Soil Type and Moisture Regime Effects on Fertilizer Efficiency Calculation Methods in a Nitrogen-15 Tracer Study

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ABSTRACT

Research was conducted to determine the extent to which the method of calculation affects estimates of fertilizer N efficiency using ^{15}N as a tracer. Corn (*Zea mays* L.) was grown at three locations in Illinois that varied widely in soil type. Three early-season moisture regimes (ambient, ambient + 100 mm of excess water, and ambient + 150 mm of excess water) were established to obtain different fertilizer N efficiencies on each soil. Application of ^{15}N-enriched KNO_3 (168 kg N ha^{-1}) was made to a Drummer silty clay loam (fine-silty, mixed, mesic Typic Haplaquoll) at DeKalb, a Cisne silt loam (fine, montmorillonitic, mesic Mollic Albaqualf) at Brownstown, and a Plainfield sand (mixed, mesic Typic Udipsamment) at Havana, IL. Fertilizer N efficiency was calculated from the difference between N uptake by fertilized versus unfertilized plants, from the amount of ^{15}N recovered in the plant, and from the recovery of ^{15}N in both the plant and soil. For the Drummer and Cisne soils, the three calculation procedures gave different percent fertilizer N efficiencies when averaged across moisture treatments, and different trends among moisture treatments. For the Plainfield soil, percent fertilizer N efficiency values were lower than those obtained for the Drummer or Cisne soil, and the method of calculation had very little effect. The results indicate that, for most soils, N fertilizer efficiency ratings vary with the method by which they are calculated. The present study demonstrates a need for standard terminology to help identify parameters used to define fertilizer efficiency.

PUBLIC CONCERN regarding NO_3 contamination of ground and surface water has drawn attention to the need for quantitative data concerning the fate of N applied to agricultural soil as fertilizer, and a growing number of investigations are being conducted to obtain such data (e.g., Hills et al., 1983; Sharpe et al., 1988; Walters and Malzer, 1990). A major goal of these investigations is to improve the efficiency of N fertilizers, on the assumption that higher efficiency will permit high yields while minimizing the pollution potential. N fertilizer efficiency can be defined in several ways, however, depending on the method by which it is calculated.

Fox and Piekielek (1987) found that the effects of tillage treatments on N fertilizer efficiency depended on the way in which efficiency was defined, either as (i) crop yield per unit of N fertilizer applied at economically optimum N rates, or (ii) the difference between N uptake by the N-fertilized crop and uptake by the non-fertilized crop, expressed as a percentage of the amount of fertilizer N applied. Both definitions are subject to limitations. In the former case, efficiency is defined strictly in terms of crop yield, without regard to the amount of N utilized or the pollution potential of the fertilizer. In the latter case, the definition of efficiency is based on the assumption that addition of fertilizer N will not alter the availability or uptake of native soil N. Yet this assumption can be invalid due to an added N interaction (ANI) with soil N (Jenkinson et al., 1985), also known as the so-called "priming effect" of fertilizer N (Hauck and Bremner, 1976).

Increasingly, ^{15}N-tracer techniques are being employed in research on the fate and behavior of fertilizer N. Compared to non-tracer studies, determinations of labeled fertilizer N can be made more accurately (Hauck and Bremner, 1976), treatment effects can be detected with greater sensitivity (Russelle et al., 1981), and studies of the transformations and fate of fertilizer N can be conducted without need for a check plot (Hauck and Bremner, 1976). Moreover, N in the crop derived from fertilizer can be distinguished from soil-derived N, allowing fertilizer N efficiency to be calculated without regard to residual fertilizer N in the soil. However, interpretation of data is complicated by the fact that fertilizer N applied to soil undergoes exchange with native soil N through mineralization-immobilization turnover (MIT) (Jansson and Persson, 1982; Walters and Malzer, 1990), which accounts for the fact that estimates of N fertilizer efficiency based on ^{15}N uptake are usually lower than those calculated by difference (Terman and Brown, 1968; Westerman and Kurtz, 1974; Dowdell and Webster, 1980).

