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Rapid Indices of Potential Nitrogen Mineralization for Intensively Managed Hardwood Plantations

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Abstract: Short-rotation hardwood plantations generally require repeated applications of nitrogen (N) fertilizer to maintain desired growth and are being installed on two previous land uses: agricultural fields and cutover forest lands. Because the soil organic matter chemistry is different between agricultural field and cutover soils, indices of N availability developed for one land use or the other may not work well across both land use types. The standard aerobic incubation index is time consuming and costly. Therefore, three rapid methods were tested for estimating it on six converted agricultural fields and seven cutover pine sites currently in intensively managed sweetgum plantations on the eastern coastal plain of the United States. Two procedures (anaerobic incubation and hot KCl extract) were not useful for estimating mineralizable N in either agricultural field soils or cutover pine soils. The third index, a 3-day incubation of rewetted soils previously dried, was linearly correlated to mineralizable N ($p < 0.0001$, $R^2 = 0.88$). This method, which had not been tested in forest soils previously, worked best for the cutover soils ($p < 0.002$, $R^2 = 0.82$) and less so for the agricultural field soils ($p < 0.097$, $R^2 = 0.66$). However, none of

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the procedures estimated potentially mineralizable N better, across all sites, than total N ($p < 0.0001$, $R^2 = 0.93$). Total N was not effective, however, in estimating mineralizable N within the agricultural field sites ($p < 0.220$, $R^2 = 0.44$). Further work will be needed to assess if potentially mineralizable N, total N, or the drying-rewetting index can be used to help predict fertilizer rates and timings in intensively managed hardwood plantations, especially on cutover forest lands.

Keywords: Nitrogen availability indices, nitrogen mineralization potential, land-use history, short-rotation woody crops

INTRODUCTION

Nitrogen (N) fertilizer applications to forest systems are generally limited to the correction of diagnosed tree deficiencies, and then only in intensively managed plantation systems. Traditional plantation forest systems have been structured around relatively nutrient-efficient species, (e.g., *Pinus* spp.), that achieve acceptable production with relatively little input (Bowen and Nambiar 1984). Because N demand reaches a maximum when stands fully occupy sites, plantations become N-limited during or shortly after canopy closure, if not before. A combination of thinning and fertilization is generally sufficient to synchronize N supply with plant N demand (Allen 1987).

Short-rotation woody crop (SRWC) systems are the most intensively managed forest system and are usually grown in 5- to 20-year cycles for rapid wood production suitable for pulp or fuel. The tree species used for SRWC in North America and Europe are generally deciduous hardwoods. These hardwoods are less N efficient than pines because hardwoods renew their foliage each year and thus require more N. The high N demand of these intensively managed hardwoods often creates an asynchrony between soil N supply and tree N demand before canopy closure (van Miegroet, Norby, and Tschaplinski 1994). Repeated applications of fertilizer are needed to minimize these N deficiencies, but the optimal N fertilizer rate and timing that will maximize plantation productivity and minimize N export from the system is not known, especially on a species- and site-specific basis.

Across the United States, but especially in the Atlantic coastal plain region, two general classes of sites are being explored for SRWC production: abandoned or converted agricultural fields and cutover forest lands. In general, agricultural fields are more desirable for SRWC production than cutover forest lands because inherent fertility and past fertilization practices have made agricultural fields more fertile with respect to phosphorus and basic cations, the fields have little to no woody competition, and the fields are easily accessible for management operations. However, in certain geographic areas, agricultural fields are not as plentiful or available for conversion to SRWC

(Donald Kaczmarek, MeadWestvaco Corporation and Michael Kane, International Paper Corporation, personal communication). In these areas, productive forest lands may be converted to SRWC production. Cutover forest sites tend to have much higher quantities of soil organic matter (Richter et al. 2000). However, the organic matter in the cutover forest sites is generally more recalcitrant and has a much higher C:N ratio than agricultural field soils, especially when N-fixing legumes have been grown.

