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OPTIMAL COMPOST RATES FOR ORGANIC CROP PRODUCTION BASED ON A DECAY SERIES

by

Jeffrey B. Endelman

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Plant Science

Approved:

Jennifer Reeve Major Professor	Daniel Drost Committee Member
James Powell Committee Member	Byron Burnham Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

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ABSTRACT

Optimal Compost Rates for Organic Crop Production Based on a Decay Series

by

Jeffrey B. Endelman, Master of Science

Utah State University, 2009

Major Professor: Dr. Jennifer R. Reeve
Department: Plants, Soils, and Climate

One of the more challenging aspects of organic farming is the development of an appropriate fertility plan, which may include crop rotation, cover crops, and/or soil amendments. When fertility is maintained by applying manure and/or compost, a pressing question is how much should be used. A framework was developed to address this question based on the idea of a decay series, which is a sequence of numbers quantifying the effects of compost on crop yield over a multi-year period. Prior research has focused on decay series expressed in nitrogen fertilizer equivalents. Given this information, I show how to calculate what manure/compost rates are needed to meet the nitrogen targets in a multi-crop rotation. Analogous results are presented for when the objective is profit rather than yield maximization.

The planning framework is then generalized to include decay series where the carryover effects of manure/compost are measured, not against nitrogen fertilizer, but against new applications of the amendment. This change of basis, from nitrogen fertilizer equivalents to manure/compost equivalents, allows for field research on organically certified land and quantifies non-nutritive effects in a more meaningful way. Two case studies are presented to illustrate how this new type of decay series may be estimated and used to optimize crop production. By using data from a continuous corn (*Zea mays* L.) system amended with cattle manure slurry, the case study in estimation explores the methodological challenges that arise when the yield response to nitrogen fertilizer is not available as a benchmark. The case study in optimization looks at profit-maximizing compost rates for dryland, organic wheat (*Triticum aestivum* L.) in northern Utah.

(69 pages)

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Jeffrey Endelman

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CHAPTER 1

INTRODUCTION

One of the more challenging aspects of organic farming is the development of an appropriate fertility plan (Gaskell et al., 2006). Although sometimes narrowly equated with nutrient management, fertility is a far more dynamic phenomenon with physical, chemical, and biological dimensions (Weil and Magdoff, 2004). The difficulty lies, not in building fertility *per se*, but in balancing the cost of improving fertility with the revenue generated by cash cropping. Some fertility-enhancing strategies, such as cover cropping and crop rotation, incur opportunity costs because land is not used for maximum profit at all times. Amendments such as compost, fish meal, bone meal, etc., incur direct costs when they are purchased. With so many options, there is no one formula for fertility. A plan that is economically and ecologically sound in one context may be ill-advised in another.

In many situations, manure or compost is used to maintain fertility (Kuepper, 2003). Although questions about what kind of manure or compost should be used are important, they receive little attention here. The focus of this thesis is, given a particular material, how much of it should be used.

Previous attempts to address the question of manure/compost rate have involved adapting conventional nutrient management to the unconventional properties of these amendments. One such property is that manure and compost contain many nutrients, although this is not without parallel in conventional agriculture. For a multi-nutrient fertilizer such as ammonium phosphate, which supplies the macronutrients nitrogen (N) and phosphorus (P), one rate would be needed to meet the N recommendation while a different rate would be needed to meet the P recommendation. To prevent over-fertilization, the smaller of these two rates would be used, and the remaining nutrient deficit would be met with a synthetic fertilizer containing only that nutrient (Tisdale et al., 1993).

Because manures have a P/N ratio larger than that for plants, the rate needed to supply adequate plant P is typically smaller than the rate needed for adequate N (Eghball and Power, 1999; Toth et al., 2006). Concerns about phosphorus accumulation and leaching might therefore lead one to apply manure/compost based on the P recommendation, but there is no organic fertilizer that supplies only N (Gaskell and Smith, 2007). Approximate solutions to this problem include high N/P organic fertilizers such as fish meal (Hartz and Johnstone, 2006), as well as nitrogen-fixing cover crops. Even so, it is clear that the N and P targets are difficult to consider independently.

A further complication is that, unlike synthetic fertilizer, not all of the nutrients present in manure/compost are immediately available for plant uptake. Of the three macronutrients, potassium is the most bioavailable, with 80–100% of it present in soluble, inorganic form (Laboski et al., 2006; Mikkelsen, 2007). Next is phosphorus, 70–100% of which is bioavailable depending on soil reactions (Eghball et al., 2002; Nelson and Janke, 2007). Nitrogen is the least bioavailable, with anywhere from 10% to 50% of the total N in solid manure/compost available for plant uptake within the season of application, this fraction tending to decrease with the extent of decomposition (Gale et al., 2006).

The partial bioavailability of manure/compost nitrogen complicates the development of guidelines for organic fertility management. Phosphorus aside, many extension publications suggest applying manure/compost at a rate where the estimated bioavailable N meets the N fertilizer recommendation (Baldwin, 2006; Gaskell et al., 2006; Andrews and Foster, 2007). This approach builds on conventional N management, which aims to apply enough N fertilizer to fill the gap between what the soil can provide and what is needed to reach a yield goal (Tisdale et al., 1993).

A potential difficulty is that early-season soil tests may not accurately predict the soil's capacity to supply inorganic N (Bundy and Meisinger, 1994; Williams et al., 2007; Osterhaus et al., 2008). One can measure the amount of inorganic N present before planting, but this will not account for organic N that mineralizes during crop development. By sampling the soil later in the season, the presidedress N test improves upon this limitation (Magdoff et al., 1984), but sidedressing with manure/compost is not generally feasible. Because the N targets for crops are readily found in agricultural handbooks, a grower may simply use these in conjunction with published estimates of bioavailable N. Such an approach will not account for organic N mineralization in the years after application.

To characterize the long-term fertilizing value of manure, agronomists have developed the idea of a N decay series (Pratt et al., 1973; Klausner et al., 1994; Cusick et al., 2006). This is a sequence of numbers describing what fraction of the manure/compost N is bioavailable in the first, second, third, etc., years after application. N decay series are most readily measured by comparing the yield or N uptake of crops fertilized with manure/compost with the response to N fertilizer. As an example, a decay series of 0.40, 0.20, …, means that plots receiving 200 kg manure N ha^{-1} would on average yield the same as plots receiving 200 × 0.40 = 80 kg fertilizer N ha^{-1} for the year in which the manure was applied. In the following year, provided no new manure was added, the manured plots would have the same average yield as plots receiving 200 × 0.20 = 40 kg fertilizer N ha^{-1}.

Conventionally, the parameters in the N decay series are multiplied by the manure/compost rates from years past to estimate how much bioavailable N may be expected for the current season (Laboski et al., 2006). This credit is then applied to the N target for the crop, and the balance is met using N fertilizer. As indicated earlier, this strategy could be adapted to an organic system by converting the N fertilizer recommendation into a manure/compost rate based on a short-term estimate of bioavailable N (Hue and Silva, 2000).

One certainly expects to meet N targets this way, but whether this strategy makes the most efficient use of manure/compost is *a priori* unclear. The conventional N credit system was designed to make efficient use of N fertilizer, not manure/compost. The concerns of an organic grower who purchases manure/compost are very different than those of a grower who applies manure to dispose of it. The first objective of this thesis was thus to develop a framework for calculating *optimal* manure/compost rates based on a decay series. The results of this research are presented in Chapter 2.

This framework can accommodate more general descriptions of manure/compost carryover than those couched in terms of N fertilizer. This is significant because a paradigm based on N fertilizer equivalents has several drawbacks for organic agriculture. For one, N fertilizer equivalency experiments cannot be conducted on organically certified land because N fertilizer is prohibited. A second concern is that nitrogen is not the only factor contributing to the long-term fertilizing value of manure/compost. By increasing soil organic matter, manure/compost can increase the soil's capacity to hold water and nutrients (Weil and Magdoff, 2004), and such changes can dramatically affect the yield of unirrigated crops (Stukenholtz et al., 2002). Biological influences such as organic matter-mediated disease suppression may also be active on long time scales (Stone et al., 2004).

When non-nutritive factors are significant, quantifying carryover in N fertilizer equivalents is not particularly meaningful. A more useful benchmark for organic growers who rely upon a consistent source of manure/compost is the equivalency between carryover and prospective applications of the amendment. This leads to a paradigm in which the yield response and decay series are based on manure/compost equivalents. The second objective of this thesis was to demonstrate how this new type of decay series may be estimated from yield records. The results of this research are presented in Chapter 3 using data from the literature. In addition, a field experiment was initiated on organically certified land to measure the decay series of compost. A report on the first year of this experiment is included in the Appendix.

CHAPTER 2

OPTIMAL COMPOST RATES FOR ORGANIC CROP PRODUCTION BASED ON A DECAY SERIES

One of the more challenging aspects of organic farming is the development of an appropriate fertility plan, which may include crop rotation, cover crops, and/or soil amendments (Baldwin, 2006; Gaskell et al., 2006). Determining how to best use these various tools requires intimate knowledge of the physical, chemical, biological, and economic dimensions of a farm. When fertility is maintained by applying manure and/or compost (Kuepper, 2003), a pressing question is how much should be used.

Most attempts to address the question of manure/compost rate have focused on adapting conventional nutrient management to the unconventional properties of these amendments. Because manures have a P/N ratio larger than that for plants, the rate needed to supply adequate plant P is typically smaller than the rate needed for adequate N (Eghball and Power, 1999; Toth et al., 2006). Concerns about phosphorus accumulation and leaching might therefore lead one to apply manure/compost based on the P recommendation, but there is no organic fertilizer that supplies only N (Gaskell and Smith, 2007). Approximate solutions to this problem include high N/P organic fertilizers such as fish meal (Hartz and Johnstone, 2006), as well as nitrogen-fixing cover crops. Even so, it is clear that the N and P targets are difficult to consider independently.

A further complication is that, unlike synthetic fertilizer, not all of the nutrients present in manure/compost are immediately available for plant uptake. Of the three macronutrients, potassium is the most bioavailable, with 80–100% present in soluble, inorganic form (Laboski et al., 2006; Mikkelsen, 2007). Next is phosphorus, 70–100% of which is bioavailable depending on soil reactions (Eghball et al., 2002; Nelson and Janke, 2007). Nitrogen is the least bioavailable, with only 10% to 50% of the total N in solid manure/compost available for plant uptake within the season of application, this fraction tending to decrease with the extent of decomposition (Gale et al., 2006).

To characterize the long-term N-fertilizing value of manure, agronomists have developed the idea of a N decay series (Pratt et al., 1973; Cusick et al., 2006). This is a sequence of numbers describing what fraction of the manure/compost N is bioavailable in the first, second, third, etc., years after application. One way of measuring N decay series involves comparing the yields of manured plots with the yields of plots receiving N fertilizer (Klausner et al., 1994). As an example, a decay series of 0.40, 0.20, …, means that plots receiving 200 kg manure N ha^{-1} would on average yield the same as plots receiving 200 × 0.40 = 80 kg fertilizer N ha^{-1} for the year in which the manure was applied. In the following year, provided no new manure was added, the manured plots would have the same average yield as plots receiving 200 × 0.20 = 40 kg fertilizer N ha^{-1}.

Conventionally, the parameters in the N decay series are multiplied by the manure/compost rates from years past to estimate how much bioavailable N may be expected for the current season (Laboski et al., 2006). This credit is then applied to the N target for the crop, and the balance is met using N fertilizer. This strategy could be adapted to an organic system by converting the N fertilizer recommendation into a manure/compost rate based on a short-term estimate of bioavailable N, i.e., the first term in the decay series (Hue and Silva, 2000; Andrews and Foster, 2007).

One certainly expects to meet N targets this way, but whether this strategy makes the most efficient use of manure/compost is *a priori* unclear. The conventional N credit system was designed to make efficient use of N fertilizer, not manure/compost. The concerns of an organic grower who purchases manure/compost are very different than those of a grower who applies manure to dispose of it. To address these concerns, I have developed a framework for calculating optimal manure/compost rates based on a decay series.

Two different kinds of production goals are considered. In the first, N targets are specified for each crop in a rotation. In the second, the goal is profit-maximization, in which manure/compost is added until the cost of one additional unit exceeds the revenue from additional crop yield. Although the theory for maximizing profit when "fertilizer" carries over between cropping periods was developed decades ago (Taylor, 1983; Kennedy, 1986), I am unaware of any reports in which it has been applied to manure/compost, only synthetic fertilizer.

Results are presented in two sections. The mathematical development of the planning framework is presented under THEORY, followed by numerical examples under RESULTS AND DISCUSSION.

