APPENDIX VI

BIOMASS AND YIELD CALCULATION

The AEZ methodology for the calculation of potential net biomass and yields is derived from Kassam (1977). This model, based on eco-physiological principles, is outlined below:

To calculate the net biomass production (B_n) of a crop, an estimation of the gross biomass production (B_g) and respiration loss (R) is required:

$$B_n = B_g - R \tag{1}$$

The equation relating the rate of net biomass production (b_n) to the rate of gross biomass production (b_g) and the respiration rate (r) is:

$$b_n = b_g - r \tag{2}$$

The maximum rate of net biomass production (b_{nm}) is reached when the crop fully covers the ground surface. The period of maximum net crop growth, i.e., the point in time when maximum net biomass increments occur, is indicated by the inflection point of the cumulative growth curve. When the first derivative of net biomass growth is plotted against time the resulting graph resembles a normal distribution curve. The model assumes that the average rate of net production (b_{na}) over the entire growth cycle is half the maximum growth rate, i.e., b_{na} = 0.5 b_{nm}. The net biomass production for a crop of N days (B_n) is then:

$$B_n = 0.5\ b_{nm} \times N \tag{3}$$

The maximum rate of gross biomass production (b_{gm}) is related to the maximum net rate of CO_2 exchange of leaves (P_m) which is dependent on temperature, the photosynthesis pathway of the crop, and the level of atmospheric CO_2 concentration.

For a standard crop, i.e., a crop in adaptability group I with P_m = 20 kg ha^{-1} hr^{-1} and a leaf area index of LAI = 5, the rate of gross biomass production b_{gm} is calculated from the equation:

$$b_{gm} = F \times b_o + (1 - F)\ b_c \tag{4}$$

where:

- F = the fraction of the daytime the sky is clouded, $F = (A_c - 0.5\ R_g) / (0.8\ A_c)$, where A_c (or PAR) is the maximum active incoming short-wave radiation on clear days (de Wit, 1965), and R_g is incoming short-wave radiation (both are measured in cal cm^{-2} day^{-1})
- b_o = gross dry mater production rate of a standard crop for a given location and time of the year on a completely overcast day, (kg ha^{-1} day^{-1}) (de Wit, 1965)

b_c = gross dry mater production rate of a standard crop for a given location and time of the year on a perfectly clear day, (kg ha^{-1} day^{-1}) (de Wit, 1965)

When P_m is greater than 20 kg ha^{-1} hr^{-1}, b_{gm} is given by the equation:

$$b_{gm} = F\,(0.8 + 0.01 P_m)\, b_o + (1 - F)\,(0.5 + 0.025\, P_m)\, b_c \qquad (5)$$

When P_m is less than 20 kg ha^{-1} hr^{-1}, b_{gm} is calculated according to:

$$b_{gm} = F\,(0.5 + 0.025\, P_m)\, b_o + (1 - F)\,(0.05\, P_m)\, b_c \qquad (6)$$

To calculate the maximum rate of net biomass production (b_{nm}), the maximum rate of gross biomass production (b_{gm}) and the rate of respiration (r_m) are required. Here, growth respiration is considered a linear function of the rate of gross biomass production (McCree, 1974), and maintenance respiration a linear function of net biomass that has already been accumulated (B_m) When the rate of gross biomass production is b_{gm}, the respiration rate r_m is:

$$r_m = k\, b_{gm} + c\, B_m \qquad (7)$$

where k and c are the proportionality constants for growth respiration and maintenance respiration respectively, and B_m is the net biomass accumulated at the time of maximum rate of net biomass production. For both legume and non legume crops k equals 0.28. However, c is temperature dependent and differs for the two crop groups. At 30 ^oC, factor c_{30} for a legume crop equals 0.0283 and for a non-legume crop 0.0108. The temperature dependence of c_t for both crop groups is modelled with a quadratic function:

