INTERNAL REPORT 158

DOCUMENTATION FOR A COMBINED CARBON-WATER FLOW STAND LEVEL CONIFEROUS FOREST MODEL

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The following report introduces a documentation scheme for flow oriented ecosystem models and shows its application to a carbon-water model developed within the coniferous biome. This documentation scheme has remained operative through revision of this model and expansion of it to include nutrient flows. This model and subsequent versions are operative simulations on the CDC 6400 at the University of Washington using SIMCOMP (Gustafson & Innis (1971)).and give reasonable output.

The purpose of this report is mainly to introduce the reader to the documentation scheme which we have found so effective in maintaining a running history of the modeling process for large scale models. We hope that it will lead to the adoption of this or a similar documentation scheme as a standard for ecological modeling.

Introduction to the documentation scheme

The approach introduced here will be called the flow control diagram. Generally speaking it is a series of compartment diagrams showing the flow of each of the materials of importance in the model with special focus on what elements "control" the flow between the compartments. An example of such a set of compartment diagrams is given in Figure 6.1 for a model which deals with crop-water interaction showing flows of water and crop biomass.

Each of the compartments in the subdiagrams in Figure (6.1) is labeled and numbered. The letter X is used to identify a compartment. For example the subsoil H_2O compartment in the waterflow submodel is labelled X_2. Flows between compartments are identified by an F followed by two numbers in parentheses separated by a comma, the first denoting where the flow comes from and the second where it is going to. For example F(2,3) denotes waterflow between compartment X_2 (subsoil H_2O) and X_3 (transpired H_2O) in the waterflow submodel. This is a transpiration flow.

The letter S is used to denote both sources and sinks in the diagram. These are either an infinite supply or an infinite storage area for what is flowing. They are external to the system and are where the material circulating comes from or goes to. We are not especially concerned in the model over how much of the material there is in the source or sink—it is assumed to be an "arbitrarily large" quantity. The flow F(S,5), for example, represents the flow from the biomass source to the crop biomass; this represents crop growth. It is important that the compartments within a compartment submodel are in the same units so that you have the same thing flowing out of one compartment that flows into another. A good case in point is in animal growth models, where animal weights are kept in kilograms but energy requirements are kept in kilocalories. With the proper conversion factors all flow and compartment units can be kept uniform in a particular submodel. The units should be noted after the flow description as seen in Figure 6.1 where waterflow is in centimeters per square meter per hour and crop biomass is in grams per square meter per hour.

There are five types of elements that are used in the flow control diagram. These are:

(1) Driving variables—elements that change over the running time of the model independently of the system but having major effects on the system; Z's are used in the flow control diagram.

(2) State variables—elements that comprise the structure of the system. They are the compartments in the diagram; X's are used for notation.

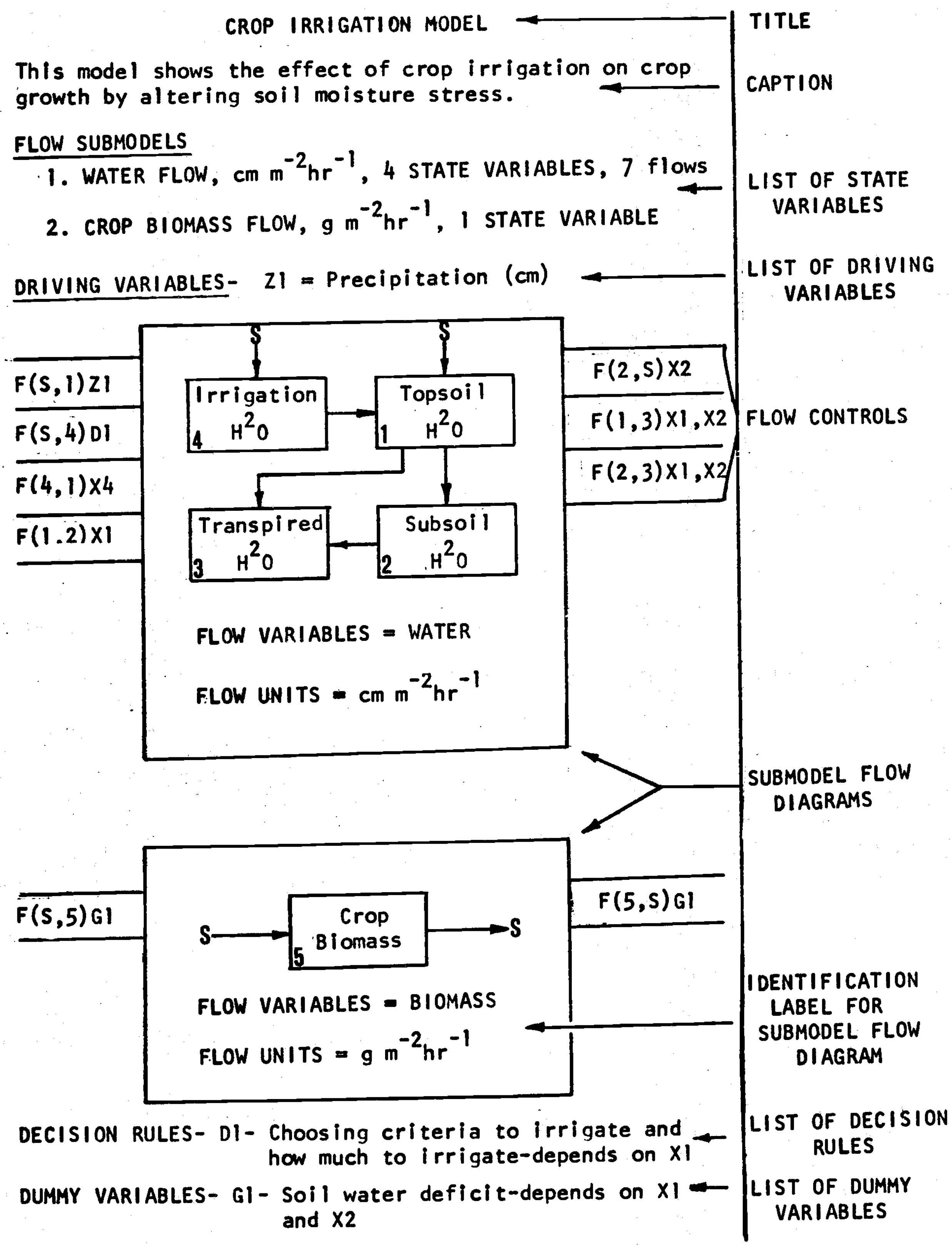


Figure 6.1. An example of a flow control diagram

(3) Flows—represent transfer of material between the state variables per unit time chosen in the model; F is used to denote these.

(4) Decision rules—rules whereby control is affected over the system by an external manipulator (usually human) based on monitoring of state and/or driving variables; D is used for notation.

(5) Intermediate variables—these are variables which, while not of primary importance to the structure of the system are important in the control of a flow within the system. They are denoted by G. The driving variables are listed and each is numbered with a Z followed by a numeral. They appear above the submodel diagram.

The decision variables, labeled D followed by a number, are listed directly below the flow diagram. Directly below this comes a listing of intermediate variables, labeled G followed by a number. In Figure 6.1 the sole model driving variable, labeled Z_1, is precipitation in cm. A decision variable D_1 relates to irrigation policy while an intermediate variable G_1 keeps tract of soil water deficit, computed from soil H_2O quantities and soil characteristics.

Alongside each of the compartment submodels are a set of flow controls which tell which variable and/or decision rules affect that flow. In Figure 6.1 we see that F(S,4), flows between the water source and irrigation water is "controlled" by D_1, the irrigation decision policy. F(1,2), the flow between topsoil and subsoil water (infiltration), is "controlled" in this model by X_1, topsoil water.

Labeling. At the top of the flow control diagram there is a title which describes in general the essence of the model. Below this is a caption which describes important features of the model. This is followed by a list of the flow submodels including variable flowing, units for the flow, the number of state variables on each submodel and the number of flows. Below this is the list of driving variables followed by the submodel diagrams. Each submodel flow diagram also has an identification label which indicates the variable flowing, the mnemonic for that variable and the units for the flows. Time is denoted by t and the time step for the model is given implicitly by giving the units for the flows since these are always flows per unit time. These might be different for different modules. In case they are variable within a flow submodel the smallest time unit is used for all flow rates in that submodel. Figure 6.1 has all the proper labeling for the flow control diagram.

Figure 6.1 represents the description of a model that outlines the basic flows and structure of the model and gives information about driving variables, management control devices (decision rules) and dummy variables of importance to flow control. It also indicates what elements control the various flows in the compartment diagram. One could get an idea of the basic structure of the model by looking only at the compartment diagrams, while others would examine the model in more detail by examining the driving and intermediate variables and the decision rules, and looking at the flow controls alongside the diagram. By removing these controls from the compartment diagrams you significantly "clean up" the appearance of the diagram, transferring the "information flow" detail of Forrester type diagrams to the flow controls where they can be examined singly without following connections all around the diagram.

For those who want to know more about the model a description such as given above is incomplete. They often want to know how the flows are affected by various variables. This has been provided through the device of flow control pages which further develop the information indicated in the flow controls. Each flow control page gives a set of diagrams showing how the flows are affected by each of the flow control variables. An example flow control page is given in Figure 6.2 for flow F(S,5) in Figure 6.1.

In Figure 6.2 the relationship between F(S,1), the flow representing crop growth and its control variable G_1, the soil H_2O deficit, is shown. This relationship is given in a general graph, with the most rudimentary labels, to give an idea of the qualitative type of relationship. Then the page gives the equation representing the relationship with parameter values (the values are not given in this example since we are only dealing with a hypothetical model). The parameters are always represented by a small b followed by a number. There can also be "pages" describing the dummy variables and decision rules in greater detail, with information given on what factors affect these elements and how (for example, soil H_2O deficit G_1 would be computed from soil H_2O conditions X_1 and X_2--the graph and equations describing this relationship would appear on a dummy variable "page" for G_1). **Also included in the flow control pages are comments on how the relationship works and biological documentation for the relationship.**

A complete description of the model would generate many "pages" if the model were reasonably complex (more than 25 flows), but this is not too cumbersome since a "page" doesn't have to take a page; also only the more important relationships need be focussed on if a published description of the model is desired.

<u>Application to real models</u>. It is hoped this diagrammatic technique will become more flexible as it becomes more tried and tested. It is only fair, however, to list some of the possible disadvantages of a standardized approach such as this to model development and description.

The rigidity of the choice of units, kinds of elements, and the ways the elements interrelate (flows and controls) may limit the creative thinking process in some models especially for models of an abstract nature.

There is time required in learning the notation and symbols.

The time devoted to developing and updating may be considerable--it may slow down insight implementation.

The approach is not time-tested and flaws and lack of generality may show up in time testing.