THEORY

Modeling Carryover

When modeling the effects of manure/compost rate on yield, it is convenient to link these two quantities through a state x representing the fertility of the soil. In the case of nitrogen management, the state would be measured in units of bioavailable N, or N fertilizer equivalents. Adding manure/compost increases the fertility state, which in turn influences the yield. The relationship between state and yield is succinctly represented by a response model $Y(x)$, such as a quadratic or exponential function (Cerrato and Blackmer, 1990; Dillon and Anderson, 1990).

When specifying the relationship between rate and state, the very idea of a decay series suggests a particular mathematical structure. If one claims that 1 unit of manure/compost N is equivalent to b_0 units of N fertilizer in the first season, b_1 units of N fertilizer one year later, b_2 units of N fertilizer two years later, etc., this implies a linear relationship between rate and state. When successive cropping periods (e.g., years) are indexed by a discrete time variable $t = 1, 2, 3, \ldots$, the linear carryover model can be written as

$$x(t) = b_0 u(t) + b_1 u(t-1) + b_2 u(t-2) + \cdots \qquad [2.1]$$

where $u(t)$ and $x(t)$ denote the rate and state, respectively, in period t.

The way Eq. [2.1] is written reflects conventional use of the N decay series. Given the manuring history $u(t)$, $u(t-1)$, $u(t-2)$, …, these rates are multiplied by the appropriate decay series parameters b_0, b_1, b_2, …, to calculate the N fertilizer equivalents $x(t)$. For the organic grower, it is the inverse of Eq. [2.1] that needs to be solved, i.e., what manure/compost rates are needed to meet one or more N targets? The focus here is steady-state solutions, recognizing that higher rates will be needed during the transition to organic management.

Note that the state is a relative, not absolute, measure of fertility. When no manure/compost is applied, the state is zero according to Eq. [2.1], but other processes will still contribute bioavailable N (Brady and Weil, 2002). As a result, crop-specific N targets should be reduced by the amount of bioavailable N expected in the unmanured system, e.g., from leguminous cover crops.

For continuous cropping, where the same compost rate u is applied every year to meet a single N target x^*, inverting Eq. [2.1] shows that the N target should be divided by the sum of the entire decay series:

$$u = \frac{x^*}{b_0 + b_1 + b_2 + \cdots} \qquad [2.2]$$

Recall the strategy mentioned in the introduction, in which the N fertilizer recommendation is divided by the first term in the decay series to calculate the manure/compost rate. If N credits are awarded for the manuring history, this approach will converge to the steady-state solution in Eq. [2.2].

For rotations with more than one crop, one needs to look for periodic rather than stationary solutions to Eq. [2.1]. Each crop will potentially have a different N target x_i^* and receive a different manure/compost rate u_i, where the subscript i denotes the position in the rotation. For two crops, Eq. [2.1] becomes a system of two equations:

$$\begin{aligned} x_1^* &= u_1(b_0 + b_2 + b_4 + \cdots) + u_2(b_1 + b_3 + b_5 + \cdots) \\ x_2^* &= u_1(b_1 + b_3 + b_5 + \cdots) + u_2(b_0 + b_2 + b_4 + \cdots) \end{aligned} \qquad [2.3]$$

For an arbitrary number of crops, denoted by R, the governing equations are more easily written in matrix form:

$$\begin{bmatrix} x_1^* \\ x_2^* \\ x_3^* \\ \vdots \\ x_R^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 & h_3 & \cdots & h_R \\ h_R & h_1 & h_2 & \cdots & h_{R-1} \\ h_{R-1} & h_R & h_1 & \cdots & h_{R-2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ h_2 & h_3 & h_4 & \cdots & h_1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ \vdots \\ u_R \end{bmatrix} \qquad [2.4]$$

which in vector notation would be $\boldsymbol{x}^* = H\boldsymbol{u}$ (H is the $R \times R$ matrix in Eq. [2.4]). The parameters h_i are sums over those terms in the decay series for which the same crop is planted in the rotation. This was shown explicitly for the $R = 2$ case in Eq. [2.3], where $h_1 = b_0 + b_2 + b_4 + \cdots$ and $h_2 = b_1 + b_3 + b_5 + \cdots$.

Formally, one may invert Eq. [2.4] to solve for the manure/compost rates, $\boldsymbol{u} = H^{-1}\boldsymbol{x}^*$, but in practice the equation would be solved numerically. There is a complication here, however, that does not arise in the continuous cropping case. With only one crop, it is always possible to calculate what rate will, on average, precisely meet the N target. With multiple crops, it may not be possible, even in theory, to apply manure/compost at rates that precisely meet the N targets. This is because applying enough manure/compost to meet one crop's N target may generate more carryover N than is needed for a subsequent crop. The solution to Eq. [2.4] in this case would involve negative manure/compost rates, which are nonphysical. In the case study presented below, I adopt a strategy of finding the smallest rates that meet or exceed the N targets.

Maximizing Profit

As an alternative to meeting N targets, now consider the goal of maximizing profit. The spirit of the approach adopted here is the same as that widely used to calculate optimal N fertilizer rates (Vanotti and Bundy, 1994; Hernandez and Mulla, 2008). Rather than build detailed economic models, the focus will be on those components of profit that depend on the manure/compost rate. For a single cropping period, the net profit can be modeled as the difference between the revenue from crop yield and the cost associated with purchased manure/compost. When "fertilizer" carries over, however, profit should be maximized over multiple cropping periods (Taylor, 1983; Kennedy, 1986). The novelty of the approach taken here lies in finding periodic solutions for a crop rotation at steady state. For this purpose, the profit (Π) for one complete rotation (with *R* crops) is modeled as

$$\Pi = \sum_{i=1}^{R} \left[p_{y,i} Y_i(x_i) - p_u u_i \right] \qquad [2.5]$$

which depends on one characteristic price ($p_{y,i}$) and yield response (Y_i) for each crop, as well as one characteristic manure/compost price p_u, expressed on the same basis as the rates u_i.

The objective is to maximize Eq. [2.5] with respect to the manure/compost rates. Whereas the dependence on compost rate is explicit in the cost terms, it appears implicitly in the revenue terms through the yield responses. The yield response $Y_i(x_i)$ is modeled as a function of the state variable x_i characterizing the fertility of the soil, which is then related to the rates through the linear system $\boldsymbol{x} = H\boldsymbol{u}$ in Eq. [2.4].

If the optimal rates are nonzero, the first derivative of the profit with respect to rate will be zero at maximum profit:

$$\frac{\partial \Pi}{\partial u_j} = 0 = -p_u + \sum_{i=1}^{R} p_{y,i} Y_i'(x_i^*) H_{ij} \qquad j = 1, 2, \ldots R \qquad [2.6]$$

where I have made use of the fact that $\partial x_i/\partial u_j = H_{ij}$ from Eq. [2.4], and x_i^* denotes the optimal state. The reader can verify by substitution that the solution to Eq. [2.6] is

$$Y_i'(x_i^*) = \frac{p_u / p_{y,i}}{\sum_{k=1}^{R} H_{kR}} = \frac{p_u / p_{y,i}}{b_0 + b_1 + b_2 + \cdots} = \frac{p_N}{p_{y,i}} \qquad i = 1, 2, \ldots R \tag{2.7}$$

which makes use of the fact that the sum over any column in H equals the sum of the decay series. The last equality in Eq. [2.7] follows by identifying $p_u/(b_0 + b_1 + b_2 + \cdots)$ as the unit cost for the nitrogen that becomes bioavailable over many years, denoted by p_{N}. With this substitution, Eq. [2.7] resembles the well-known formula in which the slope of the yield response at the economically optimal N rate equals the N fertilizer to crop price ratio.

Provided the yield models are concave, which includes the widely used quadratic and exponential models, then the profit is also concave with respect to the compost rates (Boyd and Vandenberghe, 2004). This means the solution to Eq. [2.7] (a first-order condition) is optimal if it is feasible. As in the previous section on N targets, a potential difficulty with Eq. [2.7] is that the optimal state is not physically attainable with nonnegative rates. In this case, the first-order condition cannot be used to find the economic optimum, and the profit should be directly maximized, subject to the constraint that $\boldsymbol{u} \geq 0$.

When a quadratic yield model of the form $Y_i = A_i + B_i x_i + C_i x_i^2$ is used for each crop in the rotation, the profit-maximization problem can be stated in the following canonical form:

$$\begin{aligned} \max_{\boldsymbol{u}} \quad & \boldsymbol{u}^T \widetilde{Q} \boldsymbol{u} + \boldsymbol{w}^T \boldsymbol{u} + d \\ & \boldsymbol{u} \geq 0 \end{aligned} \qquad [2.8]$$

The matrix $\widetilde{Q} = H^T QH$, where H is the matrix relating rate and state in Eq. [2.4], and Q is the diagonal matrix with entries $Q_{ii} = p_{y,i}C_i$. The vector $\boldsymbol{w} = H^T\boldsymbol{z} - p_u\mathbf{1}$, where the entries of vector $\boldsymbol{z}$ are $z_i = p_{y,i}B_i$, and $\mathbf{1}$ is a vector of ones. The constant term $d = \Sigma_i\, p_{y,i}A_i$. Since the parameters C_i are nonnegative for concave yield models, the matrices Q and $\widetilde{Q}$ are negative semi-definite, which guarantees a global optimum. Eq. [2.8] can also be adapted for quadratic-plateau yield models (see METHODOLOGY).

METHODOLOGY

Meeting N Targets in a Two-Crop Rotation

Optimal manure/compost rates for a hypothetical two-crop rotation were calculated for different sets of N targets. Optimal in this context means the smallest total rate that will meet the N targets (at steady state). This objective can be posed as a linear programming problem (cf. Eq. [2.4]):

$$\begin{aligned} & \min_{\boldsymbol{u}} \; \Sigma_i\, u_{\mathrm{i}} \\ & \boldsymbol{u} \geq 0 \\ & H\boldsymbol{u} \geq \boldsymbol{x}^* \end{aligned} \qquad [2.9]$$

where the last set of inequalities ($H\boldsymbol{u} \geq \boldsymbol{x}^*$) ensures all of the N targets $\boldsymbol{x}^*$ are met. Eq. [2.9] was solved using CVX (version 1.1) for MATLAB (version 2008a), a package for specifying and solving convex optimization problems (Grant and Boyd, 2008).

Profit-Maximizing Compost Rates for Dryland Wheat

Profit-maximizing compost rates were calculated for a dryland, organic wheat-fallow rotation based on yields reported by Stukenholtz et al. (2002). Their study was conducted in Box Elder County, UT, on a calcareous Thiokol silt loam (fine-silty, mixed, mesic Xerolic Calciorthid) with an average pH of 8.3 and organic matter content of 2.2%. The hard red winter wheat (*Triticum aestivum* L.) cultivar Hansel was used. The yield response to compost was measured at two different sites with no history of manuring. At one site, compost was incorporated in the fall of 1994, and yields measured in 1995. At the other site, compost was incorporated in the fall of 1995, and yields measured in 1996.

The compost used in the Stukenholtz et al. (2002) experiment was not purchased but made at Utah State University (Logan, UT) from dairy manure. On a dry weight basis, an average concentration of 1.9% was reported for total N and 2400 mg kg^{-1} for nitrate N, with a C/N ratio of 20. The compost was 45% dry matter.

To find a comparable, commercially available compost for economic analysis, I analyzed the ‘Premium’ brand, steer-manure compost sold by Miller’s in Hyrum, UT. This compost was also 1.9% total N, with a similar nitrate N concentration of 1900 mg kg^{-1}, a C/N ratio of 11, and 58% dry matter. Total C and N were determined by dry combustion (LECO TruSpec CN), while nitrate N was determined by automated colorimetry (Lachat QuickChem AE) in 5:1 compost extracts (2*M* KCl). These chemical characteristics were deemed sufficiently similar to the compost used by Stukenholtz et al. (2002) to make the comparison meaningful.

Price information was nominally taken from the 2007–2008 cropping period. On 1 January 2008, the quoted price for Premium compost delivered to Box Elder County was \$42 m^{-3} (\$32 yd^{-3}). Based on a measured bulk density of 0.56 Mg m^{-3} and the moisture content reported above, a compost price of \$130 (Mg DM)$^{-1}$ was used. This neglects variable costs associated with applying the compost. Rather than estimate these specifically, results are presented for compost costs up to 50% above the delivery price. For the price of organic wheat I used \$642 Mg^{-1} (\$17.50 bu^{-1}). This was the price received in 2008 by the grower involved in the Stukenholtz et al. (2002) study (R. Grover, personal communication), albeit for a different hard red cultivar (Weston). The effect of protein content on wheat price was not considered (Baker et al., 2004).

