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# Compost, Manure and Synthetic Fertilizer Influences Crop Yields, Soil Properties, Nitrate Leaching and Crop Nutrient Content

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From 1993 to 2001, a maize-vegetable-wheat rotation was compared using either 1) composts, 2) manure, or 3) synthetic fertilizer for nitrogen nutrient input. From 1993 to1998, red clover (*Trifolium pratense* L.) and crimson clover (*Trifolium incarnatum* L.) were used as an annual winter legume cover crop prior to maize production. From 1999 to 2001, hairy vetch (*Vicia villosa* Roth.) served as the legume green manure nitrogen (N) source for maize. In this rotation, wheat depended entirely on residual N that remained in the soil after maize and vegetable (pepper and potato) production. Vegetables received either compost, manure, or fertilizer N inputs. Raw dairy manure stimulated the highest overall maize yields of 7,395 kg/ha (approximately 140 bushels per acre). This exceeded the Berks County mean yield of about 107 bushels per acre from 1994 to 2001. When hairy vetch replaced clover as the winter green manure cover crop, maize yields rose in three of the four treatments (approximately 500-1,300 kg/ha, or 10-24 bu/a). Hairy vetch cover cropping also resulted in a 9-25 % increase in wheat yields in the compost treatments compared to clover cover cropping. Hairy vetch cover crops increased both maize and wheat grain protein contents about 16 to 20% compared to the clover cover crop. Compost was superior to conventional synthetic fertilizer and raw dairy manure in 1) building soil nutrient levels, 2) providing residual nutrient support to wheat production, and 3) reducing nutrient losses to ground and surface waters. After 9 years, soil carbon (C) and soil N remained unchanged or declined slightly in the synthetic fertilizer treatment, but increased with use of compost amendments by 16-27% for C and by 13-16% for N. However, with hairy vetch cover crops, N leaching increased 4 times when compared to clover cover crops. September was the highest month for nitrate leaching, combining high rainfall with a lack of active cash crop or cover crop growth to use residual N. Broiler litter leaf compost (BLLC) showed the lowest nitrate leaching of all the nutrient amendments tested (P= 0.05).

## *Introduction*

The Rodale Institute Compost Utilization Trial (CUT), initiated in 1993, was designed to compare the effects of composts, raw dairy manure, and synthetic fertilizer on soil fertility, soil quality, and nutrient leaching. A diversified crop rotation included grains (wheat and maize) and vegetables (peppers or potatoes). The intent was to develop management practices for using composted wastes to maintain and improve crop yield and soil quality, and prevent misbalanced nutrient levels and over-enrichment with nutrients that could result in environmental issues.

Agriculture is a major source of nitrogen (N) loss to the environment (Socolow, 1999). Two major scientific bodies[1] recently named N pollution as one of the Earth's "preeminent problems", and cite insufficient public awareness as an obstacle to managing it (Moffat, 1998). Since 1965, the doubling of agricultural food production was associated with a 6.9-fold increase in N fertilization. Improving N fertilization practices is crucial to control excessive nitrate contamination of ground water.

Phosphorus (P) can also be a significant source of nutrient contamination for surface waters. Along with N, soil P levels have a strong impact on crop yield and quality. In many aquatic environments, algal and plant growth is more limited by P than by N. Therefore, aquatic P levels are becoming a prime factor in water quality evaluation.

The effects of compost amendments and cover cropping on soil fertility, crop performance, and soil nutrient movement in this long term trial are reported in this paper.

## *Materials and Methods*

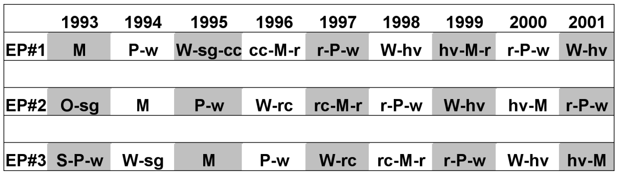
*Site Description*. The 2.0-ha experimental site was located at the Rodale Institute Experimental Farm in Kutztown, Berks County, Pennsylvania, a subhumid temperate continental climate (N 40° 38′ and W 75° 57′). The predominant soil type is a Berks shaly silt loam (Typic Dystrochrepts) with some Fogelsville silt loam (Utic Hapludalfs) found in lesser amounts. Precipitation is evenly distributed throughout the year and averages 1,000 mm annually. The mean maize growing degree units are approximately 2950. The USDA climate zone is 6.

*Treatment Descriptions and Experimental Design.* Four treatments compared for the purpose of this paper are described in Table 1. A three-year cash-crop rotation of maize-vegetable-small grain was established in the spring of 1993 (Figure 1). Research plots were set up so that each of the fertilization treatments had three different crop-entry-points. The inclusion of three entry points allows each crop in the rotation to be present each year, so that climate-treatment interactions can be determined. Each treatment by crop-entry-point comparison was replicated four times in a split-plot, randomized block design, consisting of sixteen 21.3 m x 18.3 m plots (4 fertilizer treatments x 4 replications), with three 21.3- x 6.1-m subplots in each. For this paper, we will mainly discuss results from years 1994-2001, after lysimeters were installed in the fall of 1993.