Despite these disadvantages the approach looks good especially in bringing to light missing information in model descriptions. Much of the information in a model is described in greatly condensed form. Some of the other apparent advantages of the approach are:

$$F(S,5) = b_1 - b_2\ GI^2$$

$$b_1 = 1.2$$

$$b_2 = 1 \times 10^{-4}$$

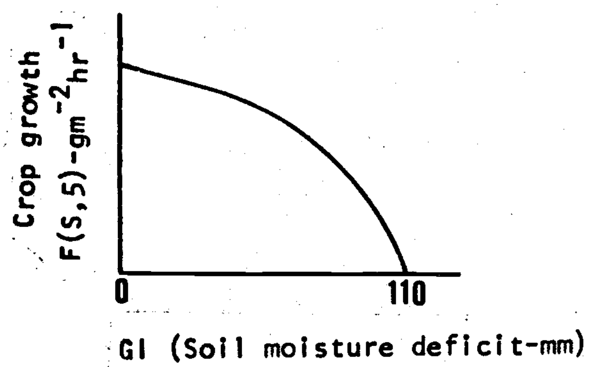


Figure 6.2. Example of a flow control page where F(S,5) (Crop growth) depends on GI (soil moisture deficit)

The complete model description can fairly readily be converted to computer code.

By offering a whole system framework it facilitates communication among modelers.

It facilitates display of progress by organizing the flow controls in flow control pages.

It is modular and changes can be made in the individual flow control pages without affecting the main flow diagrams.

The diagram focusses on flow and controls rather than state variables as in the compartment model. This is more in line with many real models most of whose development time goes into the flow control functions.

It supplies a feasible framework for describing complex models which are becoming more common today.

It puts model description in one place rather than spread all over the place as is the case in many models described in the literature today.

It offers a framework for comparing models. This might become more possible as the technique is more tested.

By putting models into a common framework, ways of describing models in terms of a few general characteristics might evolve.

Models are displayed in hierarchical form so that they can be developed at different levels of detail in different versions.

A standarized framework for model description is sorely needed in ecological and natural resource management modeling. At present, although procedures for model implementation are fairly standard, the number of different display formats used in model description are many. Standardization of display format is the only way that modeling literature can be tractable to the ordinary modeler. This is a growing area, where the need for coordination and intercommunication is especially necessary.

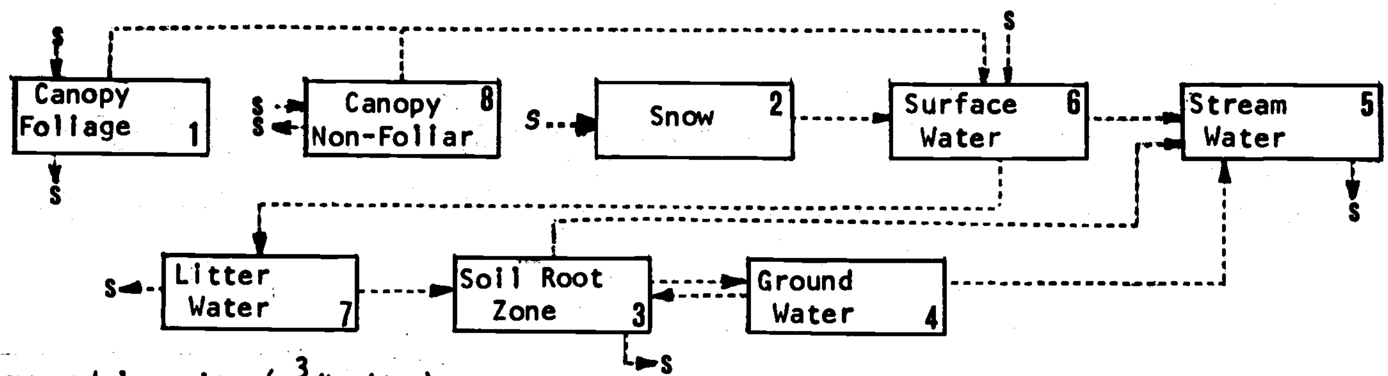
Documentation of the stand level carbon and waterflow model

We are using flow control diagrams to document our models as they develop. Figure 6.3 shows the flow control diagram for the carbon-waterflow coniferous stand model. The control pages (section 6.2.2.1) for a first version of the model are also included as an example of complete model documentation of this type.

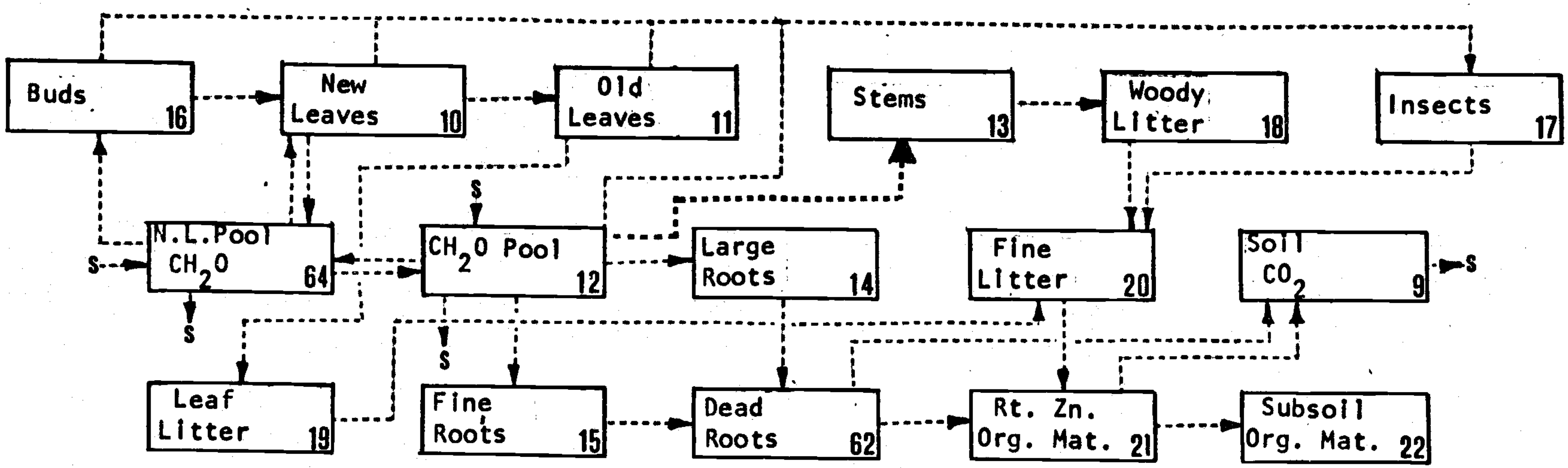
Control pages for carbon and waterflow model. The following control pages show the functions used in the model. These functions are explained in both mathematical terms and words. Table 6.1 is an index of flows and intermediate variables indicating the page numbers on which descriptions of the variables can be found.

Figure 6.3.

MODEL FOR CARBON AND WATER FLOW IN A CONIFEROUS FOREST STAND DOMINATED BY DOUGLAS FIR



Water flow module units (m^3/ha/day)



Carbon flow module (tons C/ha/wk, 1 ton=1000 kg)

FLOW MODULE

(1) WATER FLOW, m^3/ha/day, 8 State Variables, 18 Flows

(2) CARBON FLOW, metric tons/ha/wk, 16 State Variables, 30 Flows

DRIVING VARIABLES

z_1= daily precip. as rain (m^3/ha)-z_8,z_3

z_2= short wave radiation (ly/min)

z_3= canopy air temp. (deg.C)

z_4= day length

z_6= soil temp. (deg.C)-z_7

z_7= litter temp. (deg.C)-z_3,X_2,z_1,g_5

z_8= total daily precip. (m^3/ha)

INTERMEDIATE VARIABLES

g_1=foliage canopy charge rate-const.

g_2=non-foliar H_2O capacity-const.

g_3=foliar rain input-X_1,g_{23}

g_4=non-foliar rain input-X_1,g_{23}

g_5=canopy H_2O drip-z_1,g_3,g_4

g_6=adjusted potential evapotransp.-z_1,z_2,CP
CP=potential evap.

g_7=foliage evap. rate-X_1,g_3,g_6

g_8=non-foliar evap rate-X_8,g_4,g_6,g_7

g_9=potential snow melt-z_3,z_1,g_5,RAD
RAD=radiation effect on snow melt

g_{10}=actual snow melt-g_9,z_8,z_1

g_{11}=potential litter infiltration-g_5,g_{10},z_1

g_{12}=percolation to ground H_2O-X_3,g_{15}

g_{13}=litter inflow-g_{11},X_{19},X_3,X_7,g_{22}

g_{14}=litter PET-z_7,CP

g_{15}=soil infiltration-g_{13},X_3,X_7,g_{22},X_{19}

g_{16}=lag effect of percolation on ground H_2O lateral flow-g_{12},g_{16}(t-1)

