NUTRIENT EFFICIENCY CONCEPTS FOR PHOSPHORUS AND POTASSIUM

T. Scott Murrell
U.S. Northcentral Director
International Plant Nutrition Institute

ABSTRACT

Two measures of phosphorus (P) and potassium (K) efficiency that are of interest to producers are agronomic efficiency (*AE*) and partial nutrient balance (*PNB*). Agronomic efficiency considers crop response to a nutrient addition while *PNB* measures nutrient removal to nutrient use. Proper evaluation of *AE* requires long term monitoring. A single, large application of P or K can, over many years, result in an AE similar to smaller, annual applications. A larger initial dose will increase soil test levels higher than a smaller annual dose, which can result in higher crop yields sustained over a longer period of time, depending on initial fertility levels. Applications that replace the quantity of P and K removed by crop harvest are termed maintenance applications. It can be shown that for a maintenance application to at least break even economically in one crop season, *AE* must be equal to or great than the nutrient to crop price ratio. For banded applications to have a constant improvement in *AE* over broadcast ones across a given set of nutrient rates, certain conditions must be met. Such conditions have seldom been reported. Improvements that have been reported do not present a complete picture of improved efficiency and are of limited use in production settings. Improvements in efficiency must be weighed against impacts on the long term sustainability of soil fertility levels.

DEFINITION OF RESIDUAL EFFECTS

Phosphorus and K are retained by soils and can therefore impact crop yields and soil fertility many seasons subsequent to their application. Such impacts are termed “residual.” Consequently, the efficiency of an application can be evaluated for one season or many. Proper evaluations of residual effects require longer time periods to truly capture their full impact (Syers et al., 2008). This paper considers two measures of efficiency: agronomic efficiency and partial nutrient balance. They were selected because they are central to the aspects of P and K nutrient management of most concern to farmers and their advisers.

Agronomic Efficiency (*AE*)

Agronomic efficiency considers how much the yield of a crop is increased per unit of nutrient applied. It is defined as (Snyder and Bruulsema, 2007):

$$AE = (Y_F - Y_0) / F \quad [1]$$

where Y_F = the fertilized yield (bu/acre), Y_0 is the unfertilized yield (bu/acre), and F is the rate of nutrient applied (lb/acre). Therefore, *AE* for grains is in units of bu/lb.

To demonstrate some of the different ways *AE* can be evaluated for nutrients like P and K, we consider a study comparing the effects on maize yield of a one-time application of 300 lb P_2O_5/acre to annual applications of 23 lb P_2O_5/acre made on the same experimental unit over time (Webb et al., 1992). Both rates were broadcast and incorporated. The tillage practices consisted of chisel-plowing in the fall followed by disking in the spring. A check was included (Y_0), allowing the *AE* to be calculated for both P rates. A total of 13 years were considered so that the cumulative total of the smaller, annual application rates equaled the single, larger one, keeping the total amounts of P comparable in both treatments.

Figure 1 shows the results of calculating *AE* in different ways. The top line with the greatest *AE* calculates efficiency using only the ($Y_F - Y_0$) observed in a given year and an F = 23 lb P_2O_5/acre. It therefore represents an annual efficiency that does not take into account the fertilization or yield response history (short-term). In the remaining two cases, ($Y_F - Y_0$) is a running total of yield response for all years up to and including the year of interest. Similarly, F represents the sum of all rates up to and including the year of interest (long-term).

Figure 1 points out that short-term evaluations that ignore fertilization history and historical yield responses may produce artificial values of *AE*. Additionally, it is demonstrated that a single, large application of P produced a long-term *AE* essentially equal to the same total P rate broken up into smaller, annual applications. Consequently, evaluating annual applications must consider fertilization history to be properly compared to larger, more periodic doses.

Another important difference between a single, larger P application and smaller, annual ones is their relative effects on soil test levels (Figure 2). In the same study cited above, the 300 lb P_2O_5/acre dose initially increased soil test levels well above the critical level of 20 ppm Bray P1. This level was the point in the study below which greater probabilities existed that soil P levels were too low to fully supply crop needs. Over time, with no subsequent fertilization, soil test levels dropped in an exponential manner and by year 8 were below the critical level. Such exponential decreases have been observed by others (McCollum, 1991; Syers et al., 2008). Conversely, annual applications of 23 lb P_2O_5/acre never did raise soil test levels higher than the critical level. Instead, they resulted in steady declines in soil fertility. By the end of the time period considered, both rates resulted in nearly identical and low final soil test levels.

