater availability of Ca phosphates as compared to Fe phosphates.

The authors also found that when biosolids from facilities using $FeCl_3$ additions were added to soils already high in P, certain forms of extractable P decreased (relative to the control). In acid soils like those found in the southern United States, most P is bound to naturally occurring Fe and Al. Evidently some of the Fe and Al added via biosolids had not reacted with P in the wastewater and was available to react with native soil P.

Maguire et al. (Maguire 2001) conducted similar studies with some of the same biosolids and found basically the same results: lowest P availability was in biosolids from facilities using $FeCl_3$ to remove P from wastewater.

Leytem et al. (Leytem 2004) added biosolids to a loamy sand at rates to supply 60mg total P/kg soil and incubated the mixture for 8 weeks. The samples were then extracted with Mehlich 3 and water. Results are shown in Table 7. Estimates of bioavailability by these extractions were in the order: lime-stabilized > $FeCl_3$+lime > $FeCl_3$. As was found in studies cited above, (1) addition of $FeCl_3$ during the treatment process greatly reduces P availability in biosolids and (2) lime stabilization of biosolids generated with this treatment process increased P availability. The authors concluded that the concentration of P in biosolids is a poor indicator of extractability after incubation.

Triner et al. (Triner 2001) working in Scotland also found P availability was related to the method of P removal used in the wastewater treatment facility. They added biosolids to soil, incubated the mixture, and then extracted P. Biosolids from facilities using BNR resulted in greater extractable P (41%) than did biosolids from facilities using Fe for P removal (33%).

Table 1.7. Effect of $FeCl_3$ used in the treatment process and lime stabilization of biosolids on P extractability from biosolids. Data from Leytem (2004).

$FeCl_3$ used in process	Lime stabilized	P concentration		Extractable at 8 weeks	
		Total	Water soluble	Mehlich 3	Water
		-------- mg/kg ---------		-- % of applied --	
No	Yes	14,000	138 (1)[1]	61	5
Yes	Yes	14,300	357 (2.5)	49	4
Yes	No	35,000	108 (0.3)	26	1

[1]. Percent of total P

Lu and O'Connor (Lu 2001) conducted experiments on availability of biosolids P on sandy soils. Biosolids high in Fe and Al increased P retention in soils for one to three years. The temporary increase may be due to production of organic acids due to biosolids applications, which lead to loss of Al and Fe from the topsoil. Phosphorus in biosolids containing abundant Fe and Al behave as a slowly available P source.

Nutrient Loading Rates

Problem: N/P Ratio

In the past, biosolids have been applied at a rate to supply the N needs of crops. This practice has resulted in over-application of P because the P/N ratio in biosolids is much higher than that required by crops. Most crops require a P/N ratio of about 0.1. Although the ratio in biosolids varies, a ratio of total P to total N of 0.25 is typical. If one assumes the P and N in biosolids are equally plant-available, then an application of biosolids to supply the N needs of the crop would supply 2.5 times the P needs of the crop. In the 1993 EPA guidelines, this over-application was not considered a problem because it was believed that best management practices would prevent erosion – the main pathway of P into surface water (Shober 2003). However, more recently this over-application has raised concerns about possible water pollution due to P losses from fields (Pierzynski 1994; Shober 2003).

Buildup in Soil

Several studies have shown the buildup of soil P when biosolids are applied based on N content. Land application of biosolids was begun in the late 1970s at the Neuse River Wastewater Treatment Plant serving Raleigh, NC. A review of the land application system was conducted in 1989 (King 1989). Soil analyses showed Mehlich 3-extractable[1] P concentrations up to 1500 mg/dm^3 in the top 15 cm of the soil in some fields. The Agronomic Division of the NC Department of Agriculture does not recommend P fertilization for any crop if concentrations are 80 mg/dm^3 or higher.

In a review of land application of biosolids in North Carolina, Zublena et al. (Zublena 1994) reported that at 14 sites P loading rates varied from 9 to 1460 kg/ha annually. Soil analysis showed elevated P levels at most of the sites.

A similar survey of biosolids-amended farm soils in the mid-Atlantic region of the US was conducted (Maguire 2000). Mehlich 1-extractable P was excessive in many of the treated soils but

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[1] Soil testing laboratories in the southern United States and in the Mid-Atlantic states commonly use extracting solutions known as Mehlich 1 or Mehlich 3 to determine if fertilizer additions are needed to achieve good crop growth.

excessive concentrations also were found in soils that had not received biosolids. The authors also determined oxalate-extractable P. This P is associated with amorphous Fe and Al and is not readily available to plants. The biosolids-treated fields averaged 560 mg/kg and untreated fields averaged 300 mg/kg. Therefore, the high concentration of Mehlich 1-extractable P was mitigated to some extent by the elevated concentrations of oxalate-extractable P.

Erosion and Runoff

Loss of P from soils over-fertilized with biosolids P was determined in a study in Wisconsin (Bundy 2001). A rainfall simulator was used to measure P runoff from a control site receiving no biosolids, a site that had received liquid biosolids for 5 years, and a site receiving fertilizer P. Corn had been grown for three years prior to making the measurements. Results are shown in Table 8. P loss increased as soil test P increased.

Table 1.8. Dissolved reactive P in runoff from soil amended with fertilizer or biosolids. Data from Bundy (2001).

Treatment	Soil test P in 0-2 cm layer	Dissolved reactive P	Surface residue
	mg/kg	g/ha	% cover
Control	20	8	28
Fertilizer P	60	25	63
Biosolids	110	100	44

Elliott et al. (Elliott 2002) conducted a study to determine the rate of P leaching when biosolids were applied to sandy soils. Biosolids were applied at rates to supply 56 or 224 kg P/ha, i.e., rates based on crop P requirements or N requirements, respectively. From 80 to 90% of the P in the biosolids was in the inorganic form. A soil with a moderate P fixing capacity and one with a very low fixing capacity were used. Bahiagrass was grown for 4 months. None of the biosolids treatments resulted in P leaching as great as that from fertilizer P (Table 9.). For each of the biosolids, the authors calculated a P saturation index: the molar ratio of readily soluble P/amorphous Al and Fe.

These values are estimated by oxalate extraction. They found no appreciable leaching when the P saturation index was ≤1.1. They also reported that biosolids from treatment facilities using BNR had more leachable P than did biosolids from facilities using Fe and Al for P removal.

Table 1.9. Phosphorus leached from sandy soils amended with biosolids or fertilizer P. Data from Elliott (2002).

	Soil P fixing capacity	
	Moderate	Very low
	% of applied P leached	
Biosolids (56 to 224 kg P /ha)	0.05 to 0.45[1]	0.05 to 11
Fertilizer P		
at 56 kg/ha	1.7	14
at 225 kg/ha	22	21

[1]. Total amount leached was not different from that leached from the control treatment.

Regulations

Animal manures, like biosolids, have P/N ratios greater than those required by crops. The concern of over-application of P has resulted in Delaware, Maryland, and Virginia requiring that manure rates be P-based (Shober 2003). The authors conducted a survey in 2000 to see if biosolids applications also were being regulated based on P. Fifty one of the 54 states and territories responded and 24 of these had regulations, guidelines, or legislation that restrict biosolids applications based on P. Four other states have proposed guidelines. The guidelines are based on soil test P concentrations above which no application is allowed. In contrast, restrictions on manure application generally are based on a P site index. This index combines several factors that affect P loss from fields, e.g., soil P, soil type, slope, distance from drainage/streams, conservation practices, etc.

In North Carolina, the concern that excessive soil P poses a water pollution hazard has prompted the development of the Phosphorus Loss Assessment Tool (PLAT) (Osmond 2004). A computer program uses soil, landscape, and management parameters to estimate P losses by soil erosion, surface runoff, and leaching and to calculate a PLAT rating for a given field. This rating is then used to determine acceptable rates of P applications to the field.

In considering regulations on P-based loading rates for biosolids, mitigating factors should be considered. The P in biosolids usually is less plant-available than that in fertilizers. The availability of biosolids P is related to the wastewater treatment process and/or the biosolids stabilization process (Shober 2003). When $FeCl_3$ and alum $[Al_2(SO_4)_3]$ are used in wastewater treatment to remove P, the resulting Fe and Al phosphorus compounds have low solubility and thus pose less of a runoff hazard than does fertilizer P. Also, the positive effect of biosolids on physical properties increases infiltration and thus reduces runoff and erosion (the same is true for manures).

P-based loading rates will result in much more land being required for biosolids application – thus increasing the cost of disposal.

Crop response

Nitrogen

As noted in the Introduction, interest in agricultural use of biosolids increased dramatically from the late 1960s through the 1980s. Consequently, much of the yield response data are from that period. During that period, loading rates generally were based on biosolids N content rather than P content for several reasons:

1. N was seen as the plant nutrient most likely to cause water pollution.
2. Municipalities wanted to apply maximum rates to reduce disposal costs.
3. Biosolids were distributed without cost, so farmers had no incentive to maximize the use of all the nutrients in the biosolids.
4. Over-application of P was not considered a problem because fixation by Fe and Al in soil and use of erosion control practices would prevent the excess P applied from becoming a water pollutant.

