Background for *KSU-NPI_CropBudgets.xls*

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Purpose

University agronomy departments and soil testing laboratories long have provided recommended fertilizer rates, but rarely have provided information how such rates may need to change in the face of rapidly changing crop and/or fertilizer prices. *KSU-NPI_CropBudgets.xls* (hereafter referred to as *NPI_CB*) is an Excel spreadsheet to help decision-makers select optimal fertilizer and irrigation rates based on prices of crops, fertilizer N and P, and irrigation pumping costs. Simply put, *NPI_CB* starts with the fertilizer rates recommended by KSU's Agronomy Department, and adjusts them by price. Cell comments within *NPI_CB* generally provide sufficient information for using it as a tool to determine fertilizer and irrigation rates. However, this paper provides additional information behind *NPI_CB* so that its users better understand the connection between agronomy-developed rates and those suggested by *NPI_CB*. To expedite understanding, this paper is mostly non-mathematical. Readers or users of *NPI_CB* who desire more mathematical detail should consult related papers of the authors or the authors themselves.

Connections with Agronomy

Crop and fertilizer prices assumed consistent with KSU's fertilizer recommendations

We start with the publication from KSU's Agronomy Department, *MF-2586 Soil Test Interpretations and Fertilizer Recommendations*, June 2003. Among other recommendations and information, *MF-2586* provides yield-goal-based fertilizer N and fertilizer P (phosphate, P2O5) rates given soil tests. In *NPI_CB* these rates are simply referred to as KSU recommended nitrogen or phosphate rates. Although *MF-2586*-recommended fertilizer rates do not explicitly account for price, we assume that their authors had some long term prices in mind. After all, if fertilizer were sufficiently expensive or crops sufficiently devalued, recommended rates likely would have been much lower or 0. In particular, we assume agronomists implicitly expected prices similar to those seen in the prior 10 years (1993-2002). So, we use harvest-time (June for wheat, June-August for alfalfa, and October for corn, grain sorghum, soybeans, and sunflowers). Sunflower (oil-type) prices were taken to be those observed at Goodland, Kansas and all other crop prices were statewide values from Kansas Agricultural Statistics. Fertilizer prices are taken from USDA's monthly U.S. fertilizer prices. N price is a weighted-average of 50% anhydrous ammonia (82% N), 25% urea (45% N), and 25% UAN (32% N). Phosphate (P2O5, hereafter sometimes referred to simply as P) price is a weighted-average of 50% APP (ammonium polyphosphate, 10-34-0, 34% P2O5) and 50% DAP (diammonium phosphate, 18-46-0, 46% P2O5) after adjusting for the value of N contained.

Based on the above description, the prices we assume KSU agronomists had "in mind" when constructing their *MF-2586* fertilizer rate recommendations were as follows: wheat $3.22/bu, corn $2.35/bu, grain sorghum $2.01/bu, soybeans $5.46/bu, sunflowers $9.69/cwt, and alfalfa $79.37/ton. The fertilizer prices were $0.2094 per lb of N and $0.2445 per lb of P2O5. That is, even though KSU agronomists do not explicitly mention prices, we assume the KSU-recommended fertilizer rates are consistent with these price levels.

Fertilizer response models

In a given site-year, fertilizer trial crop yield often is observed to respond linearly to fertilizer, where each additional unit of fertilizer induces the same incremental increase in crop yield – at least up to some point, whereupon additional units of fertilizer no longer elicit a response in yield. If crop producers expected such a linear plateau response then economically they would either apply 0 or the full amount required to reach peak crop yield. It all depends on price, i.e., if the value of the first unit of yield response is sufficient to cover the cost of the first unit of fertilizer, then so will each successive unit of cost be covered. Unfortunately, other factors, most notably weather, greatly impact the slope of the fertilizer response (e.g., some years there is no response; a 0 slope) and the inflection point (the fertilizer rate where yield response goes to 0) in any given year. Since, producers do not know future growing conditions at the time of fertilizer decision-making, they likely behave as though they expect fertilizer response to be an average of a series of linear plateaus (they expect average weather). Put another way, it is equally likely that the fertilizer response in the upcoming year will look like the fertilizer response in any historical year. Such an average is no longer a linear plateau, but rather a collection of line segments eventually reaching a plateau equal to the average plateau across site-year trials. This collection of line segments looks rather like a curvilinear response curve, effectively reflecting diminishing returns to fertilizer, where each additional unit of fertilizer induces a smaller yield response than the preceding unit, and so on. In the case of N, this idea has been documented and mathematically described in a publication entitled *N Response Functions for Today's Production Costs*, available at www.agmanager.info.