In studies involving use of ^{15}N as a tracer, fertilizer efficiency is typically calculated from plant recovery of ^{15}N (e.g., Russelle et al., 1981; Hills et al., 1983; Walters and Malzer, 1990). However, as pointed out by Walters and Malzer (1990), such estimates should be made with caution because of the effect of MIT on the isotopic composition of the N taken up by the plant. To avoid this problem, Walters and Malzer (1990) recommended that N fertilizer efficiency be calculated from the difference between N uptake by fertilized and non-fertilized plants. Such calculations are based on the assumptions that application of fertilizer N has no effect on uptake of native soil N and that the treatments under consideration do not affect N uptake when no N is applied. There is evidence that the former assumption is often invalid (Hauck and Bremner, 1976), and recent work by Fox and Piekielek (1987) illustrates that the latter assumption can also be invalid, as N fertilizer efficiencies calculated by difference for various tillage treatments were found to depend largely upon differences in N uptake when N was not applied (i.e., among check plots receiving different tillage treatments). Recent work by Varvel and Peterson (1990) with different crop rotations further illustrates the difficulties involved in estimating N fertilizer efficiency by the difference method or from plant recovery of ^{15}N.

To properly interpret N fertilizer efficiency esti-

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Abbreviations: ANI, added N interaction; and MIT, mineralization—immobilization turnover.

Table 1. Physical and chemical characteristics of the Illinois soils used in this study.

Location	Soil Series	Soil Subgroup	Surface texture	pH	Organic C	Total N	Available P	Available K	Permeability
					— g kg^{-1} —		— kg ha^{-1} —		— mm s^{-1} —
DeKalb	Drummer	Typic Haplaquoll	silty clay loam	6.7	22.6	2.50	116	233	0.004–0.014†
Brownstown	Cisne	Mollic Albaqualf	silt loam	6.5	7.1	0.83	92	446	0.001–0.004‡
Havana	Plainfield	Typic Udipsamment	sand	6.4	2.0	0.18	56	325	0.042–0.141§

†From Hinkley (1978)
‡From Downey and Odell (1969)
§From Calsyn (1989)

mates, the limitations associated with the method of calculation must be recognized. The primary objective of the work reported here was to compare the difference method and the ^{15}N recovery method for estimating N fertilizer efficiency on contrasting soil types. An additional objective was to determine how N fertilizer efficiency estimates may vary with changes in the soil moisture regime.

MATERIALS AND METHODS

Field experiments with corn were conducted in 1987 and 1988 at DeKalb, Brownstown, and Havana, IL, on major soil types for which inefficient N fertilizer use is a common occurrence. At DeKalb and Brownstown, substantial loss of N can occur by denitrification following heavy rainfall in the spring and early summer, either because of slow internal permeability, as is the case for the Drummer silty clay loam at DeKalb, or because of the presence of a relatively impermeable claypan, as is the case for the Cisne silt loam at Brownstown. At Havana, rapid leaching of NO_3 leads to serious loss of fertilizer N from the excessively well drained Plainfield sand. Chemical and physical characteristics of the soils (Table 1) were determined from surface (0–15 cm) samples at each site. In the analyses reported in Table 1, pH was determined with a glass electrode (soil-to-water ratio, 1:1), organic C by the Walkley-Black procedure (Nelson and Sommers, 1982), total N by a permanganate-reduced iron modification of a semimicro-Kjeldahl procedure (Bremner and Mulvaney, 1982), available P by the Bray-1 method (Knudsen, 1980), and available K by flame photometry following NH_4OAc extraction (Carson, 1980).

Three moisture treatments were imposed to change the effectiveness of fertilizer N application at each location. Early-season moisture regimes were established on approximately 1 June to simulate heavy rainfall events that commonly occur in Illinois. The moisture regimes used were ambient rainfall; ambient rainfall plus 100 mm of excess water, applied over a 3-d period as simulated rainfall; and ambient rainfall plus 150 mm of excess water, applied over an 8-d period as simulated rainfall. Table 2 shows monthly totals of rainfall and irrigation during May and June prior to establishment of moisture regimes. Plot size was 15.2 by 4.6 m for the Cisne and Drummer soils and 10.7 by 4.6 m for the Plainfield soil. Nitrogen as KNO_3 was broadcast-applied (168 kg N ha^{-1}) at the 1 to 3 leaf stage to all but a 2.3- by 3.5-m area (microplot) in the center of each plot. To each microplot, ^{15}N-enriched KNO_3 was applied in solution as uniformly as possible with a compressed air spray gun applicator. The KNO_3 applied to the Drummer and Cisne soils contained 2.79 atom % ^{15}N; the KNO_3 applied to the Plainfield soil contained 2.29 atom % ^{15}N. In each case, a check plot receiving no fertilizer N was established.

