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An integral method for estimating total leaf area in bananas

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A method that measures total leaf area of banana plants quickly and accurately would be widely adopted. Kumar *et al*. (2002) proposed such a method based on a measurement of the area of the third most recently emerged leaf and the number of leaves present on the plant.

My aim here is to show, firstly, that the 'new factor', suggested by Kumar *et al*. (2002), is restricted by the assumptions on which it is based. Secondly, I wish to propose an integral method that requires two leaves to be measured, but which avoids the problems I perceive exist in the new factor method. Thirdly, I compare the two methods on a limited set of data to illustrate the issues and to show the expected errors in using the two equations.

The 'new factor' method

The formula that Kumar *et al*. (2002) proposed to estimate total leaf area of a single plant was:

$$TLA = \times B \times 0.80 \times N \times .662 \quad (1)$$

where TLA is the total leaf area of the plant, N is the number of leaves on the plant (and also the leaf number of the youngest leaf when leaves are numbered from the oldest (leaf 1) to the youngest (leaf N) as is the case in this paper), L and B are the length and breadth of the third youngest leaf (A_{N-3}), and 0.8 is the proportionality factor proposed by Murray (1960). The new factor is the coefficient with the value of 0.662. To derive the new factor, Kumar e*t al*. (2002) used 25 plants on which they measured A_{N-3} and N to calculate, using the 0.80 factor, the estimated total leaf area and they measured the actual total leaf area (A_m) using a leaf area meter. For each of the 25 plants, the ratio of the actual total leaf area to the estimated total leaf area was calculated and the mean of these values gave the new factor 0.662. This new factor was then used to calculate the total leaf area for each of the 25 plants that had been used to derive it and, not surprisingly, the authors found very good agreement.

Since the new factor of 0.662 was locally derived, extension to other situations may give incorrect estimates of leaf area per plant. The new factor is also determined by the relationship between the size of the third youngest leaf and the remainder of the leaf system, and this can be expected to change during plant ontogeny. Kumar *et al*. (2002) do point out that leaf size varies during development and also add that the new factor was derived to take this into account.

Mathematically the new factor is derived from $(A_m/N)A_{N-3}$ in which A_m/N is the arithmetic mean area per leaf. Therefore, the calculation of the new factor assumes that the increase in leaf area from leaf to leaf during plant ontogeny is linear because it uses the arithmetic mean for its derivation. However, a plot of the increase in leaf area against leaf number during plant ontogeny (Figure 1.15 in Stover and Simmonds, 1987) reveals that the increase in area is not linear but exponential over at least 75% of the plant's vegetative cycle, i.e. the exponential phase ends at leaf 30, after which the leaves are of similar size until leaf 42.

The new factor will be influenced by the exponential nature of the increase in leaf area, number of leaves used in the calculation and plant stage. If the new factor is calculated by using the leaves of the exponential phase, it will decrease from 1.2 to 0.4 as the number of leaves included in the calculation increases from 3 to 30. If the leaves that have reached a plateau are used to calculate the new factor, its value will be 1.0 and the number of leaves included will have no effect. Since experimental treatments such as fertilizer or irrigation will also influence the leaf system, the new factor is likely to be influenced by treatment and so the use of a single value could give misleading results.

A credible method for estimating the leaf area of a whole plant needs to take account of 1) the exponential nature of the increase in leaf area from one leaf to the next, 2) the change from one growth phase to another, and 3) the variable number of leaves.

The integral method

If the area of each leaf in a given ontogenetic sequence increases exponentially then a plot of the area of each leaf against leaf number becomes linear if leaf area is log-transformed. This can be described using the equation:

$$A_n = A_0 e^{Rn} \quad (2)$$

where A_n is the area of the nth leaf, A_0 is the area of the initial leaf, R is the relative rate of increase in leaf area that quantifies the increase in area from one leaf to the next. R is calculated as follows:

$$R = (\ln A_N - \ln A_i)/(\quad N-1) \quad (3)$$

where A_N is the area of the youngest leaf and A_i is the area of the oldest green leaf on the plant.

To estimate the leaf area between any two leaves on a plant, the area under the curve formed by equation (2) can be determined by integration with respect to N:

$$A_{i,N} = A_i[(\exp(RN) - \exp(Ri))/R] \quad (4)$$

$A_{i,N}$ is the integration of the leaf areas between leaf i, the oldest leaf at the time of measurement, and leaf N, the youngest leaf. A_i is the area of the oldest leaf on the plant. To implement the integral method for estimating leaf area on a plant, measurements of the areas of A_i, A_N and N are required. The value of R is then calculated. Leaf i can be taken as 1 and N represents the number of green leaves on the plant.

R is likely to vary with factors such as cultivar, water or nutrient supply environment or stage of plant ontogeny. Because R is estimated for each plant, the effect of an experimental treatment on R is automatically taken into account in the estimation of total leaf area, making the integral method adaptive. The integral method and the new factor proposed by Kumar *et al*. (2002) can now be compared.

Test of the integral method

The data set used for the comparison of the methods is a simulated reconstruction of the data in Fig 1.15 of Stover and Simmonds (1987). Leaf 1 was set at 100 cm^2 and the area of each leaf was incremented by 20% of the area of the preceding leaf. Thus:

$$A_n = A_{n-1} + 0.2(A_{n-1})dN \quad (5)$$

For leaves 31 to 42, the area was fixed at 17 000 cm^2 per leaf.

The total area of any consecutive number of leaves within the range 1 to 42 was added to provide the actual area. This would be the same as measuring the area of every leaf present on a plant and then summing them. The estimates of the area using the new factor and the integral method were compared with the actual area. The difference between the actual area and the area obtained with each method was then expressed as a percentage (Figures 1a and 1b).