$$c_t = c_{30}\,(0.0044 + 0.0019\, T + 0.0010\, T^2). \qquad (8)$$

It is assumed that the cumulative net biomass B_m of the crop (i.e., biomass at the inflection point of the cumulative growth curve) equals half the net biomass that would be accumulated at the end of the crop's growth cycle. Therefore, we set B_m = 0.5 B_n, and using (3), B_m for a crop of N days is determined according to:

$$B_m = 0.25\, b_{nm} \times N \qquad (9)$$

By combining the respiration equation with the equation for the rate of gross photosynthesis, the maximum rate of net biomass production (b_{nm}) or the rate of net dry matter production at full cover for a crop of N days becomes:

$$b_{nm} = 0.72\, b_{gm} / (1 + 0.25\, c_t\, N) \qquad (10)$$

Finally, the net biomass production (B_n) for a crop of N days, where 0.5 b_{nm} is the seasonal average rate of net biomass production, can be derived as:

$$B_n = (0.36\, b_{gm} \times L) / (1/N + 0.25\, c_t) \qquad (11)$$

where:

b_{gm} = maximum rate of gross biomass production at leaf area index (LAI) of 5

L = growth ratio, equal to the ratio of b_{gm} at actual LAI to b_{gm} at LAI of 5

N = length of normal growth cycle

c_t = maintenance respiration, dependent on both crop and temperature according to equation (8)

Potential yield (Y_p) is estimated from net biomass (B_n) using the equation:

$$Y_p = H_i \, x \, B_n \tag{12}$$

where:

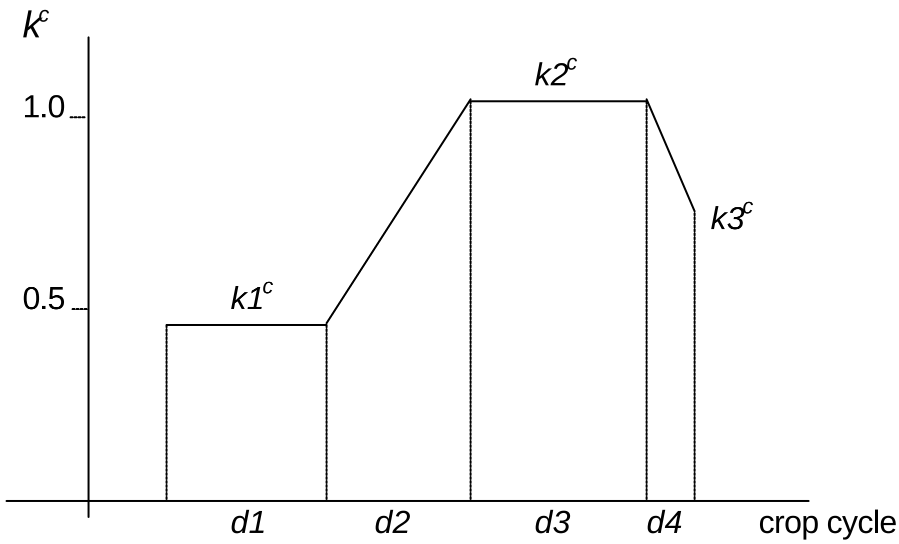
H_i = harvest index, i.e., proportion of the net biomass of a crop that is economically useful

Thus, climate and crop characteristics that apply in the computation of net biomass and yield are: (a) heat and radiation regime over the crop cycle, (b) crop adaptability group to determine applicable rate of photosynthesis P_m, (c) length of growth cycle (from emergence to physiological maturity), (d) length of yield formation period,.(e) leaf area index at maximum growth rate, and (f) harvest index.

The calculation of moisture limited yields follows the procedures described in FAO (1992a), known as the CROPWAT method. In this approach, the crop-specific potential evapo-transpiration ETo^c is related to reference evapotranspiration ETo as,

$$ETo^c = k^c x \, ETo \tag{13}$$

where k^c is calculated from a piecewise linear function as sketched below:



The function is paramerized by means of seven parameters. Four coefficients, *d1*, …, *d4*, relate to the characteristics of the crop cycle, denoting the length (in days) of four crop development stages, namely, initial stage, vegetative stage, reproductive stage, and maturation stage. Another three parameters, $k1^c, k2^c$ *and* $k3^c$, define relationship (13) respectively for the initial stage, the reproductive phase, and the end of the maturation stage.