Soil N supply, or the quantity of mineral N available for plant uptake through time, is highly dynamic and represents only a very small fraction of total soil N. Soil N is mostly contained within soil organic matter, but chemical and physical constraints to microbial decomposition limit the potentially mineralizable N to 5–40% of total soil N (Stanford and Smith 1972). The rate at which soil N becomes available can be estimated with a measure of potentially mineralizable N (N_0) (Stanford and Smith 1972) and soil climate (Campbell, Jame, and De Jong 1988). Unfortunately, the standard measure of N_0 involves a minimum 24-week laboratory incubation and field moist soil. Shorter incubation times generally only measure the contribution of microbial biomass and soluble N sources, whereas longer incubations may measure the whole active fraction. Field moist soil is needed to avoid disturbing or modifying the microbial biomass. For these reasons, several rapid methods of estimating potential soil N availability have been studied. Most indices were originally developed for agricultural soils, but several have been tested in forest soils as well (Binkley and Hart 1989; Keeney 1980).

Because the soil organic matter chemistry of agricultural field and cutover forest soils is different, indices that work well within each soil type may not work well when both soil types are tested simultaneously. Since both agricultural fields and cutovers are being converted to SRWC plantations, we need to determine whether a single N_0 index can be used across site types or whether separate indices for the two site types would be more appropriate.

The most common indices include short-term incubations in aerobic or anaerobic conditions and chemical extractions. Of the incubation indices, the 7-day anaerobic incubation (Waring and Bremner 1964) is common and has been used with success in both agricultural soils and forest soils. Because nitrification is not as dominant in some acidic forest soils as in agricultural soils, the measurement of NH_4^+-N in the anaerobic technique has appealed to forest soils scientists (Powers 1980). The hot KCl extraction (Gianello and Bremner 1986) has also been tested in several studies in both agricultural (Jalil et al. 1996; Sembiring, Johnson, and Raun 1998) and forest soils (Hart and Binkley 1985), although they did not find it to be a useful index in pine plantations. Recently, CO_2 released after oven-drying and rewetting soils has been shown to be closely related to N mineralization and microbial biomass (Franzluebbers et al. 1996), and the active fraction of soil organic matter (Franzluebbers et al. 2000). Therefore, the objectives of this study were to determine the ability of these three indices to estimate

N_0 determined by a 24-week aerobic incubation on agricultural fields and cutover forest lands converted to short-rotation intensively cultured sweetgum (*Liquidambar styraciflua* L.) plantations across the Atlantic coastal plain.

MATERIALS AND METHODS

Site Descriptions

Surface soils (0–20 cm) were collected from five converted agricultural fields and seven pine cutover sites in southeast Virginia and central and southern South Carolina (Table 1) that had all been converted to short-rotation, intensive-culture sweetgum plantations. The sites selected for this study represent the gradient of site types currently explored by forest industry for sweetgum plantations on the Atlantic coastal plain (Donald Kaczmarek, MeadWestvaco Corporation, and Michael Kane, International Paper Corporation, personal communication). The soils on these sites vary widely due to landscape position, parent material, and prior land use. The particular soils sampled in this study represented more specific site types. Within the converted agricultural fields sampled, the Norfolk, Goldsboro, and Lynchburg series represented the upper, middle, and lower portions, respectively, of a catena common throughout the upper and middle coastal plain. The Coxville soil was a poorly to very poorly drained soil found in depressional areas within the Lynchburg soils. Within the loblolly pine cutover sites sampled, the Argent, Meggett, Mouzon, Yauhannah, and Yemassee soils were found in proximity to each other. The Argent, Meggett, and Mouzon soils were found on low-lying clay flats and were similar to the Coxville series in landscape position and drainage. The Mouzon and Meggett soils were very poorly drained, while the Argent was poorly drained. The Yauhannah and Yemassee soils, found on slightly elevated positions, are similar to the Lynchburg and Goldsboro soils. The Byars series represented soils found in Carolina Bays, while the Myatt series was found on a broad stream terrace. Both series were selected, in part, due to their extremely acidic nature. The sandy, well-drained Wagram series was found on a river terrace.