In a curvilinear diminishing returns response function (yield on the y-axis and fertilizer on the x-axis) it is easily shown that the profit-maximizing fertilizer rate is determined by the ratio of fertilizer price to crop price. The optimal rate is the point where a linear line with a slope equal to that ratio is tangent to the response function. For example, when the ratio is larger (e.g., an increase in fertilizer price not coupled with an increase in crop price), the point of tangency will be farther to the left, implying a lower optimal rate of fertilizer.

Unfortunately, mathematically there are an infinite number of curvilinear response functions, with each one leading to a different recommended optimal fertilizer rate. But, our work discussed in the paper *N Response Functions for Today's Production Costs* strongly suggests that the quadratic plateau response model is a reasonable mathematical model to use, at least for N. Since we did not have sufficient empirical P-response data to reliably determine which response function to use, we simply assumed that expected P-response, like N-response, can reliably be represented using a quadratic plateau model.

Irrigation response models

Regarding response of crop yield to irrigation water, we rely on data and research from soil and water management specialist in KSU's Agronomy Department, Lloyd Stone. If more detail is desired, the reader can easily locate a number of Stone's papers that display his research. The relevant aspects of his work for us is that it provides yield response to water information and makes it clear that the response reflects diminishing returns and a quadratic mathematical functional form. In *NPI_CB* we normalize the response so that users of our tool can input their own yield goals. Also, note that, unlike with fertilizer, KSU did not provide recommended irrigation rates. So, we had no need to posit particular irrigation pumping prices in our model development. Rather, our yield-response-to-irrigation models could be developed without knowing pumping cost. Then, pumping cost is brought in to determine where on a response curve a producer should operate to maximize profit. Finally, note that Stone's models (hence, ours in *NPI_CB*) depend on a user-input of annual rainfall.

Limiting factors

We assume that KSU agronomists make their crop input recommendations (fertilizer N and P) and develop response models (irrigation water) under the assumption that other management factors are not limiting. Supporting this assumption is the fact that KSU agronomists do not elicit information regarding soil test P (ppm) when making nitrogen recommendations. Likewise phosphate recommendations do not depend upon soil test N and organic matter information. For example, a recommended N fertilizer rate would assume that P is not limiting and vice versa. Similarly, we believe yield response to irrigation water assumes soil fertility is not limiting. Hence, yield is considered to respond essentially independently to each of N, P, and irrigation. Then, we expect crop yield to be the minimum of the three expected yields coming from the three response models. This is referred to as a limiting factor model, where the input that is most limiting caps crop yield and hence is the factor whose rate needs increased if a producer is to obtain a higher yield. We recognize that there has been a body of research suggesting interdependence among input factors, but we assume that the meaningful aspects of such interdependencies can be captured by a limiting factor approach.

Yield plateaus

As with many agronomists, we assume that crop yield plateaus at some point, i.e., it no longer responds with increases in yield from increases in a crop input. Agronomists routinely refer to *yield goals*, even though such yield goals are generally defined more subjectively than objectively. Indeed, KSU's recommended fertilizer rates from *MF-2586*, for both N and P, explicitly depend on a user-determined yield goal.

In *NPI_CB* we also require the user to provide a crop-specific yield goal. We define that value to be the expected yield associated with the application rate a producer would use if the crop input in question were free. Using N as an example, we would ask the question of a producer, What yield would you expect (i.e., averaged over multiple years) if you could always put on as much N as you desired with no consideration of the cost of N (i.e., if it were free)?

Even though we conceptualize yield goals around specific crop inputs, we might ask a similar question across multiple management inputs. For example, for an irrigator we would ask, Given that water, fertilizer N, and fertilizer P were free, what would you expect your crop yield to be? Hence, we consider the producer's yield goal for a crop to <u>not</u> be input-factor specific. Thus, each of our three response models (N, P, and irrigation water) are designed to plateau at the same crop yield, which we refer to as the yield goal. Note that we <u>do</u> expect irrigators to insert different yield goals than non-irrigators – since an irrigator presumably controls one more extremely relevant crop production factor, water.