As noted earlier, one method of assessing the effectiveness of biosolids as an N source is to determine the N efficiency ratio, NER, the ratio of fertilizer N rate and biosolids N rate that produce the same yield. Data from a number of field studies measuring crop response to fertilizer N and biosolids N are presented below. From these data, values of NER have been estimated. In studies with multiple rates of fertilizer N or biosolids N, regression analysis was used to quantify the yield responses. The resulting regression equations were used in the calculation of NER. For example, consider a study on response of fescue grass to fertilizer N or biosolids N at the Biltmore Estate near Asheville, NC (Mays 1988). The data are shown in Figure 1 and the yield data are presented in Appendix Table A. The 3-year study included a control treatment, three rates of fertilizer N, liquid biosolids applied spring and fall, and liquid biosolids applied in the fall only (1985 and 1986 only).

Using the 1984 data, NER was estimated by:

1. Using the yield at the highest fertilizer N rate as the common yield (3573 kg/ha)
2. Substituting that yield in the regression equation for fescue grass response to biosolids N and solving for N: $3573 = 1620 + 4.8N$; $N = 407$ kg/ha
3. Calculating the ratio of fertilizer N to biosolids N: $NER = 270/407 = 0.66$

Similar calculations were made with the data from 1985 and 1986 to produce values of NER shown in Table 10. Note in Figure 1 that the response to biosolids applied spring and fall in 1985 was nonlinear. The slope of the line between the control yield and the yield at the lowest biosolids rate was used in the calculations.

Values of NER for biosolids applied only in the fall were higher than those for biosolids applied spring and fall. The higher rates applied in the spring/fall treatments account for some of the difference, i.e., N use efficiency decreases as N loading rate increases. In 1985, fall-applied biosolids N was as effective as fertilizer N.

Generally, NER values were higher than those that will be seen in other experiment to be discussed below. One reason for these high values is the fact that 56% of the N in the biosolids was in the NH_4-N form. [The mean NH_4-N percentage of total N for several other biosolids was 20% (King

1972a; King 1983; Mays 1988)] Although some of this N would be lost by NH_3 volatilization, a significant amount would be available to the fescue grass immediately.

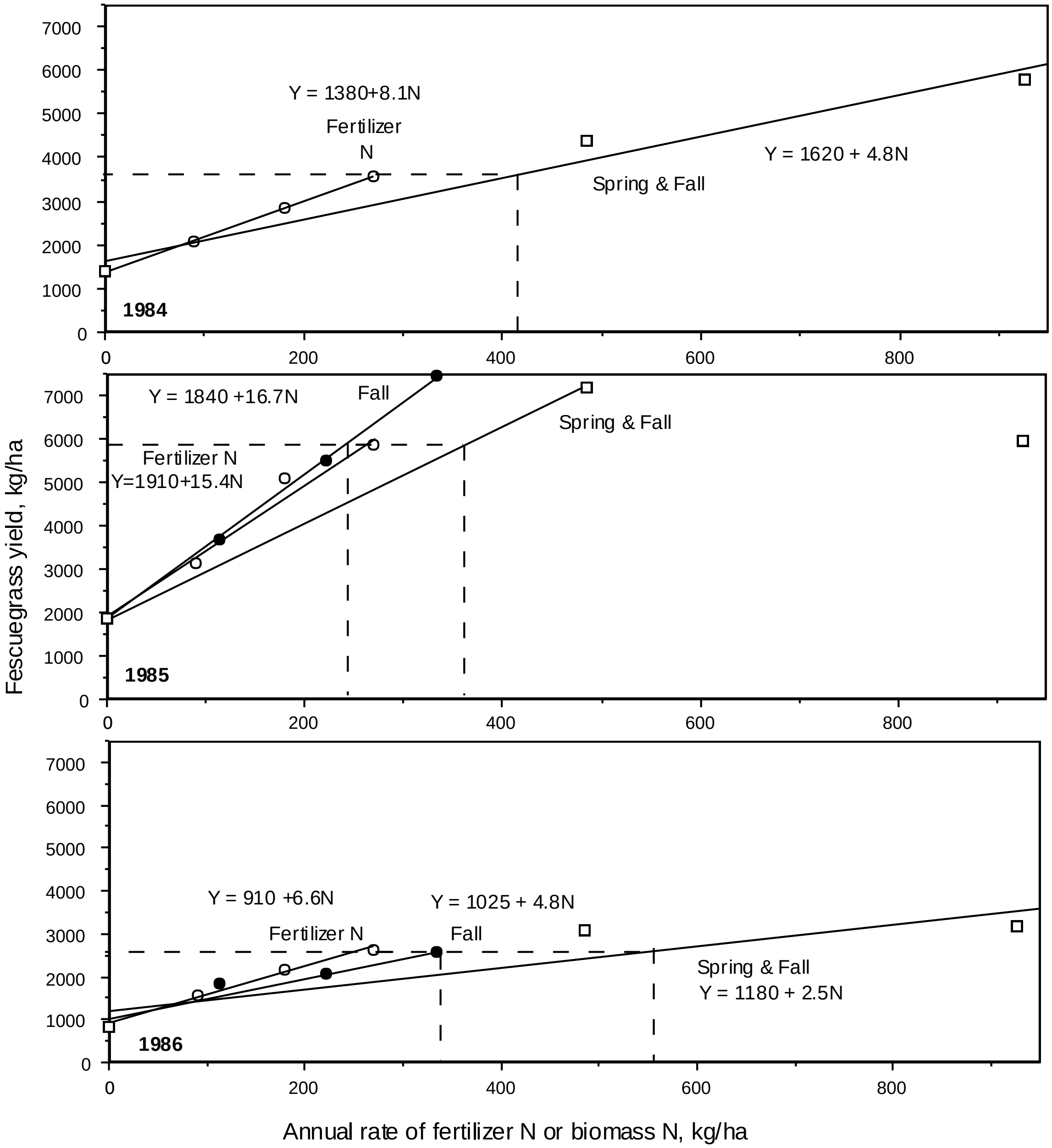

Figure 1.1. Response of fescue grass to fertilizer N and biosolids N, Biltmore Estate, Asheville, NC. Data from Mays (1988).

Table 1.10. Nitrogen efficiency ratios (NER) for biosolids from several studies.

Location	Crop	Year	Biosolids	Common yield	N rate for common yield		NER[1]
					Fertilizer	Biosolids	
				------------	kg/ha	------------	
Biltmore Estate			Liquid, applied:				
Asheville, NC	Fescue	1984	Spring & fall	3573	270	407	0.66
(Mays, 1988)		1985	Spring & fall	5858	270	365	0.74
			Fall only			241	1.12
		1986	Spring & fall	2621	270	576	0.47
			Fall only			333	0.81
State of Washington	Fescue	1993	Heat-dried	6000	202	549	0.37
(Cogger, 2001)		1994	"	12900	336	689	0.49
		1995	"	13100	336	816	0.41
		1996	"	10900	336	547	0.61
		1997	"	12100	403	518	0.78
		1998	"	12100	403	633	0.64
		1999	"	13000	403	721	0.56
		1993	Dewatered	6000	202	619	0.33
		1994	"	12900	336	618	0.54
		1995	"	13100	336	739	0.45
		1996	"	10900	336	473	0.71
		1997	"	12100	403	506	0.80
		1998	"	12100	403	614	0.66
		1999	"	13000	403	662	0.61
Georgia Piedmont (King, 1972a, 1972b; Touchton, 1976)	Coastal bermuda	1969	Liquid	6300	224	615	0.36
		1970	"	13200	358	944	0.38
	(Residual effect)	1971	none	17210	224	4800	0.05
(Residual effect of biosolids applied to bermuda)	Rye	1969	none	2260	140	1480	0.09
	Rye	1970	none	2000	140	954	0.15
Warren Wilson College Swannanoa, NC (Mays, 1988)	Corn	1985	Liquid	6270	84	57	1.48
		1986	“	5420	168	122	1.38
Neuse River WTP Raleigh, NC (King, 1983)	Corn	1982	Liquid	8757	168	423	0.40
		1983	"	2079	84	504	0.33

[1] NER = N efficiency ratio: fertilizer N rate/biosolids N rate that result in the same yield.

The same biosolids used in the fescue grass study at the Biltmore Estate were used on corn at Warren Wilson College, Swannanoa, NC (Mays 1988). Yield data are presented in Appendix Table B. The first year, corn yield was increased significantly by fertilizer N and biosolids as compared to the control but differences among fertilizer and biosolids rates were not significant. Yields at the low fertilizer N rate and the low biosolids rate were the same and based on those data the NER was 1.47 (Table 10). Results from the second year are shown in Figure 2. Again, biosolids were more effective in raising corn yields (NER=1.38) than was fertilizer N. Several factors may have contributed to these high NER values. As noted above, 56% of the biosolids N was in the NH_4-N form. Secondly, the biosolids were injected below the soil surface, so NH_3 volatilization was minimal. Also, as cautioned above, biosolids contain other plant macro- and micronutrients and these will stimulate crop growth if these elements are deficient in the soil. Finally, the injection process had a tillage effect, which might have benefited crop growth.