g_{17}=ground H_2O lateral flow-X_4,g_{12},g_{16}

g_{20}=transpiration rate-g_6,g_7,g_8,X_3

g_{22}=litter evaporation-g_{14},X_{19},X_7

g_{23}=rain held by canopy as fraction of holding capacity-g_1,z_1

g_{24}=new leaf photosyn.-z_4,g_{39},X_{10},g_{41},g_{43},X_{11}

g_{25}=new leaf night resp.-z_4,g_{39},X_{10},g_{43}

g_{26}=new leaf growth-g_{45},g_{46},g_{47}

g_{27}=new leaf resp. loss-g_{45},g_{47}

g_{28}=n.l. photosyn. to CH_2O pool-g_{45},g_{47},g_{49}

g_{29}=o.l. photosyn. to CH_2O-z_4,g_{39},X_{11},X_{12},g_{52},g_{51},X_{10}

g_{30}=o.l. resp.-z_4,g_{39},X_{11},X_{12},g_{52}

g_{31}=non leaf resp.-g_{35},g_{36},g_{37}

g_{32}=CH_2O pool to n.l. CH_2O pool-g_{48},g_{46},g_{55} g_{45},g_{47}

g_{33}=bud growth-g_{49}

g_{34}=n.l. maturation-X_{10},t

g_{35}=stem transloc.-g_{39},X_{12}

g_{36}=large root transloc.-X_{12},g_{53}

g_{37}=fine root transloc.-X_{12},g_{53}

g_{38}=n.l. consumption-X_{10},g_{39}

g_{39}=temperature effect on photosyn.-z_3

g_{40}=leaf fall phenology-t

g_{41}=light-b'mass effect on photosyn.-z_2,X_{10},X_{11}

g_{42}=moisture stress and temp. effect-X_3,z_6

g_{43}=n.l. resist.-g_{42}

g_{44}=bud limit on n.l. growth-X_{16},t

g_{45}=CH_2O avail. to satisfy n.l. growth-X_{12}

g_{46}=n.l. growth demand-g_{44},X_{10}

g_{47}=surplus photosyn after n.l. resp-g_{24},g_{25}

g_{49}=n.l. CH_2O pool to CH_2O pool-g_{46},g_{47}

g_{50}=moisture temperature effect on soil processes -x_3, g_{53}

g_{51}=light biomass effect on old leaf photosyn. -z_2, x_{10}, x_{11}

g_{52}=old leaf resistance -g_{43}

g_{53}=temp effect on soil processes-z_6

FLOW VARIABLES

F(S,1)-g_{23},X_1,g_5

F(S,2)-z_1,z_8

F(S,6)-z_1

F(1,S)-g_3,g_6,X_1

F(S,8)-g_2,z_1,X_8

F(8,S)-g_4,X_8,g_6,g_7

F(7,S)-g_{14},X_7,X_{19}

F(1,6)-z_1,g_3,g_4

F(2,6)-g_9,X_2,z_1,z_8

F(S,64)=g_{24}

F(64,10)=g_{26}

F(64,12)=g_{28}

F(12,S)-g_{30},g_{31}

F(12,64)=g_{32}

F(16,10)-X_{16},t

F(12,14)=g_{36}

F(10,17)=g_{38}

F(12,17)-X_{12},g_{39}

F(11,19)-X_{11},g_{40}

F(15,62)-X_{15}

F(18,20)-X_{18},g_{50}

F(20,21)-X_{20},g_{50}

F(62,21)-X_{62},g_{50}

F(21,22)-X_{21},g_{50}

F(9,S)=0

F(64,S)=g_{25}

F(10,64)=g_{27}

F(S,12)=g_{29}

F(64,16)=g_{33}

F(6,7)-g_{11},X_7,X_3,g_{22},X_{19}

F(7,3)-g_{13},X_3,X_7,g_{22},X_{19}

F(3,S)-g_6,g_7,g_8,X_3

F(3,4)-X_3,g_{15}

F(4,5)-X_4,g_{12},g_{16}

F(4,3)-X_4,g_{12},g_{17}

F(3,5)-g_{18},g_{12}

F(6,5)-X_3,X_{19},g_{11},g_{12},g_{18},g_{19},g_{20},g_{22}

F(10,11)=g_{34}

F(12,13)=g_{35}

F(12,15)=g_{37}

F(11,17)-X_{11},g_{39}

F(14,62)-X_{14}

F(17,20)-const.

F(19,20)-X_{20},g_{50}

F(20,9)-X_{20},g_{50}

F(62,9)-X_{62},g_{50}

F(21,9)-X_{21},g_{50}

F(16,17)-X_{16},g_{39}

Table 6.1. Index of flows and intermediate variables with reference to the flow control pages.

Variable	Equation No.	Page
g_1	1.3	13
g_2	5.2	16
g_3	1.1	12
g_4	5.1	15
g_5	9.1	22
g_6	6.2	17
g_7	6.1	16
g_8	7.1	18
g_9	10.2	23
g_{10}	10.1	22
g_{11}	11.2	25
g_{12}	14.1	27
g_{13}	11.1	24
g_{14}	8.2	20
g_{15}	12.1	25
g_{16}	15.2	29
g_{17}	15.1	28
g_{18}	16.1	30
g_{19}	17.1	31
g_{20}	13.1	26
g_{21}	18.1	32
g_{22}	8.1	19
g_{23}	1.2	13
g_{24}	20.1	33
g_{25}	21.1	37
g_{26}	22.1	38
g_{27}	23.1	42
g_{28}	24.1	43
g_{29}	25.1	44
g_{30}	26.1	46
g_{31}	26.2	47
g_{32}	28.1	52
g_{33}	27.1	51
g_{34}	29.1	54
g_{35}	26.3	48
g_{36}	26.4	49
g_{37}	26.5	49
g_{38}	22.6	41
g_{39}	20.2	34
g_{40}	38.1	57
g_{41}	20.3	34
g_{42}	20.5	36
g_{43}	20.4	35
g_{44}	22.5	40
g_{45}	22.2	39
g_{46}	22.3	39
g_{47}	22.4	40

Table 6.1. (contd.)

Variable	Equation No.	Page
g_{49}	24.2	43
g_{50}	42.1	59
g_{51}	25.2	45
g_{52}	25.3	46
g_{53}	26.6	50

F(S ,1), rain input to canopy storage

$$F(S,1) = g_3 \quad (1)$$

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g_3, foliar rain input

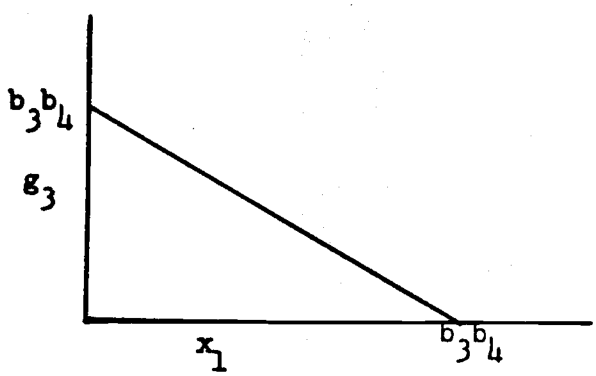
$$\boxed{g_3 = (b_3 b_4 - x_1)(1 - \exp(-g_{23}))} \quad (1.1)$$

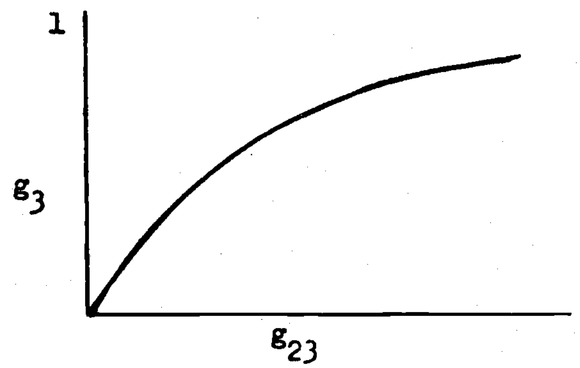
x_1 = canopy H_2O storage

b_3 = maximum canopy storage = 100 m^3/ha

b_4 = proportion of canopy storage in foliage = 0.3

g_{23} = rainfall absorbed as a fraction of canopy capacity (see 1.2)





c: rate of charge depends on amount in storage already in foliage and rain in–it can absorb less per unit rainfall the more comes in. The maximum input is $b_3b_4 - x_1$, the difference between the storage capacity and the amount of water already in the canopy. This is modified by rainfall in (related to g_{23}) such that the maximum cannot quite be reached, although the greater the rain the closer it is to maximum. (From Overton & White (1974))

g_{23} = canopy foliage as a fraction of total foliage holding capacity

$$g_{23} = g_1 z_1 \tag{1.2}$$

g_1 = foliage canopy charge rate (see 1.3)

z_1 = precipitation as rain (see 1.4)

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g_1 = foliage canopy charge rate

$$g_1 = (1-b_2)b_5/b_3b_4 \tag{1.3}$$

b_2 = proportion of rain direct to forest floor = 0.25

b_3, b_4 - (see 1.1)

b_5 = proportion of canopy interception by foliage = 0.7

<u>c</u>: a constant depending on carrying capacity of foliage and foliage interception ability for water--will eventually depend on foliage properties.

z_1 - precipitation as rain (m^3/ha)

$$z_1 = 254. \begin{cases} z_8 & \text{if } z_3 > 3.3 \\ 0.3 z_8 z_3 & \text{if } 0 \le z_3 \le 3.3 \\ 0 & \text{if } z_3 < 0 \end{cases} \qquad (1.4)$$

where z_8 = total precipitation ('') - data record

z_3 = air temperature (°C) - data record

c: precipitation as rain depends on temperature and varies in 0-3.3 °C range. The 254 is to convert inch / ha to m^3 / ha. (Based on U.S. Army Corps of Engineers (1956)).

F(S, 2) - SNOW INPUT

$F(S,2) = 254.z_8 - z_1$ (2.)

z_8 = total precipitation ('') - data

z_1 = precipitation as rain (see 1.4)

c:

What is not rain is snow.

F(S,6) - rain direct to forest floor (m^3/ha/day)

$$F(S,6) = b_2 z_1 \qquad (4)$$

b_2 = % rain through canopy

z_1 = rainfall in (1.4)

F(S,8) - non-foliar canopy rainfall input (m^3/ha/day)

$$F(S,8) = g_4 \qquad (5)$$

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g_4 - non-foliar canopy rain input (m^3/ha/day)

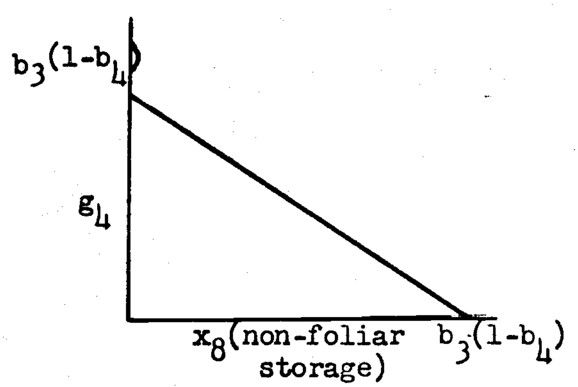
$$g_4 = (b_3(1-b_4) - x_8)(1 - \exp(-g_2 z_1)) \qquad (5.1)$$

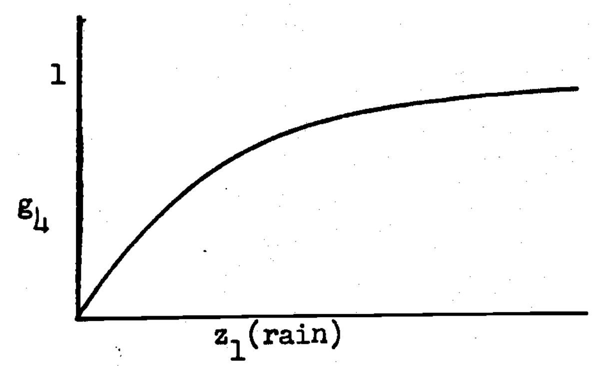
b_3, b_4 - canopy storage capacity, fraction in foliage (see 1.1)

x_8 - non-foliar canopy H_2O storage (m^3/ha)

z_1 - rain input (m^3/ha/day) (see 1.4)

g_2 - fraction of non-foliar H_2O capacity per unit rain input (see 5.2)





c: analogous to g_3

g_2 - fraction of non-foliar H_2O capacity per unit rain input

$$g_2 = (1-b_2)(1-b_5)/b_3(1-b_4) \qquad (5.2)$$

c:

a constant, analogous to g_1 - will also change when foliage characteristics are considered

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F(1,S) - evaporation from foliage (m^3/ha/day)

$$F(1,S) = g_7 \qquad (6)$$

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g_7 - foliage evaporation rate m^3/ha/day