TABLE 1.
Treatment names and descriptions

| Name | Description |
|---|---|
| Broilter litter/leaf compost (BLLC) | 1 part broiler chicken: 3 parts leaves (by volume)<br>(litter contains chicken manure and coarse sawdust bedding) |
| Dairy manure/leaf compost (DMLC) | 1 part dairy manure and bedding: 4 parts leaves (by volume)<br>(bedding was straw, newspaper, or chopped corn stalks) |
| Raw dairy manure (RDM) | Fresh dairy manure and bedding<br>(bedding was straw, newspaper or chopped corn stalks) |
| Conventional mineral fertilizer (CNV) | 30-30-10 dry starter and UAN[1] liquid sidedress on maize, UAN liquid (preplant and/or sidedress) on spinach, pepper and oats |

[1] UAN: Urea and ammonium nitrate nonpressure solution containing 28-32% N.



| | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
|---|---|---|---|---|---|---|---|---|---|
| EP#1 | M | P-w | W-sg-cc | cc-M-r | r-P-w | W-hv | hv-M-r | r-P-w | W-hv |
| | | | | | | | | | |
| EP#2 | O-sg | M | P-w | W-rc | rc-M-r | r-P-w | W-hv | hv-M | r-P-w |
| | | | | | | | | | |
| EP#3 | S-P-w | W-sg | M | P-w | W-rc | rc-M-r | r-P-w | W-hv | hv-M |

FIGURE 1. Crop rotation used in The Rodale Compost Utilization Trial 1993-2001. Capital letters are crops that were harvested that year; lower case letters are cover crops and green manure. Legend: cc: crimson clover, hv: hairy vetch, M: maize, O: oat, P: pepper, r: rye, rc: red clover, S: spinach, sg: Sorghum sudangrass, W/w: wheat. The rotation was changed in 1995 to include legume green manure after wheat and in 1996 a rye cover crop was added after maize. The crimson clover planted the fall of 1995 did not over winter. Entry points 1, 2, and 3 occurred each year for each treatment.

*Crop Rotation Modifications*. Spinach (*Spinacea oleraceae* L.) was grown as the vegetable crop in 1993, but from 1994 to 2001 the vegetable crop was bell pepper (*Capsicum annuum* L.). The small grain rotation was initiated with oats (*Avena sativa* L. cv. Ogle) in 1993 and winter wheat (*Triticum aestivum* L. cv. 'Cardinal, Madison') from 1994-2001. From 1993-1995, sorghum-sudan grass was planted after small grain harvest to serve as a N catch-crop. Nutrient budgets and soil tests from the fall of 1995 showed a buildup of phosphorus and potassium from cumulative additions of animal-manure-based treatments (Reider et al., 2000). To address this problem, a legume green manure was added to the crop rotation in the fall of 1995 as the N-source for maize (Figure 1). The legume was added to all treatments, including the Conventional Mineral Fertilizer (CNV) and the Raw Dairy Manure (RDM), to clarify plus/minus compost effects. Several species of legumes were used during the experiment: crimson clover (*Trifolium incarnatum* L.) in 1995/1996, red clover (*Trifolium pratense* L.) in 1996/1997 and 1997/1998, and hairy vetch (*Vicia villosa* Roth) in 1998/1999, 1999/2000, and 2000/2001. (The crimson clover planted in the fall of 1995 did not over-winter.) In the fall of 1996, cereal rye (*Secale cereale* L.) was inserted as a N-catch crop following maize. These adaptations were part of a continuing effort to improve the sustainability of the cropping practices as new information and results became available.

*Lysimeter Design, Installation, and Sample Collection*. The impact of fertilization amendments and legume cover crops on water quality was assessed with intact soil monolith lysimeters. Detailed description of the construction and installation of these lysimeters are reported elsewhere (Moyer et al. 1996). A schematic of the basic design appears in Figure 2. Lysimeters were installed in the fall of 1993 in all blocks and rotation points of the four treatments (48 total – 4 treatments x 3 entry points x 4 blocks). Placement was along the centerline of the plot, approximately 4.6 m from the plot edge. The lysimeter body consists of steel well casing and the collection device is a 21-L polyethylene carboy. The topsoil (0-25 cm) was removed by hand from each lysimeter site and set aside prior to installation. The pre-cut lengths of well casing were then inserted with a pile driver to a depth of about 1 m below the soil surface. An access hole (38 cm-diameter by 161 cm deep) was then augered next to the inserted casing for the installation of the collection device. The soil-filled cylinder was removed and a prefabricated base

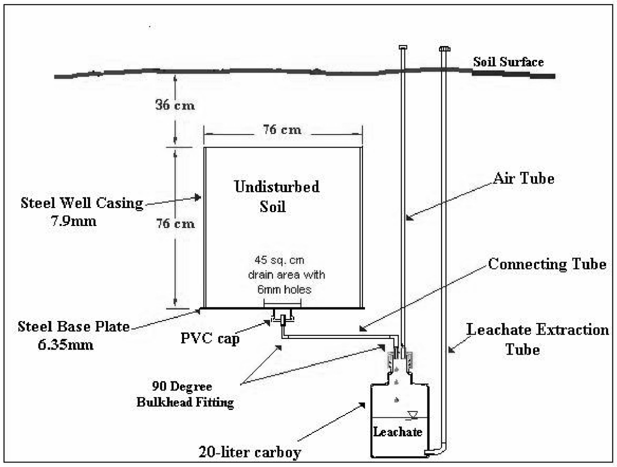


FIGURE 2. Anatomy of intact core lysimeter, a device to measure water flow and quality as influenced by agricultural practices (Moyer *et al.* 1996).

was welded in place. A flexible hose was run from a drain on the base of the lysimeter body to the top of the collection device. An air tube was attached to a fitting on the carboy cap to allow for free exchange of air during leachate extraction, and an extraction tube was run from the bottom of the carboy for removal of leachate. The body and carboy, with all the attached tubes, were lowered simultaneously into their respective cavities and the topsoil was replaced. The leachate access tubes were buried to a depth of 30 cm before field operations were performed. All primary tillage and cultivations were performed right over the lysimeters. Sample collection occurred approximately every two weeks throughout the year, dependent upon rainfall amounts and weather conditions. Leachate was extracted via a marine utility pump powered by a portable generator. At each pumping date, the total leachate volume was measured and a 1-L subsample was saved for analysis.