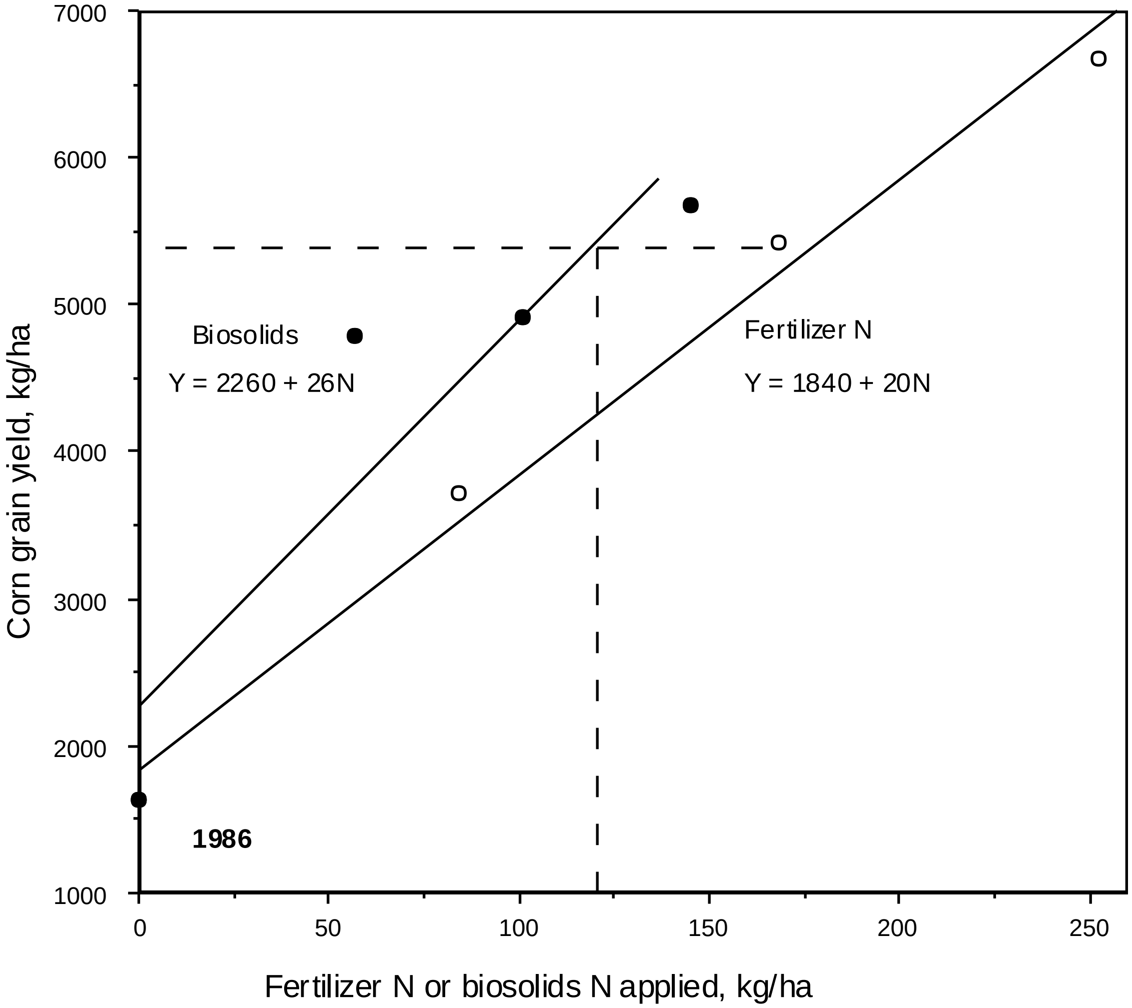

Figure 1.2. Response of corn to fertilizer N or biosolids N, Warren Wilson College, Swannanoa, NC. Data from Mays (1988).

A study of corn response to fertilizer N or biosolids N was conducted at the Neuse River Wastewater Treatment Plant farm, Raleigh, NC from 1981 through 1983 (King 1983). Due to inadequate rainfall in 1981 fertilizer N and biosolids did not increase yields above that in the control (yield data are presented in Appendix Table C). In 1982 response to fertilizer N was linear, but with biosolids, yields did not respond above the lowest application rate (Figure 3). Therefore the slope of the response between zero and the lowest rate was used in NER calculations. NER was 0.4 in 1982 and 0.33 in 1983 (Table 9).

In this study, uptake of N by the corn crop was reported, so the N use efficiency (NUE, the percentage of the biosolids-applied N taken up by the crop) could be calculated. NUE decreased with increasing rate of biosolids-applied N (Figure 4.) During the dry years of 1981 and 1983 when crop growth was low, NUE was 10% or less. In 1982 when rainfall was plentiful and therefore yields were higher, NUE was much higher. Because of the lower rate of application of fertilizer N and the fact that the fertilizer N was water-soluble, NUE was always higher for fertilizer N than for biosolids N.

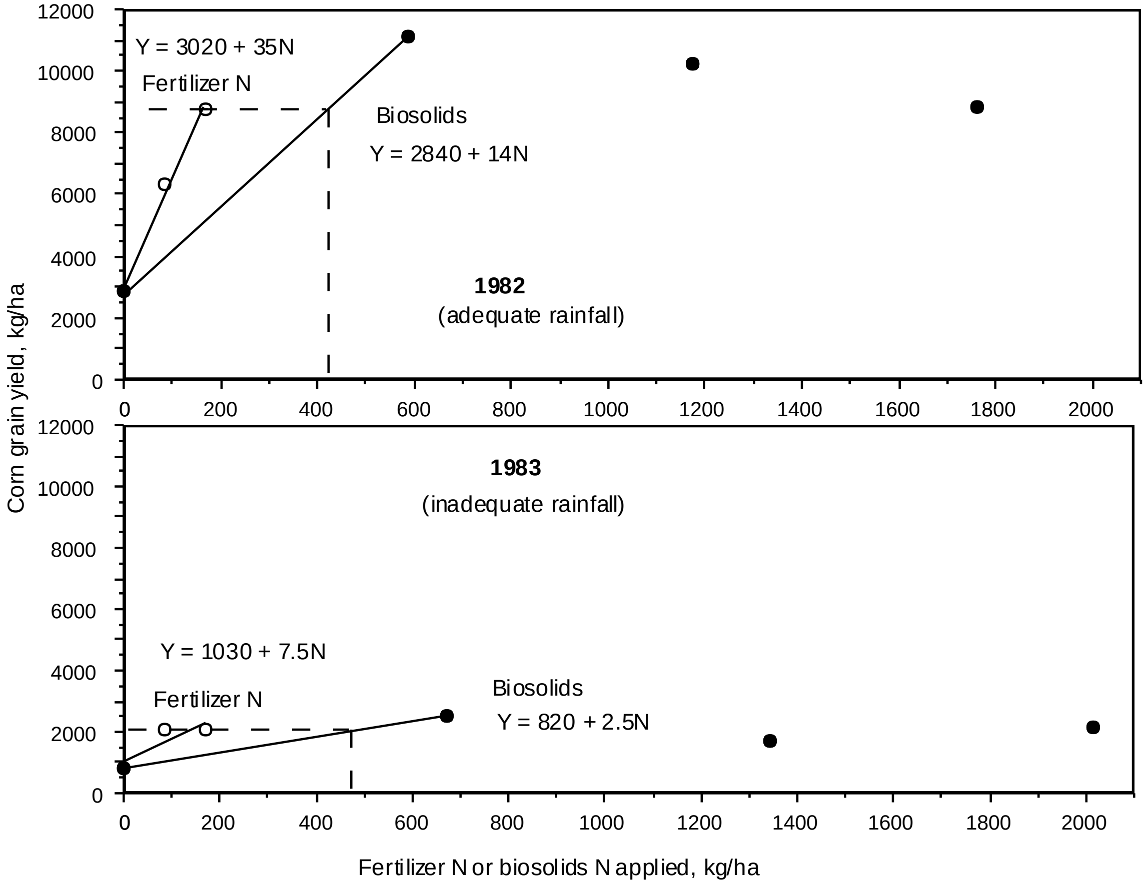

Figure 1.3. Response of corn to fertilizer or biosolids N, Neuse River Wastewater Treatment Plant farm, Raleigh, NC. Data from King (1983).