Development of response models underlying *NPI_CB*

As partially described above, our response models can be characterized as quadratic plateau models. With a quadratic mathematical function (think of Y on the vertical axis responding to X on the horizontal axis), the Y value increases at a diminishing rate with increased X. At some sufficient level of X, the function "turns over" and Y begins to fall with increased levels of X. However, at the point where slope becomes 0 (the apex), we cause the function to become horizontal rather than "turn down." This makes the function a quadratic *plateau*.

A quadratic response model is of the form $Y = A + B X - C X^2$, where A, B, and C represent positive numerical constants and X represents the level of some input. To completely specify such a model the values of A, B, and C must be known. Mathematically, this requires three constraints or independent pieces of information.

Technically, our models compute response to the total relevant input rather than only the user-supplied input. For example, our N-response models compute yield as a function of what we refer to as total usable N (TUN), not just fertilizer N, where TUN brings in also soil test N, the N expected to be mineralized from soil organic matter, and other N credits such as those from manure (TUN is the "X" in the preceding paragraph). Similarly, our P-response models compute yield response to both fertilizer P and soil test P. Also, irrigation response accounts for rainfall. An important benefit to working with total input is that we essentially can use functions with a y-intercept of 0 – since a truly-0 level of any N, P, or water amount likely would lead to a yield of 0. Hence, assuming a 0 y-intercept provides our first piece of information and so A = 0. That the function's apex must equal the user-determined yield goal is the second piece of information. The third piece of information is that the function at KSU's recommended fertilizer rate must have exactly the same slope as the fertilizer-to-crop price ratio assumed from the prices discussed earlier. That is, if a user of *NPI_CB* injects the crop price and fertilizer price we assumed to be underlying a KSU fertilizer recommendation, then *NPI_CB* should suggest an economically optimal fertilizer rate equal to that of *MF-2586*. But, it should be reminded that this only is true when other factors are not limiting, e.g., for N when the P price is set to \$0 (and irrigation water cost set to 0, if relevant) and only true for P when the N price is set to \$0, and so on – to ensure other factors are not limiting.

For documentation purposes we should briefly discuss how we aggregated the managed input with the associated unmanaged intrinsic one so that they could be combined to provide a singular input in our response models. For N, the aggregation was straightforward from *MF-2586* information, as can be seen from an *MF-2586* N rate recommendation (i.e., Nrec) formula:

Nrec = D1 x YG – SOM x D2 – STN – MN – Other Adjustments + Previous Crop Adjustments,

where YG is bu/acre yield goal, “x” denotes multiply, SOM is soil organic matter percentage, STN is profile (0-24 inches) nitrogen from a soil test, MN is nitrogen from manure, other terms are as stated, and all N measures are as lb/acre. D1 and D2 are crop-specific numerical constants. For example, for corn, D1 is 1.6 and D2 is 20, with the latter indicating that each percent soil organic matter is expected to mineralize to 20 lb/acre of usable N during the growing season. In the above formula it is immediately apparent that soil test N and other N credits (e.g., manure) trade off one-for-one with fertilizer N. Similarly, it depicts the rate at which soil organic matter mineralizes to N and hence how that component can be aggregated. So, where fertN denotes lb/a fertilizer N, the TUN formula is

TUN = fertN + SOM x D2 + STN + MN + Other Adjustments – Previous Crop Adjustments.

For P, the aggregation rule was not as easy to discern. An *MF-2586* sufficiency P recommendation (lb/a P2O5: Prec) is of the form:

Prec = F1 + F2 x YG – F3 x F1 x STP – F3 x F2 x YG x STP,

where YG is again yield goal, STP is soil test P in ppm Bray 1P, and F1, F2, and F3 are numerical constants. For corn, F1 is 50, F2 is 0.2, and F3 is 0.05. To generate our aggregation rule we mathematically calculated the first derivative of Prec with respect to STP, which results in the following statement. For each additional unit (i.e., ppm) of STP, Nrec drops by F3 x (F1 + F2 x YG) units (i.e., lb/acre). Hence, using fertP to denote lb/a P2O5 fertilizer, the total usable P (TUP) formula, for ultimate use in the yield-response-to-P function, is

TUP = fertP + F3 x (F1 + F2 x YG) x STP.