Quadratic-plateau models were fit to the wheat yields using MATLAB's System Identification Toolbox (version R2008a). Profit-maximizing compost rates based on these models were calculated by modeling the system as five wheat crops in rotation, with the compost rate for all but the first wheat crop constrained to be zero. For a wheat-fallow rotation, this simulates one compost application per decade. Results are presented for different values of the cumulative carryover $CC = b_1 + b_2 + b_3 + \cdots$, which for simplicity was split evenly over the five crops in the rotation. This corresponds to a 5×5 matrix H (cf. Eq. [2.4]) with main diagonal entries of $1 + CC/5$ and remaining entries of $CC/5$.

Optimizations were solved using CVX (version 1.1) for MATLAB (version R2008a). To use a quadratic-plateau model with Eq. [2.8], first the problem was solved as if the yield response had no plateau, using only the quadratic function parameters. If the optimal state for the wheat crop receiving compost was in the range where the yield response should have been flat, the problem was resolved using the plateau portion of the yield response for this wheat crop. This new problem still has the form shown in Eq. [2.8] because a constant function can be written as a quadratic one with zero slope and curvature. For the wheat crops grown between compost applications, yield never reached the plateau.

RESULTS AND DISCUSSION

Meeting N Targets in a Two-Crop Rotation

To illustrate how the theory may be used to meet N targets, consider a rotation with two crops (A and B), one of which (A) has a target of 50 kg N ha^{-1} (adjusted for N contributions in the unmanured system). Fig. 2.1 shows the optimal manure/compost rates for the two crops as the N target for crop B varies from 50 to 150 kg N ha^{-1}. By optimal, I mean the smallest total rate that will meet the N targets at steady state. As noted previously, higher rates would be needed until the levels of soil organic matter stabilize.

These results are based on a hypothetical N decay series of 0.20, 0.10, …, which might represent aged dairy manure or chicken manure compost (Klausner et al., 1994; Gale et al., 2006). Rather than specify decay series parameters beyond the first two, the problem was solved for different assumptions about what fraction of the total N eventually becomes bioavailable. For a decay series b_0, b_1, b_2, …, the cumulative bioavailable N is the sum $b_0 + b_1 + b_2 + \cdots$. The curve marked 50% in Fig. 2.1 assumes 20% of the total N is released in year one, 10% in year two, and the remaining 30% split evenly between the two crops. Similar calculations hold when 70% or 90% of the total N

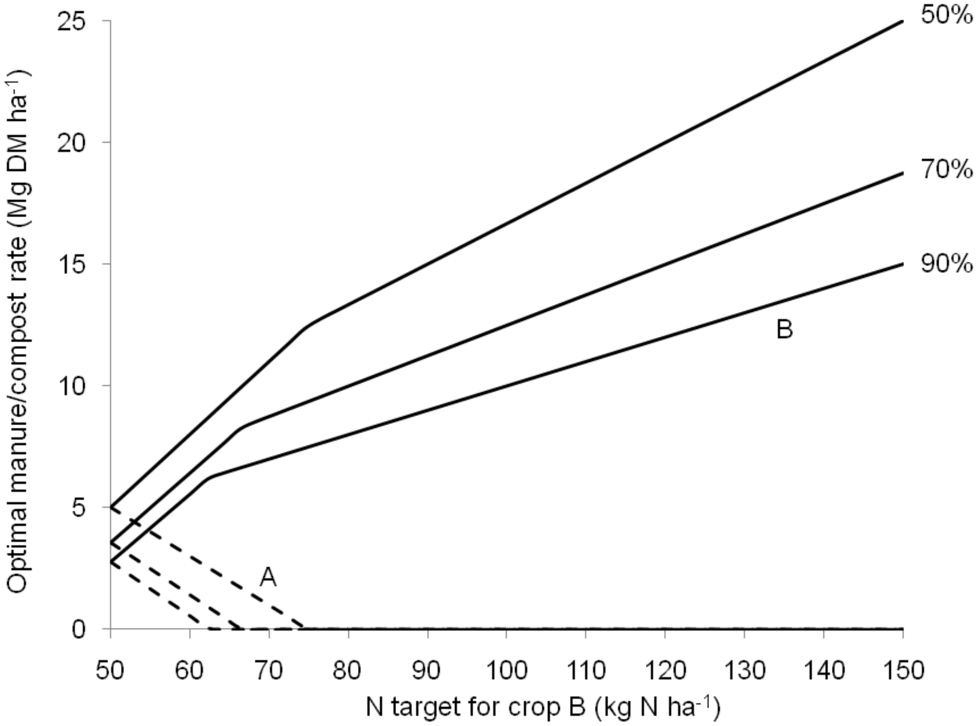


Fig. 2.1. Meeting nitrogen targets in a two-crop rotation. Two crops A and B are grown in rotation, with the N target for A fixed at 50 kg N ha^{-1}. The solid curves (labeled B) show the optimal rate for B as a function of the N target for B, while the dashed curves (labeled A) show the optimal rate for A. Manure/compost rates were calculated based on 2% total N (dry weight), for three different assumptions (50%, 70%, 90%) about the percentage of total N that becomes bioavailable. As the disparity between the N targets for B and A increases, more amendment is applied to B than A.

ultimately becomes bioavailable.

As seen in Fig. 2.1, when the N targets for the two crops are equal (50 kg N ha^{-1}), the same rate would be applied to each crop. For manure/compost with 2% total nitrogen on a dry weight basis, the optimal rate would be 3–5 Mg DM ha^{-1}. As the N target for B increases relative to A, more manure/compost would be applied to B (solid lines) than A (dashed lines).

If the disparity between N targets is large enough, it is not possible to meet both of them exactly. In this example, when the N target for crop B exceeds 65–75 kg N ha^{-1} (depending on the cumulative bioavailable N), the total amount of manure/compost can be minimized by applying amendment only to B. This is because the N fertilizing value of the carryover from B to A exceeds the N target for A. Because this excess N has the potential to degrade the environment (Di and Cameron, 2002), in certain contexts the objective of meeting all N targets may be inappropriate.

When crop B has a high N target, the optimal manure/compost rate strongly depends on what fraction of the total N becomes bioavailable. In this situation, when the sum of the decay series doubles, the optimal manure/compost rate is cut in half. The cumulative bioavailable N is an important parameter that needs to be measured in different contexts, but N fertilizer equivalency experiments spanning a few years are inadequate for this purpose. Although decay series terms fall to a few percent after several years (Klausner et al., 1994), they can remain at this low level for over a decade because the time scale for organic matter decay slows down dramatically (Paustian et al., 1992; Brady and Weil, 2002). One percent per year for 10–20 years adds up to substantial bioavailable N.

One approach to estimating the cumulative bioavailable N in a continuous cropping system is via the N fertilizer equivalency of plots that have received fixed, annual manure/compost applications over long periods of time (Schröder, 2005). Extrapolations of experimental data based on this idea suggest 70–80% of the total N may eventually mineralize in different contexts (Schröder et al., 2005; Schröder et al., 2007). Measurements of cumulative bioavailable N based on long-term N mass balances have produced estimates in the range 50–60% (Chang and Jenzen, 1996; Peu et al., 2006). The range of values considered in Fig. 2.1 spans these predictions.

How does one estimate the cumulative bioavailable N in a multi-crop rotation? Naively, one might use the average N fertilizer equivalency of the crops in the rotation: $(1/R)\ \Sigma_i\ x_i/u_i$ (cf. Eq. [2.4]). By summing the rows in Eq. [2.4], however, one finds that the correct answer is the ratio between the average N fertilizer equivalents and the average manure/compost rate:

$$\frac{(1/R)\sum_i x_i}{(1/R)\sum_i u_i} = b_0 + b_1 + b_2 + \cdots \qquad [2.10]$$

Profit-Maximizing Compost Rates for Dryland Wheat

Knowing the long-term fertilizing value of manure/compost is just as critical to maximizing profit as meeting N targets. This point is illustrated with a case study based on the work of Stukenholtz et al. (2002), who measured the yield response of dryland, organic wheat to composted dairy manure (Fig. 2.2). Data were collected from two neighboring fields staggered in a wheat-fallow rotation. Yields were higher in 1995 than 1996, and the 1995 crop also responded more sharply to compost, as illustrated by the

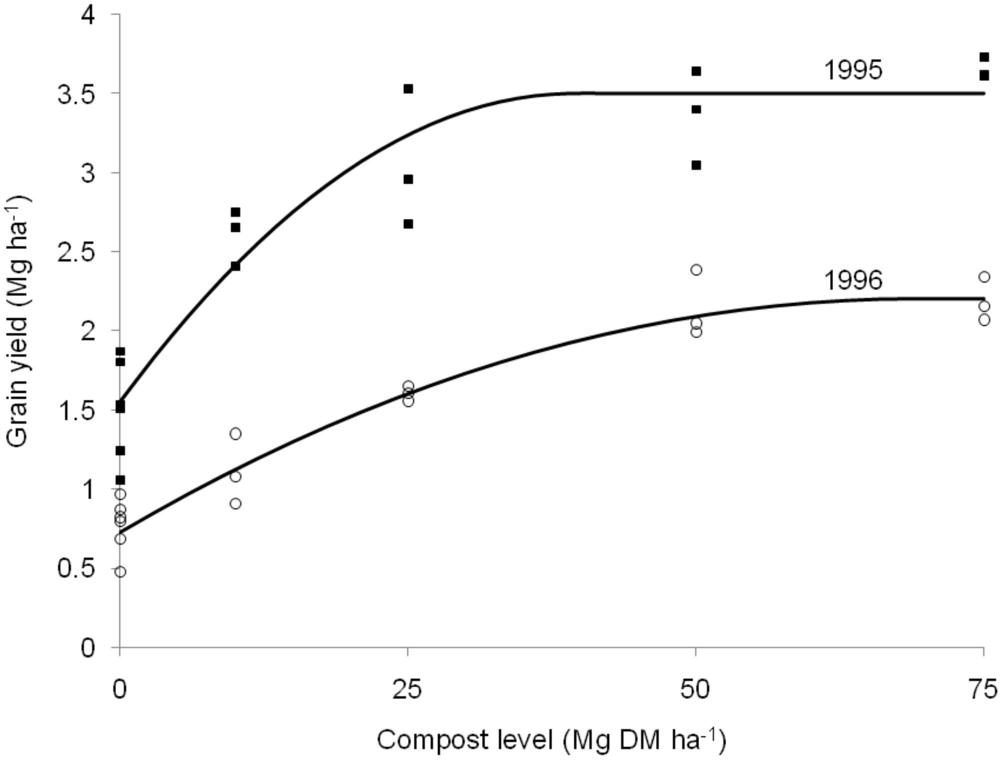


Fig. 2.2. Wheat yield response to compost. Data points indicate the individual plot yields for one site in 1995 (filled squares) and a second site in 1996 (open circles). Quadratic-plateau models were separately fit for each site-year, in which yield $Y = Y_{max} - (1/2)\, k\, (x_{max} - x)^2$ when $x \leq x_{max}$, and $Y = Y_{max}$ when $x > x_{max}$. The point estimates (and standard errors) for the 1995 regression model parameters are Y_{max} = 3.5 (0.1) Mg grain ha^{-1}, x_{max} = 40. (8) Mg DM ha^{-1}, and $k = 2.5 \times 10^{-3}$ (0.9×10^{-3}) ha (Mg grain) (Mg DM)$^{-2}$. Estimates (and standard errors) for the 1996 regression model parameters are Y_{max} = 2.2 (0.1), x_{max} = 69 (10.), and $k = 6.2 \times 10^{-4}$ (1.7×10^{-4}), with the same units as above. The average yield model for the two site-years (not shown) is Y_{max} = 2.8 (0.2), x_{max} = 52 (19), and $k = 1.2 \times 10^{-3}$ (0.9×10^{-3}).

quadratic-plateau models fit to the data. Stukenholtz et al. (2002) attributed these differences primarily to the effect of precipitation, which was 56 cm for the 1995 season but only 26 cm in 1996.

Because these experiments were conducted on certified organic land, the yield response to N fertilizer was not measured. Although not emphasized earlier, this is not a requirement of the theoretical framework developed here. For an organic farm where yield is measured as a function of manure/compost, a more natural basis for the fertility state is manure/compost *equivalents*. This entails comparing the carryover effects of manure/compost against new applications of the amendment, rather than N fertilizer. In an experiment where plots that received 10 units of compost in year one and no compost in year two have the same average yield as plots that received no compost in year one and 5 units in year two, the second term in the decay series would be $b_1 = 0.5$. The first term in the decay series ($b_0 = 1$) is not meaningful in this case because one unit of manure/compost is trivially equivalent to itself in the first year.