An important difference between the two dosage distributions in Webb et al. (1992) arose in yield response. Figure 3 shows that the larger, single rate resulted in higher cumulative yields by year 4 that remained higher during the rest of the 13-year period. Economic analysis in the study examined only short-term returns to annual applications. However, there are implications upon long-term profitability. Higher yields sustained earlier are capable of providing revenue that has a higher value when considered over the entire 13 year period, since currency tends to devalue over time. Additionally, a one-time purchase of P could have been timed to match with favorable crop price and nutrient price conditions if sufficient capital were available and if the land were owned or under a long-term rental agreement. In some cases, a single, larger investment in fertilizer that is well timed in the market can be more profitable over the long term than smaller, annual purchases more subject to fluctuating economic conditions. Profitability analyses should examine such long-term factors to provide a complete picture of risk.

Partial Nutrient Balance (*PNB*)

Partial nutrient balance is the ratio of the quantity of nutrient removed in harvested crop portions (U_H) to the quantity of nutrient applied (Snyder and Bruulsema, 2007):

$$PNB = U_H / F \quad [2]$$

Accuracy in determining *PNB* primarily entails 1) measuring, rather than estimating the concentration of nutrients in harvested crop portions and 2) accounting for all applications of nutrients, including manure and commercial fertilizer.

The primary goal of this measure of efficiency is to determine how close a system is to one. A *PNB* value close to one indicates that mass balance exists – nutrient applications to a unit of land approximately equal nutrient removal. Such a balance is necessary for the fertility level of a system to be sustained.

A *PNB* value of one does not guarantee that soil test levels will remain static, however. In a study of irrigated alfalfa, Ludwick and Fixen (1983) found that to maintain P soil test levels on the two soils studied, *PNB* values of 2.2 and 1.4 were needed. For K, these *PNB* values were 0.75 and 0.22. This study used larger broadcast and incorporated fertilizer rates initially, follow by annual applications that were broadcast but not incorporated. Moncrief et al. (1985) demonstrated that for the same total quantity of K applied to a tilled and untilled soil, an unincorporated application to the surface of the untilled soil resulted in higher soil tests when evaluated by a 15 cm deep sample. These two studies demonstrate that the distribution of nutrients within the soil can greatly affect whether or not soil test levels will remain constant or change when maintenance applications, those that keep *PNB* near one, are made.

Agronomic Efficiency of a Profitable Maintenance Application

When efficiencies are examined, it is often difficult to know how to interpret them. How much efficiency can reasonably be expected? In this section, we examine the minimum *AE* to be expected for a profitable maintenance application.

As discussed above, a maintenance application rate is one that strives to maintain mass balance, keeping *PNB* close to one. This rate may be defined as:

$$F_{\mathrm{maint}} = rY_F \quad [3]$$

where F_{maint} is the maintenance rate, r is the rate of nutrient removal per harvested crop unit, and Y_F is the fertilized crop yield.

To begin with, we consider a single season. For F_{maint} to be profitable in that season, the revenue from the increase in yield due to the application must be at least equal to the nutrient cost. This can be expressed as:

$$P_c(Y_F - Y_0) \geq P_F(F_{\mathrm{maint}})$$

where P_c is the price of the crop, Y_F and Y_0 are the fertilized and unfertilized yields, respectively, and P_F is the price of the nutrient applied at the maintenance rate. Rearranging this equation and defining a new variable R to be the ratio of fertilizer price to crop price ($R = P_F / P_c$) which is a unitless quantity, we obtain the following:

$$(Y_F - Y_0) / F_{\mathrm{maint}} \geq R, \text{ or } AE \geq \mathrm{R} \quad [4]$$

Thus, for a maintenance fertilizer application to be profit neutral, it must have an *AE* at least equal to *R*. An *AE* value greater than *R* is profitable within one crop season.

These relationships are demonstrated graphically in Figure 4. During the first increments of nutrient addition, *PNB* decreases rapidly as both Y_F and the nutrient rate increase. As the rate approaches F_{maint}, PNB reduces to 1. Simultaneously, *AE* becomes smaller as both the rate increases and as the crop response begins to level off, but because a profitable scenario is depicted, AE remains above R by the time F_{maint} is reached.