We should note the following. Despite the fact that our TUN and TUP formulas were calculated from *MF-2586* “recommended” fertilizer rate formulas, we assume that they hold at fertilizer rates that are different from recommended rates, which is required to make yield everywhere a mathematical function of N or P. We believe this is justified by the fact that *MF-2586* rates (given yield goal) are linearly related to soil test (i.e., the derivative referenced is a constant). In particular, given yield goal and using P for an example, if *MF-2586* believed otherwise, then it would need to recommend a different tradeoff (derivative) between Prec and STP than it does, e.g., one that would depend also upon STP.

A Graphical Representation

Figure 1 graphically shows a rendition of corn yield response to irrigation water, fertilizer N, and fertilizer P. Underlying assumptions are 18 inches of annual rainfall, 20 lb/a soil test N, 2% soil organic matter, 12 ppm soil test P. The yield goal is 225 bu/acre and the corn price is $4.44/bu. Irrigation pumping cost is $6.00 per acre-inch. Fertilizer N and fertilizer P prices are $0.71 and $1.09 per lb of nutrient, respectively. The x-axis shows 0 to 100% of the maximum (yield peaking) input values, which are 19.9 inches of irrigation water, 330 lb/acre for fertilizer N, and 40.2 lb/acre for fertilizer P.

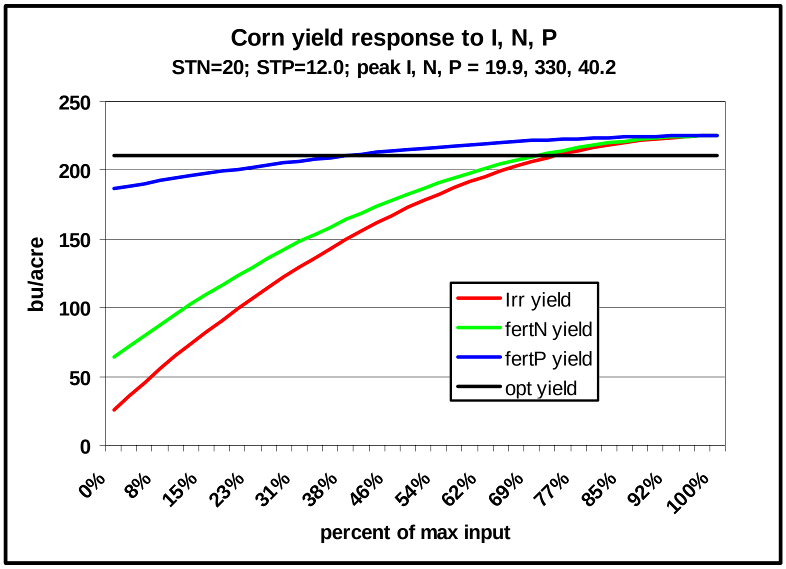

Figure 1

In figure 1, the lines show a positive y-intercept because the figure is showing only the inputs applied and not the intrinsic associated amounts of rainfall, soil test N, and soil test P. And, since we had assumed a fairly high soil test P level of 12 ppm ("high" in the sense that fields treated using *MF-2586* sufficiency P recommendations will equilibrate around 13 ppm over time), that line appears fairly flat. Starting at 0 percent, if all inputs advanced at the same percentage of maximum rate, expected yield would follow the Irr yield line since it represents the lowest yields and hence is the most physically limiting factor in this sense. At the maximum input levels all lines converge on a yield equal to the designated yield goal, or 225 bu/acre. Conceptually (actually, computationally, i.e., what the computer spreadsheet is actually doing to find its solution) one might consider moving a horizontal line incrementally upwards from say 50 bu/acre. The points of intersection between such a horizontal line and the curved lines give the associated crop input rates. At 50 bu/acre, only irrigation water is applied, whereas at higher yields the other two inputs come into the mix. At each yield level the computer computes the crop revenue less the cost of the associated crop inputs, providing a net profit measure at that point. Then, the computer keeps raising the horizontal line until profit no longer increases with each incremental yield increase.

