Development of a fertiliser optimisation technique using multi-nutrient factorial trials and leaf tissue nutrient analysis in commercial oil palm plantations

Michael J Webb

CSIRO Land and Water, Davies Laboratory, Aitkenvale, QLD, Australia, Email michael.webb@csiro.au

Abstract

Ensuring fertilisers are applied at optimal rates makes economic sense as well as minimising the chance of excess nutrients causing environmental damage. A technique has been developed which uses information from factorial fertiliser trials and nearby commercial plantings of oil palm to determine the optimal economic application rates of three nutrients simultaneously, thus accounting for interactions. The technique is based on a spreadsheet application that can be analysed as often as required in response to climate variation, oil price, and fertiliser costs. It also allows for scenario testing by allowing changes in these costs and prices.

Key Words

Fertiliser response, regression models, economic optimum, nitrogen, potassium, phosphorus

Introduction

Optimising fertiliser use to obtain optimum economic yield usually has the added benefit of ensuring that excess fertiliser is not available for loss to the environment. Often factorial fertiliser trials are used where there is the likelihood of multiple nutrient deficiencies (Corley and Tinker 2003, p342). Such trials can also be used to determine a critical leaf nutrient concentration (CLNC) for diagnosis of plant nutrient status.

Webb (2009) developed a conceptual framework for a novel way of using factorial trials to determine optimum economic fertiliser rates for two nutrients in the oil palm industry; based on work by Wilkie and Foster (1989). The advantage of this technique is that it allows use of all of the trial data rather than just those few data, for each nutrient being tested, that are available at the optimum rates of the other nutrients – a common requirement for determining maximum yield. By having these trials near commercial blocks of palms, they can be used on an annual basis to make 'basal' (standard annual application) economically optimum fertiliser decisions in relation to fertiliser costs and oil prices. In addition to this, leaf nutrient analysis in commercial blocks, can be used to make 'corrective' (based on leaf analysis) fertiliser decisions; without the usual issues of soil type, plant age, climate etc, which limit the usefulness/versatility of the common usage of CLNCs (Smith and Loneragan 1997). For example, leaf nutrient concentration in oil palm fronds can vary greatly from month to month (Foster 2003) and these variations may not be consistent from year to year.

This paper extends the framework of Webb (2009) from determining the economically optimum fertiliser rates for two nutrients, to the economically optimum for three nutrients, simultaneously.

Concept

The conceptual framework underpinning this approach is given in Webb (2009) for two nutrients, so only a brief description will be given here. The nutrient requirement (for each nutrient of interest) is made up of a 'basal' amount that should be added each year to maintain optimum growth plus, if necessary, a 'corrective' amount to alleviate any deficiencies (as determined by leaf analysis). The key processes are:

1. Use field trials and multiple linear regression to produce a yield response surface to the three fertilisers applied. Convert this yield to a crop value ($/ha).
2. Subtract fertiliser costs, re-analyse the response surface to obtain an optimum economic yield and determine the rate of application of each of the three fertiliser-nutrients to obtain that yield – this determines the basal fertiliser-nutrient requirements that should be added each year.
3. Analyse leaf tissues from the trial and nearby commercial blocks at the same time.
    a. Use the trial data (on a representative soil type) to produce a leaf-nutrient concentration response surface (for each nutrient) to the three fertiliser-nutrients applied.
    b. For each leaf-nutrient determine its leaf concentration at the rates of the three fertiliser-nutrient application which gave optimum economic yield (from 2 above). This determines the target leaf nutrient concentration (TLNC) for each leaf-nutrient.
    c. Use commercial leaf sampling data and the surface produced in 3a above to determine the 'equivalent' fertiliser-nutrient application rate for each leaf-nutrient.

4. Use the difference between the optimum fertiliser rate and the ‘equivalent’ fertiliser rate to calculate the amount of fertiliser required to raise the leaf-nutrient concentration to the TLNC – this determines the corrective fertiliser requirement.

Theoretical framework

Modelling profit in response to fertiliser-nutrient application

Again, a detailed theoretical framework is given in Webb (2009) for two nutrients, so only that which specifically relates to three nutrients is given here.

Yield (t/ha) can be described by the equation:

$$Yield = a + bN + cN^2 + dK + eK^2 + fP + gP^2 + hNK + iKP + jPN \tag{1}$$

Where N, K, and P represent fertiliser-N, -K and -P respectively; NK, KP, PN represent the interactions and *a-j* are the parameters to be estimated by multiple linear regression (see Webb 2009 for details). This is converted to a crop value ($/ha) by multiplying by *u*, the unit value of the crop ($/t). Thus, crop value is:

$$CropValue = u\left[a + bN + cN^2 + dK + eK^2 + fP + gP^2 + hNK + iKP + jPN\right] \tag{2}$$

Profit is calculated by subtracting the cost of fertiliser application ($/ha). Thus

$$Profit = u\left[a + bN + cN^2 + dK + eK^2 + fP + gP^2 + hNK - iKP + jPN\right] - rN - sK - tP \tag{3}$$

Where *r*, *s*, and *t* are the cost ($/ha) of applying N, K, and P fertiliser respectively.