Let D_1, …, D_4 denote the days belonging to each of the four crop growth stages,

$D_1 = \{ j \mid 1 \le j \le d1 \}$,
$D_2 = \{ j \mid d1 < j \le d1 + d2 \}$,
$D_3 = \{ j \mid d1 + d2 < j \le d1 + d2 + d3 \}$, and
$D_4 = \{ j \mid d1 + d2 + d3 < j \le d1 + d2 + d3 + d4 \}$,

then the value of k^c for a particular day j is defined by:

$$k_j^c = \begin{cases} k1^c & j \in D_1 \\ k1^c + (j - d1) \cdot \dfrac{k2^c - k1^c}{d2} & j \in D_2 \\ k2^c & j \in D_3 \\ k2^c + (j - (d1 + d2 + d3)) \cdot \dfrac{k3^c - k2^c}{d4} & j \in D_4 \end{cases} \tag{14}$$

Using (13) and (14), crop-specific potential evapotranspiration over the four crop growth stages, $TETo_k^c$, and the entire crop cycle, $TETo^c$, can be calculated:

$$TETo_k^c = \sum_{j \in D_k} k_j^c \cdot ETo_j \qquad k = 1, \ldots, 4 \tag{15}$$

$$d0 = d1 + d2 + d3 + d4$$
$$TETo^c = \sum_{j=1}^{d0} k_j^c \cdot ETo_j \tag{16}$$

Similarly, applying a crop-specific soil water balance, actual evapotranspiration is calculated:

$$TETa_k^c = \sum_{j \in D_k} ETa_j^c \qquad k = 1, \ldots, 4 \tag{17}$$

$$TETa^c = \sum_{j=1}^{d0} ETa_j^c \tag{18}$$

where ETa^c is determined according to (see also Chapter 3.4):

$$W_{j+1}^c = \min \left(W_j^c + P_j - ETa_j^c,\ Sa \right) \tag{19}$$

$$ETa_j^c = \begin{cases} ETo_j^c & \text{if } (W_j^c + P_j) \cdot d \ge Sa \cdot d \cdot (1 - p_j^c) \\ r_j \cdot ETo_j^c & \text{else} \end{cases} \tag{20}$$

with,

$$r_j = \frac{ETa_j^c}{ETo_j^c} = \frac{W_j^c + P_j}{Sa \cdot (1 - p_j^c)} \tag{21}$$

j number of day in year
Sa available soil moisture holding capacity (mm/m)
d rooting depth (m)
p_j^c soil water depletion fraction below which $ETa < ETo$
r_j actual evapotranspiration proportionality factor.

Sa and d are defined by the respective values of the soil units in individual grid-cells. The computation of water-limited yields Y_a is now easily obtained, following FAO (1979 and 1992a):

$$1 - \frac{Y_a}{Y_p} = k^y \cdot (1 - \frac{ETa^c}{ETo^c}) \quad (22)$$

We evaluate (22) in two variants, first over the entire growth cycle and then according to individual growth stages. The more severe of the two conditions determines Y_a. The respective reduction multipliers f_0 and f_1 are defined by,

$$f_0 = 1 - k_0^y \cdot (1 - \frac{TETa^c}{TETo^c}) \quad (23)$$

and

$$f_1 = \prod_{k=1}^{4} (1 - k_k^y \cdot (1 - \frac{TETa_k^c}{TETo_k^c})) \quad (24)$$

where the coefficient expressing the sensitivity of crop yield to moisture deficit, k^y, are based on FAO (1992a).

Applying (23) and (24) to potential yield from (12), we obtain the final results,

$$Y_a = \min(f_1, f_2) \cdot Y_p \quad (25)$$

The parameters for lengths of crop stages, crop-specific evapotranspiration, and for sensitivity of yield to moisture deficit, used in this study, are listed in Appendix 7.