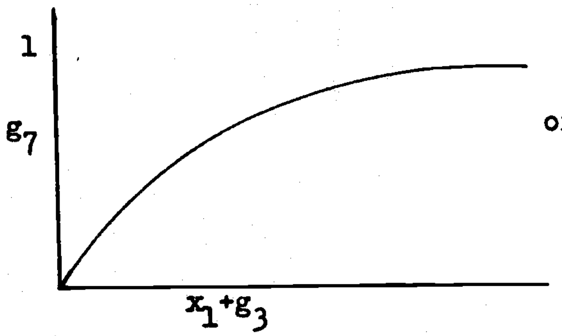
$$\min \begin{cases} x_1 + g_3 \\ g_6[1-\exp(-b_7(x_1+g_3))] \end{cases} \qquad (6.1)$$

x_1 = canopy foliage storage

g_3 = rain input to foliage (see 1.1)

g_6 = adjusted potential evapotranspiration (see 6.2)

b_7 = evaporative rate = 0.3 ha/m^3



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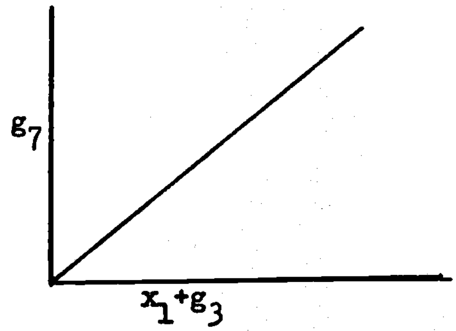

comment: potential evapotranspiration g_6 times an increasing (negative exponential) function of total water in canopy is evaporated unless the demand is larger than the supply in which case only the H_2O supply is evaporated. (Adopted from Overton & White (1974))

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g_6 - adjusted potential evapotranspiration (m^3/ha)

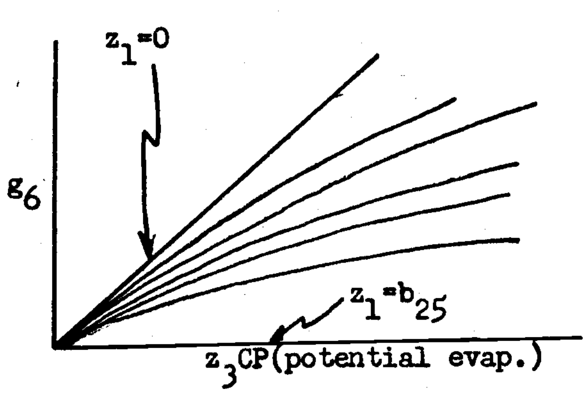
$$g_6 = \max \begin{cases} 0 \\ [z_3\ CP \quad] + 1 - [z_3\ CP \quad + 1]^{z_1/b_{25}} \end{cases} \qquad (6.2)$$

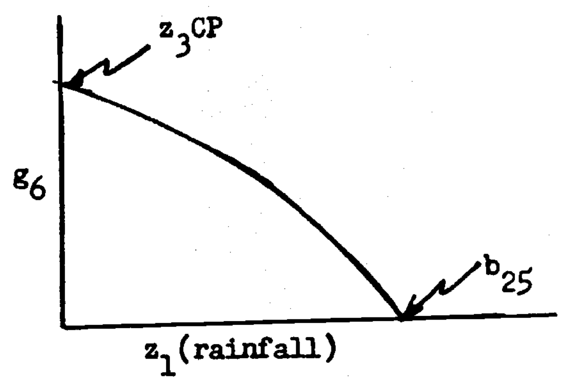
z_3 = air temperature (°C) - data

z_1 = precipitation (m^3/ha/day) (see 1.4)

CP = potential evaporation (table look up - Hargreaves equation)

b_{25} = factor chosen so that $g_6 = 0$ when z_1 = 3" = 762 m^3/ha





comments:

The relationship is from Overton Watershed model (1973). As temperature goes negative, P.E.T. is zero. As rainfall increases it decreases. As potential evapotranspiration increases it increases. CP is based on Viehmeyer (1964).

F(8,S) - non-foliar evaporation

$$F(8,S) = g_8 \qquad (7)$$

---

g_8 - non-foliar evaporation

$$g_8 = \min \begin{cases} x_8 + g_4 \\ b_8(g_6 - g_7) \end{cases} \qquad (7.1)$$

x_8 = non-foliar H_2O storage

g_4 = rain input to non-foliar canopy (see 5.1)

g_6 = adjusted P.E.T. (see 6.2)

g_7 = evaporation from foliage (see 6.1)

b_8 = proportion of atmosphere demand satisfied by non-foliar canopy = 0.2

c: part of P.E.T. not satisfied by foliage (20%) is satisfied by non-foliar canopy (unless that too is depleted). This makes evaporation of non-foliar canopy storage slower than canopy storage. (From Overton & White (1974)).

F(7,99) - litter evaporation

$$F(7,99) = g_{22} \tag{8}$$

---

g_{22} - litter evaporation

$$g_{22} = \begin{cases} g_{14} & \text{if } x_7 > b_{11}x_{19} \\ \dfrac{g_{14}(x_7 - b_{12}x_{19})}{b_{11}x_{19} - b_{12}x_{19}} & \text{if } b_{12}x_{19} \le x_7 \le b_{11}x_{19} \\ 0 & \text{if } b_{12}x_{19} < x_7 \end{cases} \tag{8.1}$$

where x_7 = litter H_2O storage

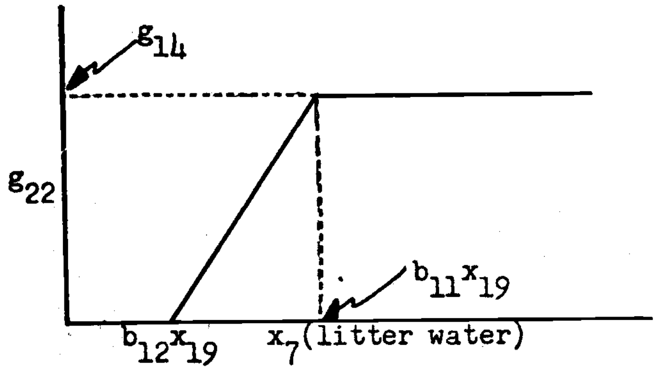
x_{19} = litter carbon (dry wt)

b_{11} = litter evaporation resistance pt - fraction of litter dry wt. x_{19} of H_2O above which there is resistance to further increase in evaporation = 0.43

b_{12} = litter H_2O retention capacity - fraction of litter dry wt x_{19} below which there is no effective litter evaporation = 0.05

c: Coefficients are from Cromack and Fogel (pers. comm.)

g_{14} = litter potential evapotranspiration (see 8.2)



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g_{14} = litter potential evapotranspiration

$$g_{14} = \max \begin{cases} 0 \\ z_7 \cdot CP \end{cases} \tag{8.2}$$

z_7 = litter temperature (see 8.3)

CP = potential evaporation - table look up

c: the same as canopy potential evaporation except without the rainfall modification and with litter temperature

---

z_7 - litter temperature

$$z_7(K) = \begin{cases} z_7(K-1)(1-A) + z_3A & \text{if} \quad x_2 \leq 100 \\ 1 & \text{if} \quad x_2 > 100 \end{cases} \tag{8.3}$$

where $A = \min \begin{cases} \dfrac{b_{92}(1+b_2z_1+g_5)}{b_{93}} \\ 1 \end{cases}$

and K = time

z_3 = air temperature - data

z_1 = precipitation as rain (see 1.4)

x_2 = snow H_2O storage

b_2 = fraction of rain falling through directly to ground (see 1.3)

g_5 = rain dripping from canopy (see 9.1)

b_{92} = factor showing effect of air temperature on litter temperature = 0.5 (weekly lag effect)

b_{93} = relative effect of precipitation on litter temperature = 5.

c: litter temperature change lags behind air temperature change. As rain dripping on the litter increases, the air temperature effect is more important until at 500 m^3/ha and above they are equal. When snow cover is greater than 100 m^3/ha the litter temperature is set to 1°C. This is an approximate solution to a partial differential equation where change in temperature with depth is related to change of temperature with time. There is an analogous relationship for calculating soil temperature.

F(1,6) - canopy H_2O drip

$$F(1,6) = g_5 \qquad (9)$$

g_5 - canopy H_2O drip

$$\boxed{g_5 = (1-b_2)z_1 - g_3 - g_4} \qquad (9.1)$$

where $(1-b_2)z_1$ = rain intercepted by canopy (see 1.3)

g_3 = input to foliage of rain - (see 1.1)

g_4 = rain increment to non-foliar canopy - (see 5.1)

c: everything intercepted by the canopy and not staying there drips out of the canopy.

F(2,6) - snow melt

$$F(2,5) = g_{10} \qquad (10)$$

---

g_{10} - snow melt

$$\boxed{g_{10} = \min \begin{cases} g_9 \\ -x_2 + 254z_8 - z_1 \end{cases}} \qquad (10.1)$$

g_9 = potential snow melt (see 10.2)

$x_2 + z_8 - z_1$ = total snow [see (2)]

x_2 = snow storage

c: snow melt is equal to potential snow melt unless all snow is depleted.

g_9 - potential snow melt

$$g_9 = \max \begin{cases} z_3(b_{73}\text{RAD} & + b_{74}(b_2 z_1 + g_5) \\ 0 \end{cases} \qquad (10.2)$$

where z_3 = air temperature (data)

$b_2 z_1 + g_5$ = water drop on snow (see 1.3 and 9.1)

RAD = monthly data record of effect of radiation on snow melt. RAD is high in the winter and low in the summer - it is based on information by Eggleston et al (1971).

b_{73} = influence of RAD on snow melt per °C = 457 m^3/°C

b_{74} = influence of waterfall on snow melt = 0.025

c: the 454 is to convert inches/ha to m^3/ha and °F to °C.

The RAD function maybe backwards - it may be too high in the winter and too low in the spring. Also it appears to potential snow melt from RAD is much too high. (RAD is in the range of 5.18-0.61). There is no factor in this for the amount of snow. Perhaps RAD being high in the winter is a factor assuming snow presence in water. Remember, RAD only is effective only when temperatures are above freezing. The relationship is from Riley and Shih (1972).

F(6,7) - flow into litter layer

$F(6,7) = g_{13}$ (11)

---

g_{13} - flow into litter layer

$$g_{13} = \min \begin{cases} g_{11} \\ b_{15} + b_{23}x_{19} - x_7 - x_3 + g_{22} \end{cases} \quad (11.1)$$

where g_{11} = potential infiltration (see 11.2)

b_{15} = soil H_2O storage capacity = 3445 m /ha

b_{23} = litter H_2O storage capacity as a fraction of litter dry wt (x_{19}) = 2.3

x_7 = litter H_2O

x_3 = soil H_2O

g_{22} = litter evaporation (see 8.1)

c: litter inflow is equal to potential infiltration unless that is so large as to overflow both soil and litter capacity and litter evaporation in which case soil and litter are filled to capacity. Coefficients are from Cromack and Fogel (pers. comm.)

g_{11} - potential litter infiltration (11.2)

$$g_{11} = g_5 + g_{10} + b_2z_1$$

where g_5 = canopy drip (see 9.1)

g_{10} = snow melt (see 10.1)

b_2z_1 = water direct to forest floor (see 1.3)

F(7,3) - infiltration to soil

$$F(7,3) = g_{15} \tag{12}$$

---

g_{15} - infiltration to soil

$$g_{15} = \begin{cases} \min\{g_{13}, b_{15} - x_3\} & \text{if } x_7 - g_{22} > b_{24}x_{19} \\ \max\{0, x_7 + g_{13} - b_{24}x_{19} - g_{22}\} & \text{if } x_7 - g_{22} < b_{24}x_{19} \end{cases} \tag{12.1}$$

where x_7 = litter H_2O

g_{13} = litter inflow (see 11.1)

x_3 = soil H_2O

b_{15} = soil H_2O storage capacity = 5608 m^3/ha

b_{24} = litter H_2O holding capacity as a fraction of litter dry wt = 0.82

x_{19} = litter dry wt

g_{22} = litter evaporation (see 8.1)

c: when litter H_2O is above holding capacity all water coming in flows through unless soil is saturated (then it runs off). If litter is below holding capacity then it fills to holding capacity and the rest goes into the soil. Coefficients are from Cromack and Fogel (pers. comm.)

