Although invaluable as fertilizer in traditional agriculture, animal manure was largely perceived as waste in the decades following World War II due to the availability of inexpensive synthetic fertilizer. Heightened awareness of the environmental consequences of over-fertilization refocused attention on manure utilization in the 1990s. In recent years, the rising cost of synthetic fertilizer has reinforced the idea that efficient use of manure, and compost derived from it, can have both economic and ecological benefits. The economic imperative to use manure and compost efficiently is perhaps greatest on organic farmland, where no synthetic fertilizer is used, but current approaches to organic fertility management are based on meeting nutrient targets designed to maximize yield, not profit.

A fundamental result from agricultural production economics is that the fertilizer rate that maximizes profit—the economically optimal rate (EOR)—is less than the rate that maximizes yield because of diminishing returns with respect to additional fertilizer. In other words, as more fertilizer is added, at some point the cost of an additional unit of fertilizer exceeds the revenue gained from the additional yield. Within a single season, the slope of the yield response at the EOR equals the fertilizer/crop price ratio. When a fertilizer affects yield in the years after its application, however, the optimality criterion for the EOR must be modified. Intuitively, one can see that carryover effects with a multi-year planning horizon change the EOR because even if the cost of an additional unit of fertilizer cannot be recouped in the current year, it can be paid off by carryover effects in subsequent years. Although the theory for EORs with fertilizer carryover is not well known, it has been used on occasion to account for the carryover effects of synthetic fertilizer. Because two of the main fertilizers used in organic agriculture—manure and compost—have pronounced carryover effects, the theory is particularly important to organic crop production.

Figures 1 and 2 (next page), which are based on data from a certified organic dryland wheat–fallow system in northern Utah, illustrate the potential for carryover effects with compost. In the fall of 1994, compost was incorporated before planting the winter wheat at several rates. This site was harvested in 1995, and that fall, the same experiment was conducted at an adjacent site, harvested in 1996. Figure 1 shows that in both years, the yield increased in response to the compost, but only up to a point, after which there was no further increase. The large yield difference between the two harvests reflects year-to-year variability in precipitation.

In the fall of 1996, after a year of fallowing, the first site was replanted with winter wheat, but no additional

Abbreviations: CC, cumulative carryover; EOR, economically optimal rate.
compost was applied. Figure 2 shows the 1995 and 1997 harvest data as a function of the compost applied in the fall of 1994. The yield increase due to the carryover effects of the compost in 1997 was comparable to the yield increase in 1995. These data and subsequent research at the site have confirmed that the carryover effects of compost can be detected for many years in dryland wheat.

**Decay series**

Of the primary macronutrients (N, P, and K) in manure and compost, N has the most pronounced carryover effect. Compared with 70 to 100% of the total K and P, anywhere from 0 to 50% of the total N is bioavailable within the season of application, depending on the materials and extent of decomposition. A N decay series describes what fraction of the total (or organic) N is available for plant uptake in the first, second, third, etc., years after application. Nitrogen decay series have traditionally been measured by comparing the yield in plots receiving manure with the yield in plots receiving N fertilizer. For example, a N decay series of 0.4, 0.2, … means that plots receiving 200 lb manure N/ac had the same average yield as plots receiving 200 × 0.4 = 80 lb fertilizer N/ac in the first year. In the following year, provided no new manure was added, the manured plots had the same average yield as unmanured plots receiving 200 × 0.2 = 40 lb fertilizer N/ac. In practice, a regression model is used to interpolate between the N fertilizer rates used in the experiment.

Even if a decay series is not fully known, it may be possible to estimate the cumulative carryover (CC) for a manure or compost. CC measures the cumulative fertilizing value in the years following an application relative to the fertilizing value in the first year. In principle, the CC encompasses both nutritive and non-nutritive effects, but almost no quantitative information is known about the latter. Because well-composted manures have a low N-fertilizing value in the season of application and release a greater proportion of their total N for plant uptake in the years after application, these materials are expected to have a higher CC than fresh manure. As an example of how the CC would be calculated based on N, consider a compost that releases 10% of its total N in the first year. If one credits 50% of the total N as eventually available for plant uptake, then the CC based solely on N would be (50 – 10)/10 = 4.