At each site, a bulk soil sample of the surface 20 cm was collected from five 7-cm diameter auger samples. Each sample was subdivided into two replicate samples, which were prepared differently. One of the replicate samples was kept at field moisture and room temperature until analyzed within 1 week, while the other was air-dried.

Because some sites were very young (less than 3 years old) while others were approaching canopy closure (5 to 7 years old) and were not originally part of designed fertilizer experiments, the indices could not be correlated to growth data.

Table 1. Surface soil (0–20 cm) properties of 12 sites that represent the range of operational conditions for operational sweetgum plantations in the Atlantic coastal plain of the United States

Site type	Soil series	Taxonomy	Total C	Total N	C:N	pH	Texture
			$g\,kg^{-1}$				
Converted agricultural fields	Norfolk 1	Typic Kandiudult	5.7	0.20	28.4	5.23	Sandy loam
	Goldsboro	Aquic Paleudults	8.2	0.30	27.3	5.76	Sandy clay loam
	Norfolk 2	Typic Kandiudult	5.1	0.19	26.8	5.21	Sand
	Coxville	Typic Paleaquult	9.1	0.42	21.6	6.14	Sandy clay
	Lynchburg	Aeric Paleaquult	10.1	0.36	28.1	6.00	Sandy loam
Cutover loblolly pine plantations	Wagram	Arenic Kandiudult	8.3	0.25	32.8	4.83	Loamy sand
	Argent	Typic Endoaqualf	30.9	0.86	35.8	5.56	Sandy loam
	Meggett	Typic Albaqualf	24.5	1.13	21.6	4.77	Silt loam
	Yauhannah	Aquic Hapludult	24.9	0.62	39.9	4.57	Sandy loam
	Yemassee	Aeric Endoaquult	27.3	1.12	24.3	5.15	Sandy loam
	Byars	Umbric Paleaquult	37.0	1.54	24.1	4.53	Sandy clay loam
	Myatt	Typic Endoaquult	56.0	1.55	36.2	3.84	Loam
	Mouzon	Typic Albaqualf	55.3	2.92	19.0	4.46	Clay loam
Agricultural fields	Mean		7.6**	0.30**	26.4	5.67**	
Cutover sites	Mean		33.0**	1.25	29.2	4.71	

*,**Significant at the 0.01 probability level.

Soil Characterization

The dry soil samples were analyzed for total carbon (C), N, pH, and texture. Total carbon was determined via infrared analysis (LECO Total Carbon Analyzer, LECO Corp., Saint Joseph, MI). Total N was determined on a 5-g soil sample using the macro-Kjeldahl digestion method (Bremner 1996) followed by colorimetric analysis (Bran+Luebbe TRAACS 2000, Oak Park, IL). Soil pH was determined with a combination electrode in the supernatant of a 1:2 soil:water mixture (Thomas 1996). Texture was determined by the hydrometer method (Gee and Or 1992).

Aerobic Incubation (N_0)

Potential N mineralization (N_0) was determined on the fresh soil samples. The samples were sieved through a 2-mm sieve at the field moisture content. Approximately 40 g of field-moist soil were mixed thoroughly with 150 g silica sand to ensure good drainage and placed in 5-cm diameter by 15-cm long polyvinyl chloride (PVC) tubes and sealed with one-hole rubber stoppers. A separate 10-g subsample was dried at 105°C to determine moisture content. The samples were leached when prepared and every 2 weeks thereafter with 250 mL of 0.01 *M* $CaCl_2$, followed by 100 mL of a minus-N Hoagland solution (Burger and Pritchett 1984). After the solution was allowed to leach through the samples gravimetrically, a vacuum was applied to drain the samples to field capacity (−0.03 MPa). The leachates for the second through twenty-fourth week were collected and analyzed for NH_4 and NO_3-N with a TRAACS 2000 colorimetric autoanalyzer (Bran+Luebbe Corp., Oak Park, IL). A first-order model for N_0 (Equation 1) was fit to the cumulative N production using PROC NLIN in SAS (SAS Institute 2000) to determine N_0. In all cases, the first-order model fit the data well.

$$N_T = N_0 \times (1 - e^{-kT}) \tag{1}$$

where: N_T = cumulative N production in mg N kg^{-1} soil at time T

N_0 = potentially mineralizable N

K = N mineralization rate at 35°C and −0.03 MPa water tension

T = time

Extractable Nitrogen

Extractable NH_4^+ and NO_3^- were measured by placing 5 g soil and 50 mL 2 *M* KCl in a 100-mL centrifuge tube. The tubes were shaken for 30 minutes and the extracts filtered through Whatman #2 filters. The concentrations of NH_4^+-N and NO_3^--N were determined on a colorimetric autoanalyzer. Each sample was performed in triplicate.