Prior to establishment of the water regimes, water was applied to bring the matric potential of all plots (including those designated as ambient) to −33 kPa. Corn was planted between 26 and 30 April at Brownstown (Pioneer 3297, 64500 plants ha^{-1}) and DeKalb (Pioneer 3540, 69200 plants ha^{-1}), and between 12 and 14 May at Havana (Pioneer 3377, 74100 plants ha^{-1}). Fertilizer (P and K) and limestone applications were made according to University of Illinois soil test recommendations for each location (University of Illinois, 1986).

Table 2. Monthly totals of rainfall and irrigation for the three Illinois sites during May and June.†

Month	1987 Rainfall	1987 Irrigation‡	1988 Rainfall	1988 Irrigation‡
	mm			
		Drummer		
May	119	0	61	0
June	71	0	12	0
		Cisne		
May	50	0	25	29
June	28	28	30	48
		Plainfield		
May	24	82	19	33
June	102	55	27	73

†Early-season excess water application was initiated on approximately 1 June.
‡Values reported represent water applied to all plots for corn production or for adjustment of soil moisture tension (33 kPa) prior to establishment of water regimes in June. No applications (other than excess moisture treatments) were made to Drummer soil, as irrigation facilities were limited, and rainfall in 1987 and 1988 was adequate to reduce soil moisture tension to <33 kPa by 1 June.

The microplots were arranged to include four rows of corn. Plant samples (grain, cob, and remaining plant parts) were collected from a 1.52-m section of the two center rows within the microplots at harvest. The samples were dried at 65°C (until weight loss was complete), ground in a Wiley mill to pass a 0.44-mm screen, and analyzed for total N using a salicylic acid-thiosulfate modification of a semimicro-Kjeldahl method (Bremner and Mulvaney, 1982). Uptake of N in the aboveground portion of the plant was calculated from the relation, plant N uptake = $(N_g \times W_g) + (N_c \times W_c) + (N_r \times W_r)$, where the concentration of N (kg kg^{-1}) was multiplied by dry weight (kg ha^{-1}) of the grain, cob, and remaining plant parts, indicated by the subscripts, g, c, and r, respectively.

At harvest, six soil cores were collected from within the microplot to a depth of 120 cm. Each core was sectioned into four 30-cm increments. Immediately after collection, the soil samples were frozen for transport to the laboratory at Urbana, IL. Prior to analyses for NO_3–N and total N, the samples were screened (<1 mm) in the field-moist condition. Following extraction with 2 *M* KCl (soil:solution ratio, 1:5), inorganic N concentrations were determined by steam distillation of the extracts with MgO and Devarda's alloy as described by Keeney and Nelson (1982). The total N content of soil samples was determined using a permanganate-reduced iron modification of a semimicro-Kjeldahl method (Bremner and Mulvaney, 1982). Distillates were concentrated for isotope-ratio analyses, which were per-

Table 3. Effects of early-season excess moisture and method of calculation on the efficiency of fertilizer N applied to corn on Drummer silty clay loam, Cisne silt loam, and Plainfield sand soils in Illinois.

Moisture treatment	Method of calculation† 1	2	3
	N fertilizer efficiency (%)		
	Drummer 1987		
Ambient	41.7 a‡	79.1 a	66.7 a
Ambient + 100mm	23.6 b	48.3 b	30.9 b
Ambient + 150mm	30.4 b	43.1 b	40.1 c
Mean	31.9 A§	56.8 B	45.9 C
	1988		
Ambient	40.0 a	87.7 a	39.2 a
Ambient + 100mm	36.2 a	60.4 b	37.6 a
Ambient + 150mm	34.0 a	53.1 b	51.6 a
Mean	36.7 A	67.1 B	42.8 A
	Cisne 1987		
Ambient	53.7 a	65.5 a	57.4 a
Ambient + 100mm	53.4 a	64.0 ab	76.0 b
Ambient + 150mm	41.6 b	50.2 b	68.3 b
Mean	49.6 A	59.9 B	67.2 C
	1988		
Ambient	65.1 a	94.9 a	89.5 a
Ambient + 100mm	49.1 b	71.7 b	52.2 b
Ambient + 150mm	49.4 b	67.0 b	74.7 ab
Mean	54.5 A	77.9 B	72.1 AB
	Plainfield 1987		
Ambient	15.6 a	17.5 a	30.3 a
Ambient + 100mm	5.7 a	8.4 a	9.2 a
Ambient + 150mm	6.5 a	8.2 a	7.6 a
Mean	9.3 A	11.4 A	15.7 A
	1988		
Ambient	63.3 a	69.6 a	88.7 a
Ambient + 100mm	11.8 b	13.3 b	21.3 b
Ambient + 150mm	4.5 b	7.4 b	12.2 b
Mean	26.5 A	30.1 A	40.7 B