Maintenance applications are important for sustaining nutrient mass balance in soils. This discussion demonstrates that it is possible to define at least a minimum *AE* that may be expected if a maintenance application is to be profitable in a single season.

Nutrient Placement Effects on *AE* and *PNB*

In many states in the western U.S. Corn Belt, recommendations exist for reducing fertilizer rates if they are applied in a band, rather than broadcast (Gerwing and Gelderman, 2002; Rehm et al., 2006; Shapiro et al., 2003). Sometimes the degree of reduction varies by soil test level (Rehm et al., 2006) and sometimes it does not (Shapiro et al., 2003). Often, banded rates are reduced to half of the broadcast rate.

The primary assumptions behind this recommendation are that banded applications (b) are generally more efficient than are broadcast applications (B) and that both produce essentially the same yield response. These assumptions are shown graphically in Figure 5. In this figure, the commonly used quadratic-plateau function ($Y_F = \beta_0 + \beta_1 F + \beta_2 F^2$ for $F \leq F_{max}$; $Y_F = Y_{max}$ for $F > F_{max}$) was chosen to model crop response. The figure shows the case where a banded application has twice the *AE* as a broadcast application ($AE_b = 2AE_B$ in the bottom graph). This doubling in efficiency arises strictly from the half rate of banded fertilizer needed to produce maximum yield (Y_{max}) compared to a broadcast application ($F_{max\text{-}b} = 0.5F_{max\text{-}B}$ in the top graph). The higher efficiency of the banded application can be expressed by the ratio $F_{max\text{-}b} / F_{max\text{-}B}$ which equals, in this case, 0.5.

It can be demonstrated that under the crop response scenario described above, the following relationships hold. First, the intercepts (β_0) of the two equations are the same:

$$\beta_{0B} = \beta_{0b} \qquad [5]$$

where β_{0B} is the intercept of the broadcast response curve and β_{0b} is the intercept of the banded one. Next, the coefficient of linear slope (β_1) for the crop response to the broadcast rates can be described as:

$$\beta_{1B} = (F_{max\text{-}b} / F_{max\text{-}B})\ \beta_{1b} \qquad [6]$$

where β_{1B} is the coefficient of linear slope for the broadcast rates and β_{1b} is the same coefficient for the banded rates. Similarly, the coefficient of curvature (β_2) for the two response equations are related as follows:

$$\beta_{2B} = (F_{max\text{-}b} / F_{max\text{-}B})^2\ \beta_{2b} \qquad [7]$$

As long as these relationships hold, then the improved *AE* of the banded rate relative to the broadcast one is a constant across all rates in the response. The practical implication of this relationship is that if farmers have to reduce rates below those producing maximum yield, banded rates will still have the same efficiency as those producing maximum yield.

The increased efficiency of banded applications compared to broadcast ones has been investigated previously (Welch et al., 1966a; Welch et al., 1966b, Peterson et al., 1981). All of these investigations compared broadcast to banded applications during one crop year and did not consider residual effects. All of these studies also reported crop response as a quadratic function, allowing the theoretical relationship described above to be tested.

Across all three reported studies, 12 site-years of data existed – 9 investigating P and 3 investigating K. Of these 12, only one site-year conformed to the theoretical response described in Figure 5. The study showed that $F_{max\text{-}b}$ / $F_{max\text{-}B}$ = 0.63, demonstrating that at this site, which had a low soil test P level, banded applications could be slightly less than two-thirds of a broadcast application and produce the same yield response. At 5 of the remaining site-years, rates were not selected that maximized yield response to one or both of the placement methods. At 2 site-years, no significant difference existed between placement methods. At the remaining 4 site-years, maximum yields attained by placement methods differed, with banded applications producing higher maximum yields than broadcast ones at 3 of the site-years.

Investigators involved in these studies did not use the theoretical relationship in Figure 5 to evaluate broadcast and banded applications. Instead, a yield level was selected, and broadcast and banded rates needed to attain that yield were compared. While a F_b / F_B ratio can be calculated in this manner for a given set of rates, such a ratio does not provide a complete picture of the crop responses involved and can be misleading. For instance, it is important for the farmer to know that regardless of the efficiency, a broadcast application will not equal the yield response of a banded one or vice versa. Additionally, if the improved efficiency of one application method over another is not constant across all rates, then unexpected results can occur if a rate is chosen that is not the one upon which the comparison was based.