Anaerobic Incubation Index (ANI)

The anaerobic incubation method (Powers 1980) was used as one rapid index of N_0. Five g of air-dried, sieved (2-mm) soil were added to 1-cm diameter by 10-cm length glass tubes, which were then filled with deionized water. The samples were incubated at 40°C for 7 days. After incubation, the samples were extracted with 50 mL of 2 *M* KCl and analyzed for NH_4^+-N using a colorimetric autoanalyzer. Each sample was performed in triplicate.

Hot KCl Extraction (HKCL)

This procedure was modified from the original analysis (Gianello and Bremner 1986). A 3-g portion of an air-dried and sieved (2-mm) soil and 20 mL of 2 *M* KCl were added to 150-mL digestion tubes. The tubes were heated at 100°C for 4 hours in a digestion block. The tubes were cooled, and the extract was filtered through Whatman #42 filter paper. Ammonium (NH_4^+) and nitrate (NO_3^-) in the extracts were determined with a colorimetric autoanalyzer. Each sample was performed in triplicate.

Drying Rewetting CO_2 Flush (CFLUSH)

The N_0 was indirectly measured with a microbial activity index (Franzluebbers et al. 1996). A 50-g portion of an air-dry, sieved soil was placed in a 50-mL plastic beaker and dried at 60°C for 24 hours. The samples were wetted to 60% water-filled pore space. The total pore space was determined by subtracting the volume of soil particles from the total soil volume in the beaker (Equation 3). The amount of water needed to fill 60% of these pores was determined using the density of water (1.0 g cm^{-3}).

$$\text{Pore space} = V_T - \frac{\text{Soil}_{\text{Mass}}}{\text{Soil}_{\rho_p}} \qquad (2)$$

Where: V_T = Total volume (cm^3)

$\text{Soil}_{\text{Mass}}$ = mass of soil dried at 60°C (g)

Soil_{ρ_p} = particle density of soil (2.65 g cm^{-3})

The samples were placed in a sealed glass jar (475 cm^{-3}) along with another 50-mL plastic beaker containing 10 mL of 0.5 *M* NaOH and incubated for 72 hours at 35°C. The CO_2 released was captured in the alkali trap and measured by titrating to a phenolphthalein endpoint with HCl. To do this, 1 mL of concentrated $BaCl_2$ solution and five drops phenolphthalein indicator were added to the NaOH and then titrated with 0.5 *M* HCl.

Data Analysis

The influence of previous land use on N_0 and the three indices was analyzed using t-tests with pooled variances or Satterthwaite's method for unequal variances when necessary. The accuracy and usefulness of each method for estimating N_0 was determined by linear regression. All procedures were performed in SAS (SAS Institute 2000).

RESULTS AND DISCUSSION

The soil properties related to mineralizable N were strikingly different between the cutover pine plantations and the converted agricultural fields. Total soil C and N were four-fold greater in the surface 20 cm of the cutover pine plantations compared to the converted agricultural sites (Table 1). Total N ranged from 0.19 to 0.42 and 0.25 to 2.92 g kg^{-1} on the agricultural field and cutover soils, respectively. Soil substrate quality, as measured by the C:N ratio, was not different between the two land use categories but varied from 19.0 to 39.9 and averaged 28.1. Soil pH averaged 5.7 at the agricultural fields compared to 4.7 at the cutover pine sites. Soil textures ranged from fine sand to sandy clay, but most soils were loams across both site types.