†1 = from plant recovery of ^{15}N; 2 = from plant and soil recovery of ^{15}N; 3 = from difference in N uptake between fertilized and non-fertilized plots. Values are means calculated from 3 replicates.
‡Values within the same column followed by the same lower case letter do not differ significantly (0.05 level).
§Values within the same row followed by the same upper case letter do not differ significantly (0.05 level).

formed as described by Mulvaney et al. (1990), using an automated mass spectrometer (Nuclide Model 3–60–RMS; Measurement and Analysis Systems, Bellefonte, PA).[1] Soil bulk density, used in calculation of fertilizer N recovery, was determined for each soil type from intact soil cores collected to a depth of 120 cm. Recovery of fertilizer N as organic forms was calculated as the difference between total soil N and inorganic N.

The experimental design was a randomized complete block with three replications. Statistical analysis of data was performed by the least significant difference (LSD) procedure (SAS Institute, 1982).

Fertilizer N efficiency was calculated by three methods: (i) from plant recovery of ^{15}N, calculated as ^{15}N in plant/^{15}N applied; (ii) from recovery of ^{15}N in both the plant and soil, calculated as ^{15}N in plant + soil/^{15}N applied; and (iii) by difference, as (TPN_{fert} − $TPN_{nonfert}$)/fertilizer N applied, where TPN_{fert} is total plant N for fertilized plots, and $TPN_{nonfert}$ is total plant N for non-fertilized plots.

[1]Trade names and products are mentioned solely for information. No endorsement by the USDA is implied.

Table 4. Effect of early-season excess moisture on recovery of fertilizer ^{15}N at harvest, 1987 and 1988, from Drummer silty clay loam, Cisne silt loam, and Plainfield sand soils in Illinois.†

Pool	Moisture treatment: Ambient	Ambient + 100 mm	Ambient + 150 mm
	Fertilizer ^{15}N (kg ha^{-1})		
	Drummer 1987		
Total soil N	62.8 a‡	41.4 ab	21.9 b
Organic soil N	61.7 a	40.7 ab	20.8 b
Plant N	70.1 a	39.7 b	50.5 b
N deficit§	35.1 a	86.9 b	95.6 b
	1988		
Total soil N	80.2 a	40.6 b	32.0 b
Organic soil N	37.7 a	33.1 a	24.2 a
Plant N	67.1 a	60.8 a	57.1 a
N deficit	20.6 a	66.6 b	78.9 b
	Cisne 1987		
Total soil N	19.9 a	17.7 a	14.4 a
Organic soil N	13.9 a	9.4 a	7.6 a
Plant N	90.1 a	89.7 a	69.9 b
N deficit	57.9 a	60.5 ab	83.8 b
	1988		
Total soil N	50.0 a	38.1 a	29.7 a
Organic soil N	29.9 a	20.1 a	24.6 a
Plant N	109.4 a	82.5 b	82.9 b
N deficit	8.6 a	47.5 ab	55.4 ab
	Plainfield 1987		
Total soil N	3.2 a	4.6 a	2.8 a
Organic soil N	1.8 a	1.9 a	1.2 a
Plant N	26.3 a	9.5 a	11.0 a
N deficit	138.5 a	153.9 a	154.3 a
	1988		
Total soil N	10.5 a	2.6 b	4.5 b
Organic soil N	8.9 a	2.4 b	1.8 b
Plant N	106.4 a	19.8 b	8.0 b
N deficit	51.1 a	145.6 b	155.4 b

†Values represent means of 3 replicates.
‡Values within a row followed by the same letter do not differ significantly (0.05 level).
§N deficit (kg ha^{-1}) = 168 − (plant N + total soil N).