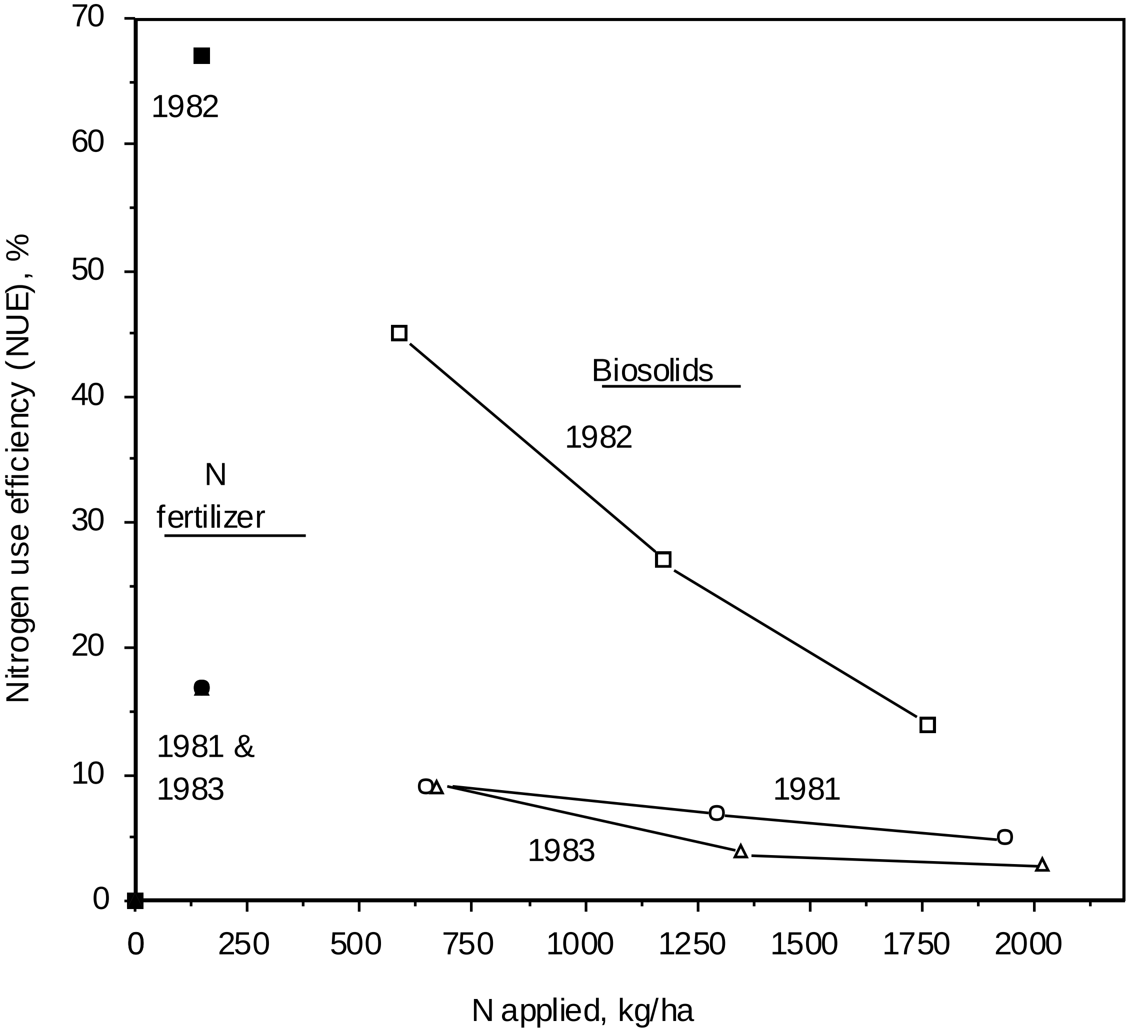

Figure 1.4. Nitrogen use efficiency (NUE) of fertilizer N and biosolids N applied to corn, Neuse River Wastewater Treatment Plant, Raleigh, NC. Data from King (1983).

In the studies discussed above, fertilizer N was applied at several rates. However, in studies discussed below, only one fertilizer N rate was used. This rate was usually the locally recommended rate for the crop. Results from the first year of a 7-year study with fescue grass in the state of Washington are shown in Figure 5 (yield data are presented in Appendix Table D) (Cogger 2001). NER in 1993 was 0.37 for the heat-dried biosolids and 0.33 dewatered biosolids. NER for all years is shown in Table 10. Regression of NER on years of biosolids application shows a trend of increasing NER with years (Figure 6). The regression models were significant at the 10% level of probability but explained only about 45% of the variation. This increasing trend suggests that the residual effect of prior biosolids applications is causing an increase in NER.

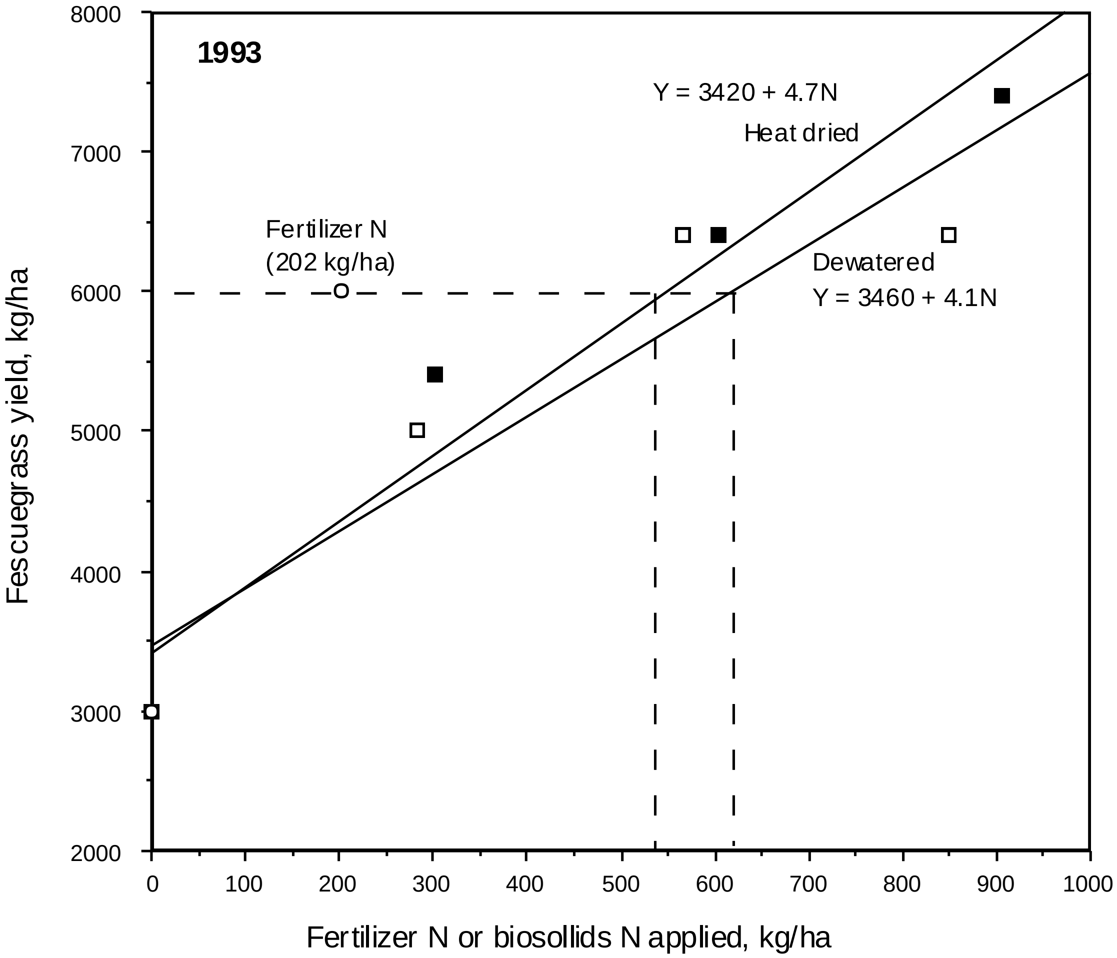

Figure 1.5. Response of fescue grass to fertilizer N and N in heat-dried or dewatered biosolids, state of Washington. Data from Cogger (2001).