Work by Anghinoni and Barber (1980) has demonstrated that when lower rates of fertilizer are applied to nutrient deficient soils, banded applications that fertilize a smaller soil volume produce higher yields than the same low rates mixed more thoroughly with a larger soil volume. However, as the application rate increases, fertilization of a greater soil volume is necessary to maximize yield, and the yield attained with that higher rate is greater than the yield attained with a lower, banded rate. Banded and broadcast applications used together may provide more complete nutrition than either one alone. Banded nutrients near the seed provide the early season positional availability of a concentrated supply needed to satisfy high nutrient influx rates early in the season (Mengel and Barber, 1974). More thoroughly incorporated broadcast rates increase the quantity of nutrients available to the more extensive root system developed later in the season.

In cases when one fertilizer placement method results in improved *AE*, the reduced rate must be examined carefully to determine how it compares to the *PNB* of 1.0 needed to sustain soil fertility levels. In cases where the more efficient rate is less than this *PNB* value, short-term efficiency gains need to be weighed against the longer-term implications on declining soil fertility should that rate be repeatedly implemented.

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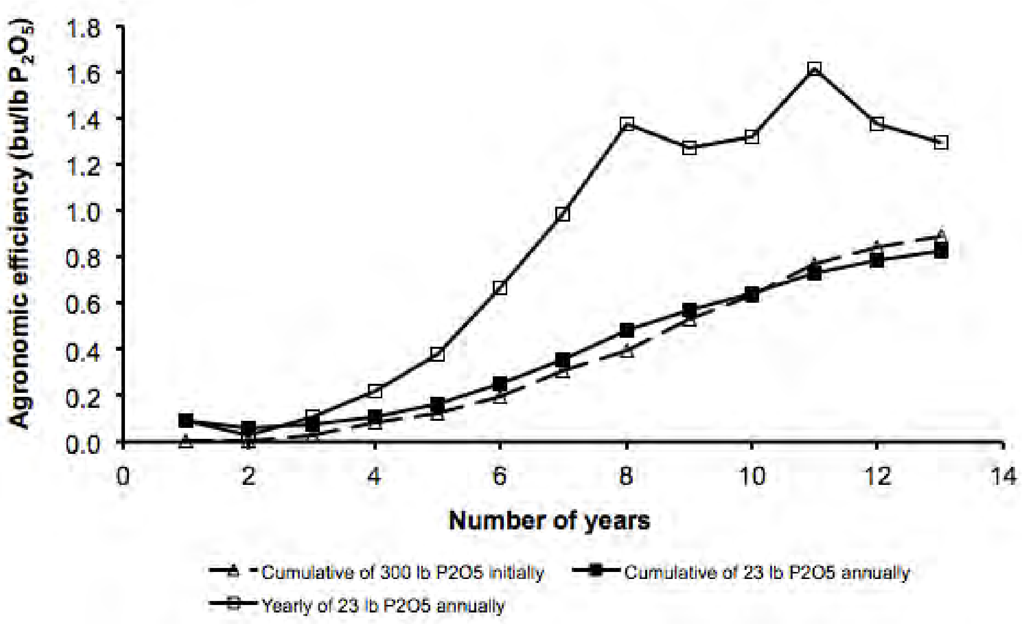

Figure 1. Agronomic efficiency (*AE*) for a one-time application of 300 lb P_2O_5/acre and annual applications of 23 lb P_2O_5/acre. The *AE* of the annual application was evaluated two ways: 1) each year considered individually with no prior fertilization history (yearly of 23 lb P_2O_5/acre annually) and 2) *AE* based on the cumulative sum of annual rates up to and including the current year (cumulative of 23 lb P_2O_5/acre annually). (Webb et al., 1992).