F(3,S) transpiration

$$F(3,S) = g_{20} \tag{13}$$

---

g_{20} - transpiration rate

$$g_{20} = \begin{cases} g_6 - g_7 - g_8 & \text{if } x_3 > b_{18} \\ \dfrac{(g_6-g_7-g_8)(x_3-b_{17})}{b_{18} - b_{17}} & \text{if } b_{17} \leq x_3 \leq b_{18} \\ 0 & x_3 < b_{17} \end{cases} \tag{13.1}$$

where g_6 = adjusted P.E.T. (see 6.2)

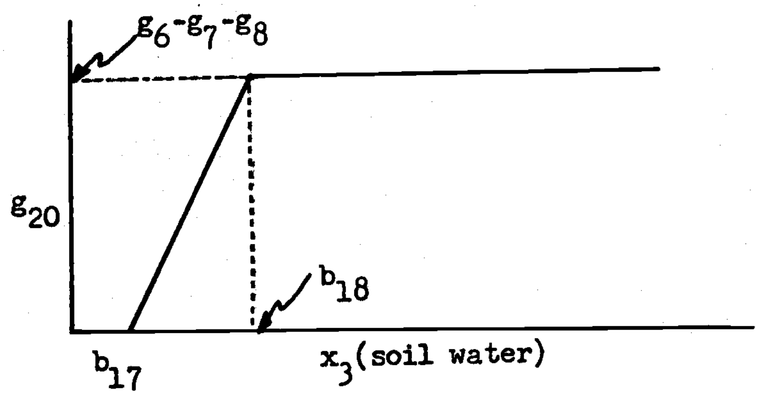
g_7 = foliage evaporation rate (see 6.1)

g_8 = non-foliar evaporation (see 7.1)

b_{17} = soil H_2O wilting pt = 1117 m^3/ha

b_{18} = transpiration resistance pt = 1288. m^3/ha

x_3 = soil H_2O



c: All P.E.T. not evaporated in canopy is transpired if soil H_2O is greater than resistance pt and none is if it is less than wilting pt.

F(3,4) - percolation to ground H_2O

$$F(3,4) = g_{12} \quad (14)$$

---

g_{12} - percolation to ground H_2O

$$g_{12} = \max \begin{cases} (1 - \exp(-b_9)(x_3 - b_{13} + b_{19} g_{15}) \\ 0 \end{cases} \quad (14.1)$$

where b_9 = soil H_2O flow rate = 2.16/day

x_3 = soil H_2O

b_{13} = soil H_2O retention capacity = 3204 m^3/ha

b_{19} = resident time for infiltration = 0.5

g_{15} = flow into soil (see 12.1)

c: percolation proceeds at rate b_9 on soil H_2O above retention capacity b_{13} with b_{19} of what comes in also available to percolate out - this is the significance of residence time - it relates to how much of incoming infiltration is available (per time step) to percolate out.

F(4,5) - ground H_2O lateral flow

$$F(4,5) = g_{17} \qquad (15)$$

---

g_{17} - ground H_2O lateral flow

$$g_{17} = \max \begin{cases} 0 \\ (1-e^{-b_{10}})[(x_4-b_{14}) + b_{20}g_{12} + b_{22}(b_{20}g_{12}-g_{16})] \end{cases} \qquad (15.1)$$

b_{10} = ground H_2O lateral flow rate = 1.08/day

x_4 = ground H_2O

b_{14} = ground H_2O retention capacity = 9970 m^3/ha

g_{12} = percolation rate (see 14.1)

b_{20} = resident time for percolation = 0.5

b_{22} = spatial weighting factor = 0.5

g_{16} = lag effect of percolation on ground H_2O lateral flow (see 15.2) c: ground H_2O flows out at a (continuous) rate b_{10} operating on the water over retention capacity (b_{14}) plus a part of the percolation in (b_{20}). Another part of the percolation is also available subject to spatial weighting factor b_{22} but the rate is slowed by a lag factor g_{16} (see 15.2). This function is from Overton & White (1974) adapted from Riley & Shih (1972).

---

g_{16} - lag effect of percolation on ground H_2O lateral flow

$$g_{16}(K) = b_{20}\, b_{22}\, g_{12} + b_{22}\, g_{16}(K-1) - g_{16}(K-1) \qquad (15.2)$$

where g_{12} = percolation rate (see 15.1)

b_{20} and b_{22} are resident time and spatial factor (see 15.1)

c: The lag effect is directly proportional to the percolation rate. Basically $b_{20}\, b_{22}$ (resident time x spatial factor) or percolation go into the lag effect at time K which then retains b_{22} of the previous times lag effect. It acts as a smoothing effect on large perturbations to ground H_2O.

F(4,3) - ground H_2O resistance

$$F(4,3) = g_{18} \quad (16)$$

---

g_{18} - ground H_2O resistance (capillary) flow upward

$$g_{18} = \max \begin{cases} x_4 + g_{12} - g_{17} - b_{16} \\ 0 \end{cases} \quad (16.1)$$

x_4 = ground H_2O

g_{12} = percolation (see 14.1)

g_{17} = ground H_2O lateral flow (see 15.1)

b_{16} = ground H_2O storage capacity = 11896 m^3 ha^{-1}

c: ground H_2O above storage capacity after lateral flow moves upward.
(From Overton & White (1974))

F,(3,5) - soil water lateral flow

$$F(3,5) = g_{19} \quad (17)$$

g_{19} - soil H_2O lateral flow

$$g_{19} = \begin{cases} g_{18} & \text{if } g_{18} < g_{12} \\ g_{12} + b_{21}\ (1-e^{-b_9})(g_{18}-g_{12}) & \text{if } g_{18} < g_{12} \end{cases} \qquad (17.1)$$

where

g_{12} = percolation (see 14.1)

g_{18} = ground H_2O resistance (see 16.1)

b_9 = soil H_2O (low rate (see 14.1)

b_{21} = resident time for resistance = 0.5

c: if net flow is down lateral flow = resistance, if net flow is up lateral flow = percolation + difference between resistance and percolation weighted by a resident time for resistance. The percolation part of resistance is subject to no resident time on lateral flow because in fact no net percolation actually occurred. (From Overton & White (1974))

F(6,5) - surface runoff

$$F(6,5) = g_{21} \qquad (18)$$

g_{11} - surface runoff

$$g_{21} = \max \begin{cases} 0 \\ g_{11} - g_{13} \end{cases} \qquad (18.1)$$

x_3 = soil H_2O

b_{15} = soil H_2O capacity

b_{23} = litter capacity as percentage dry weight

g_{11} = potential infiltration

g_{12} = percolation

g_{18} = ground H_2O resistance

g_{19} = soil H_2O lateral flow

g_{20} = transpiration

c: after all soil and litter needs are taken out the excess flows off as surface runoff.

F(5,99) - stream flow

$$F(5,99) = x_5$$

c: all H_2O in stream flows out of system in one day

$F(S,64)$ - net daytime photosynthesis input to N.L. CH_2O pool

$$F(S,64) = g_{24} \qquad (20)$$

---

g_{24} - net daytime new leaf photosynthesis

$$g_{24} = \frac{-b_{32}\, b_{33}\, z_4\, g_{39}\, x_{10}\, g_{41}}{b_{35}(x_{10}+x_{11})\, g_{43}^2} \qquad (20.1)$$

z_4 = daylength (fraction of 24 hours)

g_{39} = temperature effect on photosynthesis(see 20.2)

x_{10} = new leaf carbon

g_{41} = light-biomass effect on photosynthesis (see 20.3)

x_{11} = O.L. carbon

g_{43} = new foliage resistance (see 20.4)

b_{33} = maximum photosynthesis rate = 0.4661 t ha^{-1} wk^{-1}
(based on cuvette data)

b_{35} = light extinction coefficient = 0.4605 ly min^{-1} [assumes 5% light penetration and exponential attenuation with total leaf biomass (x_{10} = x_{11})]

b_{32} = factor to make annual field budget accurate = 121.6
(includes factor of 40 because of resistance effect)

c: photosynthesis directly proportional to fraction of total leaves comprised of new leaves. The minus sign is because g_{41} is negative.

g_{39} = temperature effect on photosynthesis

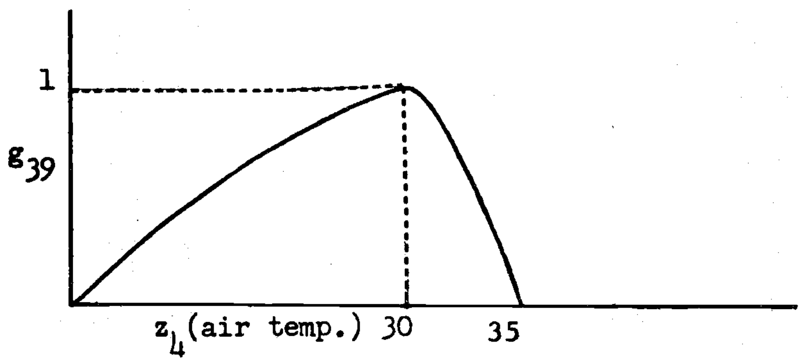
$$g_{39} = \max \begin{cases} b_{36}\, z_4 (b_{76} - z_4)^{(b_{77}-1)} \\ 0 \end{cases} \qquad (20.2)$$

b_{76} = temperature above which photosynthesis is zero = 35°C

z_4 = an temperature - weekly average - data

b_{36} = air temperature factor chosen so that g_{39} = 1 at 30°C (based on Dinger cuvette data (1971)) = 0.01541