*Nitrogen Target Application Rates and Legume Green Manure.* Nitrogen target rates were calculated to provide similar levels of available N in all treatments (Table 2). A 40% N availability factor for compost was used based on previous work at the Rodale Institute (Reider et al., 1991; Reider et al., 1992). A 50% N availability was used for raw dairy manure, and carryover N in subsequent years was based on published guidelines for fresh manure (Penn State Agronomy Guide, 1993-1994). The target rate for legume N was 146 kg $ha^{-1}$. The N application rates were based on Pennsylvania State University guidelines (1993-1994 Penn State Agronomy Guide, and 1993 Commercial Vegetable Production Recommendations, Pennsylvania State Cooperative Extension) adjusted for soil type and historic farm yield goals. From 1993-1996, maize received soil fertilization amendments (compost, raw manure, or mineral fertilizer) and from 1997-2001 legume green manure was used as the N source. Vegetables (spinach followed by pepper in 1993 and pepper alone from 1994-2001) always received soil fertilization amendments. Small grains (oats and wheat) always received only carryover nutrients from previous applications, except for oat in 1993, which received soil fertilization amendments. Starting in 1996, compost N-target rates were reduced by one third because nutrient budgets and soil test results indicated a nitrogen buildup in soil to high levels (Reider et al., 2000). The RDM and CNV N-target rates were unchanged as N buildup did not occur (Table 2).

*Compost and Manure Production, Sampling, and Application.* Composts were produced annually. During the active composting phase, composts were turned 3 times each week. Thereafter, they were turned monthly until spreading. The dairy manure used for the RDM treatment was hauled in on the day of spreading from the same farm that provided the manure for the Dairy Manure/Leaf Compost (DMLC). To calculate application rates, composts were tested for total Kjeldahl N (TKN) one to two weeks before their field application.

TABLE 2.
Nitrogen target application rates for compost, raw manure, legume green manure and mineral fertilizer, 1993-2001

| Nitrogen Type | Maize 1993-1995 Total -N | Maize 1996 Total -N | Maize 1997-2001 Total -N | Pepper 1993-1995 Total -N | Pepper 1996-2001 Total -N | Spinach 1993 Total -N | Oats 1993 Total -N | Wheat 1993-2001 Total -N | Percent Assumed Available |
|---|---|---|---|---|---|---|---|---|---|
| | kg/ha | | | | | | | | % |
| Compost | 364 | 244† | – | 280 | 187[†] | 280 | 211 | 0 | 40[‡] |
| Raw dairy manure | 291 | 291 | – | 224 | 224 | 224 | 168 | 0 | 50[§] |
| Legume | – | – | 146 | – | – | – | – | – | 100[‡‡] |
| Conventional mineral fertilizer | 146[¶] | 146[¶] | – | 112[#] | 112# | 112[#] | 84[††] | 0 | 100 |

[†] Compost target rates were reduced by 1/3 starting in 1996 because the N-budget and soil test results indicated a buildup of excess N (Reider et al., 2000).

[‡] Based on previous work at The Rodale Institute (Reider *et al.* 1991; Reider *et al.* 1992). Carryover N from previous applications was not credited.

[§] Based on guidelines for manure applied and plowed in the same day and for carryover N as follows: 12% of manure N applied 1 year previous and 5% of N applied 2 years previously (Penn State Agronomy Guide 1993-1994).

[††] Total amount applied pre-plant.

[¶] Applied as 34 kg/ha starter fertilizer and 112 kg/ha sidedress.

[#] Applied as 56 kg/ha pre-plant and 56 kg/ha sidedress.

[‡‡] Availability based on previous work at The Rodale Institute (unpublished data).

RDM application rates were based on previous analyses. All materials were resampled on the day-of-spreading to determine actual application and nutrient loading rates. Application rates were confirmed in 1993 by metering the spreader for each amendment and measuring actual deposition with tarps placed in the plots, and from 1994-2001, by weighing the materials in the manure spreader using wheel-weight scales. In Table 3, manure and compost characteristics are summarized. The manure and composts were surface-applied with a tractor drawn manure spreader and plowed under on the day of application.

*Nitrogen Loading Rates from Soil Amendments and Legumes.* Nitrogen-loading rates from the various soil amendments and legume green manures are presented in Table 4. N contributed by the legumes varied according to species. Clover failed to meet the N-target rate and was replaced with hairy vetch starting in1999 maize.

*Nitrogen Accumulated by Grass Cover Crops*. Two different catch crops were used: Sorghum sudangrass was planted in July after wheat harvest from 1993-1995 and grain rye (*Secale cerale* L. common) was seeded in mid-November following maize grain harvest from 1996-2001, except in 1999 when it was seeded in August after maize was removed as silage due to drought. Biomass production and N concentration of both cover crops are summarized in Table 5.

TABLE 3.
Analyses of finished composts and raw manure (1993-2001)
and average annual compost and manure dry matter loading rates on maize and pepper

| | | Compost and Manure Characteristics | | | | | Annual Dry Matter Loading Rate | |
|---|---|---|---|---|---|---|---|---|
| Amendment | | Solids % | TKN % | C % | C:N Ratio | Age at Spreading (Days) | Maize | Pepper |
| | | | | | | | dry t ha$^{-1}$ yr$^{-1}$ | |
| | | 1993-2001 | | | | 1993-1996 | | 1993-2001 |
| Broiler litter/leaf compost | Mean | 43.13 | 2.26 | 30.42 | 13.7 | 180-240 | 16 | 11 |
| (BLLC) | SE | 1.07 | 0.09 | 0.96 | 0.5 | | | |
| Dairy manure/leaf compost | Mean | 36.32 | 1.71 | 30.80 | 18.8 | 180-240 | 29 | 14 |
| (DMLC) | SE | 0.91 | 0.05 | 0.83 | 0.6 | | | |
| Raw dairy manure | Mean | 20.31 | 3.63 | 48.52 | 13.9 | 1 | 9 | 6 |
| (RDM) | SE | 0.57 | 0.14 | 0.51 | 0.4 | | | |