To find the point of maximum profit, the derivates of the equations are solved for the point at which slope is zero. For two nutrients this is simple (see Webb 2009), but for three these equations become complicated and cumbersome. A simpler way is to use matrix operations. Differentiation of equation (3), equating to zero, and rearranging gives:

$$2cN + hK + jP = r/u - b \quad \text{with respect to N} \tag{4}$$

$$hN + 2eK + iP = s/u - d \quad \text{with respect to K} \tag{5}$$

$$jN + iK + 2gP = t/u - f \quad \text{with respect to P} \tag{6}$$

In matrix form this can be written: $\begin{bmatrix} 2c & h & j & r/u-b \\ h & 2e & i & s/u-d \\ j & i & 2g & t/u-f \end{bmatrix}$. By using Gauss-Jordan row operations (Kalmanson and Kenschaft 1978, p96-101), this is transformed to $\begin{bmatrix} 1 & 0 & 0 & N \\ 0 & 1 & 0 & K \\ 0 & 0 & 1 & P \end{bmatrix}$ where the N, K, and P now represent the application rate which give maximum profit. These thus become the basal rate of fertiliser application resulting in maximum profit.

Modelling leaf nutrient concentrations in response fertiliser-nutrient application

Tissue nutrient concentrations are also fitted to a multiple linear regression of quadratic equations thus:

$$[n] = a + bN + cN^2 + dK + eK^2 + fP + gP^2 + hNK + iKP + jPN \tag{7}$$

Where [n] represent tissue N concentration, and *a-j* are the parameters to be estimated. By substituting N, K, and P with the values that give maximum profit, the corresponding value of leaf N concentration is determined; this is the TLNC. TLNCs for K and P are calculated similarly. It is now necessary to calculate the “nutrient-fertiliser equivalent” of the plantation leaf samples. This is fertiliser-nutrient application rate that would be expected to produce the observed tissue-nutrient concentration. This is determined by solving the quadratic for the above equation (7) rewritten as:

$$0 = cN^2 + (b + hK + jP)N + \left(a + dK + eK^2 + fP + gP^2 + iKP - [n]\right) \tag{8}$$

where [n] is the commercial plantation leaf N concentration. This can also be written as

$$0 = Ax^2 + Bx + C \tag{9}$$

where *x* is the fertiliser-N application rate, $A = c$, $B = (b + hK + jP)$, and $C = a + dK + eK^2 + fP + gP^2 + iKP - [n]$. The solution to this quadratic is

$$x = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$, thus using the original parameters: (10)

$$\text{Fertiliser-N rate} = \frac{-(b + hK + jP) \pm \sqrt{(b + hK + jP)^2 - 4c(a + dK + eK^2 + fP + gP^2 + iKP - [n])}}{2c} \quad (11)$$

Where K is fertiliser-K and P is fertiliser-P, both at optimum rate. Each of these solutions will give two answers but the answer chosen will be the smallest positive. The difference between the fertiliser-N calculated above (11) and the optimum fertiliser-N, represents the corrective fertiliser-N and should be added to the basal fertiliser-N rate. Corrective fertilizer-K and fertilizer-P are calculated in the same way.

In Practice

Brief description of field trial

Full details of the trial are available in PNG Oil palm Research Association Inc. (2005). Trial 209 was set up as a factorial combination of three rates of N (0.42, 0.84, 1.68 kg/palm/yr), three rates of K (0, 1, 2 kg/palm/yr), three rates of P (0, 0.8, 1.6 kg/palm/yr), and three rates of Mg (0, 0.68, 1.36 kg/palm/yr). Yields of fresh fruit bunches (FFB) were averaged for 2003-2005 (Table 1). Treatments N, K, and P main effects produced significant differences ($p < 0.05$) but Mg did not; thus results for the Mg treatment were averaged. Leaf tissues were collected and analysed by standard methods (see Webb 2009).

Table 1. Effects* of N, K, and P treatments on average yield of fresh fruit bunches (FFB) from 2003-2005.

Rate level	FFB (t/ha/yr)		
(see text for actual rates)	N	K	P
1	27.0	27.3	28.2
2	29.9	30.3	30.0
3	31.7	30.9	30.4

* Significance levels were p = 0.001, 0.013, 0.001 for main effects of N, K, and P, respectively.

Analysis of the full data set by multiple linear regression provides the parameter estimates (p value) as follows: a, 20.12 (<0.001); b, 10.24 (0.003); c, -3.31 (0.03); d, 2.61 (0.04); e, -0.91 (0.109); f, 5.77 (<0.001); g, -2.06 (0.01); h, 0.48 (0.41); i, -0.12 (0.80); j, -0.23 (0.75), which, when substituted into (1), predict yield.