To calculate profit-maximizing compost rates for the wheat yield models shown in Fig. 2.2, one must know the cumulative fertilizing value of the compost in the years after application ($b_1 + b_2 + b_3 + \cdots$) relative to its fertilizing value in the first year (b_0). This *cumulative carryover* (*CC*) was unknown for this system, so results are presented for a range of values. Even though Stukenholtz et al. (2002) surmised that non-nutritive effects were present in their study, nitrogen may serve as a guide. A typical N fertilizer equivalency for dairy manure compost in the season of application is $b_0 = 0.1$, meaning 10% of the total N is bioavailable (Gale et al., 2006). If 50% of the total N is eventually mineralized, then based on nitrogen alone one would expect $CC = (0.5-0.1)/0.1 = 4$. If 80% of the total N is eventually mineralized, then $CC = (0.8-0.1)/0.1 = 7$.

The dashed curves in Fig. 2.3 are *ex post* optimal rates, meaning they depict what compost rate would have maximized profit for each site-year (Bullock and Bullock, 1994), for different values of *CC*. The solid curve is economically optimal for the average yield response of the two site-years (cf. Fig. 2.2 caption), making it the optimum under conditions of uncertainty (Bullock and Bullock, 1994). These results assume compost is applied once every 10 years (5 wheat crops), which means only one-tenth of a producer's acreage would need to be amended per year. More frequent compost applications would lead to smaller optimal rates than those shown in Fig. 2.3.

Based only on the observed yield responses, with no accounting for carryover ($CC = 0$), the most profitable rate is zero. However, for a wide range of plausible *CC* values (4–8), the optimal rate based on the average yield is 15–20 Mg DM ha^{-1} 10 yr^{-1}. As the *CC* increases within this range, the difference between the optimal strategies for the two site-years tends to decrease.

An interesting feature of the curves in Fig. 2.3 is that the optimal rate passes through a local maximum as the cumulative carryover increases. This is because of two competing effects. As the carryover increases, the marginal cost of the compost that must be recouped in the year of its application decreases (Kennedy, 1986). This decreases the slope of the yield response at the economic optimum (cf. Eq. [2.8]), leading to higher levels of production. For the quadratic-plateau model, higher yield requires a more fertile is both proportional to the state and inversely proportional to the cumulative carryover (cf. Eq. [2.2-4]), which exert opposite influences.

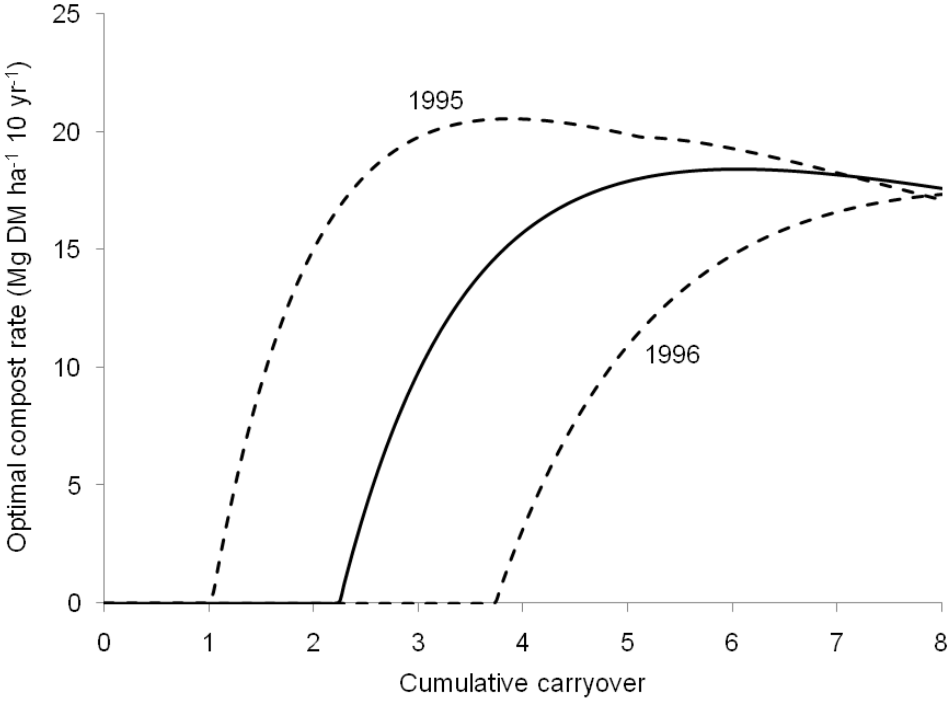


Fig. 2.3. Economically optimal compost rates. *Ex post* optimal rates (dashed curves) were calculated for the two site-years as a function of the cumulative carryover (*CC*), assuming compost would be applied once every 10 years. The solid curve shows the economic optimum for the average yield. Larger cumulative carryover leads to monotonically higher optimal levels of the soil fertility state, but the optimal compost rate exhibits a local maximum because it is both proportional to the state and inversely proportional to the cumulative carryover. The optimal rate was higher in 1995 because the yield exhibited a sharper response to compost. The kink in the curve for 1995 at *CC* $\approx$ 5 is where the optimal state reaches the plateau in the yield model. Because the optimal rate is related to the first derivative of the yield, a discontinuity in the curvature of the yield leads to a discontinuity in the slope of the optimal rate.

Fig. 2.4 shows the sensitivity of the optimal rate to changes in the compost/wheat price ratio. As the price ratio increases, the cost of the compost relative to the value of the wheat increases, and therefore the optimal rate declines. At higher values of cumulative carryover, the optimal rate is less sensitive to changes in the price ratio.

CONCLUSIONS

A framework has been developed for planning manure/compost applications in which efficient use of the amendment is an explicit goal. Achieving this objective requires knowledge of the decay series, which is an estimate of the impacts a particular manure/compost will have on crop yield over the course of many years. In principle, decay series can be measured in any cropping system, with many possible standards for measuring carryover. In practice, most experimental studies have focused on continuous corn, with the carryover measured relative to N fertilizer. Thus, a significant gap exists between our current ability to optimize organic crop production and what may eventually be realized with the framework developed here.

Depending on the complexity of the cropping system, full knowledge of the decay series may not be required. For continuous cropping, it is only the sum of the decay series that is relevant. As more crops are added to the system, each with potentially different production goals, matching the carryover effects of manure/compost against the changing needs of the rotation becomes less intuitive. The framework presented here provides a starting point for tackling these problems.

One of the most interesting features of the economic theory is that it suggests a new standard for the decay series, in which the carryover effects of manure/compost are

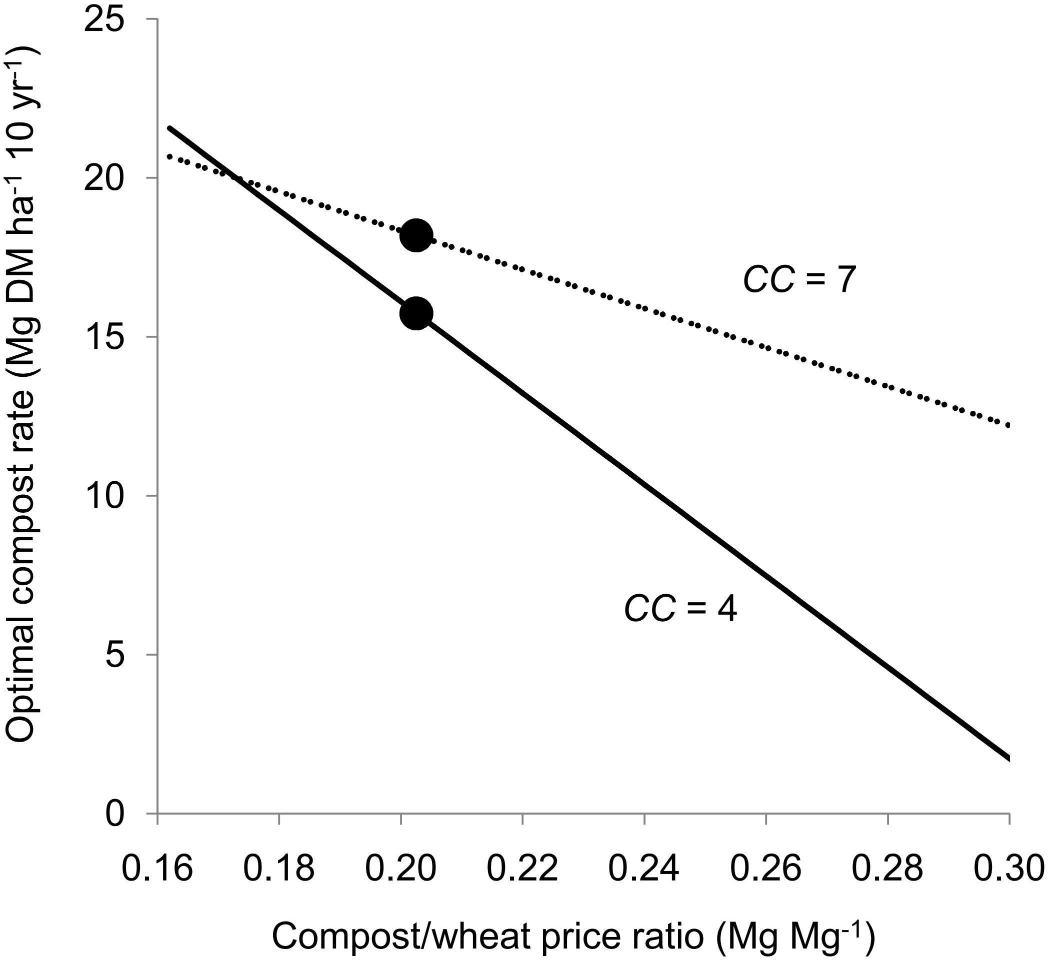


Fig. 2.4. Sensitivity analysis. The solid circles indicate the economically optimal compost rate at a compost/wheat price ratio of 0.20 (Mg grain)(Mg DM)$^{-1}$, which was the base case used in Fig. 2.3. The curves here show how the optimal rate changes as the price ratio ranges from 20% below to 50% above the base case. As the price ratio increases, the compost becomes more expensive relative to the value of the wheat, and therefore the optimal rate declines. Note that the optimal rate is less sensitive to changes in the price ratio at higher values of cumulative carryover (*CC*).

measured relative to new applications of the amendment. I have shown how this idea may be used in fertility planning for a dryland, organic wheat-fallow rotation. Although valuable in theory, future research must address the practicality of measuring decay series based on manure/compost equivalents. The next chapter is a step in this direction.

CHAPTER 3

ESTIMATION OF DECAY SERIES BASED ON MANURE/COMPOST EQUIVALENTS

An important strategy for maintaining fertility on organic farms is the judicious use of manure and/or compost (Kuepper, 2003; Gaskell et al., 2006). A defining feature of these amendments is that their effects on crop yield are evident for many years after application (Sullivan et al., 2003). One reason for this carryover is that, unlike synthetic fertilizers, some nutrients present in manure/compost are not readily available for plant uptake. For phosphorus and potassium, 70–100% of the nutrient is available upon application (Eghball et al., 2002; Mikkelsen, 2007; Nelson and Janke, 2007). By contrast, only 10–50% of the nitrogen (N) in solid manure/compost is bioavailable within the season of application, this fraction tending to decrease with the extent of decomposition (Gale et al., 2006; Laboski et al, 2006). The remaining nitrogen is found in organic forms that slowly mineralize over the course of many years.

This multi-year effect can be quantified by a N decay series, which is a sequence of numbers describing what fraction of the manure/compost N is expected to be bioavailable in the first, second, third, etc., years after application (Pratt et al., 1973; Cusick et al., 2006). One way of measuring N decay series involves comparing the yields of manured plots with the yields of plots receiving N fertilizer (Klausner et al., 1994). As an example, a decay series of 0.40, 0.20, …, means that plots receiving 200 kg manure N ha^{-1} would on average yield the same as plots receiving 200 × 0.40 = 80 kg fertilizer N ha^{-1} for the year in which the manure was applied. In the following year, provided no new manure was added, the manured plots would have the same average yield as plots receiving 200 × 0.20 = 40 kg fertilizer N ha^{-1}.

Conventionally, the parameters in the N decay series are multiplied by the manure/compost rates from years past to estimate how much bioavailable N may be expected for the current season (Laboski et al., 2006). This credit is then applied to the N target for the crop, and the balance is met using N fertilizer. For an organic system, one could convert the N fertilizer recommendation into a manure/compost rate based on the first term in the decay series (Hue and Silva, 2000). Alternatively, one may choose to apply manure/compost at a rate that maximizes profit. In Chapter 2 I showed how N decay series may be used to achieve both economic and yield objectives.