SE = standard error of the mean, TKN = total Kjeldahl nitrogen

TABLE 4.
Nitrogen loading rates from all sources on maize, vegetable, and small grain

| | Annual Nitrogen Applications | | | | | | | | | Total Applied |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1993[†] | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 1993-2001 |
| | kg ha$^{-1}$ | | | | | | | | | kg ha$^{-1}$ |
| BLLC | | | | | | | | | | |
| Maize | 367 | 337 | 365 | 241 | 101 | 112 | 244 | 194 | 258 | 2220 |
| Vegetable | 402 | 205 | 289 | 232 | 159 | 209 | 201 | 353 | 207 | 2256 |
| Small Grain | 298 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 298 |
| total/year | 1067 | 543 | 655 | 473 | 260 | 321 | 445 | 547 | 465 | 4774 |
| DMLC | | | | | | | | | | |
| Maize | 370 | 872 | 372 | 281 | 82 | 136 | 219 | 219 | 267 | 2819 |
| Vegetable | 417 | 548 | 304 | 235 | 130 | 206 | 214 | 111 | 187 | 2353 |
| Small Grain | 254 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 254 |
| total/year | 1041 | 1420 | 676 | 517 | 212 | 342 | 433 | 330 | 454 | 5426 |
| RDM | | | | | | | | | | |
| Maize | 432 | 455 | 288 | 266 | 113 | 137 | 221 | 185 | 217 | 2314 |
| Vegetable | 402 | 305 | 108 | 138 | 128 | 217 | 169 | 189 | 189 | 1845 |
| Small Grain | 238 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 238 |
| total/year | 1071 | 760 | 396 | 404 | 241 | 354 | 390 | 374 | 406 | 4396 |
| CNV | | | | | | | | | | |
| Maize | 146 | 146 | 146 | 146 | 106 | 124 | 174 | 194 | 194 | 1375 |
| Vegetable | 224 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 1121 |
| Small Grain | 84 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 84 |
| total/year | 454 | 258 | 258 | 258 | 218 | 236 | 286 | 306 | 306 | 2580 |

[†] Nitrogen application on 1993 vegetable for all treatments reflects additions to spinach and pepper. Vegetable was pepper alone from 1994-2001. Additions on maize were from various soil amendments through 1996, after the additions were from legume green manure. Additions on vegetable were from soil amendments all year. Small grain in 1993 received soil amendments, but after that it received only carryover nutrients. BLLC=Broiler litter leaf compost, DMLC=Dairy manure leaf compost, RDM=Raw Dairy Manure, CNV=Synthetic chemical fertilizer

TABLE 5.
Biomass production and N accumulated by grass catch crops

| Type | Year | Cultivar | Dry Wt kg ha$^{-1}$ | Biomass N % | N captured kg ha$^{-1}$ |
|---|---|---|---|---|---|
| Sorghum sudangrass | 1993 | Sudax | 2607 | 0.93 | 24 |
| (summer-seeded) | 1994 | HT999SS | 1989 | 1.15 | 25 |
| | 1995 | Greentreat III | 6238[†] | 0.69 | 44 |
| Grain rye | 1996/1997 | VNS | 406[‡] | 2.44 | 10 |
| (fall-seeded) | 1997/1998 | VNS | 4088 | 1.25 | 51 |
| | 1998/1999 | VNS | 2311 | 1.49 | 34 |
| | 1999/2000 | VNS | 7307[§] | 1.45 | 107 |
| | 2000/2001 | VNS | 2852 | 1.80 | 52 |

[†] Pepper yield was poor in 1995 and probably resulted in more carryover N for sorghum sudangrass. [‡] Reduced biomass production was probably due to frost heaving. [§] Early planting (August instead of mid-November) resulted in more rye biomass than usual in 2000. VNS= Variety not stated

*Plot Management and Data Collection.* Maize grain yield was determined by mechanically harvesting the four center rows of each plot. In 1999, maize silage yield and nutrient content was determined from two 5-m sections of the two center rows of each plot. Small grain yield was determined from a single pass (2.4-m wide) from the center of the plot. Plot yields were determined from weights of combine-mounted scales. At harvest, grab samples of all grains were collected to determine moisture and nutrient content.

Pepper transplants were grown at a commercial greenhouse and were mechanically transplanted. The pepper plots were irrigated with overhead irrigation if rain did not equal at least 12.7 mm/week. Pepper fruit were harvested once a week starting in early August for 5-8 consecutive weeks depending on plant growth and weather. Data collection areas were centrally located within each 8-row plot, and were 7.6-m long x 4-rows wide. All fruit of marketable size (at least 10-cm long) were harvested each week and separated into marketable and non-marketable categories. Fresh weight of culls and marketable fruit was recorded. Pepper fruit moisture and nutrient content were estimated from 10 randomly chosen marketable fruit/plot.

Cover crop aboveground biomass production and nutrient content were estimated from two 0.5-m$^2$- cuts per plot, taken just prior to mowing and/or incorporation. Soil N and C were measured in October 1992 to document initial levels, and again in November 2001 to measure changes. Ten cores (2.5-cm diameter x 20-cm deep) from each plot were combined, air-dried, and passed through a 2.0-mm screen.

*Analytical Methods.* Nitrate concentration in leachate was measured using the Ion Selective Electrode Method (EPA Method 353.3) at Hydro Analysis, Kutztown, PA, from 1993-1998, and the cadmium reduction method (Lachat Instruments, EPA Method 353.2) from 1999-2001 at Michigan State University, East Lansing, MI. Compost and manure analyses were performed by A&L Labs in Richmond, VA. Nitrogen was determined by Kjeldahl digestion (EPA method 351.3) and total organic C by loss-on-ignition. Soil C and N were determined by dry combustion (Fisons NA1500 Elemental Analyzer) at The Agricultural Analytical Services Lab, The Pennsylvania State University, University Park, PA. Plant moisture was determined gravimetrically. Plant tissue N and C were analyzed at The Agricultural Analytical Services Lab, The Pennsylvania State University, University Park, PA from 1993-1996. Tissue N concentration was determined by Kjeldahl digestion (Isaac and Johnson, 1976) and C by loss on ignition. From 1997-2001 plant tissue C and N were measured by dry combustion (Leco Corporation, St. Joseph, MI) at the Rodale Institute.