The black horizontal line in figure 1 depicts the economically optimal (profit-maximizing) yield of 210 bu/acre. The associated optimal input rates, i.e., the points of intersection with the curved lines, are 14.5 inches of irrigation water, 231 lb N per acre, and 15.4 lb fertilizer P per acre. KSU's comparable *MF-2586*-recommended fertilizer rates, which do not account for price, would be 300 lb N per acre, and 38 lb fertilizer P per acre. The large reductions in recommended fertilizer rates from *MF-2586* to *NPI_CB* are due chiefly to the much higher prices of fertilizer today than when *MF-2586* was published and that the *MF-2586* rates do not account for changes in prices. But, the reductions in rates also are due to the fact that *NPI_CB* considers all inputs to have a cost, which is discussed below. The profit (return over only N, P, and I cost) is $666/acre. With inputs of 300 lb N per acre, 38 lb fertilizer P, and 18.5 inches of irrigation water, model-estimated yield would be 224 bu/acre and return over N, P, and I cost would be $623/acre. It should be noted that a lower price for any input would induce higher levels of all inputs and thus a higher yield and higher profit.

Extensions to Enhance Understanding

That *NPI_CB* will provide the same fertilizer rate recommendation as *MF-2586* as long as the prices used are the same is technically only correct if a user considers only one input. The pragmatic problem is this. When crop inputs have a cost, they always will be limiting. So, it is practically impossible to consider "What is the optimal rate of one factor assuming the other factor is not-limiting?" However, an *NPI_CB* user can get back a particular KSU recommendation using the historical fertilizer price for one input while setting the price of other factor(s) of interest to 0, which ensures other factors will not be limiting. Nonetheless, even though plugging in the historical prices we noted will result in *NPI_CB* optimal rates that generally are lower than those suggested by *MF-2586*, we believe they are defensible. That is because we believe KSU's underlying empirical yield response research generally was designed around "other factors not being limiting."

We should note that there is no direct mathematical solution to establishing optimal input rates except in the case of a single input. The solution must be developed iteratively, systematically trying different combinations of input levels until profit appears to be maximized. In *NPI_CB*, this could be done using Excel's add-in called *Solver*. Indeed, *NPI_CB* has a section that allows a user to solve for optimal rates using *Solver*. But, since *Solver* is not always reliable to develop the correct solution in such settings, and since many potential users may not have the *Solver* add-in installed in their software, we opted to go with lookup tables instead. As such, we consider 1000 increments of yield, ranging from 0 to the desired yield goal, and compute each of the crop inputs that would be consistent with the incremented yield. This is the exercise described conceptually before, where a horizontal line in the figure is incrementally raised. Then, we find the maximum net return and associated inputs at that level. Because we only consider discrete yield possibilities, we likely will be "off" by some small amount. This is not a large problem, but we do wish for users to be aware of it.

Optimal fertilizer rates suggested by *NPI_CB* are most appropriate for a land tenancy period of one year. That is because, depending upon soil tests, fertilizer application rates often exceed the amount actually removed by the crop taken off a field. This implies that a portion of value obtained by fertilization may not be captured until future years. Generally, due to environmental losses of N, especially in wetter areas, this argument of deferred value is not made in the case of N fertilization (though some are beginning to make it in the High Plains). But, it often is expressly noted in the case of P. Moreover, given sufficient length of land tenancy, it might be profitable to apply more fertilizer P than recommended by *NPI_CB*. In fact, *MF-2586* actually purports two fertilization programs for P, a "sufficiency" one (the one underlying *NPI_CB* yield response models) and a "build and maintain" one. Unfortunately, establishing an economically optimal build and maintain P fertilization program is much more complicated than procedures used in *NPI_CB* and would depend especially upon expected length of land tenancy. Moreover, *MF-2586* makes no claim that its build and maintain program is more profitable than its sufficiency program. Rather it merely depicts *how* to build to a 20 ppm soil test P level by some future time period given some starting soil test level. Consequently, *NPI_CB* does not consider multi-year benefits of either a) optimal one-year fertilizer rates that increase soil test N or P or b) targeting higher fertilizer P application rates than the not-impacted-by-price *MF-2586* rates or the impacted-by-price economically optimal fertilizer P rates suggested by *NPI_CB*. But, the tool does show the expected change in soil test P from the current crop to the next so that a user can gain some understanding of such potential benefits.

Finally, *NPI_CB* does not account for different methods of fertilizer application. Loosely speaking, like those of *MF-2586*, its recommendations are consistent with fertilizer primarily applied via broadcast methods. But, *NPI_CB* does allow a user to proportionately adjust *MF-2586* recommendations, and thus also the economically optimal rates provided by *NPI_CB*. So, an astute user should still be able to use *NPI_CB* to his advantage in making fertilizer decisions.