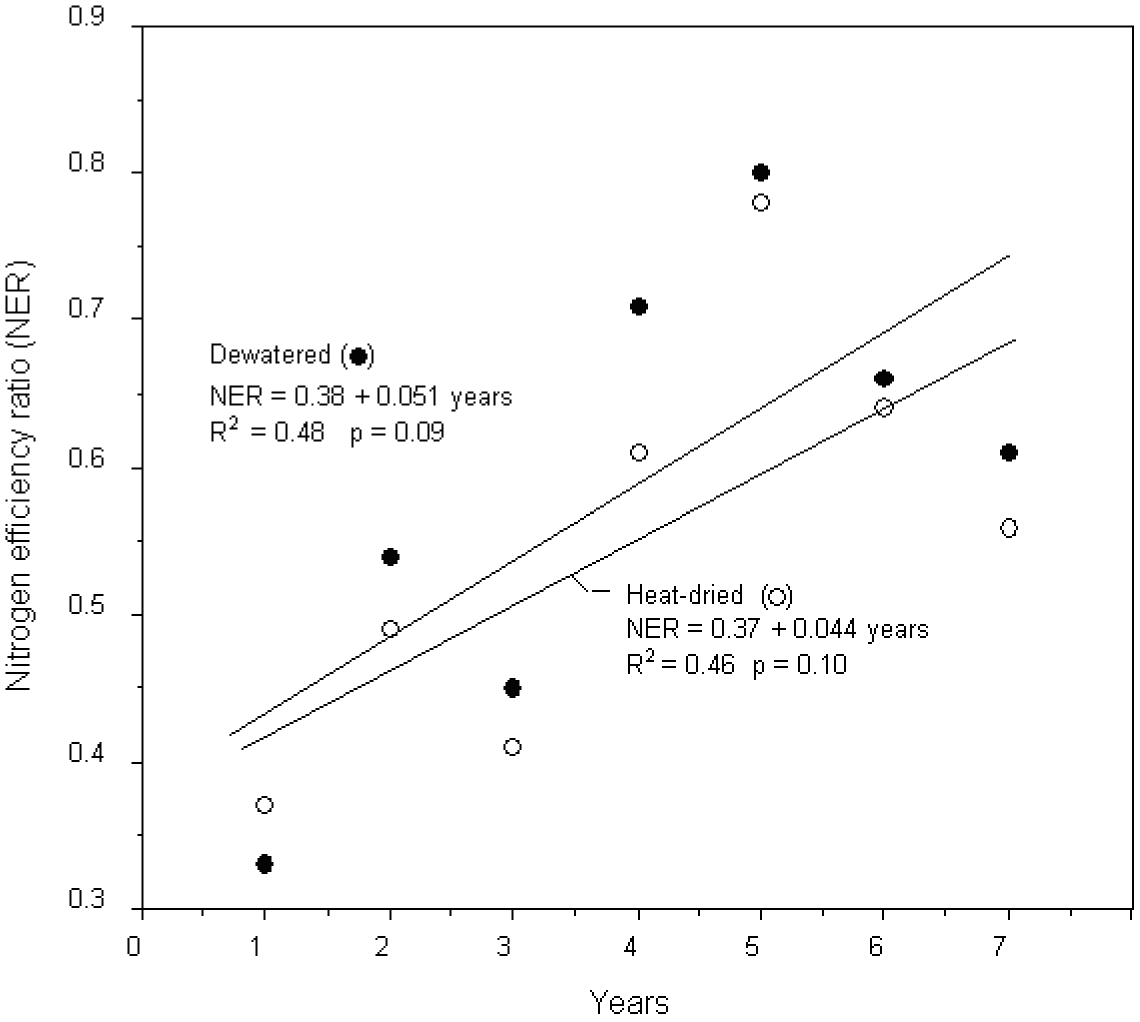

Figure 1.6. Relationship between N efficiency ratio (NER) and years of biosolids application to fescue grass, state of Washington. Derived from Cogger (2001).

Response of Coastal bermudagrass to fertilizer N and biosolids N is shown in Figure 7 for a study in the Piedmont of Georgia (yield data are shown in Appendix Table E) (King 1972a). High rates of biosolids resulted in nonlinear responses so only the linear portions of the response curves were used to determine NER. Values were 0.36 in 1969 and 0.38 in 1970 (Table 10).

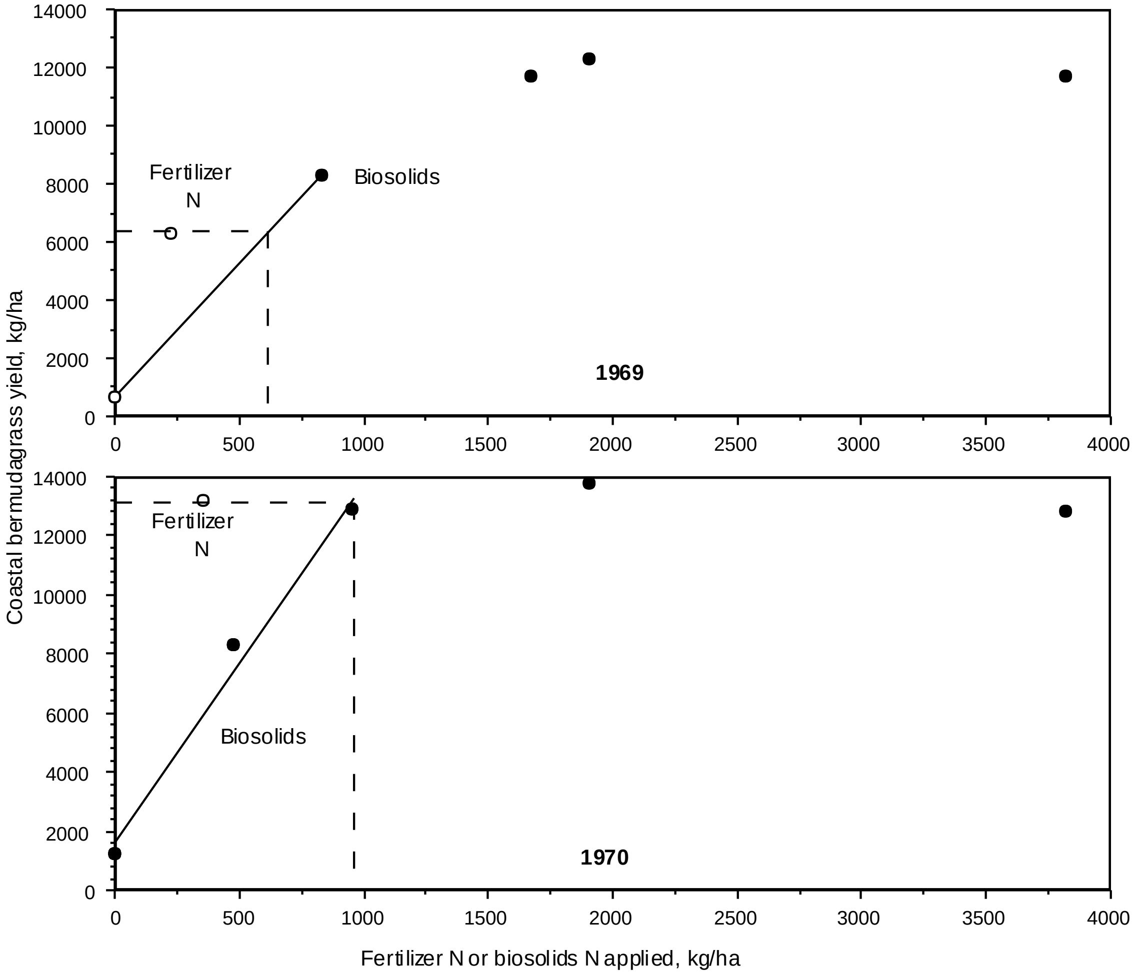

Figure 1.7. Response of Coastal bermudagrass to fertilizer N or biosolids N, Georgia Piedmont. Data from King (1972a)

This study was continued in 1971 to determine the residual effect of the biosolids applications. The response to fertilizer N applied in 1971 and to the residual effect of biosolids applied in 1969 and 1970 is shown in Figure 8 (yield data are shown in Appendix Table E.) (Touchton 1976). The response was quadratic and NER was determined using the regression equation. The value was 0.05 (Table 10).

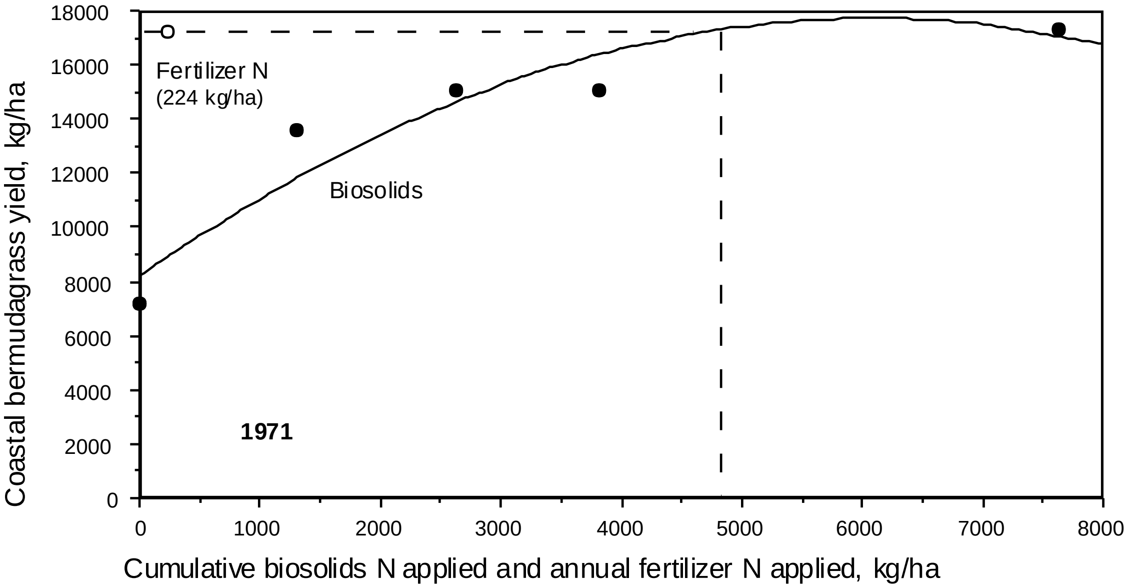

Figure 1.8 . Response of Coastal bermudagrass to fertilizer N applied in 1971 and to the residual effect of biosolids N applied in 1969 and 1970. Data from Touchton (1976)

In this same study, rye was over-seeded into the bermudagrass after the last harvest in 1969 and 1970 (King 1972b) The fertilizer N treatment received 140 kg N/ha each year. Response of rye to the annual N application and to the residual effect of biosolids is shown in Figure 9 (yield data is shown in Appendix Table F). In 1969 response to biosolids N was nonlinear so only the linear portion of the curve was used to determine NER. In 1970 yields were lower with biosolids than with fertilizer N, so the slope of response to fertilizer N was used in calculating NER. Values were 0.09 in 1969 and 0.15 in 1970 (Table 10).