Potentially mineralizable N (N_0) was about three-fold greater in the cutover sites compared to the agricultural field sites. Within the agricultural field sites, N_0 averaged 36.9 mg kg^{-1} and only varied by 16 mg N kg^{-1} (30.7 to 46.7 mg kg^{-1}), while N_0 averaged 107.2 mg kg^{-1} and varied by 176 mg N kg^{-1} in the cutover sites (46.9 to 223 mg kg^{-1}) (Table 2). The original goal was to test each index across the range of site types without regard to previous land history. The relative lack of variation in N_0 on the agricultural field soils suggests that, compared to cutover forest soils in the region, converted agricultural fields have about 37 mg kg^{-1} of N_0. The agricultural field soils all varied less than 20% from the mean, while the cutover soils varied as much as 92% from the mean.

Total soil N was first tested to see if it could predict N_0. Total N can be used to index N availability across a regional scale (Binkley and Hart 1989). On a local scale, differences in substrate quality may be more important, and total N may not adequately index N_0. We hypothesized that,

Table 2. Measurement and indices of potentially mineralizable N (N_0) in the surface soil (0–20 cm) of six converted agricultural fields and seven cutover pine plantations representing operational conditions for sweetgum plantations in the Atlantic coastal plain of the United States

Site type	Soil series	N_0^a	ANI[b]	HKCL[c]	CFLUSH[d]
		mg N kg^{-1}			mg C kg^{-1}
Converted agricultural fields	Norfolk 1	30.7	4.9	9.9	87
	Goldsboro	34.0	10.6	9.3	103
	Norfolk 2	34.6	9.3	12.5	91
	Coxville	38.7	28.8	14.9	146
	Lynchburg	46.7	18.8	12.0	138
Cutover loblolly pine plantations	Wagram	46.6	9.6	10.5	117
	Argent	46.9	30.5	22.3	243
	Meggett	87.4	32.4	52.7	229
	Yauhanna	94.4	19.0	26.6	197
	Yemassee	101.7	35.9	27.0	246
	Byars	123.5	31.4	29.5	307
	Myatt	134.3	8.3	35.2	365
	Mouzon	222.5	112.4	223.0	452
Agricultural fields	Mean	36.9**	14.5	11.7	113**
Cutover sites	Mean	107.2**	34.9	53.4	269**

*,**Significant at the 0.01 probability level.

[a]N_0 was determined by a 24-week incubation and first-order kinetics, where cumulative N supply = N_0*$(1 - e^{-kt})$.

[b]ANI refers to a 7-day anaerobic incubation and extraction index of N_0.

[c]HKCL refers to a Hot KCl extraction index of N_0.

[d]CFLUSH refers to the CO_2 released (expressed as mg C kg^{-1}) after drying at 60°C and rewetting to 60% water-filled pore space.

although soil organic matter varied widely across the site types, the difference in substrate quality between the agricultural fields and cutover sites would limit the usefulness of using total N as an estimate of N_0. However, total N was a good predictor of N_0; linear regression explained 93% of the variance in N_0 (Figure 1). Furthermore, the greatest residual was only 32 mg N kg^{-1}, and only two soils (Argent and Yauhannah) had residuals over 10 mg N kg^{-1}. The close mathematical relationship between N_0 and total N across the two site types was partly due to the relative importance of the cutover soils.

The anaerobic index (ANI), which has been used in both forested and agricultural soils as an index of N_0, was not a good indicator across the soils studied, especially for forest soils. Extracted N was, as with N_0, about three-fold greater in the cutover pine sites than in the agricultural fields

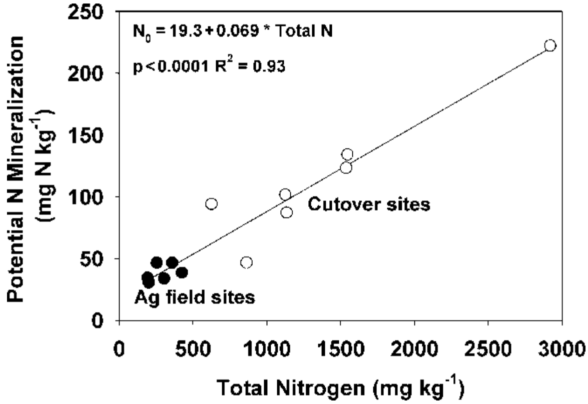

Figure 1. Relationship of potential N mineralization determined aerobically using first-order kinetics (N_0) and total nitrogen for 13 surface (0–20 cm) soils representing the range of operational conditions for sweetgum plantations in the Atlantic coastal plain of the United States.