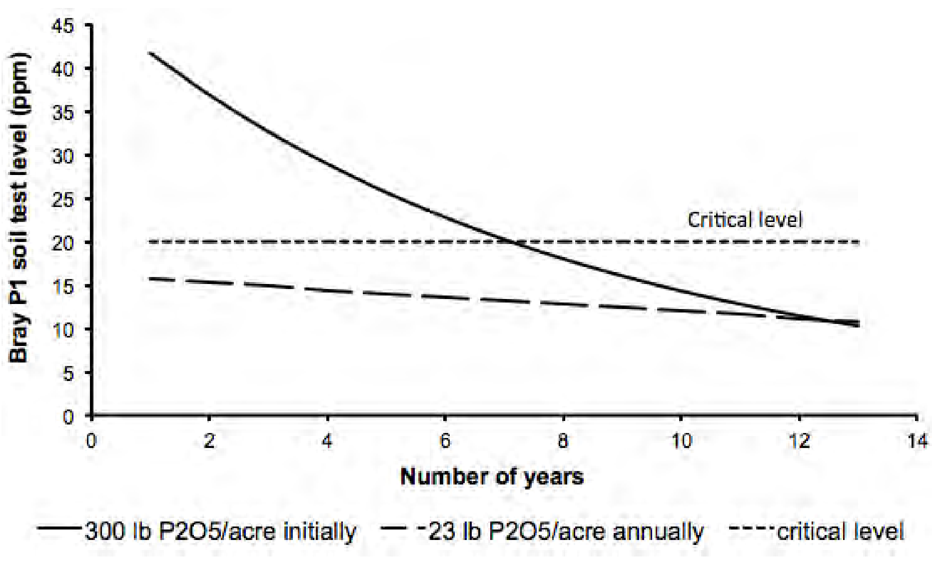

Figure 2. The effect on Bray P1 soil test levels of a single larger P application and a series of smaller, annual ones. The total applied over the time period considered was the same for both application rates (Webb et al., 1992).

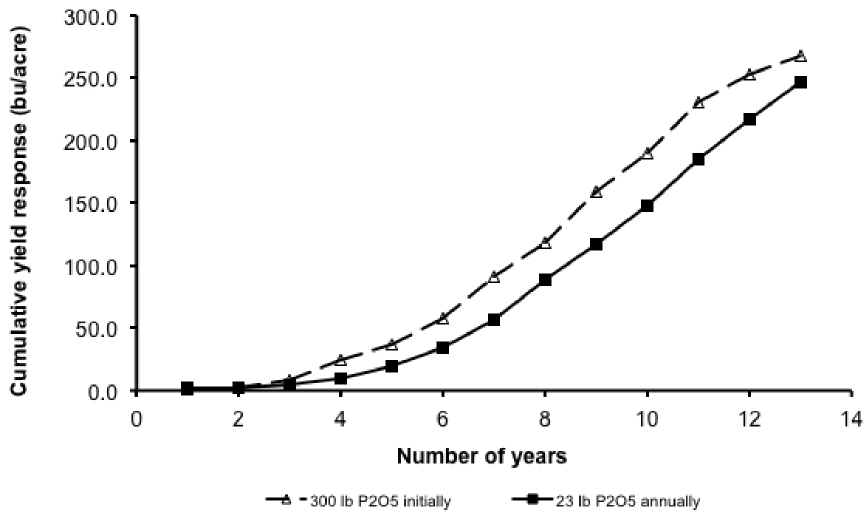

Figure 3. Cumulative yield response to a one time, larger dose of P and to smaller, annual doses of P (Webb et al., 1992).