A compelling reason to use N decay series in organic fertility planning is that such information is widely available. As a paradigm for the future, however, it has some disadvantages. For one, N fertilizer equivalency experiments cannot be conducted on organically certified land because N fertilizer is prohibited. A second concern is that nitrogen is not the only factor contributing to the long-term fertilizing value of manure/compost. By increasing soil organic matter, manure/compost can increase the soil's capacity to hold water and nutrients (Weil and Magdoff, 2004), and such changes can dramatically affect the yield of unirrigated crops (Stukenholtz et al., 2002). Biological influences such as organic-matter mediated disease suppression may also be active on long time scales (Stone et al., 2004).

When non-nutritive factors are significant, quantifying carryover in N fertilizer equivalents is not particularly meaningful. A more useful benchmark for organic growers who rely upon a consistent source of manure/compost is the equivalency between carryover and prospective applications of the amendment. Since manure/compost is trivially equivalent to itself in the first year, the first term in this kind of decay series is simply 1. In an experiment where plots that received 10 units of compost in year one and no compost in year two have the same average yield as plots that received no compost in year one and 5 units in year two, the second term in the decay series would be 0.5. Higher order terms could be generated by continually comparing carryover effects against the yields of plots receiving amendment for the first time, but other experimental designs are also possible.

Given its potential importance in organic fertility planning, the objective of this chapter was to explore how decay series based on manure/compost equivalents may be estimated from yield records. To frame the discussion, I have re-analyzed data from a long-term experiment (Schröder et al., 2005) in which cattle manure slurry was applied to continuous corn (*Zea mays* L.). This example was chosen because its unique design is well-suited to the methodological challenges encountered when the response to N fertilizer is unavailable as a benchmark.

METHODOLOGY

The field experiment of Schröder et al. (2005) was conducted in Hengelo, Netherlands, on a slightly loamy, moderately fine sandy soil (cambic Spodosol) with 2.7% organic matter and pH 5.5 (0–30 cm). From 1997 to 1999, one of three slurry rates (none, low, high) was applied annually to 21-row plots measuring 11.0 m long by 15.75 m wide, in a randomized block design with four replicates. From 2000 to 2002, each 21-row plot was subdivided into three 7-row plots (11.0 m by 5.25 m), to which one

Table 3.1. Manuring history for plots of silage corn. The average low slurry rate was 2 Mg DM ha^{-1}, and the average high slurry rate was 4 Mg DM ha^{-1}.

	Treatment								
Year	1	2	3	4	5	6	7	8	9
‘97-‘99	None	None	None	Low	Low	Low	High	High	High
‘00-‘02	None	Low	High	None	Low	High	None	Low	High
‘03	None	Low	High	None	Low	High	None	None	None

of the three slurry levels was applied. The slurry rate was changed again for some of the subplots in 2003. In total, nine different slurry sequences, or treatments, were used (see Table 3.1). The average low slurry rate was approximately 2 Mg DM ha^{-1}, and the average high slurry rate was approximately 4 Mg DM ha^{-1}. On average the slurry was 9.0% dry matter, with 4.9% total N and 2.6% NH_4-N on a dry weight basis, and a C/N ratio of 7. Manure slurry was injected 10–15 cm deep following moldboard plowing each spring. Since Schröder et al. (2005) were interested in nitrogen management, the plots also received annual applications of phosphorus and potassium fertilizer at rates calculated to meet crop demand. Corn silage was harvested at 35% moisture in late September each year.

Statistical Analysis

In the analytical framework used here, the manure rate *u* and yield *Y* are linked through a state variable *x*, representing soil fertility in manure equivalents. For a decay series of 1, b_1, b_2, …, the effect of the manure on soil fertility was modeled as

$$x(t) = u(t) + b_1 u(t-1) + b_2 u(t-2) + \cdots \qquad [3.1]$$

where $u(t)$ and $x(t)$ denote the rate and state, respectively, in year *t*. Similar results were obtained using both exponential and quadratic-plateau yield models, so only the latter are presented here:

$$Y = Y_{max} - (1/2)\, k\, (x_{max} - x)^2, \qquad x \le x_{max}$$
$$Y = Y_{max}, \qquad x > x_{max}. \qquad [3.2]$$

Nonlinear regression analyses, carried out using MATLAB's System Identification Toolbox (version 2008a), involved simultaneously fitting yield models and decay series (Eq. [3.1-2]) to the data. Prior to 2000, although rate varied across plots, it did not vary substantially with year. This had important implications for the regression. For example, in 1999 the state would be $x(1999) \approx (1 + b_1 + b_2)\langle u\rangle_{97-99} = \lambda\langle u\rangle_{97-99}$, where $\langle u\rangle_{97-99}$ is the average rate before the change in 2000 and λ is the sum of the decay series. When the decay series parameters only enter the model through their sum, they cannot be resolved. Furthermore, under these conditions even the decay series sum cannot be estimated independently of the parameters in the yield model. This is because upon making the substitution $x = \lambda u$ in Eq. [3.2], x_{max} and k can be rescaled by an appropriate power of λ to produce the same functional form.

After the change in rate in 2000, the situation is different. If $\langle u\rangle_{00-02}$ denotes the average (approximately constant) slurry rate from 2000 to 2002, the state can be modeled by

$$x(2000) \approx (1)\langle u\rangle_{00-02} + (b_1 + b_2 + b_3)\langle u\rangle_{97-99}$$
$$x(2001) \approx (1 + b_1)\langle u\rangle_{00-02} + (b_2 + b_3 + b_4)\langle u\rangle_{97-99} \qquad [3.3]$$
$$x(2002) \approx (1 + b_1 + b_2)\langle u\rangle_{00-02} + (b_3 + b_4 + b_5)\langle u\rangle_{97-99}$$

At first the regression was based only on 2000 yields, which allowed for the estimation of the sum $(b_1 + b_2 + b_3)$. When the fit was extended to all three years, a different yield response model was used for each of the three years to more precisely estimate the decay series. Since x_{max} and k can be rescaled for each yield model, only the ratio of the rate coefficients in Eq. [3.3] can be uniquely estimated:

$$\begin{aligned}
\tilde{x}(2000) &\approx \langle u \rangle_{00-02} + \left(\frac{b_1 + b_2 + b_{3+}}{1} \right) \langle u \rangle_{97-99} \\
\tilde{x}(2001) &\approx \langle u \rangle_{00-02} + \left(\frac{b_2 + b_{3+}}{1 + b_1} \right) \langle u \rangle_{97-99} \\
\tilde{x}(2002) &\approx \langle u \rangle_{00-02} + \left(\frac{b_{3+}}{1 + b_1 + b_2} \right) \langle u \rangle_{97-99}
\end{aligned} \qquad [3.4]$$

where $\tilde{x}$ indicates the rescaled state in each year, and b_{3+} is a lumped decay series parameter that includes higher order terms. In the end, 12 parameters were fit to the 108 plot yields from 2000 to 2002, including the 3 decay series parameters in Eq. [3.4] and 3 yield response parameters (k, x_{max}, Y_{max}) for each of the 3 years.

RESULTS AND DISCUSSION

Assessing the Adequacy of the Decay Series Model

Before estimating the decay series parameters, I investigated whether it was an appropriate model for the effects of carryover in the data of Schröder et al. (2005). The bottom panel in Fig. 3.1 shows the average silage yield for slurry treatments 1, 2, 4, and 7, from ’98 through ‘03. Only the pooled yield data for treatments 1 and 2 were available before 2000, during which time the plots received no manure. During these same years ('97−'99), treatments 4 and 7 received annual slurry applications of 2 and 4 Mg DM ha^{-1}, respectively. Focusing on the yield in '98 and '99, one sees that the unmanured treatments (1 and 2) had the lowest average yield, followed by treatment 4 (2 Mg DM ha^{-1}), and the highest average yield was recorded in treatment 7 (4 Mg DM ha^{-1}). Note that although the slurry rate in treatment 7 was twice that in treatment 4, the average yield increased by less than a factor of two relative to the unmanured plots. This is an example of the law of diminishing returns (Dillon and Anderson, 1990), which in this context can be accommodated by a nonlinear relationship between yield and state, e.g., a quadratic or exponential yield model, with little implication for the linear carryover model that defines the decay series (cf. Eq. [3.1]).

The true test of the linear carryover model, and with it the usual notion of a decay series, comes from data recorded after the change in slurry levels that occurred in 2000. As illustrated in the top panel of Fig. 3.1, treatments 4 and 7, which had been receiving manure prior to 2000, received no manure from 2000 onward. Treatment 1 continued without manure. Thus, the extent to which treatments 4 and 7 yielded more than treatment 1 from 2000 onward must be due to carryover.

Treatment 2 is included in the figure to help quantify the nature of this carryover effect. Although unmanured prior to 2000, from 2000 onward treatment 2 plots received approximately 2 Mg DM ha^{-1} annually. Although crop yields tend to saturate with increasing amounts of fertilizer, there is generally some lower range where the yield response is linear (Dillon and Anderson, 1990). The data from '98 and '99 indicate that the yield response is nonlinear between 2 and 4 Mg DM ha^{-1}, but regression modeling (see below) suggests that the yield response at fertility levels between 0 and 2 Mg DM ha^{-1} is fairly linear. Consequently, treatment 2 serves as a benchmark for where nonlinear behavior in the relationship between yield and state may show up after the step change in rate. If the carryover were to have nonlinear effects on yield below this benchmark, it

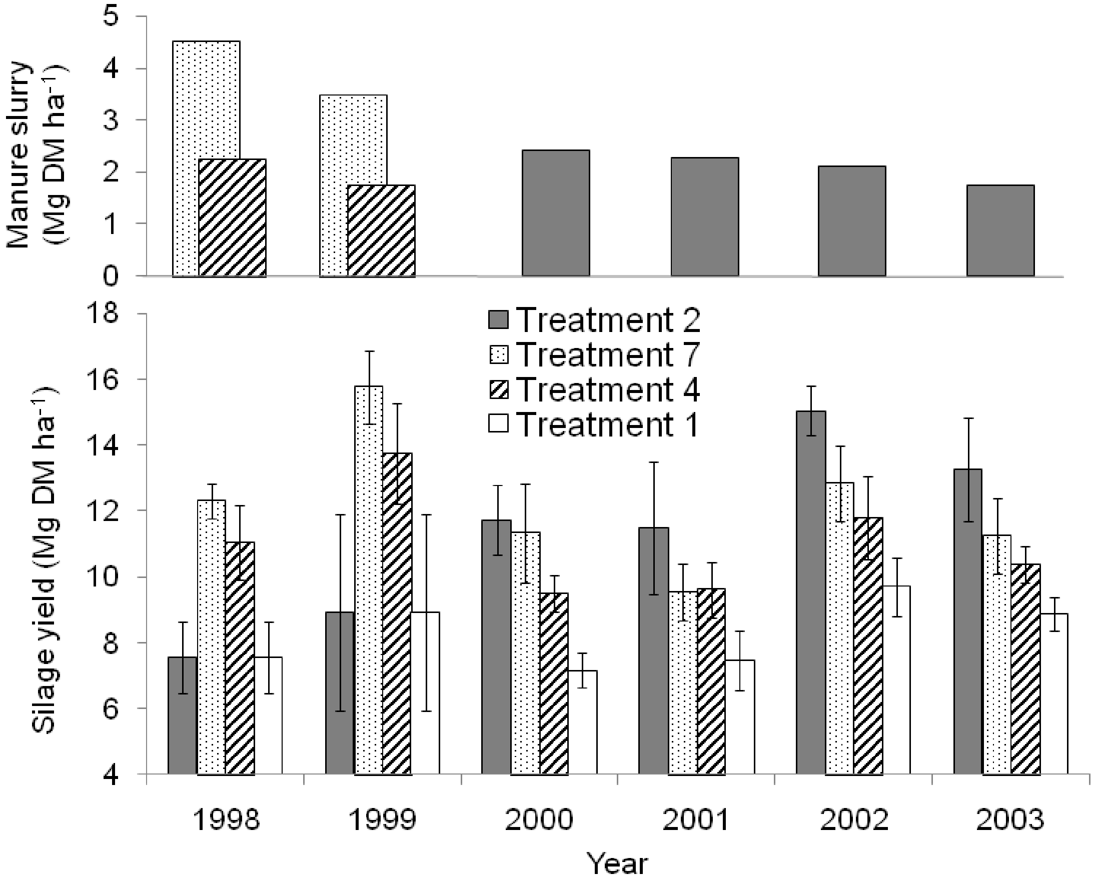


Fig. 3.1. Manure rates and silage yields for select treatments. Treatment 1 received no manure from 1997 to 2003. Treatment 2 began to receive annual manure applications beginning in 2000. Treatments 4 and 7 received manure from 1997 to 1999 but none beginning in 2000. Treatment means based on four replicates are shown for the yield data, with the error bars representing +/- one standard deviation. The data from 1997 are not shown.