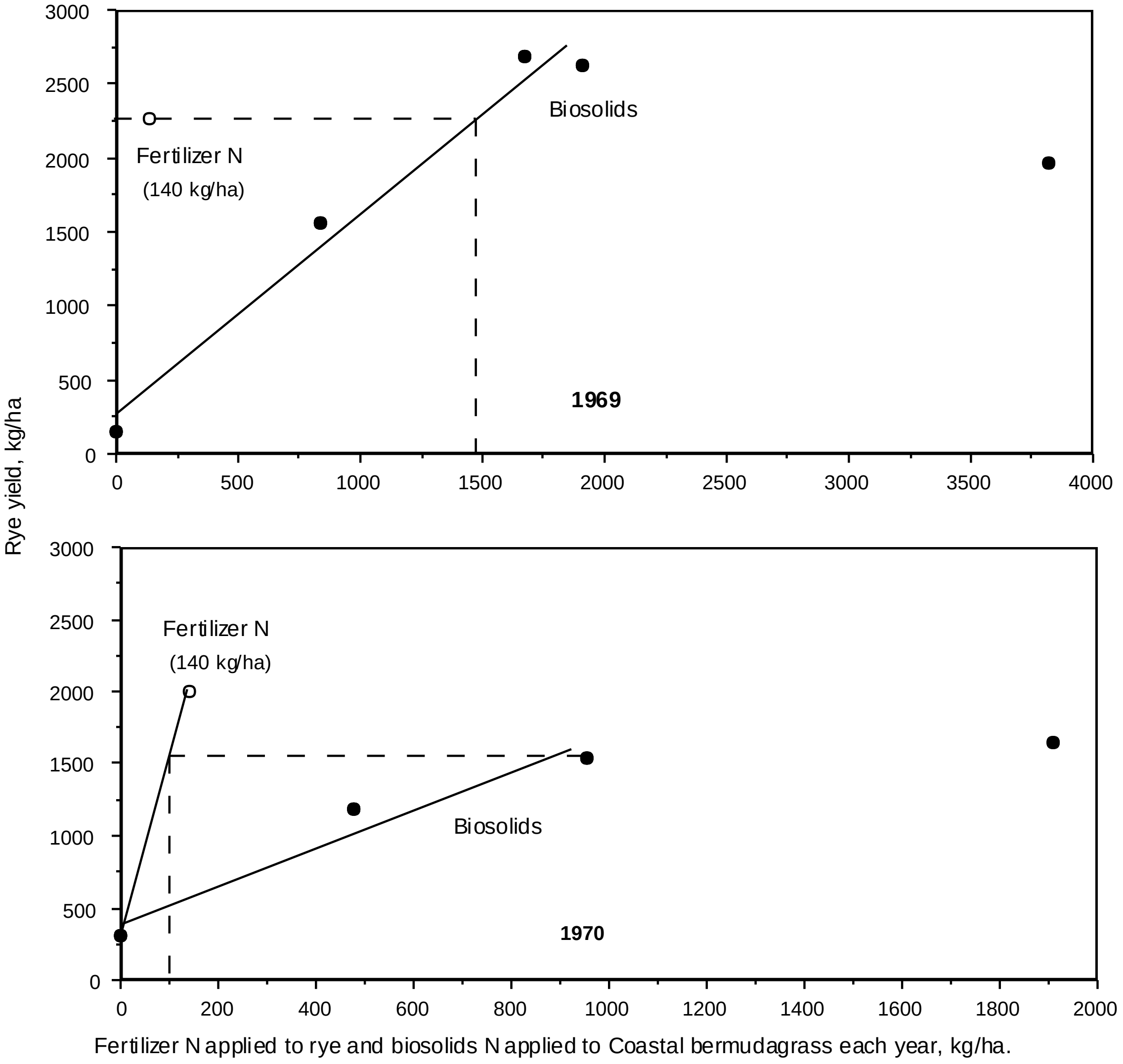

Figure 1.9. Response of rye over-seeded in Coastal bermudagrass to fertilizer N applied to the rye and to the residual effect of biosolids N applied to the Coastal bermudagrass each year. Data from King (1972b).

Data on crop yields and NER values for several other studies are shown in Table 11. Only one fertilizer N rate and one biosolids rate were used in these studies. In most cases the yield with fertilizer N and biosolids were similar and were assumed comparable for calculation of NER. Values ranged from a low of 0.15 with cotton to 0.90 with corn. Note that in the Minnesota study, NER was 0.33 when the biosolids N rate was 700 kg/ha (1974-1982) but increased to 0.90 when the rate was reduced to 240 kg/ha (1983-1992). This trend is another example of reduced N efficiency at high N rates.

Table 1.11. Estimates of biosolids N efficiency ratio from various studies.

		Total						N efficiency
Location & citation	Nitrogen source	N	P	K	Yield, kg/ha			ratio (NER)
					---------- Cumulative yield -----			
					Corn	Soybean	Cotton	
		Annual application			(4 years)	(4 years)	(3 years)	
Alabama	Control	0	0	0	12,000	9000	6000	---
Piedmont	Fertilizer	168	45	112	21,000	10,000	10,000	---
Giordano	Biosolids	275	209	22	24,000	13,000	8000	0.61
(1981&1983)								
					Corn			
Georgia					(1 yr)			
Piedmont	Control	0	0	0	4,570	---	---	---
Sims (1980)	Fertilizer	217	20	74	10,100	---	---	---
	Biosolids	820	530	122	11,270	---	---	0.26
Minnesota					Mean annual			
Clapp (1994)	1974-1982				corn yield			
	Biosolids	700	---	---	8,400	---	---	0.33
	Fertilizer	230	---	---	8,000	---	---	---
	1983-1992							
	Biosolids	240	---	---	8,300	---	---	0.90
	Fertilizer	215	---	---	7,600	---	---	---
					3-yr mean seed cotton			
Arizona	Control	0	---	---	2,657	---	---	---
Watson (1985)	Fertilizer	55	---	---	3,187	---	---	---
	Biosolids	361	---	---	3,037	---	---	0.15
					Cumulative yield			
					Corn	Grain Sorghum	Soybean	
Florida		cumulative application			(5 yr)	(6 yr)	(6 yr)	
Lutrick (1982)	Fertilizer	1760	330	660	18,000	24,000	---	---
	Fertilizer	0	390	360	---	---	15,000	---
	Biosolids	3180	1270	100	16,000	23,000	15,000	0.55
Georgia					Fescue, 2-yr mean			
Piedmont	Control	0	0	0	4,800	---	---	---
Boswell (1975)	Fertilizer	448	188	404	12,000	---	---	---
	Biosolids	378	138	20	6,200	---	---	??

A study in Nebraska with irrigated corn and rain-fed sorghum showed significant residual effect of biosolids on NER (Binder 2002) (Table 12).

Table 1.12. Nitrogen efficiency ratio (NER) of biosolids as determined from a field study with irrigated corn and rain-fed sorghum in Nebraska. Data from Binder (2002).

	Irrigated corn		Rain-fed sorghum	
Year	N applied kg/ha	NER	N applied kg/ha	NER
1	532	0.40	309	0.39
2	0	0.27	0	0.17
3	0	0.07	0	0.11
4	0	0.0 4	0	0.04
Total	532	0.78	309	0.71

A regional project was sponsored by the Tennessee Valley Authority to demonstrate the value of biosolids at several locations in the Tennessee Valley (Mays 1988). For the locations shown in Table 13, fertilizer N was applied at rates recommended for local crop/soil conditions. However, the specific rates were not reported. Annual biosolids N rates ranged from 460 to 570 kg/ha. Generally, yields were similar with fertilizer N and biosolids N. However, biosolids were superior to fertilizer N for wheat in 1986 and corn in 1985 at Jackson TN. In 1984 in Murry KY, soybean yield was greater with biosolids than with fertilizer but the yield was not greater than that in the control treatment.