b_{77} = coefficient determining shape of curve = 1.35



g_{41} - light-biomass effect on photosynthesis

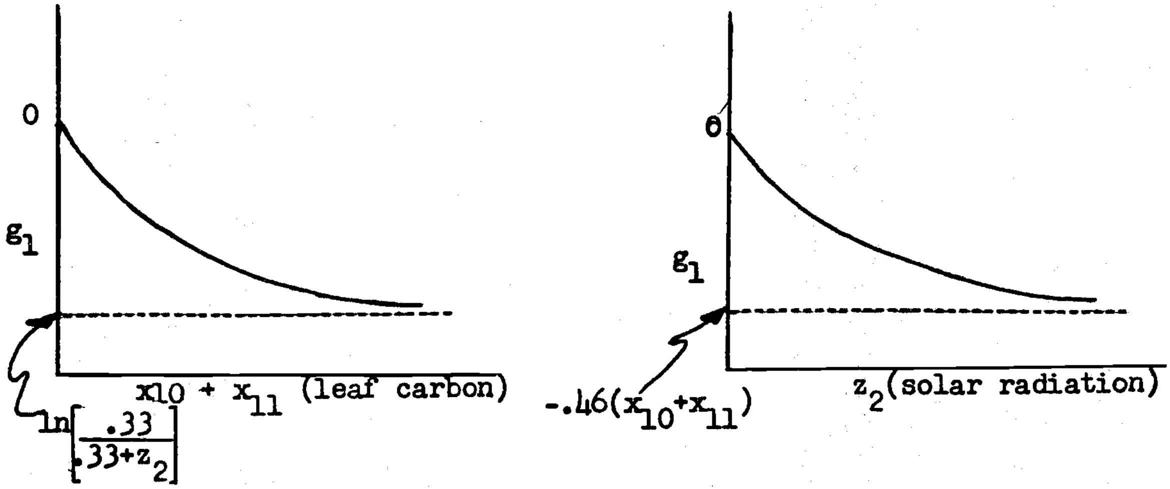
$$g_{41} = \ln \left[\frac{b_{34} + z_2\, e^{-b_{35}(x_{10}+x_{11})}}{b_{34} + z_2} \right] \qquad (20.3)$$

z_2 = solar radiation (ly min^{-1}- average for week) - data

$x_{10} + x_{11}$ = total leaf biomass

b_{34} = light intensity at which N.L. photosynthesis is 1/2 maximum rate. Based on cuvette data = 0.327 ly min^{-1} (Dinger (1971)).

b_{35} = light extinction coefficient with biomass (see 20.1)



c: z_2 range is 0.1 - 0.7

---

g_{43} - new foliage resistance (see cm^{-1})

$$g_{43} = \begin{cases} b_{88}\, e^{b_{89} g_{42}} & \text{if } g_{42} \leq b_{87} \\ b_{86} & \text{if } g_{42} > b_{87} \end{cases} \qquad (20.4)$$

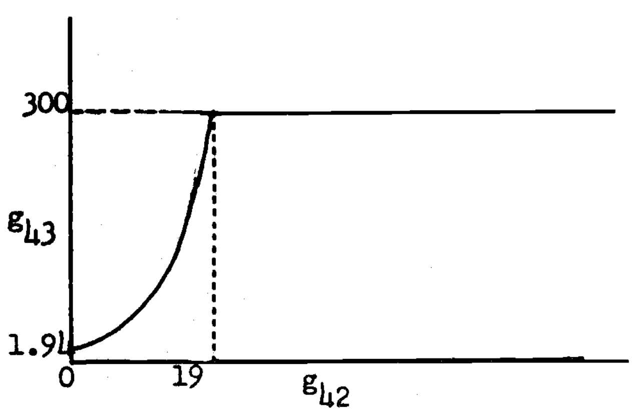
g_{42} = plant moisture stress (atm) (see 20.5).

b_{87} = moisture stress above which there is no increase in leaf resistance = 19 atm

b_{86} = leaf resistance above 19 atm = 300 sec cm^{-1}

b_{88} = leaf resistance coefficient = 1.9435 atm chosen so that g_{43} = 300 at 19 atm moisture stress)

b_{89} = coefficient showing effect of moisture stress on leaf resistance = 0.265 atm^{-1}



c: based on Running's (1973) data in Waring et al (1973).

---

g_{42} - plant moisture stress

$$g_{42} = \begin{cases} b_{84} - \dfrac{b_{85}x_3}{b_{15}} & \text{if } \dfrac{x_3}{b_{15}} \leq b_{83} \text{ and } z_6 \geq b_{79} \\ b_{78} & \text{if } \dfrac{x_3}{b_{15}} > b_{83} \text{ and } z_6 \geq b_{79} \\ -b_{80}z_6 + b_{81} & \text{if } z_6 < b_{79} \end{cases} \quad (20.5)$$

z_6 = soil temperature (weekly average - °C)

x_3 = soil root zone H_2O $-m^3\ ha^{-1}$

b_{15} = field capacity of soil H_2O (see 11.1)

b_{83} = fraction of fieldcapacity below which moisture stress begins = 0.2

b_{79} = soil temperature below which temperature rather than moisture controls plant stress = 6°C

b_{84} = maximum stress at X_3 = 0) = 32.7 (atm)

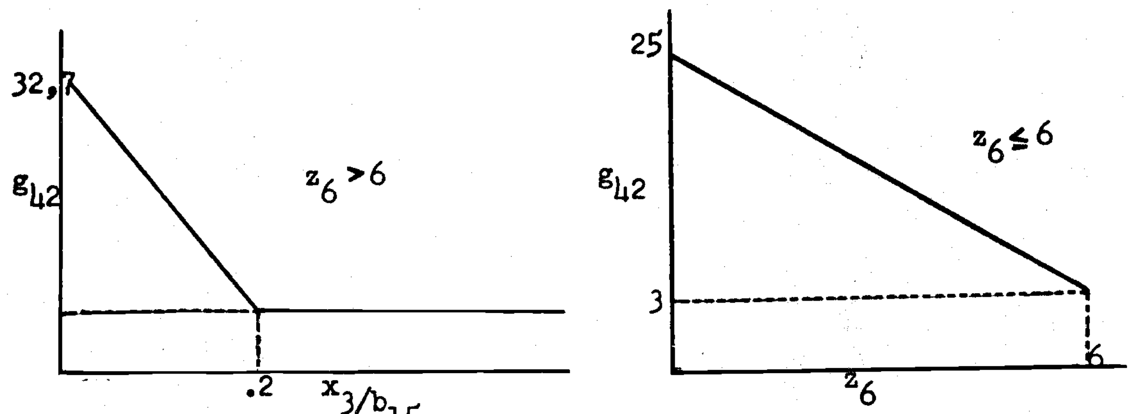
b_{85} = moisture effect on stress = 140atm

b_{78} = minimum stress at temperatures above 6°C = 4.7 (atm)

b_{81} = moisture stress at 0°C = 25 atm

b_{80} = effect of temperature on stress below 6°C = 3.85(atm day^{-1})

c: based on Waring et al. (1973)



F(64,99) - new leaf respiration

$$F(64,99) = g_{25} \quad (21)$$

$$g_{25} = \frac{b_{26}(1-z_4)g_{39}x_{10}}{g_{43}^2} \quad (21.1)$$

z_4 = day length

g_{39} = temperature function (see 20.2)

x_{10} = N.L. carbon

g_{43} = N.L. resistance (see 20.4)

b_{26} = maximum nighttime respiration = 3.18 wk^{-1} obtained by fitting curve to output from Reed (1973) cuvette CO_2 exchange model.

F(64,10) - transfer to new leaves from N.L. CH_2O pool.

$F(64,10) = g_{26}$

$$g_{26} = \begin{cases} g_{45} + g_{47} & \text{if } 0 < g_{45} + g_{47} < g_{46} \\ g_{46} & \text{if } g_{45} + g_{47} \geq g_{46} \\ 0 & g_{45} + g_{47} \leq 0 \end{cases} \quad (22.1)$$

g_{45} = CH_2O pool available for respiration and growth (see 22.2)

g_{46} = new leaf growth demand (see 22.3)

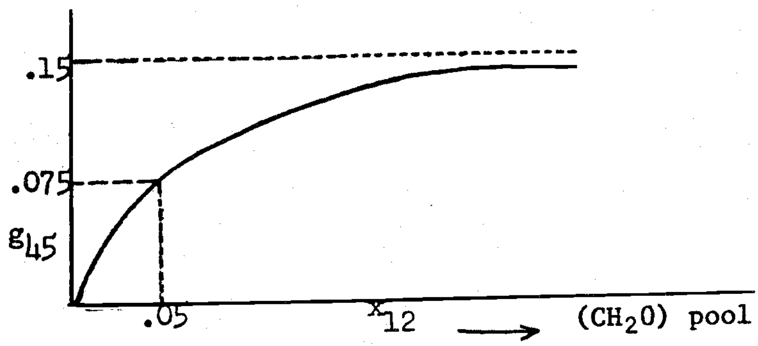
g_{47} = surplus (or deficit) photosynthate after N.L. respiration satisfied (see 22.4)

c: If there is a net deficit of photosynthate (N.L. plus old CH_2O pool) there is no transfer to new leaves. If the surplus is less than the growth demand then it is transferred to N. L. to try to meet it. If it is greater than growth demand only the demand (g_{46}) goes to N.L.--the rest goes to CH_2O pool.

g_{45} - CH_2O pool available for respiration and growth

$$g_{45} = \frac{b_{39} x_{12}}{b_{40} + x_{12}} \qquad (22.2)$$

x_{12} = CH_2O pool carbon



c: Not all of CH_2O pool is available to new leaves. Normal range of x_{12} is 8-12 t ha^{-1} (near maximum range of g_{45}).

b_{39} = maximum amount of CH_2O pool available = 0.15 t $ha^{-1}wk^{-1}$

b_{40} = CH_2O pool value at which half of maximum is allowed = 0.05 t ha^{-1}

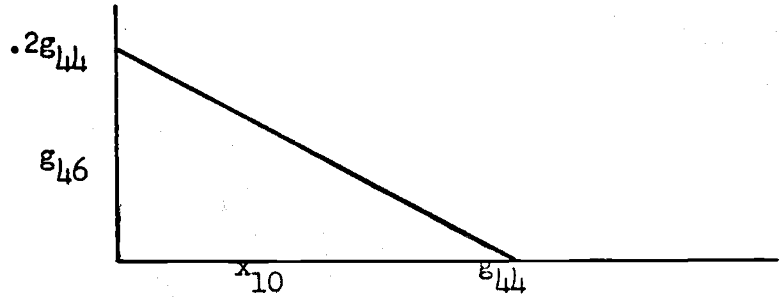
---

g_{46} = new leaf growth demand

$$g_{46} = b_{38}(g_{44} - x_{10}) \qquad (22.3)$$

g_{44} = limit to new leaf growth by previous year's bud growth (see 22.5)

b_{38} = rate at which NL growth demand decreases as NL biomass approaches the limiting value g_{44} is the maximum demand (when $x_{10} = 0$).
$= 0.2\ wk^{-1}$



g_{47} = surplus or deficit photosynthate after satisfying N.L. respiration

$$g_{47} = g_{24} - g_{25} \tag{22.4}$$

g_{24} = new leaf photosynthesis (see 20.1)

g_{25} = new leaf nighttime respiration (see 21.1)

g_{44} = limit to new leaf growth by buds

$$g_{44} = \begin{cases} 0 & 39 < KWK_{mod52} < 18 \\ b_{37}x_{16}(18) - g_{38} & \text{if } b_{37}x_{16}(18) > g_{38} \\ 0 & \text{otherwise} \end{cases} \tag{22.5}$$

$x_{16}(18)$ = bud biomass in week 18

KWK = time in weeks

g_{38} = insect consumption of N.L. (see 22.6)

$b_{37} \approx 120$ - ratio of weight of fully expanded leaf to weight of one bud at week 18.

c: Limit to NL growth -- depends on bud biomass (x_{16}) at week 18 of any given year less any new leaf consumption subsequent to that (g_{38}). b_{37} is ratio of weight of fully expanded leaf to mature bud (at week 18). Function is zero during dormant season (week 0-18, 39-52).