Results

All the necessary calculations have been incorporated into a spreadsheet. Using the above parameters and equations, it can be seen that the optimum economic fertiliser application rates (kg/palm/yr) are 1.03 N, 0.23 P (Figure 1) and 0.52 K (not shown) under set conditions of oil price, oil extraction rate and fertiliser cost. These parameters can be varied as prices change or to test various scenarios; some results of which are shown in Table 2. The spreadsheet also provides the recommendation for each commercial block, which includes the basal and corrective rates for each of the three fertiliser-nutrients. As the variable parameters change (oil price fertiliser cost, oil extraction rate), so the recommendations for basal and corrective fertiliser also change in response to the new economic optimum.

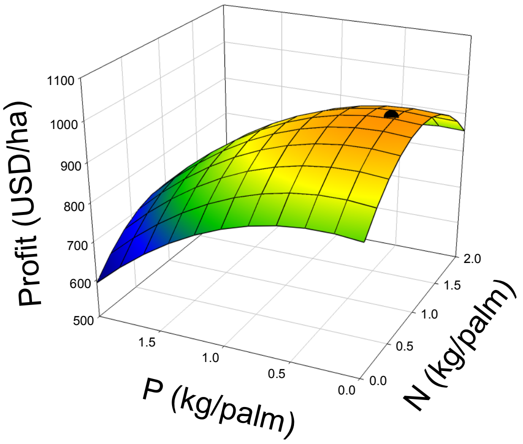

Figure 1. Relationship between profit, and N and P fertiliser.

The scenario testing described above shows that, as expected, with increasing oil price and extraction rates, profit and fertiliser use increases (Table 2). However, surprisingly, at low oil price and high fertiliser cost, profits increase. Inspection of data shows that this is because fertiliser use was reduced to zero in some cases. This clearly reflects the annual nature of the analysis and does not take into account longer term sustainability issues. Thus, sensible decisions based on long term sustainability issues should override short term accounting decisions. Indeed, a sensible approach would be add fertiliser-nutrients at rates which at least replace the nutrient removed in the harvested product.

Table 2. Effect of oil price, oil extraction rate and fertiliser costs on annual profit and fertiliser use.

Oil Price (USD/t)	450		900	
Oil extraction rate (%)	22	25	22	25
Profit (USD/ha)				
Fertiliser Cost 1*	1364	1594	4146	4840
Fertiliser Cost 2	1534	1762	3857	4495
*Fertiliser use (kg/palm)***				
Fertiliser Cost 1	7.7 (62:14:24)	9.2 (57:16:27)	14.1 (48:19:33)	14.5 (47:19:34)
Fertiliser Cost 2	2.0 (1:0:0)	2.9 (1:0:0)	10.8 (53:17:30)	11.7 (51:18:31)

* Fertiliser costs (USD/t) are: ammonium sulphate 300, KCl 400, TSP 300, for “Cost 1” and double that for “Cost 2”.
** Ratio of nutrient mix (N:K:P) in parentheses.

Conclusion

Using multiple linear regression (in this case, for three nutrients), large scale, multi-level, multi-factor fertiliser trials can be used effectively to maximise profit while minimising fertiliser use, and thus minimising the potential for negative off-site impacts. This technique allows for effects of individual nutrients as well as their interactions. These can be responsive to changes in fertiliser cost and oil price and thus used as a decision support/scenario tool for ‘basal’ fertiliser application. When used in conjunction with nearby commercial planting (on the same soil type) with regular leaf nutrient analysis, they can also be used to determine ‘corrective’ fertiliser application rates to counteract nutrient deficiencies that may occur. Although developed for oil palm, this approach could easily be adapted to other perennial crops.

Acknowledgements

The original concept for this work was developed while the author was employed by the Papua New Guinea Oil Palm Research Association. This work was, in part, supported by the Australian Centre for International Agricultural Research.

References

Corley RHV, Tinker PB (2003) The oil palm, 4th edn. Blackwell Science, Oxford.

Foster HL (2003) Assessment of oil palm fertiliser requirements. In ‘Oil palm: management for larger and sustainable yields’ (Eds. Fairhurst T, Härdter R), pp 231-257. Potash & Phosphate Institute/Potash & Phosphate Institute of Canada and International Potash Institute, Singapore.

Kalmanson K, Kenschaft PC (1978) Mathematics: a practical approach. Worth Publishers, Inc: New York.

PNG Oil Palm Research Association Inc. (2005) Annual Research Report – 2005. Dami Research Station, PO Box 97, Kimbe, West New Britain Province, Papua New Guinea, Ph +675 985 4009, Fx +675 985 4040, eMail enquiries@pngopra.org.pg.

Smith FW, Loneragan JF (1997) Interpretation of plant analysis: concepts and principles. In ‘Plant analysis: An interpretation manual’ (Eds. Reuter DJ, Robinson JB), pp 3-33. CSIRO Publishing, Collingwood.

Webb MJ (2009) A conceptual framework for determining economically optimal fertiliser use in oil palm plantations with factorial fertiliser trials. *Nutrient Cycling in Agroecosystems* **83**, 163-178.

Wilkie AS, Foster HL (1989) Oil palm response to fertilisers in Papua New Guinea. In *PORIM International Palm Oil Development Conference*, pp. 395-405.