Table 1.13. Response of wheat, corn, and soybean to fertilizer and biosolids applications. Data from Mays (1988).

		Wheat			Corn			Soybean		
Location	Treatments	1984	1985	1986	1984	1985	1986	1984	1985	1986
Cullman AL		kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
Annual N from	Control	---	538 c^1	---	NSD	3324 b	---		No significant differences (NSD)	
biosolids, kg/ha	Fertilizer	---	1075 a	---		4892 a	---			
Total: 570	Biosolids	---	1008 ab	---		5331 a	---			
NH_4-N: 200	Mean				2932			874	2218	907
Jackson TN	Control	---	941 ab	1210 b	8844 b	6209 c	3387 b	NSD	1344 b	NSD
Annual N from	Fertilizer	---	1142 a	1478 b	11,227 a	9032 b	8906 a		1680 ab	
biosolids, kg/ha	Biosolids		1478 a	2218 a	10,600 ab	10,098 a	9283 a		1814 a	
Total: 460	Mean							2580		1868
NH_4-N: 78										
Murry KY	Control	1344 b	470 b	---		No significant differences		941 ab	No significant differences	
Annual N from	Fertilizer	1344 b	874 a	---				739 b		
biosolids, kg/ha	Biosolids	1747 ab	538 ab	---				1008 a		
Total: 515	Mean				6429	9518	5519		1075	2520
NH_4-N:134										

It should be stressed that NER is not necessarily the same as plant-available N (PAN). Generally PAN is estimated using a N budget to account for all the applied N. In laboratory incubation studies, PAN is simply the quantity of applied N that is converted to NO_3-N during the study. In field studies, PAN is the quantity of biosolids N taken up by the crop plus the NO_3-N in the soil at the end of the growing season. In contrast, NER is simply a function of yield.

Values of PAN and NER can be contrasted in the experiment at the Neuse River Wastewater Plant at Raleigh (King 1983). PAN was estimated by determining the amount of N taken up by the crop and the amount of NO_3-N in the soil at the end of the growing season. Table 14 shows PAN and NER resulting from an application of biosolids, surface applied at 9000 kg/ha and incorporated after drying. Crop and soil components of PAN are shown. Even the crop uptake portion of PAN is greater than the NER. Therefore, while NER is a measure of N efficiency in increasing crop yield, it may underestimate PAN. Underestimating PAN can lead to excessive biosolids rates and subsequent pollution of groundwater by nitrate.

Table 1.14. Comparison of plant-available N (PAN) and nitrogen efficiency ratio (NER) for biosolids applied to corn. Data from King (1983).

	Biosolids	PAN			
Year	N applied	In corn	In soil	Total	NER
	kg/ha	------ % of applied N ------			
1982	588	46	5	51	0.4

Phosphorus

Studies designed to estimate the efficiency of biosolids P compared to fertilizer P are limited since over-application of P is a relatively recent concern. One study conducted in Northern Ireland compared yield response of spring barley to P from concentrated superphosphate fertilizer and to P in biosolids (Christie 2001). Several rates of fertilizer and biosolids were used but yield was not increase beyond the lowest rate. Yield and P efficiency ratio (PER) are shown in Table 15.

Table 15. Response of spring barley to P from fertilizer or biosolids. Data from Christie (2001).

	P applied	Yield	PER[1]
	-------- kg/ha -------		
Control	0	3610	---
Fertilizer	17	4510	---
Biosolids	38	4990	0.45

[1] P efficiency ratio: fertilizer P rate/biosolids P rate that result the same yield.

Tree Response

Forests can serve as an application area for biosolids. McKee and others (McKee 1986) applied liquid biosolids supplying 400 kg N/ha (170 kg NH_4-N/ha) to loblolly pine trees in the upper Coastal Plain of South Carolina. During the 4 years of the study, they observed no significant effect on trees that were 3 years old when the biosolids were applied, primarily because of weed competition. Trees initially 8 years old or 28 years old increased in breast-height diameter and basal area but not in volume. Applying biosolids prior to planting tree seedlings increased growth but the increase was dependent on insect and weed control.

Another study on response of loblolly pine and sweetgum trees to commercial fertilizer and biosolids was conducted in barrow pits (South Carolina) and on spoil from kaolin mining (Georgia) (Berry 1987). After 10 years, tree height had responded to fertilizer but diameter and volume had not (Table 16). All three measurements were significantly increased by biosolids. Similarly, all measurements of sweetgum trees in barrow pits were increased by biosolids up to the rate supplying 680 kg N/ha. After 4 years, sweetgum trees growing on kaolin mine spoil responded to biosolids but not to fertilizer.

Although tree response to sludge was greater than response to commercial fertilizer on these disturbed sites, biosolids generally were not superior to fertilizer on undisturbed sites (data not shown).

Table 1.16. Response of loblolly pine and sweetgum trees to fertilizer or biosolids on disturbed areas. Data from Berry (1987).

Species	Soil	Nutrient source	N-P-K	Height (H)		Diameter (D)		D^2H	
			kg/ha	cm		mm		cm^3 x 10,000	
Loblolly pine	Barrow	Control	0	265	c[1]	41	b	18	b
(10 years after	pit	Fertilizer	56-24-47	454	b	68	b	32	b
application)		Biosolids	680-340-170	980	a	154	a	248	a
				m					
Sweetgum	Barrow	Control	0	0.6	c	3.6	b	0.2	c
(10 years after	pit	Biosolids	340-170-85	4.1	b	8.6	a	3.6	b
application)		"	680-340-170	5.5	a	10.6	a	7.1	a
		"	1360-680-340	5.6	a	10.8	a	7.4	a
				cm					
Sweetgum	Kaolin	Control	0	76	b	17	b	0.03	b
(4 years after	mine	Fertilizer	112-49-93	86	b	17	b	0.04	b
application)	spoil	Biosolids	340-44-??	145	a	26	a	0.14	a

Effect On Grazing Animals

As noted above, fescue grass and Coastal bermudagrass respond well to biosolids applications. Application of liquid biosolids to forage crops can result in the adherence of significant quantities of biosolids to the leaves. Chaney and Lloyd (Chaney 1979) reported that when biosolids were spray-applied to fescue grass, adhering biosolids accounted for 22 to 32% of the weight of fescue grass (+ biosolids) on the day of application. The biosolids could not be removed by washing with a detergent. King (King 1982) also reported significant contamination of fescue grass hay that had received untreated industrial wastewater via spray irrigation. Contamination of forage can be greatly reduced by close grazing or cutting hay just prior to biosolids application. Even if forage is not contaminated, animals may still ingest some biosolids because they normally ingest a significant amount of soil (and any biosolids on the surface or mixed with the soil) during the grazing process.

Because of the direct ingestion of biosolids by grazing animals, studies have been conducted in which biosolids were added to animal feed to determine the effect of the additions on animal performance. Kienholz and others (Kienholz 1979) added biosolids from Denver, Colorado at rates such that it comprised 0, 4, or 12% of the feed intake by beef cattle for 94 days. At the 12% rate, animal gain was reduced but the reduction was thought to result from the biosolids containing no energy, i.e., the biosolids simply diluted the diet. No toxicities were observed but concentrations of some metals increased in the kidney and liver.

Bertrand and others (Bertrand 1980) fed steers for 141 days with three rations: corn, corn + 500 g/day dry biosolids from Chicago, and corn fertilized with biosolids. No differences on animal performance or carcass quality were found among the treatments. Compared to the corn ration, concentrations of Cd, Cu, Fe, and Pb in livers were higher with the corn + biosolids ration but not with the biosolids-fertilized corn ration. Metals in muscle of the biosolids-fed animals were within acceptable tolerances or guideline limits.

Summary

Nutrient availability

Estimates of nutrient availability are needed so appropriate biosolids rates can be selected. Studies involving incubation of biosolids and soil have been used to estimate PAN. One study of North Carolina biosolids showed PAN ranges from 4 to 39% of the total N in the biosolids. PAN was greater for aerobically digested biosolids than for anaerobically digested biosolids. Other studies showed a range of 0% for biosolids held in lagoons for long periods to 45% for biosolids dewatered on drying beds.

Field studies can be used to estimate PAN by determining the amount of N taken up by the crop and the amount remaining in the soil at the end of the growing seasons. Values ranged from 25 to 38% over a 3-year period with corn and from 42 to 50% for fescue grass over a 2-year period.

Biosolids P content and P availability are affected by the wastewater treatment process. Adding $FeCl_3$ for P removal increased the amount of P in biosolids but reduced the availability of the P. In contrast, BNR increased P in the biosolids and also increased the P availability. Generally, P availability was in the order BNR > no additions > $FeCl_3$ + lime stabilization > $FeCl_3$. For example, Mehlich 3-extractable P from biosolids was 29 to 68% of the total P in biosolids from facilities not using $FeCl_3$ but only 0.4 to 13% where $FeCl_3$ was used.