---

g_{38} - insect consumption of new leaves

$$g_{38} = b_{56}\, x_{10}\, g_{39} \qquad (22.6)$$

c: Amount of new leaves consumed by insects. This is a dummy function [depends on temperature function (g_{39}) and NL biomass only] designed solely to cause leaves to disappear in a reasonable seasonal pattern. No insect parameters appear.

b_{56} = consumption rate (5% yr assumed) = 0.005 wk^{-1}

F(10,64) - new leaf transfer to N.L. CH_2O pool (to meet respiration demand if necessary)

$$F(10,64) = g_{27} \tag{23}$$

---

g_{27} - respiration demand

$$g_{27} = \begin{cases} -g_{45}-g_{47} & \text{if} \quad g_{47} < -g_{45} \\ 0 & \text{otherwise} \end{cases} \tag{23.1}$$

g_{45} = CH_2O pool available for respiration and growth (see 22.2)

g_{47} = photosynthate after N.L. respiration demand (may be negative) (see 22.4)

F(64,12) - N.L. CH_2O pool transfer to CH_2O pool (after growth and respiration needs met)

$$F(64,12) = g_{28} \tag{24}$$

---

g_{28} - new leaf CH_2O pool surplus – transfer to O.L. (H_2O) pool.

$$g_{28} = \begin{cases} 0 & \text{if} \quad g_{47} < -g_{45} \\ g_{47} & \text{if} \quad 0 < g_{47} \leq -g_{45} \\ g_{49} & \text{if} \quad g_{47} \geq 0 \end{cases} \tag{24.1}$$

g_{45} = CH_2O pool available for respiration and growth (see 22.2)

g_{47} = N.L. CH_2O left after respiration (see 22.4)
(may be negative)

g_{49} = CH_2O pool transfer if there is surplus N.L. photosynthate
(see 24.2)

c: In case respiration is not met by N.L. photosynthate ($g_{47} < 0$) but can be met by CH_2O pool ($g_7 \leq -g_{45}$), the deficit (g_{47}) is transferred from CH_2O pool to N.L. pool. If it cannot be met ($g_{47} < -g_{45}$) then g_{28} is zero. If there is a surplus after respiration then there will be transfer of g_{49} to CH_2O pool.

---

g_{49} - surplus N.L. photosynthate available after bud growth

$$g_{49} = \begin{cases} 0 & \text{if } g_{47} \leq g_{46} \\ (1-b_{31})(g_{47}-g_{46}) & \text{if } g_{47} > g_{46} \end{cases} \tag{24.2}$$

b_{31} = 0.0124 proportion of NL photosynthate available after NL respiration and growth to be used for bud growth ($g_{47} - g_{46}$)

$g_{47} - g_{46}$ = surplus of N.L. photosynthate after respiration and growth demand (if $g_{47} > g_{46}$) (see 22.4 and 22.3)

c: ($1 - b_{31}$) is the fraction not used for bud growth and hence is available for transfer to CH_2O pool.

F(99,12) = total old leaf photosynthesis (input to CH_2O pool)

$$F(99,12) = g_{29} \tag{25}$$

$$g_{29} = \frac{-b_{55} b_{41} z_4 g_{39} x_{11} g_{51}}{b_{35}(x_{10}+x_{11}) g_{52}^2} \tag{25.1}$$

z_4 = weekly average day length

g_{39} = temperature effect (see 20.2)

x_{11} = O.L. biomass

x_{10} = N.L. biomass

g_{51} = light-biomass effect on O.L. photosynthesis (see 25.2)

g_{52} = old leaf resistance (see 25.3)

b_{41} = maximum rate of O.L. photosynthesis based on cuvette data

b_{35} = light extinction coefficient (see 20.1)

b_{55} = 1984.0 old leaf photosynthesis fudge factor (includes factor of 16 because of stomatal resistance effect).

c: This is analogous to new leaf photosynthesis.

---

g_{51} - light biomass effect on O.L. photosynthesis

$$g_{51} = \ln \left[\frac{b_{42} + z_2 e^{-b_{35}(x_{10}+x_{11})}}{b_{42} + z_2} \right] \qquad (25.2)$$

z_2 = light input

b_{42} = light value at which photosynthesis is 1/2 maximum = 0.2 ly min^{-1}

g_{51} is negative and is analogous to g_{41} (see 20.3 for curves).

g_{52} - old leaf resistance

$$g_{52} = b_{60} g_{43} \tag{25.3}$$

g_{43} = new leaf resistance (see 20.4)

b_{60} = ratio of old to new leaf resistance = 4.0 (based on guess by R.H. Waring)

$F(12,S)$ - total plant live part respiration outside of new leaves

$$F(12,S) = g_{30} + g_{31} \tag{26}$$

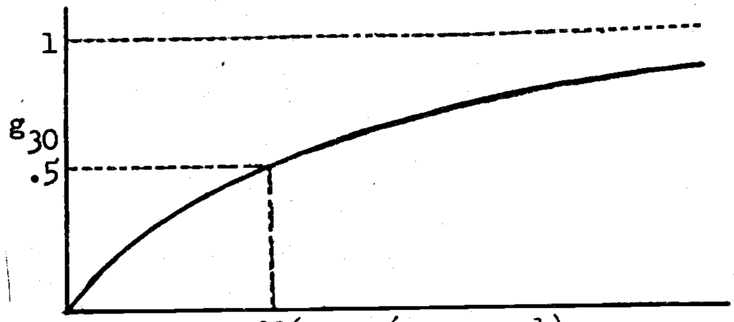
g_{30} = old leaf respiration (see 26.1)

g_{31} = total non-foliar respiration (see 26.2)

$$g_{30} = \frac{b_{27}(1-z_4) g_{39} x_{11} x_{12}}{g_{52}^2 (b_{44}+x_{12})} \tag{26.1}$$

b_{27} = maximum respiration rate from cuvette data = 25.072 [also from Reed ( ) model]

b_{44} = CH_2O pool size (x_{12}) at which respiration is half maximum = 0.026. This is chosen small so that pool size does not normally affect respiration rate



g_{52} = old leaf resistance (see 25.3)

g_{39} = temperature effect (see 20.2)

z_4 = daylength

c: Different from N.L. respiration in involvement with CH_2O pool (even though the effect is minimized). While new leaf has its own CH2O pool, old leaf does not and so surplus photosynthesis goes automatically to CH2O pool. There is no transfer to buds from old leaves.

g_{31} - total non-foliar respiration

$$\boxed{g_{31} = b_{28}g_{35} + b_{29}g_{36} + b_{30}g_{37}} \tag{26.2}$$

g_{35} = transfer to stems (see 26.3)

g_{36} = transfer to large roots (see 26.4)

g_{37} = transfer to fine roots (see 26.5)

c: These transfers account for growth and mortality only and not respiration. Respiration comes directly from the CH_2O pool.

b_{28} = ratio of respiration of stems to transfer to them (where transfer = growth + mortality) = 3.625 (based on Kira 1968)

b_{29} = ratio of large root respiration to transfer to them = 17.0 (assumes large roots and branches respire at same rate)

b_{30} = ratio of fine root respiration to transfer (mortality assumed 50%/yr) = 1.97 (Oak Ridge data).

c: respiration proportional to growth plus mortality

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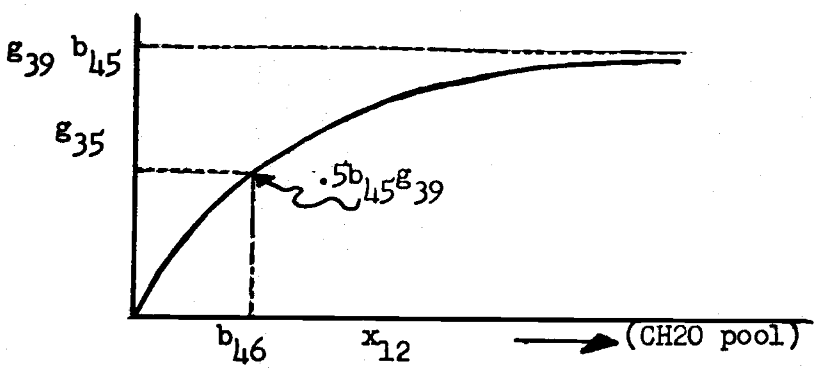
g_{35} - transfer to stems

$$g_{35} = \frac{b_{45} g_{39} x_{12}}{b_{46} + x_{12}} \tag{26.3}$$



b_{45} = maximum transfer rate = 0.044

b_{46} = CH_2O pool for half maximum transfer = 4.0 t ha^{-1}

g_{39} = temperature effect (see 20.2)

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g_{36} - transfer to large roots

$$g_{36} = \frac{b_{47} g_{53} x_{12}}{b_{48} + x_{12}} \tag{26.4}$$

b_{47} = maximum rate = 0.00505 t ha^{-1} wk^{-1}

b_{48} = half maximum CH_2O value = 4.0 t ha^{-1}

g_{53} = soil temperature effect on transfer and other soil processes. (see 26.6)

c: analogous to g_{35} (see 26.3 for curve)

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g_{37} = transfer to fine roots

$$g_{37} = \frac{b_{49} g_{53} x_{12}}{b_{50} + x_{12}} \tag{26.5}$$

b_{49} = 0.129 (maximum rate) t ha^{-1} wk^{-1}

b_{50} = 0.0259tt ha^{-1} - value at which transfer is 1/2 maximum - small value implies g_{37} is near maximum for smaller values of x_{12}. This gives transfer to fine roots precedence over other transfers when CH_2O pool is low.

g_{53} = soil temperature effect (see 26.6)

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g_{53} - soil temperature effect on soil processes

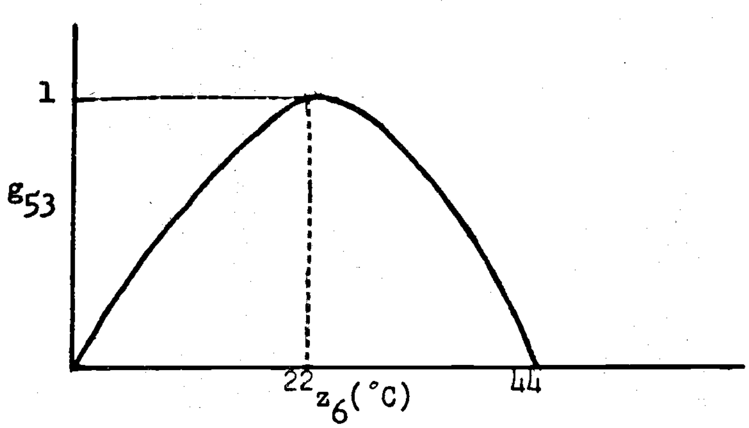
$$g_{53} = \begin{cases} b_{54} z_6 (b_{76} - z_6)^{b_{77}-1} & \text{if } b_{76} > z_6 \geq 0 \\ 0 & \text{if } b_{76} \leq z_6 \text{ or } z_6 < 0 \end{cases} \qquad (26.6)$$

z_6 = soil temperature (computed from litter temperature and previous time soil temperature).