*Nitrogen Budget.* The N-budget was prepared using a simple running balance sheet; where annual N outputs were subtracted from the annual N inputs (Figure 3). Outputs included N lost through leaching

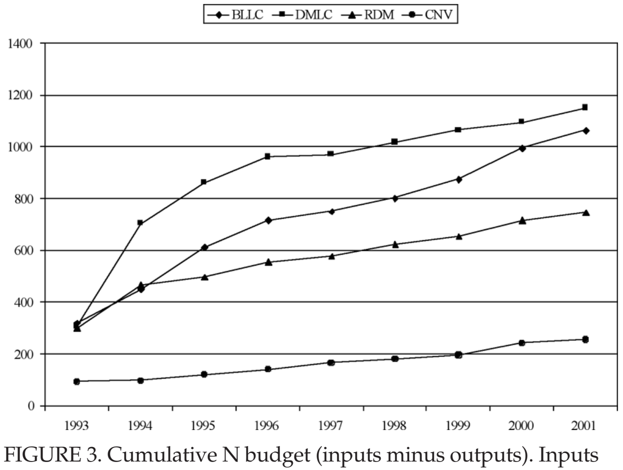


FIGURE 3. Cumulative N budget (inputs minus outputs). Inputs consist of N from mineral and organic fertilizers and legumes, outputs are N in harvested crops and N lost via leaching. (BLLC = Broiler Litter Leaf Compost, DMLC = Dairy Manure Leaf Compost, RDM = Raw Dairy Manure, CNV = Synthetic Chemical Fertilizer).

TABLE 6.
Crop yields (dry weight) in pre-vetch and vetch years and ratio of grain or fruit yield to N leached

| | | Crop yield | | | | Ratio of Grain or Fruit Yield To N Leached | | |
|---|---|---|---|---|---|---|---|---|
| Crop | Treatment | Overall | Pre-Vetch† kg ha$^{-1}$ dry matter | Vetch-Period‡ | Difference | Pre-Vetch† | Vetch-Period‡ | Difference % |
| Maize grain | BLLC | 6,296 c | 5,932 a | 7,224 ab | 22 | 4035 | 821 | -80 |
| | DMLC | 7,181 ab | 6,891 ab | 7,927 a | 15 | 3428 | 679 | -80 |
| | RDM | 7,395 a | 7,563 a | 7,076 b | -6 | 1949 | 542 | -72 |
| | CNV | 6,475 bc | 6,333 b | 6,847 b | 8 | 2827 | 574 | -80 |
| Wheat grain | BLLC | 3,166 b | 3,069 c | 3,829 a | 25 | 1841 | 737 | -60 |
| | DMLC | 3,718 a | 3,673 ab | 4,020 a | 9 | 1026 | 303 | -70 |
| | RDM | 3,728 a | 3,715 ab | 3,805 a | 2 | 695 | 538 | -23 |
| | CNV | 3,366 ab | 3,362 b | 3,386 a | 1 | 869 | 335 | -61 |
| Pepper fruit | BLLC | 1,394 a | 1,455 b | 1,549 a | 6 | 680 | 337 | -50 |
| | DMLC | 1,641 a | 1,754 a | 1,564 a | -11 | 527 | 69 | -87 |
| | RDM | 1,674 a | 1,825 a | 1,561 a | -14 | 255 | 95 | -63 |
| | CNV | 1,556 a | 1,686 a | 1,529 a | -9 | 385 | 119 | -69 |

†Pre-Vetch: maize = 1994-1998; wheat = 1994-2000; pepper = 1994-1999. ‡Vetch-Period: maize = 1999-2001; wheat = 2001; pepper = 2000-2001. During the pre-vetch period, clover was used as a winter cover crop. Treatments with same letter are not different at $P < 0.05$ within each stage and each crop. BLLC = Broiler Litter Leaf Compost, DMLC = Dairy Manure Leaf Compost, RDM = Raw Dairy Manure, CNV = Synthetic Chemical Fertilizer

and the harvested portions of the crops (maize grain and silage, oat and wheat grain and straw, pepper fruit, and the Sorghum sudangrass that was removed in 1995 to establish the legume cover crop). Inputs included legume green manure aboveground biomass, mineral fertilizer, compost, and raw dairy manure. Input from manure and compost was based on the day-of-spreading lab analyses. Plant input/output was calculated by multiplying dry weight of plant biomass by plant biomass percent N. Nitrate lost through leaching was calculated by measuring the nitrate concentration of the leachate, the volume of leachate collected on each date, and the area of the lysimeter.

*Statistical Analysis.* Statistical analyses were performed using the General Linear Model Univariate procedure of SPSS software version 10.1.3 (SPSS, Inc., Chicago, IL, USA).

## *Results and Discussion*

*Yields.* Crop yields are presented in Table 6. They show overall yield averages for each crop and are also divided into two time periods, the clover years and vetch years. In maize, the most N-demanding and responsive crop in the rotation, hairy vetch cover cropping increased grain yields under the two composts and the CNV treatment but not under the RDM fertility regime. With hairy vetch, DMLC and BLLC had the highest maize yield level. In the clover stage, RDM maize plots yielded highest.

During the clover years, DMLC and RDM had the highest wheat yields whereas the CNV treatment was intermediate and BLLC wheat yields were the lowest. The switch to hairy vetch increased wheat yields in the BLLC treatment by 25%, DMLC showed a 9% increase, and RDM and CNV stayed basically the same.