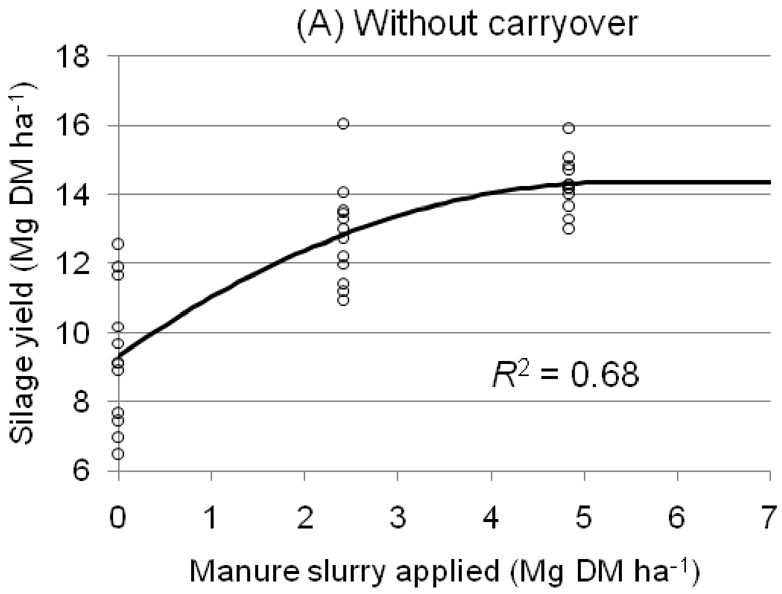
would suggest the linear carryover model is inadequate.

From 2000 onward, treatments 4 and 7 both yielded less than or equal to treatment 2. Thus, under the linear carryover model, the ratio of the yield improvements in treatments 4 and 7 relative to treatment 1 should equal the ratio of rates, which differed by a factor of two. Visual assessment of Fig. 3.1 suggests the linear carryover model is plausible, although not perfect, since the mean for treatment 4 appears to split the difference between treatments 7 and 1 in every year but 2001 after the change in slurry rate.

As an additional preliminary before presenting the regression, it is worth noting how slowly the fertilizing value of the slurry appears to decay in Fig 3.1. From 2001 onward, the improvement of treatments 4 and 7 over the unmanured treatment 1 remains fairly consistent. Although the large concentration of inorganic N in the slurry is a confounding factor, the silage yields suggest a familiar pattern of organic matter decay in which an initially rapid rate gives way to a much slower rate after a few years (Brady and Weil, 2002).

Estimating the Decay Series

Fig. 3.2A shows the silage yield in 2000 for all nine treatments as a function of the slurry applied that year. The plot yields (open circles) appear in three vertically stacked clusters corresponding to the three slurry rates (0, 2.4, 4.8 Mg DM ha^{-1}). The solid line is the best-fit quadratic-plateau model, which captures $R^2 = 0.68$ of the total variation. This is not an impressive fit and points to the inherent difficulty of explaining crop yields without accounting for carryover effects.



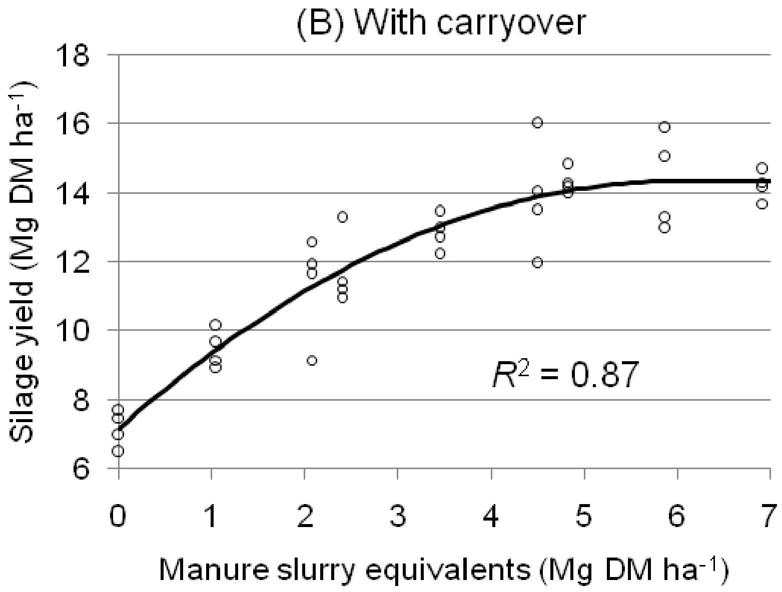


Fig. 3.2. Modeling carryover for the 2000 yields. Below its maximum, the yield model (solid line) follows $Y = Y_{max} - (1/2)\, k\, (x_{max} - x)^2$. (A) With no carryover, the state x equals the slurry applied in 2000. (B) When carryover is modeled, x = (slurry in 2000) + b (average slurry level before 2000). In this case, the parameter estimates (and standard errors) are Y_{max} = 14 (0.3) Mg DM ha^{-1}, x_{max} = 6.0 (0.8) Mg DM ha^{-1}, k = 0.40 (0.10) ha (Mg DM)(Mg DM)$^{-2}$, and b = 0.50 (0.09). An additional 20% of the variation in the data (R^2) is captured by modeling carryover.

The explanatory power of the model is dramatically improved when a decay series is included. In Fig. 3.2B, yield is plotted against manure equivalents, which is the sum of the manure applied in 2000 and the manure equivalents from slurry applied before 2000. Because a constant rate was applied for three years before the step change in 2000, manure equivalents were estimated with a single parameter b representing the sum of the first three terms in the decay series (cf. Eq. [3.3]). The regression estimate (and standard error) for b was 0.5 (0.1). With the additional yields from 2001 and 2002, I attempted to isolate the contributions from one-year-old and two-year-old slurry (see METHODOLOGY). Due to spatial and temporal variability, these decay series parameters could not be precisely estimated: $b_1 = 0.13$ (0.16) and $b_2 = 0.05$ (0.13).

It is instructive to compare these results, expressed in manure equivalents, with what might be expected from a N decay series. This requires normalizing the N decay series by its first term. As an example, Pratt et al. (1976) have reported a N decay series for manure slurry of 0.75, 0.15, 0.10, …, which becomes 1, 0.2, 0.13, …, when normalized. This means that one year after its application, 1 unit of slurry was equivalent to 0.2 units of fresh slurry, as compared with the value of 0.13 (standard error 0.16) estimated from the data of Schröder et al. (2005). Because the high inorganic N content of liquid manure creates high fertilizing value in year one, the carryover relative to year one is small compared with solid manure, which tends to have a normalized N decay series parameter b_1 in the range 0.3–0.5 (Pratt et al., 1976; Klausner et al., 1994).

Since N fertilizer plots were not part of the experimental design of Schröder et al. (2005), they used models calibrated with other data to estimate the N decay series. For a scenario where the first term in the N decay series was 0.55, the sum after 5 years was approximately 0.75. On a normalized basis, this corresponds to a cumulative carryover of (0.75–0.55)/0.55 = 0.36, as compared with the estimate of 0.5 (standard error 0.1) reported here. One would expect that how well a N decay series approximates a decay series based on manure/compost equivalents will depend on the relative contribution of factors other than nitrogen in the carryover. For the system investigated by Schröder et al. (2005), nitrogen seems to dominate the carryover, as might be expected for liquid manure.

Extension to Other Field Experiments

A natural question at this point is how the methods employed here may be applied elsewhere. The above case study serves as a model for estimating the first few decay series parameters during the transient response of an agroecosystem to a change in the manure/compost rate. This may be a “step” change in rate, as in Schröder et al. (2005), in which the rate before and after the change is constant. One may equally well track the effect of a one-time application of manure/compost, which is effectively two sequential steps (up then down), provided some plots are receiving manure/compost in every year.

Complementary to these approaches are experiments designed to measure the sum of the decay series at steady state. In Chapter 2 it was shown how this information may be used to optimize manure/compost rates. A practical design for this purpose involves applying manure/compost at regular intervals over the course of many years. To illustrate how the regression analysis might proceed, consider the case where manure/compost is applied at a fixed rate u once every three years. At steady-state, the fertility will oscillate through three (average) states, x_1, x_2, x_3, with x_1 representing the year of application and x_3 the last year before the next application. These states are related to the rate by (cf. Eq. [3.1])

$$\begin{aligned} x_1 &= u(1+b_3+b_6+\cdots)=h_1u \\ x_2 &= u(b_1+b_4+b_7+\cdots)=h_2u \\ x_3 &= u(b_2+b_5+b_8+\cdots)=h_3u \end{aligned} \qquad [3.5]$$

where the sums h_1, h_2, and h_3 pick out every third term in the decay series, as indicated.

One would like to estimate the parameters h_i based on yield records, but this is not straightforward. The complication can be illustrated using a quadratic yield model, although the difficulty also exists with other models. Substituting the rate-to-state relationship $x_i = h_iu$ into the yield model $Y = Ax^2 + Bx + C$ produces the expression $Y_i = A\,h_i^2\,u^2 + Bh_iu + C$. The parameter h_i is not uniquely determined by this regression equation because it is multiplied by the yield model parameters A and B, which are also to be fit. However, for a continuous cropping system, where yield is modeled by a response function with either the same curvature (A) or the same initial slope (B) in every year, the ratio of the coefficients of u^2 or u, respectively, in the regression equations for Y_i and Y_j can be used to estimate h_i/h_j. To form this ratio, at least two states are required in the steady-state oscillation. Thus, the interval between manure/compost applications must be at least two years.

To proceed further an approximation is needed. Because the rate of organic matter decay slows down dramatically after a few years (Brady and Weil, 2002), higher order terms in the decay series tend to be small and fairly uniform. A reasonable approximation is thus $h_1 \approx 1 + h_3$, which allows h_1 and h_3 to be calculated from the regression estimate for h_1/h_3. Since the ratio h_2/h_3 is also determined from the regression, h_2 would be available too.

CONCLUSIONS

My objective has been to demonstrate how decay series based on manure/compost equivalents may be estimated from yield records. Using data from the literature, the first few terms in a decay series were estimated from the response of a continuous corn system to a step change in manure rate. The problem of estimating the sum of the decay series for a system at steady-state was also addressed, based on the idea of applying manure/compost at regular intervals.

The primary motivation for considering a decay series based on manure/compost equivalents is its potential use in optimizing organic crop production. In addition to representing non-nutritive effects in a more meaningful way, the decay series can be measured on organically certified land. Since organic systems tend to be highly individualized, the ability to derive site-specific fertility parameters is desirable. Conversely, a potential concern is that decay series parameters based on manure/compost equivalents will be less transferrable between contexts. With a N decay series, the manure/compost rate can be adjusted to variation in total N. A decay series in manure/compost equivalents only allows for planning based on average N. Whether this proves to be a significant limitation will depend on how the variability in N compares with the overall variability in the system, as well as on the relative fertilizing value of nitrogen vs. other factors.

CHAPTER 4

CONCLUSION

My primary aim has been to lay the theoretical foundation for a new approach to organic fertility planning. The existing paradigm is essentially the same as that used in conventional agriculture, in which the fertilizing value of manure or compost is compared against a synthetic nutrient source, usually N fertilizer, over the course of several years. For the purpose of meeting nutrient targets, knowing the synthetic fertilizer equivalency of manure/compost in the years after its application is very useful. The two main drawbacks to this approach are that it cannot be implemented on organic farmland because synthetic fertilizer is prohibited, and it awkwardly measures non-nutritive effects relative to nutritive ones.

A major contribution of this thesis was to recognize that these difficulties are overcome if the carryover effects of manure/compost are compared against new applications of the amendment. This is a natural framework for organic growers because the decision they face is how much new amendment should be applied. Two questions immediately follow. One is how this new type of decay series, expressed in manure/compost equivalents, may be measured in field experiments. The second is how the decay series enables efficient use of the manure/compost.

It is the second of these questions that I addressed first, in Chapter 2. In conventional agriculture, an important concept is the economically optimal, or profit-maximizing, fertilizer rate, which is where the marginal cost of fertilizer equals the marginal revenue from crop yield. For the first time in the scientific literature, I have adapted this idea to an organic system in which the “fertilizer” is purchased compost. The carryover effects of the compost, which are captured in the decay series, must be considered to properly evaluate profitability. Using data from an organic, dryland wheat system, it was shown how the optimal compost rate varies with the properties of the decay series.