**Case study: EOR for organic dryland wheat**

The real data in Fig. 1 and 2 were used to guide the simulation of a dryland wheat system in northern Utah. In this simulation, compost was applied once every four wheat crops, which means once every eight years in the wheat–fallow system.

The EOR depends on both the CC, which was initially assumed to be 4 (see above), and the ratio between the price of compost (p_c) and the price of wheat (p_w). In early
In 2008, a commercial compost manufacturer in northern Utah quoted bulk prices equivalent to $125/dry ton for delivery to the farm site. That summer, the average price for food-grade, organic hard red wheat in the Upper Midwest was $540/ton, leading to a price ratio of $p_u/p_y = (125/dry ton compost) ÷ (540/ton wheat) = 0.23. By the summer of 2009, the price of wheat had fallen to $260/ton, which translates into a price ratio of 0.48.

Figure 3 shows the EOR for the Utah organic dryland wheat system at price ratios between 0.16 and 0.40. As the price ratio increases, the EOR decreases. This is intuitive because the higher the price ratio, the lower the value of the wheat relative to the compost, and thus a larger increase in yield is needed to pay for an additional unit of compost. Since the slope of the yield response increases as the production level decreases (see Fig. 1), a rising price ratio pushes the EOR to lower levels of production. Because a quadratic model was used in Fig. 1, the relationship between the EOR and the price ratio in Fig. 3 is linear.

The three lines in Fig. 3 correspond to the 1995 (solid), 1996 (solid), and average (dashed) yield responses in Fig. 1. The slopes of the lines, which represent the sensitivity of the EOR to changes in the price ratio, vary because of differences in the curvature of the three yield responses. The EOR based on the 1995 yield response is the least sensitive to changes in the price ratio because it had the highest curvature. For a less concave yield response, such as that observed in 1996, a larger decrease in compost rate is needed to effect the same change in the slope of the yield response, so the EOR becomes more sensitive to changes in the price ratio (the slope of the line in Fig. 3 increases). For each response, the EOR is zero above a critical price ratio, the value of which depends on the initial slope of the yield response.

Whereas the sensitivity of the EOR to changes in the price ratio is linear for a quadratic yield model (Fig. 3), the curves in Fig. 4 illustrate the nonlinear dependence of the EOR on CC. Below a certain threshold, the EOR is zero because the carryover effects are not sufficient to cover the cost of even the first unit of compost. As the CC increases above this threshold, the EOR first increases but then passes through a maximum and eventually decreases.

The presence of a maximum, which is somewhat counterintuitive, is the result of two competing effects. As the CC increases, a lower marginal revenue in the season of application can be tolerated because of the additional revenue generated by carryover, which tends to increase the EOR. On the other hand, the rate increase needed to achieve a higher fertility state decreases as the CC increases, which tends to lower the EOR.

**Discussion and conclusions**

The objective of this research has been to develop and apply a method for calculating the EOR of compost.
that properly credits its pronounced carryover effects. The results were formulated to capture essential aspects of the agronomy and economics, but additional layers of complexity could be added. For example, the price of wheat can vary depending on protein content, which is in turn affected by the level of fertility. With sufficient data to model the effect of compost rate on wheat protein content, this relationship could be included in the calculation of compost EORs.

This article has considered the problem of optimizing the compost rate for a given cropping system, but in reality, there is interplay between the design of the cropping system and the choice of an optimal rate. In any location, there are likely to be several feasible rotations for which a myriad of factors need to be considered, including environmental and economic sustainability. Such comparisons should be made after optimizing the compost rate along the lines indicated. Systems in which the EORs are so high as to warrant concern about phosphorus accumulation should be avoided when alternatives of comparable profitability and enhanced environmental protection are available.

In the case study of dryland organic wheat, it was shown that the EOR decreases as the compost/price ratio increases, and the EOR exhibits a maximum with respect to the CC. The EOR for compost sold by one of the region’s main composting facilities was predicted to be zero, although there is considerable uncertainty in this conclusion because there was a lack of empirical data for carryover in organic systems. Compared with conventional agronomic systems, the gap between the maximum-profit and maximum-yield approaches in organic systems may be wider due to the high cost of organic fertilizers. Experimental studies are needed to explore this issue and to improve the efficiency of organic fertility management.


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