In clover years, BLLC pepper yields were significantly lower than all other treatments, which were not significantly different (NSD) from each other. In hairy-vetch years, pepper yields were not statistically different ($P = 0.05$) between treatments (Table 6).

The increase of grain protein-content in maize and wheat after the transition to vetch (Table 7) indicates that high soil N resulted in greater plant absorption of N. Peppers showed no increase in fruit N-content from the clover stage to vetch stage of the experiment.

TABLE 7.
Maize and wheat grain and pepper fruit crude protein

| | | Pre-Vetch | Vetch-Period | Difference (%) |
|---|---|---|---|---|
| Maize grain | BLLC | 6.05 | 7.66 | 27 |
| | DMLC | 6.27 | 7.33 | 17 |
| | RDM | 6.94 | 7.77 | 12 |
| | CNV | 6.27 | 7.77 | 24 |
| | Average | 6.38 | 7.63 | 20 |
| Wheat grain | BLLC | 9.66 | 11.04 | 14 |
| | DMLC | 10.27 | 11.38 | 11 |
| | RDM | 10.32 | 12.71 | 23 |
| | CNV | 10.10 | 11.82 | 17 |
| | Average | 10.09 | 11.74 | 16 |
| Pepper fruit | BLLC | 15.4 | 15.5 | 0 |
| | DMLC | 16.3 | 16.6 | 2 |
| | RDM | 17.3 | 17.1 | -1 |
| | CNV | 18.2 | 16.6 | -9 |
| | Average | 16.8 | 16.4 | -2 |

†Pre-Vetch: maize = 1994-1998; wheat = 1994-2000; pepper = 1994-1999. ‡Vetch-Period: maize = 1999-2001; wheat = 2001; pepper = 2000-2001. During the pre-vetch period, clover was used as a winter cover crop. BLLC = Broiler Litter Leaf Compost, DMLC = Dairy Manure Leaf Compost, RDM = Raw Dairy Manure, CNV = Synthetic Chemical Fertilizer

*Nitrate leaching.* The level of nitrate leaching increased approximately 4-fold from clover to vetch years (Figure 4, Table 8, Table 9). During the experiment, calculated legume nitrogen inputs increased by only about 20-30%.

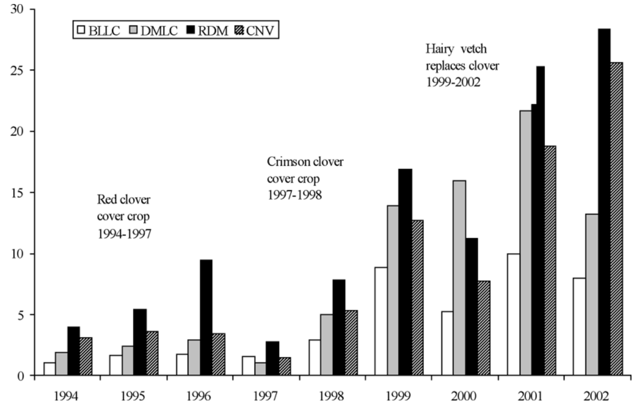


FIGURE 4. Nitrate-N concentrations in leachate by treatment and year (BLLC = Broiler Litter Leaf Compost, DMLC = Dairy Manure Leaf Compost, RDM = Raw Dairy Manure, CNV = Synthetic Chemical Fertilizer).

TABLE 8.
Total nitrate-N leached during pre-vetch and vetch periods and ratio of N input to N leached

| | Total Nitrate-N Leached from All Crops ($kg\ ha^{-1}$) | | | | |
|---|---|---|---|---|---|
| Treatment | Pre-Vetch 1994-1998 | n | Vetch-Period 1999-2001 | n | Difference (%) |
| BLLC | 1.3 a | 659 | 5.7 a | 345 | 338 |
| DMLC | 2.3 ab | 582 | 12.6 b | 346 | 448 |
| RDM | 4.3 c | 577 | 12.7 b | 345 | 195 |
| CNV | 2.8 b | 686 | 10.5 b | 336 | 275 |
| Average | 2.7 | | 10.3 | | 314 |

| | Ratio of N Input to N Leached | | |
|---|---|---|---|
| Treatment | Pre-Vetch 1994-1998 | Vetch-Period 1999-2001 | Difference (%) |
| BLLC | 87 a | 20 a | -77 |
| DMLC | 63 a | 7 b | -89 |
| RDM | 34 b | 8 b | -76 |
| CNV | 25 b | 7 b | -72 |
| Average | 52 | 11 | -79 |

During the pre-vetch period, clover was used as a winter cover crop. Treatments with same letter are not different at $P < 0.05$ within each stage. n = Number of observations

Long-term soil N build-up from previous compost and manure applications appears to contribute to the surge of nitrates in those treatments overtime, along with legume input changes. However, in the CNV treatment, where only synthetic fertilizer was applied in addition to the legume cover crops, the increase in nitrate leaching showed the same trend as the nitrate-leaching increase in the compost and manure treatments during the same time (Table 8) indicating legume inputs were most important in determining leaching response.

TABLE 9.
Mean concentration of nitrate-N in leachate, 1994-2001

| Treatment | Pre-Vetch 1994-1998 $NO_3$-N (ppm) | n | Vetch-Period 1999-2001 $NO_3$-N (ppm) | n |
|---|---|---|---|---|
| BLLC | 0.79 c | 671 | 5.0 c | 347 |
| DMLC | 1.10 b | 661 | 7.6 a | 350 |
| RDM | 1.48 a | 628 | 6.9 a | 347 |
| CNV | 1.25 b | 688 | 6.4 ab | 341 |

During the pre-vetch period, clover was used as a winter cover crop. Treatments with same letter are not different at $P < 0.05$ within each stage. n = Number of observations.