(Table 2), but the difference between land uses was not significant ($p < 0.1351$). About 14 mg N kg^{-1} was extracted after anaerobically incubating the agricultural field soils (36% of N_0), while about 39 mg N kg^{-1} (33% of N_0) was extracted from the cutover site soils. The range of index values was 23.9 mg N kg^{-1} on the agricultural field sites and 104 mg N kg^{-1} on the cutovers.

Linear regression indicated that the relationship between this index and N_0 was significant ($p < 0.0013$) and had an R^2 of 0.63 (data not shown). However, the studentized residuals, PRESS, DFFIT, and Cook's D statistics (Montgomery and Peck 1992) all indicated that the Myatt and Mouzon soils were outliers. With these two sites removed from the analysis, the relationship was still significant ($p < 0.246$) but explained only 45% of the variation (Figure 2).

The hot KCl extraction index (HKCL) was also a poor index of N_0. As with ANI, about 30% of N_0 was extracted in the agricultural field soils (11.5 mg kg^{-1}) (Table 2), while, unlike ANI, about 51% of N_0 (59.5 mg kg^{-1}) was extracted on the cutover sites. Again, the Mouzon soil, in which 100% of the N_0 was extracted by HKCL, was an outlier. The Myatt soil was not an outlier in this analysis. About 33% of N_0 was extracted from the other cutover site soils. A linear relationship between the HKCL extract and N_0 was significant ($p < 0.0056$) and had a R^2 of 0.55 (Figure 3) with the Mouzon soil removed from the analysis, but the cutover pine site soils exhibited nonlinear trends that were not related to measured soil properties.

The CO_2 flush index (CFLUSH) was a good index of $N_{0.}$ The agricultural field soils released 113 mg C kg^{-1}, while the cutover site soils released

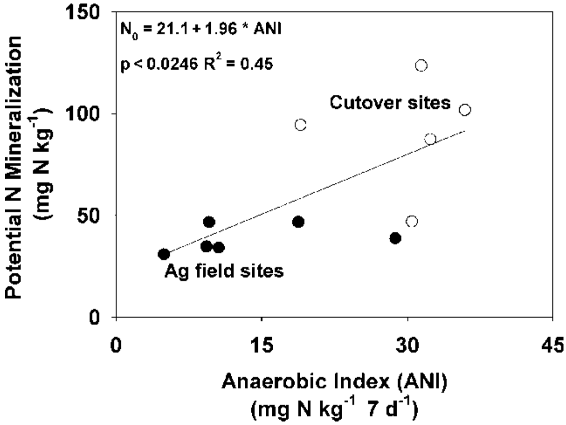

Figure 2. Relationship between potential N mineralization determined aerobically using first-order kinetics (N_0) and a 7-day anaerobic incubation for 11 surface (0–20 cm) soils representing the range of operational conditions for sweetgum plantations in the Atlantic coastal plain of the United States.

269 mg C kg^{-1} in the 3 day incubation. These values correspond to CO_2-C:N_0 ratios of 3.06 and 2.51, respectively. A linear relationship between N_0 and the CFLUSH index was significant ($p < 0.0001$) and had a good fit ($R^2 = 0.88$) (Figure 4). This method was almost as good as total N for estimating N_0. Unlike the ANI and HKCL indices, the CFLUSH index worked equally