b_{54} = temperature factor chosen so that g_{50} = 1 at z_6 = 22°C (Edwards root respiration data - ORNL) = 0.01541

b_{76} = temperature above which g_{50} = 0 = 44°C

b_{77} = shape of curve coefficient = 1.35



F(64,16) - bud growth

$$F(64,16) = g_{33} \tag{27}$$

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g_{33} - bud growth

$$\boxed{g_{33} = g_{31}g_{49}} \tag{27.1}$$

b_{31} = fraction of surplus photosynthate used for bud growth (see 24.2)

g_{49} = surplus photosynthate (see 24.2) available for bud growth

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F(12,64) - CH_2O pool transfer to N.L. CH_2O pool to meet respiration and growth demands

$$F(12,64) = g_{32} \tag{28}$$

$$g_{32} = \begin{cases} g_{46} & \text{if} \quad g_{46} \leq g_{47} + g_{45} \text{ and } g_{47} \leq 0 \\ g_{45} + g_{47} & \text{if} \quad g_{46} > g_{47} + g_{45} \ \& \ g_{47} \leq 0 \\ g_{45} & \text{if } g_{47} \leq -g_{45} \text{ or } g_{47} > 0 \text{ and } g_{46} - g_{47} > g_{45} \\ g_{46} - g_{47} & \text{if} \quad g_{47} > 0 \text{ and } g_{46} - g_{47} \leq g_{45} \\ 0 & \text{if} \quad g_{46} \leq g_{47} > 0 \end{cases} \qquad (28.1)$$

where

g_{32} = CH_2O pool transfer to N.L. CH_2O pool to meet respiration and growth demands

g_{46} = N.L. growth demand (see 22.3)

g_{45} = CH_2O pool available for respiration and growth demand (see 22.2)

g_{47} = surplus or deficit photosynthate after N.L. respiration satisfied (see 22.4)

c: <u>case 1</u> - if there is a deficit after respiration and CH_2O available minus deficit - is greater than growth demand. Then entire growth demand is met.

<u>case 2</u> - if there is a deficit after respiration but the CH_2O available minus deficit is less than growth demand then only available minus deficit flows to meet growth demand.

<u>case 3</u> - if deficit after respiration greater than CH_2O pool all available CH_2O flows (to satisfy respiration) or if there is a surplus but the growth demand minus the surplus is greater than the CH_2O available all CH_2O flows (to partially satisfy growth)

case 4 - If there is a surplus and growth demand minus surplus is less than CH_2O available the growth demand minus surplus will flow to completely satisfy growth demand.

case 5 - If there is a surplus and it is larger than the growth demand then no CH_2O is needed to flow to satisfy new leaf growth.

F(10,11) - maturation of new leaves

$$F(10,11) = g_{34} \tag{29}$$

$$g_{34} = \begin{cases} x_{10} + g_{26} - g_{27} - g_{38} & \text{if } t \bmod 52 = 40 \\ 0 & \text{otherwise} \end{cases} \tag{29.1}$$

x_{10} = new leaf carbon

g_{26} = new leaf growth (see 22.1)

g_{27} = new leaf respiration (see 23.1)

g_{38} = new leaf consumption (see 22.6)

c: all new leaf material matures to old leaves at week 40 (growth minus losses for that week are included).

F(16,10) - leafing of buds

$$F(16,10) = \begin{cases} x_{16} - b_{59}x_{16}g_{39} & \text{if } t \bmod 52 = 18 \\ 0 & \text{otherwise} \end{cases} \tag{30}$$

c: buds leaf at week 18.

$F(12,13)$ = transfer to stems

$F(12,13) = g_{35}$ (see 26.3) (31)

$F(12,14)$ = transfer to large roots

$F(12,14) = g_{36}$ (see 26.4) (32)

$F(12,15)$ = transfer to fine roots

$F(12,15) = g_{37}$ (see 26.5) (33)

$F(10,17)$ = insect consumption of new leaves

$F(10,17) = g_{38}$ (see 22.6) (34)

$F(11,17)$ = insect consumption of old leaves

$F(11,17) = b_{57}x_{11}g_{39}$ (35)

where

b_{57} = insect consumption rate = 0.0001 wk^{-1}

x_{11} = old leaf carbon

g_{39} = temperature effect (for photosynthesis) (see 20.2)

$F(12,17)$ = CH_2O pool consumption

$$F(12,17) = b_{58}x_{12}g_{39} \quad (36)$$

where

b_{58} = CH_2O pool consumption rate = 0.0001 wk^{-1}

x_{12} = CH_2O pool carbon

g_{39} = temperature effect (see 20.2)

$F(16,17)$ = bud consumption

$$F(16,17) = b_{59}x_{16}g_{39} \quad (37)$$

where

b_{59} = consumption rate = 0.0001 wk^{-1}

x_{16} = bud carbon

g_{39} = temperature effect (see 20.2)

c: temperature effect is to make consumption seasonally varying

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$F(11,19)$ - old leaf mortality

$$F(11,19) = g_{40}x_{11} \quad (38)$$

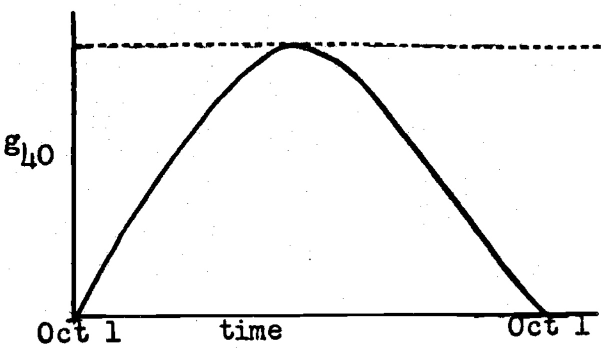
where

x_{11} = leaf carbon

g_{40} = leaf fall phenology function (see 38.1)

g_{40} = leaf fall phenology function

$$g_{40} = \begin{cases} b_{43}(t_{mod52}-(b_{90}-52))(b_{90}-t_{mod52})^{b_{91}-1} & \text{if } t_{mod52} \le b_{90} \\ b_{43}(t_{mod52}-b_{90})(b_{90}+52-t_{mod52})^{b_{91}-1} & \text{if } t_{mod52} > b_{90} \end{cases} \quad (38.1)$$



Dimensionless function giving the distribution of leaf fall through time. The area under the curve is 1.0 (all the leaves that are to fall in one year thus do so). The purpose of the IF statements is to have the pattern repeat each year. The first year Jan 1 is week 0 (K=0), the start time is -17 (Oct 1 of the previous year), and the finish time is 35 (Oct 1 of the current year). For the second year 52 is added to each.

b_{43} = factor so that area under curve integrated over 1 year is 1 (all leaves fall in one year) = 3.444×10^{-13}

b_{90} = 35 – week that leaf fall pattern begins

b_{91} = dimensionless coefficient to determine shape of the curve = 13.0

F(14,62) - large root mortality

$$F(14,62) = b_{52}x_{14} \tag{39}$$

x_{14} = large root biomass

b_{52} = mortality rate = 0.00011 wk^{-1}

c: constant mortality rate over the year

F(15,62) - fine root mortality

$$F(15,62) = b_{53}x_{15} \tag{40}$$

x_{15} = fine root carbon

b_{53} = mortality rate = 0.00966 wk^{-1}

F(17,20) = insect frass flow

$$F(17,20) = b_{75} \text{ (constant)} \tag{41}$$

b_{75} = 0.003 t ha^{-1} wk^{-1} (based on Strand's estimate for W-10)

c: Will be changed to function based on insect biomass, temp., etc.

$F(18,20)$ = woody litter decomposition

$$F(18,20) = b_{61} g_{50} x_{18} \qquad (42)$$

x_{18} = woody litter carbon

b_{61} = maximum decomposition rate = 0.0065 wk^{-1}

g_{50} = combined moisture-temperature effect for rooting zone processes (see 42.1)

$$\boxed{g_{50} = \left(\frac{x_3}{b_{67}}\right) g_{53}} \qquad (42.1)$$

g_{53} = soil temperature effect on rooting zone processes (see 26.6)

b_{67} = soil H_2O at which effect is 1.0 = 2600 ($m^3\ ha^{-1}$)

c: decomposition rates increase linearly with increasing soil moisture (x_3)

F(19,20) - leaf litter decomposition

$$F(19,20) = b_{62} g_{50} x_{19} \quad (43)$$

where

x_{19} = leaf litter carbon

b_{62} = maximum decomposition rate = 0.02 wk^{-1}

g_{50} = moisture-temperature effect (see 42.1)

F(20,21) - fine litter decomposition

$$F(20,21) = (1-b_{64}) b_{63} g_{50} x_{20} \quad (44)$$

b_{64} = fraction of decomposition lost to respiration = 0.458

b_{63} = maximum decomposition rate for fine litter = 1.18 wk^{-1}

g_{50} = moisture-temperature effect (see 42.1)

x_{20} = fine litter carbon

F(20,9) - respiration loss from fine litter decomposition

$F(20,9) = b_{64}b_{63}g_{50}x_{20}$ (see 44) (45)

F(62,21) = dead root decomposition

$F(62,21) = b_{68}b_{69}g_{50}x_{62}$ (46)

b_{68} = maximum decomposition rate for dead roots = 0.01533 wk^{-1}

b_{69} = fraction dead roots not lost to respiration = 0.5

g_{50} = moisture temperature effect (see 42.1)

x_{62} = dead root carbon

F(62,9) = dead root decomposition respiration

$F(62,9) = b_{68}(1-b_{69})g_{50}x_{62}$ (see 46) (47)

F(21,22) = root zone organic matter decomposition

$F(21,22) = b_{65}(1-b_{66})g_{50}x_{11}$ (48)

b_{65} = maximum decomposition rate = 0.00222 wk^{-1}

b_{66} = fraction lost to respiration = 0.519

g_{50} = moisture temperature effect (see 42.1)

x_{11} = soil organic matter carbon

F(21,9) - respiration loss from soil organic matter decomposition

$$F(21,9) = b_{65} b_{66} g_{50} x_{21} \text{ (see 48)} \tag{49}$$

F(9,S) - soil CO_2 loss to atmosphere

$$F(9,S) = 0 \tag{50}$$

c: The turnover rate here is very rapid. We have effectively eliminated the soil CO_2 compartment by setting flow out of it to atmosphere to 0.0 and will use rate of production of CO_2 in mineral cycling model.

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