Additionally, in 1999, the first vetch year, only the maize plots in each entry point had vetch, planted in the fall of 1998 and plowed in the spring of 1999. In these plots, nitrate-N leaching increased by 475% from 1998 to 1999 from 2 ppm to 11.5 ppm. The pepper plots, which did not have vetch, increased by only 37% from approximately 2.5 ppm to 4 ppm.

On average, from 1994-2001, September was the month of highest nitrate-N concentration in leachate (10.7 ppm), nearly twice the average concentration of the second highest month, June, and approximately 4-fold higher than the average of the remaining months (Figure 5). In September, crops are taking up N at much-reduced rates and the rye catch crop is generally not yet seeded at this time.

The RDM treatment showed the lowest rate of increase in nitrate-N leaching from the clover stage to the hairy vetch stage (195%), and the highest rate of increase (448%) was found in the DMLC plots (Table 8). However, RDM had the highest leaching of nitrates during the clover period. With the introduction of hairy vetch, N leaching surged and the N-input/N-

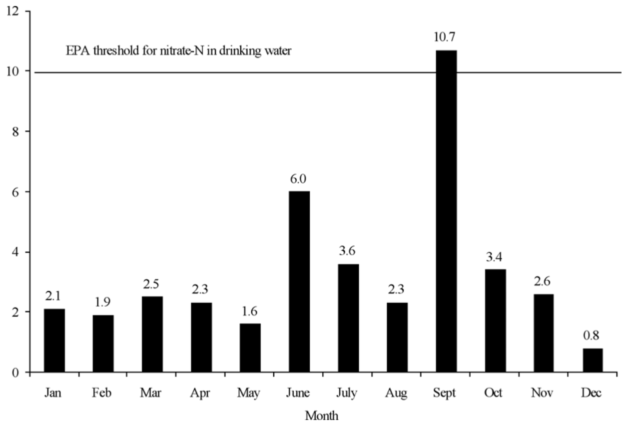


FIGURE 5. Monthly average nitrate-N concentration in leachate across all treatments, 1994-2001, based on over 4,000 observations.

leached ratios (total N leached from both cover crop and compost) fell precipitously (Table 8). Notably, the DMLC N-input/N-leached ratio, which was initially significantly higher than that of RDM and CNV, fell to a level approximately equal to RDM and CNV after the transition to vetch.

Overall, the total amount of N leached throughout the long-term trial was low when compared to other research trials with similar N loading rates (100+ kg N ha$^{-1}$ yr$^{-1}$) (Figure 4). In those studies, nitrate-N losses generally ranged from 30-150 kg ha$^{-1}$ yr$^{-1}$ (Fox et al., 2001; Power et al., 2001), while nitrate-leaching averages in the Compost Utilization Trial were below 5 kg ha$^{-1}$ yr$^{-1}$ in all treatments from 1994-1998, and during the 1999-2001 period, all treatments averaged below 13 kg ha$^{-1}$ yr$^{-1}$ (Figure 4).

The low N-leaching levels in our trial corresponded with the greater use of cover cropping such as Sorghum sudangrass and rye (Table 5). Active grass cover crops scavenge N during the high leaching months (fall, winter, early spring) and reduce nitrate leaching from crop systems by about 2/3 and often more (Martinez and Guiraud, 1990; Lewan, 1994; Wyland et al., 1996; Bergstrom and Jokela, 2001). Winter wheat also contributed to nutrient scavenging. Winter wheat received no direct nutrient application and relied only on leftover nutrients from previous soil amendments and legume additions. In plots that received hairy vetch cover crops and compost, wheat yields increased by 25% and 9% for BLLC and DMLC respectively (Table 6).

However, because winter wheat is planted after the Hessian fly free date (late September in Berks County), it has no impact on N leaching during the month of September.

*Soil N and C.* After 9 years, RDM, BLLC and DMLC treatments showed higher soil N compared to the initial levels displayed at the beginning of the trial in 1992 (Figure 6, Table 10). Compost treatments showed more improvement than the raw manure but both composts and the raw manure were significantly higher in soil N than the synthetic fertilizer treatment.

Composts, BLLC and DMLC, were more effective than either the CNV or RDM treatments in increasing soil C (Figure 7, Table 10). After 9 years, DMLC plots

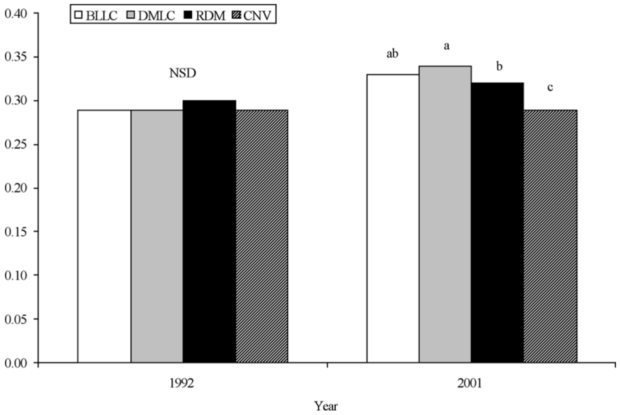


FIGURE 6. Soil-N (0-20 cm) changes from 1992 to 2001 by treatment. Within the same year, different lower case letters above bars indicate significance difference (P = 0.05) between treatments. NSD = not significantly different at P < 0.05. (BLLC = Broiler Litter Leaf Compost, DMLC = Dairy Manure Leaf Compost, RDM = Raw Dairy Manure, CNV = Synthetic Chemical Fertilizer).