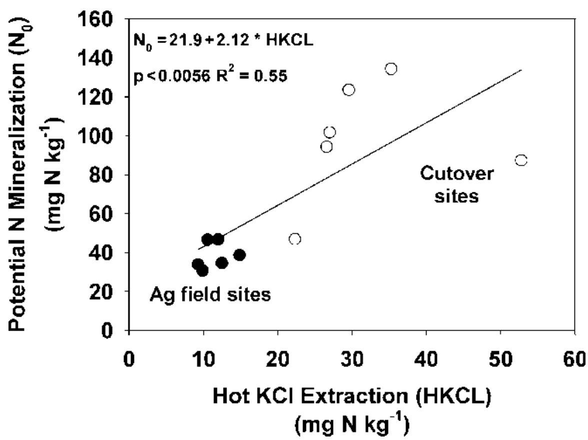

Figure 3. Relationship between potential N mineralization determined aerobically using first-order kinetics and a chemical extraction index for 13 surface (0–20 cm) soils representing the range of operational conditions for sweetgum plantations in the Atlantic coastal plain of the United States.

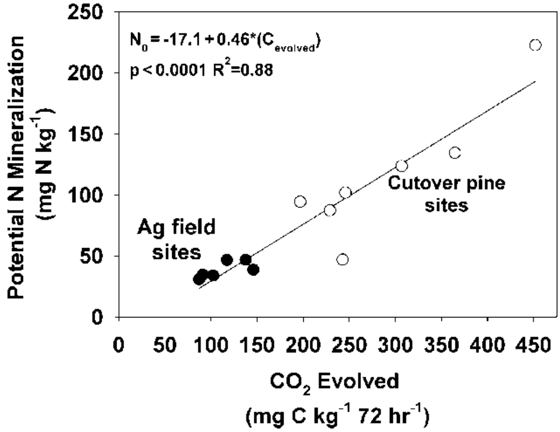

Figure 4. Relationship between potential N mineralization determined aerobically using first-order kinetics, and the CO_2 evolved in 72 hours after drying at 60°C and rewetting to 60% water-filled pore space for 12 surface (0–20 cm) soils representing the range of operational conditions for sweetgum plantations in the Atlantic coastal plain of the United States.

well across the entire range of sites. This index may also be used to estimate microbial biomass (Franzluebbers et al. 1996) and the active fraction of the SOM (Franzluebbers et al. 2000). Furthermore, this index can be performed without expensive analytical apparatuses.

Across the range of site types encountered, we found that absolute substrate amount (total N) was the best predictor for N_0 based on R^2 values, and total N is routinely offered as a soil test from commercial soil laboratories. Because the CFLUSH index does require more time than total N and is not more accurate than total N across both converted agricultural fields and pine cutovers, our findings suggest that total N is the preferred measurement. However, within a given site type, the CFLUSH technique may be the preferred index.

Separate regression analyses were performed by site type for the total N and CFLUSH techniques to investigate which technique was better within a site type. Within the cutover sites, either technique appeared to be adequate. Both total N ($p < 0.0004$) and CFLUSH ($p < 0.002$) were significant predictors of N_0 and explained about 85% of the variation in N_0 (89% and 82%, respectively). However, within the agricultural field sites, which had a much narrower range of N_0, total N was not linearly related to N_0 ($p < 0.220$) and explained only 44% of the variation. CFLUSH, on the other hand, was significant ($p < 0.097$) and explained over half the variation (66%). These results indicate that CFLUSH may be a better overall indicator of N_0 for both converted agricultural fields and cutover pine stands.

CONCLUSIONS

Repeated fertilization of SRWC is necessary to maintain high levels of productivity, and accurate fertilizer recommendations are needed across wide ranges in soil types. Across the range of sites explored for SRWC management in the southeastern United States, previous land use was the most important factor in determining potentially mineralizable N. Although the substrate quality of these two site types might have been different, the total quantity of soil organic matter was the more important influence on N_0, and thus total N had the best correlation with N_0. The anaerobic incubation and chemical extraction methods were not well correlated with N_0, even when a highly influential soil was removed from the analysis. The CFLUSH index, which measured the CO_2 produced following the rewetting of an oven-dried sample, was well correlated with N_0 and was superior to total N for estimating N_0 on agricultural field sites. This procedure may also have merit for estimating soil microbial biomass and the active soil organic matter in both agricultural and forest soils and should be explored further.

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