To be good land stewards, organic farmers must also consider issues besides profitability when setting the compost rate. As an example, the economically optimal compost rate may have unacceptable environmental consequences. If the most profitable rate is too low, and other fertility-building strategies are not adequately employed, repeated cropping will deplete nutrients and endanger the land’s ability to produce quality food for future generations. If the most profitable rate is too high, nutrients may accumulate to such high levels that runoff and leaching harm the ecosystem.

Concerning the experimental measurement of decay series in manure/compost equivalents, I have made two contributions. The first was to design a three-year field experiment specifically for this purpose and then execute the first year (described more fully in the appendix). The unique feature of this design is that in every year some plots receive compost for the first time, which allows them to be used as benchmarks for carryover effects. My second contribution has been to show that even when this feature is not present in an experiment, regression modeling may still be used to estimate decay series parameters without N fertilizer benchmarks. Future work should focus on identifying long-term data sets from which decay series parameters may be extracted based on the methods presented in Chapter 3.

Despite these accomplishments, much more research is needed before extension recommendations can be made based on the ideas developed here. Important questions concerning the robustness of the decay series parameters, and the optimal strategies based on them, to the spatial and temporal variability found in agroecosystems must ultimately be addressed empirically. Even after some of these issues are resolved in a research setting, one must still find effective ways of communicating the results to growers. This thesis is but a first step towards a new paradigm for organic fertility management.

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APPENDIX

MEASURING THE DECAY SERIES OF COMPOST

This report describes the first year of a multi-year field experiment designed to measure the carryover effects of compost against new applications of the amendment. The logic of the experiment is as follows. In year one, compost was applied to some but not all plots, at varying rates. In year two, the plots amended in year one will receive no additional compost, but their yields will be compared against the yields of plots receiving compost for the first time in year two. If a plot that received 10 units of compost in year one and no compost in year two were to have the same yield as a plot that received no compost in year one and 5 units in year two, the second term in its decay series would be 0.5. In year three, the yields of plots that received compost in year two and one will be compared against the yields of plots receiving compost for the first time in year three to estimate the second and third terms in the decay series, respectively. The key feature of this design is that the plots used as a benchmark in each year have no carryover from previous compost applications.

METHODOLOGY

In the spring of 2008, two identically designed experiments were established at the Greenville research farm of Utah State University in North Logan, UT (Fig A.1). The soil was a Millville silt loam (coarse-silty, carbonatic, mesic Typic Haploxeroll). The site had not received fertilizer for several years prior to 2008 and had been planted with various cover crops.

Four different nonzero levels of compost (10, 20, 30, 40 Mg DM ha^{-1}) were planned

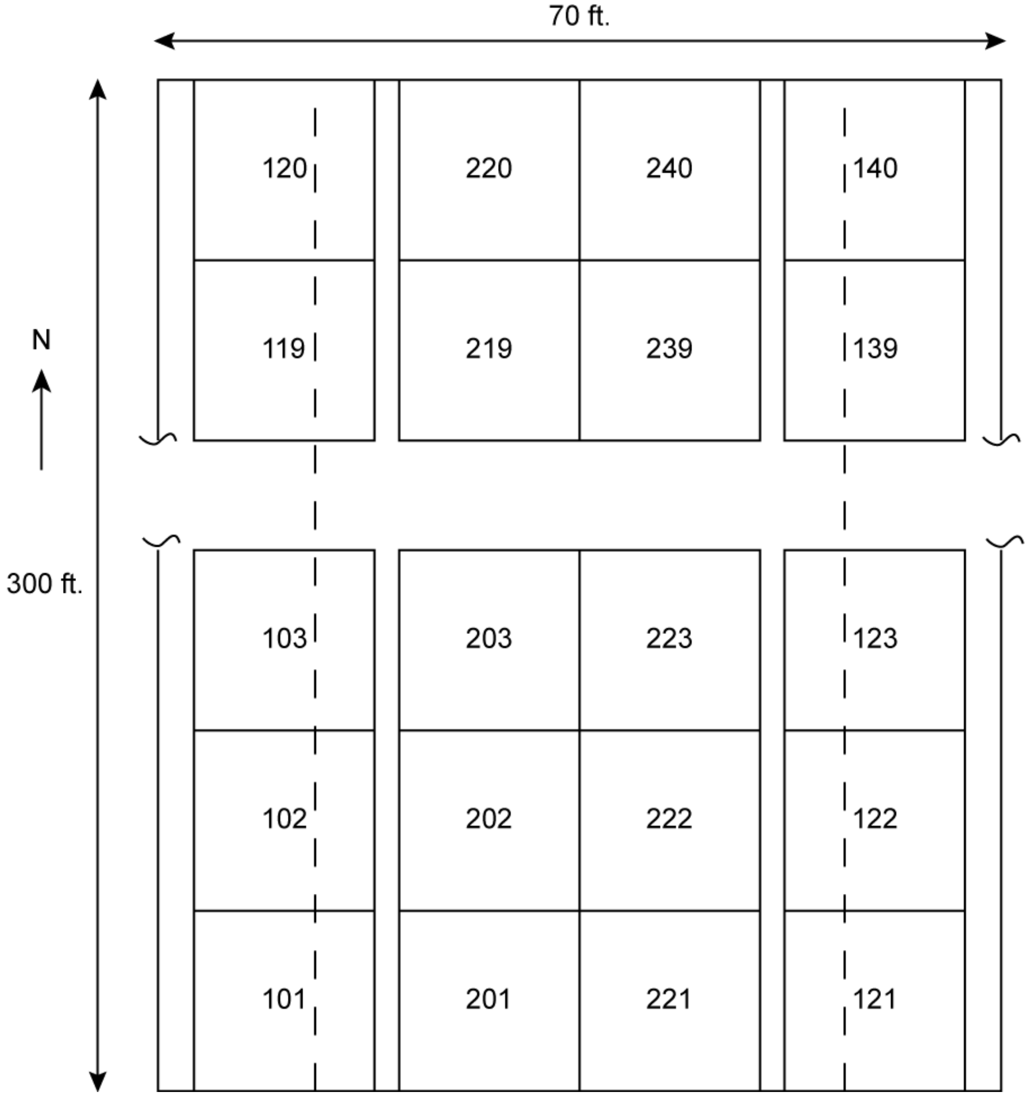

Fig. A.1. Plot layout for Greenville experiment. Four strips with 20 plots each were arranged within a rectangle 21.3 m (70 ft.) wide by 91.4 m (300 ft.) long. A 0.91 m (3 ft.) wide buffer separates the 100 series plots from the edge of the rectangle, and a 0.61 m (2 ft.) wide buffer separates the 100 series from the 200 series plots. Each plot is 4.6 m × 4.6 m (15 ft. × 15 ft.). In 2008 the 100 series plots were planted to summer squash and the 200 series plots were planted to corn. The dashed lines indicate the position of irrigation lines, with sprinkler heads spaced every 12 m (40 ft.). Note that the 100 series plots are arranged symmetrically with respect to the irrigation lines, as are the 200 series plots.

for each of the three years 2008, 2009, and 2010, for a total of 12 treatments in which compost would be applied only once during the three-year experiment. For the 13th treatment, no compost would be applied during the three years. Three plots were assigned to each of the 12 nonzero treatments and four plots to the zero treatment, for a total of 40 plots, in a completely randomized fashion (see Table A.1). As a consequence of this design, in year one there were 28 plots with no compost and 3 plots for each of the nonzero rates.

‘Premium’ brand compost was purchased in bulk from Miller’s in Hyrum, UT, at a cost of \$34 m^{-3} (\$26 yd^{-3}) in early May 2008. Laboratory analysis revealed the material to be 58% dry matter (DM) with a bulk density of 0.56 Mg m^{-3}, which means the cost per Mg DM was \$104. Select chemical analyses are shown in Table A.2. Total N and C were determined by dry combustion (LECO TruSpec CN). Nitrate N was measured in 5:1 compost extracts (2M KCl) by automated colorimetry (Lachat QuickChem AE). Olsen P and K concentrations were determined from sodium bicarbonate extracts by inductively coupled plasma spectroscopy (IRIS Intrepid II XDL).

On May 15, the compost was spread evenly over the plots with a rake and incorporated with a rototiller. No other additional amendments or fertilizers were used.

The crop in Experiment 1 was a certified organic summer squash (*C. pepo* L.) hybrid (‘Goldy Zucchini’, Seeds of Change). Plants were started in the greenhouse on May 7 in 50-cell flats. The potting mix contained peat moss, vermiculite, perlite, and a fertilizing mixture of bone, kelp, and blood meal. No synthetic fertilizers were used. On May 19, three sheets of black plastic mulch (1.2 m wide) were laid down the full length of the plot area (91.4 m) at a spacing of 1.5 m (5 ft.). Plants were transplanted into the mulch on

Table A.1. Plot assignments. Compost rates given for each year in Mg DM ha^{-1}.

Plot	2008	2009	2010	Plot	2008	2009	2010
101	0	0	0	201	0	10	0
102	0	20	0	202	0	40	0
103	0	10	0	203	0	0	30
104	0	0	40	204	30	0	0
105	0	0	20	205	0	20	0
106	20	0	0	206	0	0	30
107	0	40	0	207	40	0	0
108	0	0	20	208	0	30	0
109	0	0	0	209	0	10	0
110	0	0	10	210	0	0	0
111	40	0	0	211	20	0	0
112	30	0	0	212	0	0	10
113	40	0	0	213	0	0	40
114	10	0	0	214	0	20	0
115	0	10	0	215	30	0	0
116	0	40	0	216	0	0	20
117	0	0	0	217	0	0	40
118	0	40	0	218	40	0	0
119	0	0	30	219	0	30	0
120	0	0	0	220	0	20	0
121	30	0	0	221	10	0	0
122	0	0	10	222	0	0	10
123	20	0	0	223	20	0	0
124	0	30	0	224	0	10	0
125	0	0	40	225	0	0	20
126	30	0	0	226	10	0	0
127	40	0	0	227	0	0	0
128	0	0	20	228	0	0	30
129	10	0	0	229	0	40	0
130	20	0	0	230	0	30	0
131	0	20	0	231	40	0	0
132	0	20	0	232	0	0	10
133	10	0	0	233	0	0	0
134	0	0	40	234	0	0	20
135	0	0	10	235	0	0	40
136	0	0	30	236	30	0	0
137	0	30	0	237	0	0	0
138	0	10	0	238	0	40	0
139	0	30	0	239	20	0	0
140	0	0	30	240	10	0	0

Table A.2. Select compost properties. Concentrations given on a dry weight basis.

Property	Value
Dry matter	58%
Total N	1.9%
C/N	11
Nitrate-N	1900 mg/kg
Olsen P	1000 mg/kg
Olsen K	11,000 mg/kg
$pH_{5:1}$	8.0
$EC_{5:1}$	5.4 dS/m

May 28. Each sheet of mulch contained two rows of plants in a staggered pattern, with a spacing of 0.61 m (2 ft.) between plants within a row. This resulted in six rows per plot with a density of 21,500 plants ha^{-1}.

Squash fruit were picked twice a week from July 3 through July 31 for a total of nine harvests. All fruit larger than 15 cm in length were harvested. Most of the fruits appeared fertile based on size, and I also noticed bees pollinating the flowers on a regular basis. Although all fruit were picked, fresh weight was only recorded for the 6 plants within a 1.5 m × 1.5 m (5 ft. × 5 ft.) area within the center of each plot to minimize potential boundary effects. First the average cumulative harvest weight per plant was calculated, and then this number was scaled to a 1 ha basis using the density of 21,500 plants ha^{-1}.

The crop in Experiment 2 was a certified organic field corn (*Z. mays* L.) hybrid (Dahlco 2146). On May 28 seeds were drilled in rows 91.4 m (300 ft.) long, spaced 0.76 m (30 in.) apart. The crop was not systematically thinned but emerged with an average density of 66,000 plants ha^{-1}. On June 1, prior to corn emergence, plots were burned with a five-torch, walk-behind flamer to control weeds. After emergence, weeds were controlled by hand within the row and with a walk-behind wheel hoe between the rows.

On June 29, 32 days after planting, 2–4 whole plants were cut from the center of each plot, and their tissue N concentrations determined by dry combustion (LECO TruSpec CN). These plants were 25–30 cm tall with 7–9 leaves.

Corn plants were harvested by hand 96 days after planting (Dahlco 2146 is a short-season variety), at approximately 30% dry matter. To minimize potential boundary effects, yields were only recorded for the (on average, 14) plants within a 1.5 m × 1.5 m (5 ft. × 5 ft.) area within the center of each plot. It took nearly two weeks for the entire above-ground portion of the plant to dry in an oven at 50°C, after which the ears were shelled. First the average yield per plant was calculated for total biomass and grain, and then this number was scaled to a 1 ha basis using the density of 66,000 plants ha^{-1}.