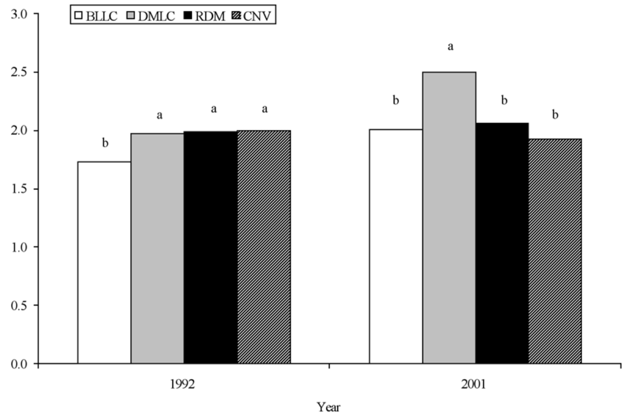


FIGURE 7. Soil-C (0-20 cm) changes from 1992 to 2001 by treatment. Letters above bars indicate significant difference within that year only. Bars with the same letter are not significantly different at P < 0.05. (BLLC = Broiler Litter Leaf Compost, DMLC = Dairy Manure Leaf Compost, RDM = Raw Dairy Manure, CNV = Synthetic Chemical Fertilizer).

TABLE 10.
Changes in soil carbon and nitrogen from 1992 to 2001

| | Soil Carbon[1] (kg ha$^{-1}$) | | Soil Nitrogen[1] (kg ha$^{-1}$) | | Change (kg ha$^{-1}$ yr$^{-1}$) | |
|---|---|---|---|---|---|---|
| Treatment | 1992 | 2001 | 1992 | 2001 | Carbon | Nitrogen |
| BLLC | 69,897 | 81,249 *** | 11,905 | 13,418 ns | 1,261 | 168 |
| DMLC | 79,578 | 100,846 ** | 11,784 | 13,681 * | 2,363 | 211 |
| RDM | 80,304 | 83,113 ns | 12,131 | 12,765 ns | 312 | 70 |
| CNV | 80,712 | 77,859 ns | 11,816 | 11,796 ns | -317 | -2 |

[1] Calculated based on the assumption that the plow layer (0-30 cm) contains 4 million kg of soil per hectare. Significant change from 1992 to 2001 noted as follows: * p <0.01, ** p <0.001, *** p <0.0001.

were significantly higher in soil C than all other treatments, which were not significantly different from each other (Figure 7).

Annual soil sequestration rates were 2363, 1261, and 312 kg of C per ha and 211, 168, and 70 kg of N per ha in DMLC, BLLC, and RDM treatments, respectively.

Soil in the CNV treatment showed net losses of 317 and 2 kg per ha per year for C and N, respectively (Table 10).

## Conclusion

Both compost treatments supported both high yields and increased soil C and N content, while synthetic chemical fertilizer and raw manure produced only high yields but did little or nothing to improve soil nutrient content. Extrapolation of these soil C and N trends suggests that, although synthetic chemical fertilization is able to stimulate high short-term yields, it will not be able to support sustainable crop productivity, crop health, or soil health over longer time periods.

The long term advantages of soil improvement through compost amendments were shown in wheat crops, which relied on residual N in the soil for fertilization. Positive residual soil nutrient impacts, as measured by wheat grain yields, were most evident in the compost treatments, intermediate in the manure treatment, and lowest in the synthetic fertilizer treatment. These results underscore the ability of compost amendments to support crop yields over time, as well as generate higher wheat protein content.

Numerous effects and trends were found when soil fertility treatments and different legume cover crop species were combined. From an environmental and agronomic standpoint, RDM was very effective in stimulating optimum yields but leached a great deal of polluting nitrate into the groundwater. On the other hand, BLLC performed best in producing both competitive yield and low nitrate leaching.

Hairy vetch cover crops were instrumental in optimizing maize crop performance but also increased nitrate leaching. Soil N buildup, stimulated by increased inputs, may reach a threshold point at which excess N begins to contribute to increased leaching. This proposed threshold effect requires further investigation because of its potential to significantly impact water nutrient pollution. The speed of legume decomposition may be another factor that stimulates leaching of N from soil. Management of vetch incorporation based on timing and use of vetch-grass mixtures are other potential tools to control total nitrogen inputs and outputs. Addition of a rye catch crop might also reduce leaching potential because active rye roots can absorb nitrates that would otherwise leach. Overseeding rye into established maize at last cultivation is feasible and deserves further investigation.

Over short- and medium-term use, synthetic chemical fertilizers are attractive due to their convenience, ease of application, and reliable high yield. However, chemical fertilizers' high energy requirement, nitrate leaching potential, and inability to improve soil nutrient levels show its long term sustainability issues.

The greatest disadvantage of synthetic chemical fertilizer use, as shown in our studies, is its effects on soil N and C levels, which do not improve, and in some cases decline with its use. Compost use increased both soil C and N levels, making it clearly superior to both chemical fertilizer and raw dairy manure in terms of long term sustainability and productivity.

The composts treatments also required no liming over the trial, while chemical fertilization acidified the soil, making lime applications necessary in the synthetic fertilizer treatment in 1999. Liming increases the atmospheric C impact of chemical fertilizer systems because the break-down of acids in the soil liberates carbon dioxide from the calcium carbonate being applied, a factor that must be added to the carbon dioxide output of chemical fertilizer production as part of C budgeting for the whole system.

While required quantities of synthetic chemical fertilization inputs tend to be static or increase over time, requirements of organic compost for crop nutrition tend to decrease due to the slow, persistent release of nutrients from composted materials, and to the build up of stable soil nutrient reserves. Soil fertility input needs are reduced as nutrients are bound and cycled within the soil humus. Use of synthetic chemical fertilizer tends to reverse this stable nutrient cycle as more soluble N inputs enhance the breakdown of soil organic matter, depleting the native soil fertility processes that are invested in soil organic material. Based on the loss of soil C and N and soil acidification, chemical fertilizer can be expected to lead to increased dependence on greater chemical inputs over time, while compost use helps to build a more self-sustaining soil nutrient cycle that provides a wide range of nutrients for healthy plant growth.

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