RESULTS AND DISCUSSION

Table 3 shows estimates of N fertilizer efficiency obtained by three different methods. With Methods 1 and 2, fertilizer N efficiency was estimated from recovery of ^{15}N in the plant or plant-soil system (Table 4). With Method 3, fertilizer N efficiency was calculated as the difference between total plant N with and without N fertilizer (Table 5). The data in Table 3 reveal significant differences between the calculation methods with all three soil types, and differences in significance levels and in trends among moisture treatments with the Drummer and Cisne soils.

As expected, fertilizer N efficiency estimates calculated from plant uptake of ^{15}N (Method 1) were lower than those based on recovery of ^{15}N in the plant plus soil (Method 2). The magnitude of the difference decreased in the order: Drummer > Cisne > Plainfield (Table 3). Recoveries of ^{15}N in organic forms followed the same order (Table 4). These findings are consistent with previous work (e.g., Stewart et al., 1963) indicating that an increase in the size of organic C and N pools promotes MIT, which can lead to an

Table 5. Effects of N application and early-season excess moisture on corn plant N in 1987 and 1988.

N applied	Moisture treatment† Ambient	Ambient + 100 mm	Ambient + 150 mm
kg ha^{-1}	Total plant N (kg ha^{-1})		
		Drummer 1987	
0	75.5	78.9	69.3
168	187.6	130.8	136.8
Difference‡	112.1 a	51.9 b	67.5 c
		1988	
0	92.6	85.7	65.7
168	158.5	148.8	152.3
Difference	65.9 a	63.1 a	86.6 a
		Cisne 1987	
0	87.9	59.6	64.4
168	184.3	187.3	179.0
Difference	96.4 a	127.7 b	114.6 b
		1988	
0	71.6	79.1	74.7
168	222.0	167.4	201.0
Difference	150.4 a	88.3 b	126.3 ab
		Plainfield 1987	
0	11.2	12.8	16.2
168	59.0	28.3	28.9
Difference	47.8 a	15.5 a	12.7 a
		1988	
0	14.7	15.1	14.4
168	163.7	50.9	34.8
Difference	149.0 a	35.8 b	20.4 b

†Values represent means of 3 replicates.
‡Values within a row followed by the same letter do not differ significantly (0.05 level).

apparent ANI (Jenkinson et al., 1985) or "priming effect" of fertilizer N. The much smaller differences observed with the Plainfield soil than with the Drummer or Cisne soil in estimating efficiency by Methods 1 and 2 can be attributed, at least in part, to extensive loss of fertilizer ^{15}N due to leaching of NO_3 (see N deficit values in Table 4), with very little loss by denitrification. Leaching cannot contribute to an apparent ANI, whereas denitrification can (Jenkinson et al., 1985).

Unlike the other two soils, N fertilizer efficiencies calculated for the Plainfield soil in 1988 by difference (Method 3, Table 3) were consistently higher than those based on total recovery of ^{15}N (Method 2, Table 3). This can be attributed in part to the low recoveries of fertilizer ^{15}N for this soil compared to the other two soils, but also to extremely limited uptake of N by non-fertilized corn plants (Table 5). Under such conditions, a real ANI can arise from increased root growth following N fertilizer application (Fried and Broeshart, 1974). This appears to have occurred with the Plainfield soil, as application of N fertilizer led to a dramatic increase in the amount of soil-derived N in the plant. Compared to N uptake in non-fertilized plots (Table 5), the increase for the three moisture treatments ranged from 86 to 290% [calculated from 1988 data as 100 × (TPN_{fert} − $TP^{15}N_{fert}$ − $TPN_{nonfert}$)/$TPN_{nonfert}$, where TPN_{fert} and $TPN_{nonfert}$ are obtained from Table 5, and $TP^{15}N_{fert}$ is plant content of fertilizer ^{15}N (Table 4)]. No significant differences were found with the Plainfield soil in 1987, due to extreme variability in the data resulting from extensive leaching.