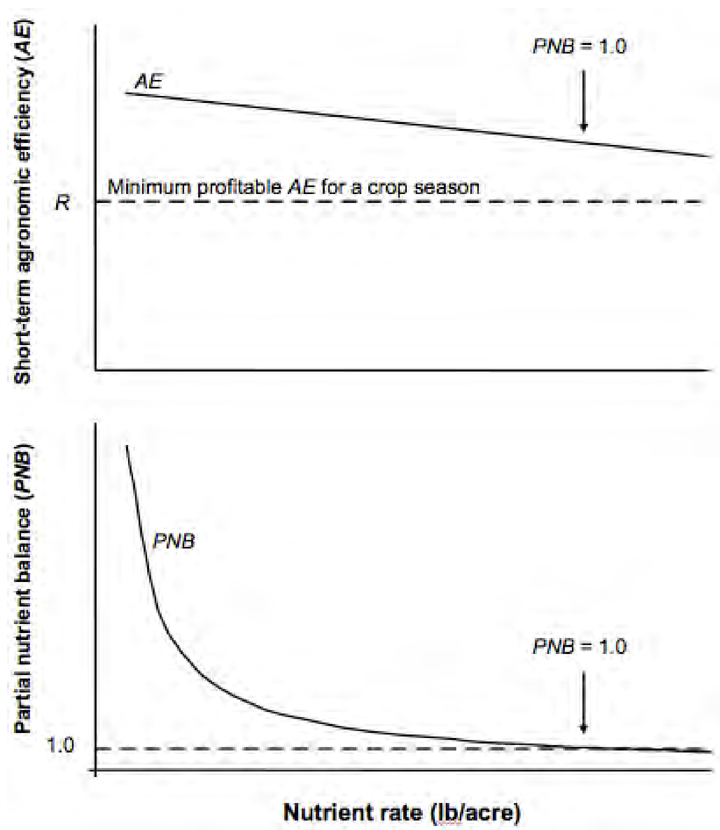

Figure 4. Theoretical relationships between agronomic efficiency (*AE*) and partial nutrient balance (*PNB*) for a situation where a maintenance rate of a nutrient (*PNB* = 1) is profitable in one crop season, resulting in an *AE* > *R*.

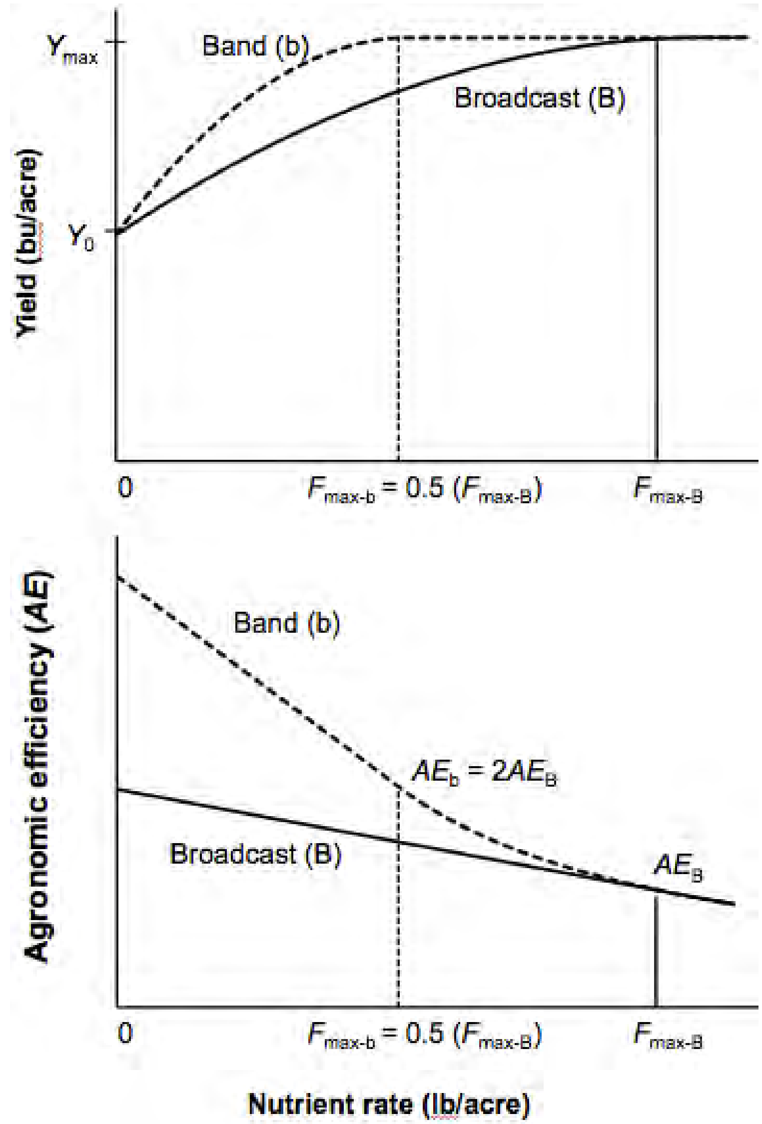

Figure 5. Theoretical relationship between a quadratic-plateau type of crop yield response to a broadcast application and to a banded application that is twice as efficient but which results in the same yield response and maximum yield as the broadcast application.