Nutrient loading rates

In the past, loading rates have been based on N content of biosolids. Because biosolids have a higher P/N ratio than that required by crops, P has accumulated to high concentrations in soils at application sites. Concern over these elevated concentrations resulting in surface water pollution has prompted 24 states to restrict biosolids based on P content.

Crop response

Values of NER were quite variable among studies and even within studies. Variability is due in part to biosolids composition. For example, the ratio of NH_4-N to total N will affect NER. Also, other nutrients in the biosolids will affect crop response. Reported values of NER ranged from 0.15 to 1.38 with a mean of 0.57 and a median of 0.55.

Since concern of over-application of P is a relatively new issue, little data was found on PER (phosphorus efficiency ratio). One study reported a PER of 0.77.

Tree response

Response of pine and sweetgum trees to biosolids applications was minimal except on disturbed sites (barrow pits and kaolin mine spoil).

Effect on grazing animals

Including biosolids in beef cattle rations did not result in toxicities. Gain was reduced because the biosolids had no energy value and thus diluted the diet.

APPENDIX

Table A. Response of fescue grass to fertilizer N and biosolids, Biltmore Estate, Asheville, NC. Data from Mays (1988).

	Mean annual rate[1]		Yield		
Treatments	Total N	NH4-N	1984	1985	1986
			------------	kg/ha	-------------
Check	0	0	1400 f[2]	1882 e	851 f
Fertilizer N	90	---	2027 e	3136 de	1557 de
"	180	---	2867 d	5096 b	2150 bc
"	270	---	3573 c	5858 b	2621 b
Biosolids					
Spring & Fall					
7.7 Mg/ha/yr	485	269	4375 b	7168 ab	3102 b
14.7	926	515	5779 a	5970 b	3158 a
Fall only					
2.7	113	63	---	3674 cd	1848 cde
5.3	221	123	---	5522 b	2050 cd
8	334	186	---	7437 a	2554 bc

[1] For biosolids, rates were estimated by multiplying the average total N concentration (6.3%) and NH_4-N concentration (3.5%) for the study period by the amount of biosolids applied.

[2] Within the same year, values followed by the same letter are not significantly different at the 10% level of probability.

Table B. Response of corn to fertilizer N and biosolids, Warren Wilson College, Swannanoa, NC. Data from Mays (1988).

	Mean annual rate[1]		Yield	
Treatments	Total N	NH_4-N	1985	1986
	---------- kg/ha	--------		
Check	0	0	4450 b[2]	1640 d
Fertilizer N	84	---	6270 a	3720 bc
	168	---	6460 a	5420 a
	252	---	7090 a	6680 a
Biosolids (Mg/ha/yr)				
0.9	57	32	6270 a	4790 ab
1.6	101	56	6650 a	4910 ab
2.3	145	81	6460 a	5670 a

[1] For biosolids, rates were estimated by multiplying the average total N concentration (6.3%) and NH_4-N concentration (3.5%) for the study period by the amount of biosolids applied.

[2] Within the same year, values followed by the same letter are not significantly different at the 10% level of probability.

Table C. Response of corn to fertilizer N or biosolids N, Neuse River Wastewater Treatment Plant farm, Raleigh, NC. Data from King (1983)

		Nutrients applied			
Year	Treatment	N	P	K	Grain yield
1981		-----------		kg/ha	-----------
(limited rainfall)	Control	0	0	0	1953
	Fertilizer N	84	---	---	3073
		168	---	---	2321
	<u>Biosolids</u>				
	9 Mg/ha injected	645	172	32	2822
	9 Mg/ha surface	0	0	0	---
	18 Mg/ha injected	1290	345	65	3261
	27 Mg/ha injected	1935	517	97	3826
	18 mg/ha surface	1290	345	65	3199
					nsd[1]
1982 (adequate rainfall)	Control	0	0	0	2835
	Fertilizer N	84	---	---	6363
		168	---	---	8757
	<u>Biosolids</u>				
	9 Mg/ha injected	588	209.44	29.12	8001
	9 Mg/ha surface	588	209.44	29.12	11,151
	18 mg/ha surface	1176	418.88	58.24	10,206
	27 Mg/ha surface	1764	628.32	87.36	8820
	18 mg/ha surface (residual)	0	0	0	11,466
	$LSD_{0.05}$ [2]				1386
1983	Control	0	0	0	819
(limited rainfall)	Fertilizer N	84	---	---	2079
		168	---	---	2079
	<u>Biosolids</u>				
	9 Mg/ha injected	672	188	31	1575
	9 Mg/ha surface	672	188	31	2520
	18 mg/ha surface	1344	376.32	62.72	1701
	27 Mg/ha surface	2016	564.48	94.08	2142
	18 mg/ha surface (residual)	0	0	0	2142
	$LSD_{0.05}$				945

---

[1]. Differences among yields were not significantly different in 1981.

[2]. Least significant difference at the 5% level of probability. Differences between treatments must equal or exceed this value to be significantly different.

Table D. Response of fescue grass to fertilizer N or biosolids N, state of Washington. Data from Cogger (2001).

			1993	1994	1995	1996	1997	1998	1999
Fertilizer N application rate (kg/ha) →			202	336	336	336	403	403	403
			Yield, kg/ha						
			6000b[1]	12,900b	13,100ab	10,900c	12,100c	12,100b	13,000b
Biosolids									
Type	Rate	Total N							
	Mg/ha/yr	kg/ha/yr							
None	0	0	3000d	5500d	4700e	4300e	6500e	4300d	3800d
Heat-dried	6.7	302	5400c	8900c	8500d	8600d	11,000d	8900c	8600c
	13.4	603	6400b	12,500b	11,200c	12,300b	13,600b	12,800b	12,800b
	20.2	905	7400a	14,800a	13,700a	14,200a	14,900a	14,300a	14,200a
Dewatered	6.7	283	5000c	9500c	8900d	9600d	11,200d	9300c	9100c
	13.4	565	6400b	13,300b	12,100bc	13,300ab	13,900b	13,200ab	13,200b
	20.2	848	6400b	14,700a	13,500a	14,100a	13,900b	13,300ab	14,100a

[1]. Within the same year, values followed by the same letter are not significantly different at the 5% level of probability.

Table E. Response of Coastal bermudagrass to fertilizer N and biosolids N, Georgia Piedmont. Data for 1969 and 1970 from King (1972a). Data for 1971 and 1972 from Touchton (1976).

		Annual rate			
Year	Treatment	N	P	K	yield
		kg/ha			
1969	Biosolids	835	198	60	8,330 b[1]
(5 harvests)		1670	396	119	11,700 a
		1908	452	136	12,300 a
		3816	904	272	11,700 a
	Fertilizer	224	37	93	6,300 c
	Control	0	0	0	640 d
1970	Biosolids	477	113	34	8,330 b
(4 harvests)		954	226	68	12,900 a
		1908	452	136	13,800 a
		3816	904	272	12,800 a
	Fertilizer	358	112	224	13,200 a
	Control	0	0	0	1,230 c
Residual effect					
(no biosolids		Cumulative rate			
applied)		N	P	K	yield
1971	Biosolids	1312	311	94	13,550 b
(2 harvests)		2624	622	187	15,050 ab
		3816	904	272	15,100 ab
		7632	1808	544	17,340 a
		Annual rate			
	Fertilizer	224	49	186	17,240 a
	Control	0	0	0	7,210 c
		Cumulative rate			
		N	P	K	yield
1973	Biosolids	1312	311	94	1,370 c
(One harvest		2624	622	187	2,560 bc
in June)		3816	904	272	2,750 b
		7632	1808	544	4,200 a
		Annual rate			
	Fertilizer	112	53	98	3,960 a
	Control	0	0	0	170 d

[1] Within the same year, values followed by the same letter are not significantly different at the 5% level of probability.

Table F. Response of rye over-seeded in Coastal Bermudagrass to fertilizer and to the residual effect of biosolids applied to the bermudagrass, Georgia Piedmont. Data from King (1972b).

		Annual rate applied to bermuda				
Year	Treatment	N	P	K	Rye yield	
1969		------------		kg/ha	--------------	
	Biosolids	835	198	60	1,560	c[1]
		1670	396	119	2,680	ab
		1908	452	136	2,630	ab
		3816	904	272	1,960	bc
	Fertilizer	224	37	93	---	---
		Annual rate applied to rye				
	Fertilizer	140	25	47	2,260	ab
	none	0	0	0	150	d
1970		Annual rate applied to bermuda				
	Biosolids	477	113	34	1,180	b
		954	226	68	1,540	ab
		1908	452	136	1,650	ab
		3816	904	272	390	c
	Fertilizer	358	112	224	---	---
		Annual rate applied to rye				
	Fertilizer	140	25	47	2,000	ab
	none	0	0	0	300	c

[1].Within the same year, values followed by the same letter are not significantly different at the 5% level of probability.

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