In Figure 1a, the effect of increasing the number of leaves included was examined by starting with the first three leaves and then ending with leaves 1 to 42 included. For example, the third youngest leaf used in the new factor calculation would be leaf 1, when only three leaves are included, and leaf 40, when all 42 leaves are included. The third youngest leaf is incremented as N increases. This approach allows us to see how each method deals with plants that have a very different number of leaves. These calculations go well beyond the maximum number likely to be found in the field.

In figure 1b, the number of leaves was fixed at 14, which is the mean leaf number in the population used by Kumar *et al*. (2002) to derive the new factor and, as such, likely to provide the 'best' evaluation of this method. Sequences of 14 consecutive leaves were selected by adding one to advance the sequence and subtracting one to maintain the number of leaves at 14. Thus the first sequence included leaves 1 to 14 and the last sequence included leaves 29 to 42. For each situation, the leaf areas were calculated in an Excel® spreadsheet using the actual area, and the new factor and integral methods.

In the exponential phase of leaf area increase, and as the number of leaves included in the assessment increased from 3 to 42, the new factor method initially underestimated total leaf area by almost 50% (Figure 1a). Then the estimates were closer to the actual area until they were similar at 13 to 14 leaves. As more leaves were included, the new factor method overestimated leaf area and reached its greatest discrepancy at the end of the exponential phase at 31 leaves. The reason for this trend is the changing discrepancy between the value of the new factor fixed at 0.662 and its actual value, which decreases from 1.2 to 0.4 as the number of leaves increased. Since leaves 30 to 42 are the same size, their inclusion forced the new factor up again towards 0.662, bringing the estimates of leaf area closer to the actual.

In contrast, the integral method was more accurate than the new factor method, especially in the exponential phase. It underestimated the actual leaf area by about 20% at 3 leaves (Figure 1a). As the number of leaves increased, the integral method approached the actual area and was similar to it at 6 to 7 leaves. Then, as the number of leaves reached 29 leaves, the integral method overestimated the actual area by less than 10%. Because the integral method included the change in R as the number of leaves increased, the method was better able to estimate the total leaf area and as a result tracked closely the actual area (Figure 1a). Beyond the exponential phase, the inclusion of the leaves that were not increasing exponentially in area from one leaf to another changed the estimation of R and the estimates of the area deviated from the actual area.

When a sequence of 14 leaves was moved progressively through plant ontogeny, both the new factor method and the integral method overestimated leaf area but the integral method was closer to the actual values, especially in the exponential phase (Figure 1b). Again, the inclusion of leaves beyond the exponential phase, caused each method to deviate. The integral method gave better estimates than the new factor method because it accounted for the exponential change in leaf area during plant ontogeny and the calculation of R was based on the leaves being measured.

Neither method deals with the change in ontogeny to the plateau phase where leaves are the same size. The integral method assumes an exponential increase in leaf area throughout ontogeny but it can be adapted to the case of linear increase by including the measurement of two leaves, which would make it more adaptive than the new factor method. If the change can be detected, then the number of leaves in the plateau phase can be counted and the total area of these leaves added to the estimations of the integral method. An addition to equation (4) and a change of terms is needed to achieve this:

$$A_{i,N} = A_i[(\exp(RN_e) - \exp(Ri))/R] + A_pN_p \quad (6)$$

where, if A_p is the area of the first leaf in the plateau phase, then only two leaves need be measured as before. N_e is the number of leaves included in the exponential phase and N_p is the number of leaves in the plateau phase.

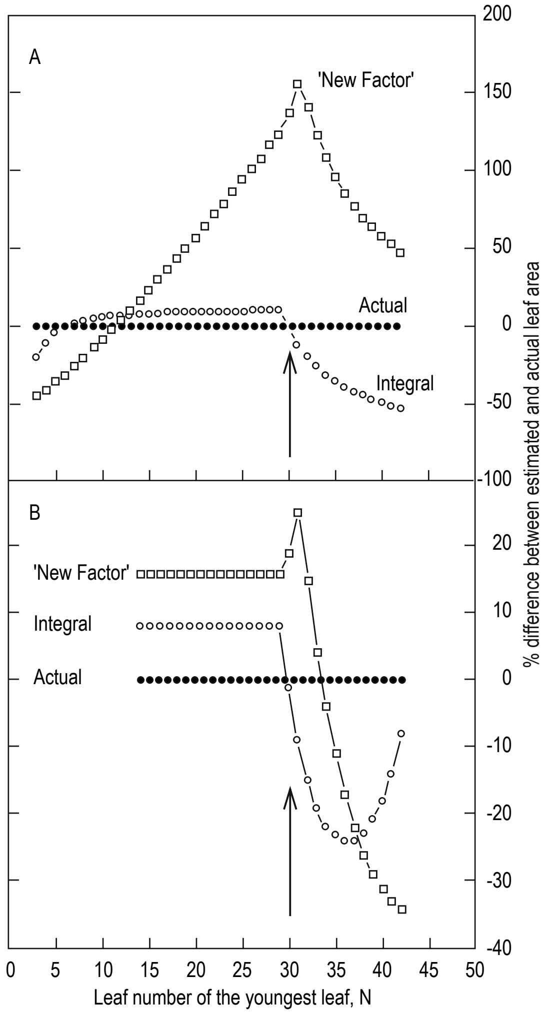

Figure 1. A comparison of the new factor and integral methods with the actual total leaf area of a banana plant, showing under and overestimates of total leaf area expressed as percentages. The exponential phase of leaf area increase is from leaf 1 to leaf 30. From leaf 31 to leaf 42, the leaves are the same size. A) The number of leaves included in the calculation is equal to the leaf number of the youngest leaf. B) Fourteen consecutive leaves are included in the calculation and this selection moves from leaf 14 to leaf 42.

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