Yield response functions were fit to the corn and squash data using PROC REG in SAS (version 9.1.3). Data from plots at the far south end of the field (101 and 121 for squash, 201 and 221 for corn in Fig. A.1) were not used in the regression models. Due to the slope of the field, irrigation water tended to pool there, and unusually high yields were observed for those plots. Because the number of observations at each compost level varied, residual error terms were weighted so that each compost level had equal weight as a group. This was accomplished by giving each error term a weight equal to the inverse of the number of observations at that compost level.

The compost/crop price ratio for squash was calculated based on a compost price of \$104 $(Mg\ DM)^{-1}$, as detailed above. The squash harvested in this experiment were sold at a local market for \$3.30 to \$4.40 kg^{-1} (\$1.50 to \$2 lb^{-1}), depending on the time of season. Using the midpoint of this range led to a compost/crop price ratio of 0.03 (Mg squash)(Mg DM)$^{-1}$.

RESULTS AND DISCUSSION

Fig. A.2 shows the effect of compost on squash yield after 2, 3, and 4.5 weeks of harvest, picking fruit twice a week. Data points represent the average yield at each of the five compost rates investigated. Production peaked in the third week of harvest, which is evident by comparing the change between 2 and 3 weeks and between 3 and 4.5 weeks. The overall shape of the yield response, in which yield seemed to reach a maximum between 20 and 30 Mg DM ha^{-1}, suggested a quadratic model would be appropriate.

For the data at 4.5 weeks, the regression model (dashed curve) had an initial slope of 0.42 (standard error 0.13), which exceeds the compost/crop price ratio of 0.03 (Mg squash)(Mg DM)$^{-1}$. This means it was more profitable to apply compost than not. Precisely how much compost would be optimal depends on the magnitude of the carryover, which will be estimated in years two and three of the experiment.

Corn grain yield responded weakly to compost, as shown in Fig. A.3. Over the range of rates considered here, the average response (dashed line) was 0.013 (Mg grain)(Mg DM)$^{-1}$, or 0.004 ha (Mg DM)$^{-1}$ when normalized by the mean yield of 3.4 Mg grain ha^{-1}. By comparison, the initial response of the squash, normalized by its mean yield, was five times larger.

Because the nutritional requirements for corn are generally higher than for squash, it is surprising that squash but not corn responded to compost at the site. One possibility is that higher levels of fertility are needed for corn to produce a clear yield response discernible against the background of variability present in the field. This could be tested by using higher compost rates in future years.

For the purpose of estimating the decay series in years two and three, the yield responses in year one are not needed. Comparisons only need to be made between plots within a single season. Nonetheless, the weak response for corn over the range 0–40 Mg DM ha^{-1} is cause for concern. If the amended corn plots were similar to the zero-rate plots in year one, then corn plots fertilized only with carryover are also likely to be indistinguishable from zero-rate plots in year two. If this happens, the second term in the decay series will appear to be zero.

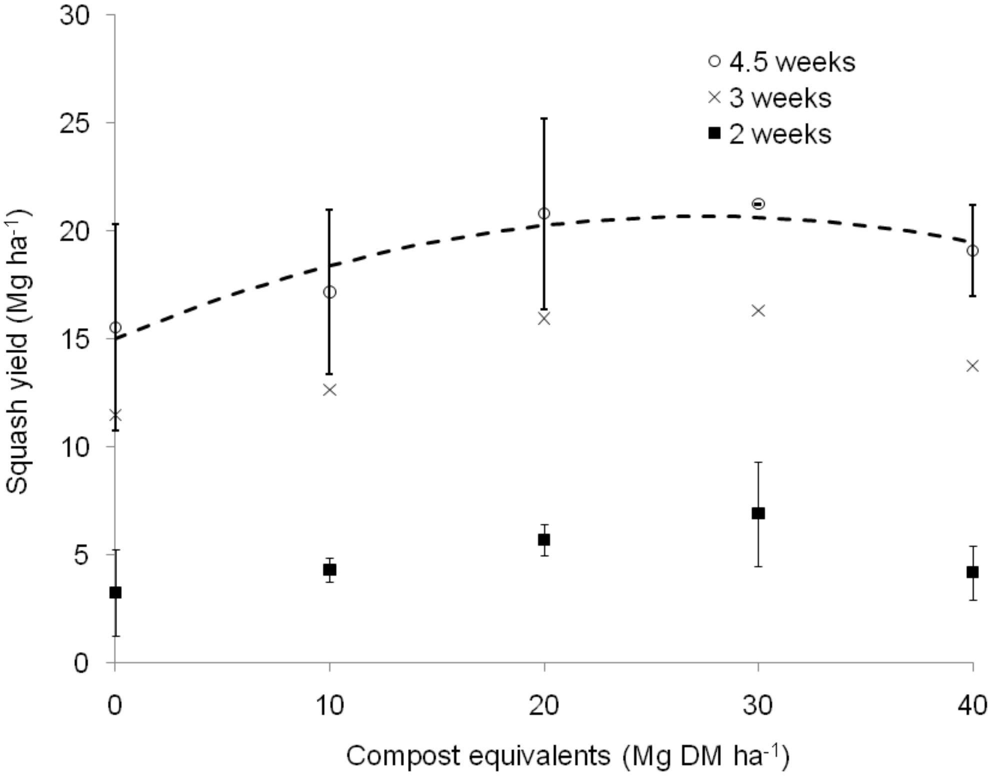

Fig. A.2. Squash yield response. The cumulative fresh weight of summer squash is plotted after 2, 3, and 4.5 weeks of harvest (individual plot yields reported in Table A.3). Data points are the average for each compost level (plots 101 and 121 not included), and the errors bars indicate +/- one standard deviation (s.d.). The s.d. at 3 weeks was omitted so that the s.d. at 4.5 weeks could be clearly seen. The dashed curve is the best-fit quadratic model ($Y = Ax^2 + Bx + C$) for the data at 4.5 weeks. The regression estimates (and standard errors) are A = -0.0076 (0.0032) ha (Mg squash)(Mg DM)$^{-2}$, B = 0.42 (0.13) (Mg squash)(Mg DM)$^{-1}$, and C = 15.0 (1.1) Mg squash ha^{-1}.

Table A.3. Squash yields. Cumulative fresh weights (Mg ha^{-1}) are reported.

Plot	Compost (Mg DM ha^{-1})	Yield (2 weeks)	Yield (3 weeks)	Yield (4.5 weeks)
101	0	1.7	10.1	18.4
102	0	2.3	9.7	13.0
103	0	2.6	13.4	18.5
104	0	3.5	14.9	22.1
105	0	3.0	11.7	16.8
106	20	6.2	15.5	22.1
107	0	0.9	7.7	10.1
108	0	0.5	9.5	11.4
109	0	0.5	7.6	12.4
110	0	1.8	8.7	11.0
111	40	2.8	12.9	17.5
112	30	5.2	16.0	21.2
113	40	4.5	12.7	18.3
114	10	4.5	13.7	19.6
115	0	0.8	5.2	10.5
116	0	2.6	11.2	14.6
117	0	1.1	7.7	13.1
118	0	1.2	6.8	9.3
119	0	3.0	11.6	14.4
120	0	1.3	7.6	9.9
121	30	7.2	22.7	35.7
122	0	5.8	17.3	26.2
123	20	6.0	19.2	24.4
124	0	8.7	21.4	26.4
125	0	6.8	15.3	18.9
126	30	8.6	16.6	21.2
127	40	5.2	15.7	21.4
128	0	3.2	11.7	16.2
129	10	3.7	13.5	19.0
130	20	4.9	13.1	15.8
131	0	4.9	14.8	21.7
132	0	4.3	12.3	14.1
133	10	4.7	10.6	12.8
134	0	5.3	15.7	21.9
135	0	4.7	14.5	17.8
136	0	5.0	12.6	15.4
137	0	4.3	12.3	16.2
138	0	3.2	9.6	11.7
139	0	3.6	11.5	13.8
140	0	2.8	7.4	12.1

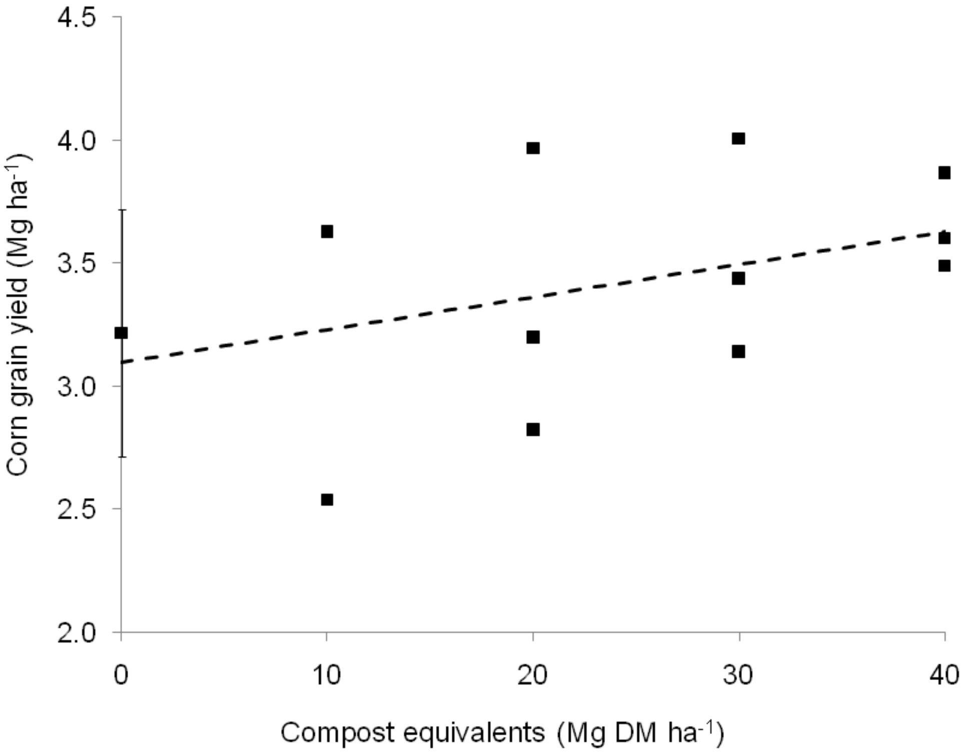

Fig. A.3. Corn grain yield response. The average yield (+/- one standard deviation) for plots with no compost is shown, as well as the individual plot yields at nonzero compost rates (plots 201 and 221 excluded from figure; see Table A.4 for full listing). A linear model ($Y = Ax + B$, dashed line) was fit to the data. The regression estimates (and standard errors) are A = 0.013 (0.005) (Mg grain)(Mg DM)$^{-1}$ and B = 3.1 (0.1) Mg grain ha^{-1}.

Table A.4. Corn data for Greenville experiment.

Plot	Compost (Mg DM ha^{-1})	Tissue %N at 32 days	Silage yield (Mg DM ha^{-1})	Grain yield (Mg ha^{-1})
201	0	3.6	15.7	4.6
202	0	3.8	14.9	4.0
203	0	3.7	14.0	3.5
204	30	3.9	16.8	4.0
205	0	3.8	14.2	3.1
206	0	3.7	12.7	3.4
207	40	4.1	15.4	3.5
208	0	3.8	13.2	3.5
209	0	4.0	10.6	2.1
210	0	3.8	11.4	2.8
211	20	3.9	13.2	3.2
212	0	3.7	12.3	3.3
213	0	4.1	13.2	3.8
214	0	3.8	11.2	2.7
215	30	3.5	15.7	3.4
216	0	3.5	13.2	3.2
217	0	3.7	12.7	2.6
218	40	3.7	16.2	3.6
219	0	3.3	10.1	2.5
220	0	2.7	9.2	3.0
221	10	3.7	17.9	4.7
222	0	3.8	16.7	3.7
223	20	3.6	16.5	4.0
224	0	3.5	14.4	3.6
225	0	3.9	18.6	3.7
226	10	3.6	13.7	3.6
227	0	3.8	11.3	3.1
228	0	3.4	14.4	3.8
229	0	3.6	13.2	3.3
230	0	3.8	15.4	4.0
231	40	3.9	15.7	3.9
232	0	3.5	16.5	3.6
233	0	3.4	11.2	2.9
234	0	3.4	13.2	3.4
235	0	3.6	11.4	2.6
236	30	3.4	14.1	3.1
237	0	3.2	12.4	3.0
238	0	3.3	10.5	2.6
239	20	3.4	13.2	2.8
240	10	2.9	9.9	2.5