Not only do different methods of calculation tend to give different numerical estimates of N fertilizer efficiency, the relative efficiencies associated with treatment effects can be influenced, as can levels of significance between efficiencies for different treatments. In our work, this was observed with the Drummer and Cisne soils. With the Drummer soil in 1987, for example, application of early-season excess water was found to significantly reduce N fertilizer efficiency compared to the ambient treatment, regardless of which method was used to calculate percent efficiency (Table 3). But the magnitude of the reduction varied with method of calculation. Fertilizer N efficiency estimates were significantly greater with the 150-mm application than with the 100-mm application when calculated by difference (Method 3), but not when efficiency was calculated from plant uptake of ^{15}N (Method 1) or from recovery of ^{15}N in the plant plus soil (Method 2). The disparity may be due, at least in part, to the extensive occurrence of MIT, because most of the fertilizer ^{15}N recovered from the Drummer soil in 1987 was found in the organic fraction (Table 4). Since MIT is not normally stoichiometric (Nommik, 1968; Riga et al., 1980), the amount of native soil N mineralized may have exceeded the amount of fertilizer N immobilized.

Environmental conditions also influenced fertilizer N efficiency calculated by the three methods. With the Drummer soil in 1988, fertilizer N efficiencies for the three moisture treatments did not differ significantly when calculated by Method 1 (i.e., from plant uptake of ^{15}N) or Method 3 (i.e., by difference) (Table 3). However, a significant difference was observed when fertilizer N efficiencies were estimated from recovery of ^{15}N (Method 2), with lower efficiency being indicated following the addition of early-season excess water. These findings can be attributed to extreme drought conditions, which resulted in the plants being under moisture stress for much of the growing season. Plant uptake of N was restricted under these conditions, and no significant differences were found between early-season excess moisture treatments in plant uptake of fertilizer N (Table 4) or in fertilizer N efficiency estimates based on uptake (Table 3, Method 1 and 3). However, application of early-season excess water to Drummer soil in 1988 led to a significant increase in the ^{15}N deficit (Table 4), with a concomitant reduction in fertilizer N efficiency estimates based on total (i.e., plant plus soil) recovery of ^{15}N (Table 3, Method 2).

The three methods of calculation gave similar results in estimating fertilizer N efficiency for the Cisne soil in 1988, but substantial differences occurred in 1987 (Table 3). When calculated by difference (Method 3), addition of early-season excess water significantly increased N fertilizer efficiency in 1987, whereas the ^{15}N methods (Method 1 or 2) indicated a significant decrease in fertilizer N efficiency due to addition of early-season excess water. The most likely explanation for this decrease would appear to be substantial fertilizer N loss by denitrification, as indicated by a significant increase in the N deficit with application of early-season excess water (see 1987 data for Cisne soil in Table 4). This loss had no effect on total N uptake at harvest (Table 5), which accounts for the fact that no decrease in efficiency was detected with the difference method. On the contrary, N fertilizer efficiency calculated by difference increased due to a decrease in total plant N for the check plots. Similar difficulties were reported by Fox and Piekielek (1987).

While numerical differences occurred with the Plainfield soil when the three methods were used to calculate fertilizer N efficiency, there was no difference between the methods in trends among moisture treatments. This can be attributed to minimal interchange of soil and fertilizer N through MIT. The implication is that, with coarse-textured soils having a low content of organic C, and hence a low level of biological activity, interpretation of N fertilizer efficiency is unlikely to depend upon the method of calculation used.

To summarize, our work indicates that the method by which fertilizer N efficiency is calculated can have a considerable effect on interpretation of treatment effects involving application of N fertilizer and that, for most agricultural soils (i.e., except those with very low content of organic C), considerable uncertainty is introduced by the effects of MIT and ANI. This uncertainty is unavoidable whenever fertilizer N efficiency is defined in terms of crop uptake of fertilizer N, either with or without ^{15}N as a tracer. In the former case, the uncertainty is due to the exchange of soil and fertilizer N through MIT. In the latter case, it is due to an ANI between the fertilizer and soil N. In studies using ^{15}N-labeled fertilizer, fertilizer N efficiency is more exactly defined in terms of the amount of fertilizer N in the plant-soil system.

The present study demonstrates a need to develop standard terminology for fertilizer N and ^{15}N research. Such terminology would help identify parameters that can be used to define fertilizer efficiency, clarify assumptions made in its calculation, and thereby aid in the interpretation of results. At the very least, the method of calculation should be clearly specified.

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